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PUBLIC HEALTH AND SAFETY EFFECTS OF HIGH-VOLTAGE OVERHEAD TRANSMISSION LINES

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AN ANALYSIS FOR THE MINNESOTA ENVIRONMENTAL QUALITY BOARD

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PUBLIC HEALTH AND SAFETY EFFECTS
OF
HIGH-VOLTAGE OVERHEAD TRANSMISSION LINES:

An Analysis for the
Minnesota Environmental Quality Board

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ABSTRACT

The concurrent trends toward extra-high-voltage (EHV) alternating current and high-voltage direct current (HVDC)--a new transmission technology in the United States--have both heightened concern over alleged adverse public health and safety effects of the overhead transmission line electrical environment. In several states, questions have been raised over proposed 500- and 765-kV AC lines; in Minnesota, however, the major concern is with a planned HVDC line and, to a lesser extent, with a 500-kV AC line. Over half of the planned expansion of Minnesota's power transmission system over the next 15 years is a combination of EHV or HVDC transmission; as a result the State should analyze these issues from a regulatory perspective. This report culminates a staff study by the Minnesota Department of Health and is intended to provide such guidance to both the Department and the Minnesota Environmental Quality Board.

This report is concerned with the electric and magnetic field effects of EHV and HVDC transmission lines. To the extent research into HVDC environmental effects exists, a balanced discussion of the two technologies is presented.

All of the fields comprising the transmission line electrical environment are capable of transmitting small amounts of electrical energy to conductive objects--including biological organisms--located with them, by their respective "coupling" mechanisms. This energy transfer is capable of creating a potential shock hazard and is also responsible for alleged, long-term human health impact.

These fields and their coupling mechanisms are described and quantified. Primary and secondary shocks are discussed, with

emphasis on secondary shock thresholds, as such shocks are of principal public concern in the transmission line environment. A summary of the literature on biological effects is provided, concluding with the position that insufficient evidence is available to indict transmission lines as a public health hazard. However, the point is also made that additional research is warranted, and a summary of both industry- and Federal government-sponsored research is included.

The report concludes with a number of recommendations to the State, generally of three types:

1. Performance standards to be applied in future transmission line construction permits.
2. Follow-on research monitoring by the Department.
3. Research that the State may wish to consider sponsoring.

Specifically not recommended is a "generic" public hearing by the Minnesota Environmental Quality Board, due to the apparent inappropriateness of such a forum to assess uncertain scientific issues.

ACKNOWLEDGEMENTS

Compiling this report, even limited as it was to the transmission line field environment, was considerably more difficult than envisioned. The large data base amassed as a result of the Department's official notice soliciting outside opinion (see Appendix D) was particularly useful and as it turns out, indispensible; consequently, special thanks are due to the 100 or so individual and institutional respondents who willingly--and in some cases, enthusiastically--provided us with a wealth of invaluable information, guidance and suggestions.

Needless to say, input from the electric utility industry itself was both necessary and appreciated. Dan McConnon, United Power Association, has over the past year forwarded numerous items of interest on both sides of the issue. Bob Grosshans, Northern States Power Company, provided useful maps showing typical field gradient isopleths for the WTC-500 project, plus a lively discussion of grounding criteria during a recent hearing for a transmission line construction permit. In the process of preparing their report as a voluntary response to our notice, Joe Torri of Commonwealth Associates spent several hours overall on the telephone discussing various facets of transmission line design and construction with us. Karen Ray Brower, formerly of the Electric Power Research Institute, was a very helpful source of information and provided several EPRI reports most willingly on request. Recently, at a visit to Project UHV, Luciano Zaffanella and Mike Comber were extremely hospitable and spent considerable time discussing their various projects, particularly the ERDA contract for characterization of

HVDC ion currents. The same trip included a tour of Ontario Hydro's Demonstration Centre, where Walt Inkis provided worthwhile demonstrations of shock effects in a field environment.

In the government sector, Bill Feero and Doug Boehm, both of the U.S. Energy Research and Development Administration, were most supportive of this project, providing useful information and ideas, as well as soliciting our involvement in their respective programs. We have had an ongoing and worthwhile exchange of information with Dane Westerdahl of California's Energy Resources Conservation and Development Commission. Within the state, the Minnesota Environmental Quality Council's Power Plant Siting Staff was involved throughout the course of the project. Will Kaul was and is maintaining close contact with the New York Public Service Commission Staff regarding its common record hearings. John Hynes, George Durfee and Larry Hartman have willingly discussed policy and critiqued draft portions of this report. The Staff's consultant, Vern Albertson, Professor of Electrical Engineering, University of Minnesota, has reviewed and commented on this material from an engineering perspective.

Also from the University of Minnesota, Otto Schmitt, Professor of Biophysics, Bioengineering and Electrical Engineering, spent two afternoons discussing research in biological effects of electric and magnetic fields, providing a useful perspective. Ed Carstensen, Professor of Electrical Engineering and Director of Biomedical Engineering and Gary Kaufman, Department of Radiation Biology and Biophysics, both of the University of Rochester, spent a morning with us following one of the Dickinson/Willmarth 345-kV AC transmission line hearings, reviewing techniques of assessing uncertain scientific issues.

Finally, of course, is the mainstay of the entire project, Marilyn Scruton, whose capable editing and typing made this report a reality. Marilyn's patience under the myriad revisions to both drafts and would-be finals is most sincerely appreciated.

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I. INTRODUCTION AND OVERVIEW

To support the increasing demand for electrical energy in the United States, the electric utility industry has vastly expanded the size and complexity of its bulk power transmission system in recent years. If its growth is measured in circuit miles, the transmission system is growing at less than half the rate of installed generating capacity. However, there is another variable in the capacity equation: operating voltage, which has also risen markedly. Both factors have resultant environmental effects. While circuit mile growth has always represented land-use impact, voltages have now reached a level where questions are also raised over possible adverse human health impact. These alleged effects result from exposure to the electric and magnetic fields existing in the vicinity of operating overhead aerial transmission lines, the predominant transmission technology employed today.

Minnesota is no stranger to these questions. They have been repeatedly raised during Minnesota Environmental Quality Board (MEQB) hearings under its transmission line routing program. The Minnesota Department of Health (MDH)--an MEQB member agency--with assistance from MEQB's Power Plant Siting Staff, has been formally studying the public health impact of high-voltage overhead transmission lines (HVTLs) since September 1976.

This report, prepared at the request of the MEQB, documents the results of this inquiry for the benefit of both decision makers in State government and Minnesota citizens concerned with the transmission line issue. Generally, it contains: (1) An overview of the current state-of-knowledge with respect to the human health and safety effects of the electric and magnetic fields associated with HVTL operation, and (2) An evaluation of the adequacy of current and anticipated standards to protect the public health and safety and the need for additional performance and/or exposure limitation standards, including an assessment of the ability of current research programs and other efforts to guide development of such standards. For a history of the transmission line issue in Minnesota and elsewhere and of the background of this study, the reader is referred to Appendix C.

To put this report in perspective, it is noted that there are numerous environmental impacts resulting from HVTL construction, maintenance and right-of-way management, but the concern herein is solely with alleged public health hazards of the aforementioned fields. Further, the broader issues of the technical and economic feasibility of alternative generation and transmission technologies and of exponential growth in electrical demand are not examined. The paramount importance of these policy-level questions is acknowledged, and it is hoped that the information provided herein will in some way serve as an impetus toward their resolution.

TRANSMISSION SYSTEMS

An electric power system is comprised of three major subsystems: generation, transmission and distribution. Basically, an alternating-current (AC) transmission system consists of: (1) Overhead aerial transmission lines and underground cables operated at 69,000 volts (69 kV), line-to-line, or higher; (2) Terminal equipment, including transformers, switchgear, lightning arrestors, reactors and capacitors; and (3) Instrumentation, including metering, communications equipment, protective relaying and control systems, necessary to operate and protect the line (*Angland, et al., 1971*). Transmission facilities tie a power system together, allowing remote generating capacity to be available to any load in the system. In addition to the obvious function of point-to-point connection between generator and load center, transmission lines play significant roles in the delivered cost of electricity and in overall system reliability.

Because of various technical and economic factors outlined below, the United States over the past decade has experienced a transmission line construction boom. While contemporary interconnecting lines are long--frequently in excess of 100 miles--transmission line mileage is nonetheless increasing at a lower rate than installed generating capacity. Between 1964 and 1975 for the United States as a whole, the latter rose from 221,567 MW to 505,245 MW, or a 7.78% increase per year, while the transmission system (66 kV and above) increased from 243,913 circuit miles to 352,946 circuit miles or only 3.42% per year (*Anonymous, 1965; Anonymous, 1976a*). Thus the growth rate in generating capacity is more than double that of the nation's transmission system, measured on a circuit mile basis. While the latter is not a total measure of capacity, it is clearly the major parameter of environmental impact.

An individual line's capacity varies approximately as the square of its operating voltage. Consequently, doubling its voltage provides four times the power transfer on essentially the same right-of-way, creating a strong incentive for higher transmission voltages. Trends in transmission voltage over the years are summarized in the Transmission Line Reference Book:

The highest transmission voltage in use in North America . . . was 10 kV in 1892. In 1965 it was 735 kV, when the Hydro-Quebec Electric Commission energized a 365 mile circuit, the first of three parallel lines built to transmit 5,700 MW from remote hydro sites to Quebec and Montreal. This occurred very soon after the first 500 kV lines were energized in the United States and Canada. In 1970 there were 8,000 circuit miles of 500 kV lines with another 1,400 projected to be built in the next decade. In 1971, 22% of the U.S. transmission capability was 500 kV.

The first 765 kV lines in the United States were built for the American Electric Power System. They comprised approximately 1,000 circuit miles of transmission added to an existing network of 138 and 345 kV lines. A NEMA survey indicates that by 1980 15% of the transmission capability in the United States will be 765 kV lines. (Anonymous, 1975b)

Operating voltages in the range from 345 through 765 kV AC are generally considered "extra-high-voltage" (EHV) technology, which is today obviously well within the state-of-the-art. Voltages as high as 2,000 kV are being considered, and extensive research in the 1,000- to 1,500-kV (ultra-high-voltage, "UHV") range is being done by General Electric's Project UHV under contract to the Electric Power Research Institute, with introduction expected in the 1980's. As a general observation, technology enhancements through operating voltage increases have kept transmission line bulk power transfer capacity on a relative par with increases in generating unit size; however, it is expected that transmission capacity will outstrip the latter in the near future.

The Federal Power Commission (FPC) indicates that EHV transmission can assume one or more of the following functions:

1. *Long distance energy transfer from remote generating sources to load centers;*
2. *Interconnections between areas previously isolated from each other, for purposes of achieving economies in the utilization of available generation resources;*
3. *Higher voltage overlay on an existing, well-developed lower voltage system so as to allow such an overlay to take over the major tasks of bulk power transfer within the system and to permit the continued integrated operation of the overall system in an economical and reliable manner. (Angland, et al., 1971)*

While transmission comprises only approximately 17% of the total investment in an electric power system (*Angland, et al., 1971*), the FPC further observes that these functions are critical to successful operation of today's systems:

> *The strategic importance of transmission is much greater than is indicated by its share in the overall cost of electricity. Adequate interconnections where economically justified provide the key to large-scale, low-cost diversity, to the sharing of reserve generating capacity, and to the most efficient utilization of existing generating capacity. In short, interconnection is the coordinating medium that makes possible the most efficient use of facilities in any area or region. (Anonymous, 1975b)*

It should be noted that for these reasons, the Federal Power Act encourages electric power system interconnection (*Anonymous, 1975a*).

In addition to functional capabilities, right-of-way utilization is also enhanced by EHV transmission:

> *Except for limitations such as thermal capacity of conductors and system stability, one 765-kV line has the equivalent load capability of five 345-kV lines or thirty 138-kV lines. Spacewise, a 765-kV line requires only about 200 feet of right-of-way, as compared with about 750 feet needed for five 345-kV lines and about 3,000 feet needed for thirty 138-kV lines. Thus, 765-kV transmission reduces the land requirements for right-of-way of 345-kV transmission by 3.75 times and for 138-kV transmission by 15 times. In many parts of the country, the scarcity of rights-of-way is becoming a compelling argument for EHV transmission. (Angland, et al., 1971)*

Of particular importance in Minnesota is the parallel trend toward high-voltage direct-current (HVDC) transmission of bulk power over extremely long distances (roughly, distances in excess of 400 miles are necessary before this mode becomes economically attractive). This is a recent technological development:

> *Modern HVDC transmission is generally still considered to be in its infancy. The first commercial link, installed between the Swedish mainland and the island of Gotland in 1954, carried only 20 MW. However, between 1960 and 1970, eight additional lines have gone into service with power transfer capabilities ranging from 78 MW to 1,400 MW. EHV*

DC projects with even larger transmission capabilities are now under construction . . . A long overhead DC transmission line (Celilo-Sylmar) has been constructed in the United States (the NW-SW Pacific Intertie). This line is nominally ±400 kV and is 846 miles long. Parameters of this magnitude are required for overhead DC transmission lines, if they are to be economically justified on the basis of the initial cost of their installation. (Angland, et al., 1971)

Minnesota lags--but not far behind--nationwide trends in EHV transmission. Presently the highest AC operating voltage is 345 kV with a 500-kV line from the Twin Cities to the Canadian border, in final planning. However, the State also contains a portion of the second HVDC line in the United States, the MP&L/Minnkota Square Butte ±250-kV line. In planning of course, is the third such line, the CPA/UPA ±400-kV line, from Underwood, North Dakota to Delano, Minnesota (*Anonymous, 1976c*). Overall, Minnesota utilities project construction of 3,914 circuit miles of transmission line rated at 230 kV AC and above and HVDC, in the 15-year period from 1976 to 1990 (*Anonymous, 1976b*):

Operating Voltage	*Approximate Circuit Miles**	*Percent*
230 kV AC	*1,923*	*49.1%*
345 kV AC	*603*	*15.4%*
500 kV AC	*515*	*13.2%*
*±250 kV DC***	*456*	*10.7%*
±400 kV DC	*417*	*11.7%*
	3,914	*100.0%*

**Not all within Minnesota*
***Recently energized*

As is apparent, slightly more than half of the planned growth is EHV or HVDC technology.

ELECTRICAL ENVIRONMENTAL EFFECTS

To reiterate, there are numerous environmental effects resulting from the construction, operation, maintenance and right-of-way management of HVTLs. Of these, the electrical phenomena associated with HVTL operation are unique to the transmission line environment and as a result, are of particular interest. These fall into two general categories--corona and field effects--which are briefly described in the following paragraphs and in further detail in Appendix B and Chapter II, respectively. Neither was considered a major problem until the commercial introduction of EHV technology with 345-kV transmission in the 1950's. At that time, audible noise started to become of concern; today, it may well be the major design constraint in the trend toward higher operating voltages. Generally, these phenomena in and of themselves (as distinct from their impact) are well understood theoretically, and through good design practice the electric utility industry can mitigate them, although not eliminate them entirely within economic constraints.

A. Corona Effects. Corona occurs at the surface of conductors and related hardware when the electric field strength intensity exceeds the breakdown strength of air. When this occurs, sufficient energy is imparted to charged particles to ionize the surrounding air. Corona generally occurs at irregularities (nicks, scrapes or concentrations of insects) on the conductor surface, where field gradients are at their maximum. Corona effects include:

1. Audible noise, characterized as a hissing or cracking sound, with a 120-hertz hum (AC transmission) occasionally superimposed;
2. Electromagnetic interference, commonly known as static, which can disrupt AM radio and television reception in areas of marginal reception;

3. Production of ozone and nitrous oxides in the air surrounding the conductor;
4. Occasional visible light; and
5. Conductor vibration.

All of these effects represent energy losses which must be supplied by generation, but are highly variable dependent upon ambient conditions (weather). Corona has been studied for many years, with basic laws formulated for over half a century. Sufficient knowledge is available to minimize corona effects through engineering design and maintenance.

B. Field Effects. An operating high-voltage overhead transmission line has associated electric, magnetic and space-charge fields, all of which are capable--through their respective "coupling" mechanisms--of inducing static charges and/or currents in nearby conductive objects, including biological organisms. Of these, the electric field is of predominant concern with AC transmission under steady-state operation; similarly, for DC transmission, the space-charge field is the major effect. With respect to public health and safety, the only magnetic field of major concern is that associated with a line-to-ground fault (e.g., a short circuit resulting from conductor breakage with earth contact) and then, only under certain low-probability conditions.

The electric field (sometimes termed "electrostatic field" in the literature) gives rise to capacitive coupling with conductive objects located within it. The field is present whenever the line is electrically energized, and its strength is a function of line geometry and operating voltage.

The principal known problem is with large metallic conductive objects, such as farm equipment, vehicles, structures with large metal components, wire fences, etc. If such an object is not adequately grounded when a person comes in contact with it, a current can flow through this connection to ground; e.g., through the body and contact electrical resistance. This is not generally regarded as a problem for lines operating at 230 kV AC or below or for HVDC lines. In the EHV range, however, electric field effects become a definite design consideration, where large ungrounded objects can produce annoying shocks.

The magnetic field (or "magnetostatic field") on the other hand, is a function of the current carried by the line. Since the trend toward higher operating voltages does not have a concurrent trend toward higher currents, the body of experience that has evolved over the years in mitigative measures to counteract the effects of inductive coupling with conductive objects located within the field--such as by redundant grounding of parallel wire fences--is directly applicable to EHV lines.

This coupling can only occur with a time-varying magnetic field and is thus of major concern overall only with AC transmission. The one situation representing a potential public safety hazard and may be applicable to DC as well as AC, is the large transient current occurring during a fault. Here, extremely high unbalanced currents can exist until the fault is cleared (0.25 seconds or less), inducing potentially hazardous voltages in improperly grounded, long, parallel conductive objects.

The space charge field (or "ion current") exists whenever a transmission line is "in corona" (and thus is also a corona effect). As the voltage gradient at the conductor surface exceeds the breakdown strength of the air surrounding the conductor, the surrounding gaseous molecules are ionized. The periodic polarity reversal of AC conductors prohibits significant net movement of these ions; for DC lines on the other hand, significant drift--ion current--can occur between the two conductors and to ground. This will couple with an insulated object inducing a static charge, which can also represent a potential--although not physiologically harmful--shock hazard to a person touching the object.

The above discussion has generally been in terms of the shock hazard represented by large metallic conductive objects located within these fields. Biological organisms--including humans--are also conductive objects, and minute currents are also introduced within them even when not in contact with the object presenting a shock hazard. This effect has given rise to much speculation over possible long-term biological impact (see Appendix C).

This report assesses only the public health and safety significance of these fields. This limitation was deliberate, because field effects are not adequately understood and addressed from a regulatory perspective, and are also of major public concern. In contrast, audible noise standards, particularly, can provide effective regulatory constraints on the entire range of corona effects, which while not inconsequential, at least appear to be well understood.

As suggested above, there are two possible field effects: the shock that may be experienced when touching a large conductive object, and alleged long-term biological effects resulting from exposure to these fields. Concern over the latter has been repeatedly expressed by some Minnesotans; paradoxically, adverse biological effects have not been satisfactorily demonstrated to exist either empirically or in the laboratory, nor has a reasonable working hypothesis for the presumption of effects been postulated, as discussed in Chapter III.

Thus, we find ourselves in the frustrating position of being asked to state conclusively that there are no such effects. This is a logical impossibility for <u>any</u> environmental factor, natural or manmade. The most that can be asked is to improve our confidence through testing hypotheses regarding specific postulated effects. Given a particular hypothesis of specific adverse, long-term biological effects from exposure to transmission line fields, scientific inquiry can either accept or reject it. Note, however, that its rejection can never imply that there are no effects. But, until effects are consistently demonstrated by some means, there is no identifiable hazard and no basis for prudent public health action.

Nonetheless, if there is a lesson for the public health profession, it is that seemingly innocuous environmental stresses at sufficient doses can be hazardous with long-term latencies. Hence, we must continue to monitor progress in research on the biological effects of electric fields, and the recommendations herein stress the need for ongoing evaluation of research sponsored by both the Federal government and the electric utility industry, described in Chapter IV.

Electric shock, on the other hand, is a well understood and readily controllable phenomenon through proper engineering design, grounding practice and conduct in the vicinity of HVTLs. It does appear to represent a possible problem to one specific risk population: operators of large farm equipment used in the vicinity of HVTLs. The magnitude and extent of this problem have not been quantitatively assessed, and regulatory controls could be inadequate. Shock is discussed in quantitative terms in Chapter II, and several specific recommendations for further addressing this problem are outlined in Chapter V.

STUDY PROJECT

The study was designed fundamentally as a literature survey, augmented by appropriate contact with organizations and individuals active in the field. Staffing included three individuals from the Minnesota Department of Health's Division of Environmental Health. With other responsibilities, their contribution to this study totals approximately 1.5 person-years of professional staff time. In addition, the Power Plant Siting Staff has maintained close contact with the New York Public Service Commission staff throughout the latter's ongoing common record hearings on the same subject and has made the services of its consultant, Professor Vernon D. Albertson, Electrical Engineering Department, University of Minnesota, available for technical review of the engineering aspects of this report.

As a strategy, maximum confidence has been placed on material in the public domain, with principal emphasis on the referred scientific and engineering literature and secondarily, on various technical reports that have received wide distribution.

In addition, three other sources of information have been extremely useful:

A. New York Public Service Commission Common Record Hearings. The Commission, through administrative hearings, has conducted an exhaustive inquiry into the health and safety effects of two proposed 765-kV AC transmission lines, as described in Appendix C. The study project has made extensive use of both the transcripts and exhibits. The transcript initially on hand covered 52 days of hearings, from February 7, 1975 through May 27, 1976, comprising 10,350 pages. It was on this record that the Commission based its Opinion and Order 76-12, June 30, 1976, allowing construction to proceed on the Power Authority's 765-kV line.

Since that time, an additional 18 days of hearings have been held including further direct testimony plus rebuttal testimony from seven witnesses. The latter included Dr. Andrew Marino, and his cross-examination was observed by three members of the MEQB staff (Mary Sullivan, Will Kaul and William E. Dorigan) on March 22-23, 1977.

The additional transcript through March 30, 1977 (3,170 pages) has also been received, reviewed and considered herein.

Initial briefs and reply briefs were submitted by all parties on August 30, and September 23, 1977, respectively. These are legal documents, providing recommendations to the two administrative law judges. They are on hand and provide worthwhile summaries and perspectives but are of limited technical value.

B. Minnesota State Register Official Notice. One of the study project's major problems--over and above limited staff time--has been the acquisition of adequate information on which to make reasoned judgments. A lot of material has been generated in the last few years, but it is fragmented and difficult to collect. Consequently, a notice was inserted in the "EQC Monitor" section of the December 27, 1976 issue of the State Register (1 S.R. 960), formally soliciting outside input. The reason for this approach was to provide an unstructured opportunity for any interested party to provide information--technical data, experiences, opinions, comment, whatever--that might be of use. Consequently, in addition to State Register subscribers, the notice was further distributed as follows:

26	*Expert witnesses before the New York Public Service Commission common record hearings on health and safety effects of EHV transmission lines.*
48	*Respondents to a somewhat similar notice by the U.S. Environmental Protection Agency in the March 18, 1975 issue of the Federal Register.*
31	*Participants in the recent revision of the National Electrical Safety Code (members of appropriate ANSI C2 subcommittees and individuals who commented on the various drafts).*
6	*Referral suggestions made by various respondents.*
1	*Electric Power Research Institute.*
1	*U.S. Energy Research and Development Administration.*
1	*U.S. Environmental Protection Agency.*
1	*Medtronic, Inc.*
1,289	*Minnesota Environmental Quality Board Power Plant Siting Staff mailing lists (primarily Minnesotans who have participated on citizen committees or have attended hearings under the Board's power plant siting and transmission line routing program).*
1,404	*Interested party recipients.*

The notice specified a February 28, 1977 suspense date; however, as late as early May, a few responses were still being received. In total, 129 responses were received. Of these, 42 are from Minnesota, 14 from New York, 11 from Washington, D.C. and the remaining 62 from 24 states and Ontario.

These responses fall into two general categories: those providing substantive technical input and those of a more general nature. Responses in both categories have been excellent and for the most part, nonrepetitious. Those of general nature particularly, have been thoughtful, pointing out legitimate issues of concern and providing many worthwhile suggestions for the study.

The technical material comprises approximately 30 inches--admittedly a poor measure of worth--of documents. These were, for the most part, already in the public domain (technical papers, reports, etc); however, Commonwealth Associates, Inc. did prepare a very useful report addressing the specific concerns outlined in the notice. In total, this material, especially when taken with documents already on hand (including transcripts from the New York Public Service Commission hearings), perhaps provides the Minnesota Department of Health with the most comprehensive set of information available to any state regulatory agency in the country.

Resource limitations prohibit a complete analysis of all this material, which covers a broad range of topics. However, all information directly bearing on field effects has been scrutinized with care; as for the material in total, it has been cataloged with abstracts as a separate report (included herein as Appendix D).

The quantity and quality of this information justifies further review. The U.S. Energy Research and Development Administration (ERDA) has expressed an interest in a joint-venture for review and synthesis of the entire record by a competent research house. One of ERDA's present contractors is currently reviewing some transmission line material and the proposed project would in essence, "piggyback" on the current contract. A recommendation to further consider ERDA's suggestion is included in Chapter V.

C. Direct Contacts. In addition to continuing monitoring of the New York hearings, contact has been established and maintained with the Electric Power Research Institute, ERDA and the Bonneville Power Administration in developing an overall assessment of their respective research programs. Contact has also been made with several professionals active on the issue.

This report represents the culmination of the formal study effort, although the Minnesota Department of Health plans to continue to monitor the issue, comments on this report are invited. They should be addressed to the Department, ATTN: HVTL Study.

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II. COUPLING EFFECTS AND SAFETY

In principle, a human subject on or near the right-of-way could be exposed to both direct and indirect effects of the electric, magnetic and/or space charge fields existing in the vicinity of an energized AC or DC transmission line. From a theoretical perspective, 60-hertz electric and magnetic fields change only slowly with time; as a result, they can be treated independently and further, wave propagation techniques are not necessary for their analysis (*Prasad et al., 1976*). In fact, the literature often describes such fields as "quasi static" or "quasi stationary" (*Sheppard and Eisenbud, 1977; Prasad et al., 1976*). For purposes herein, both AC and DC fields can be treated similarly as non-propagating phenomena, with proximity effects then, of exclusive concern for purposes of this report.

Both the direct and indirect proximity effects result from various "coupling" mechanisms whereby energy is transferred from the energized conductors <u>without contact</u> to some other partially or fully conductive object--including biological organisms--located within the field. There are three predominant coupling modes (*Anonymous, 1976a*):

1. Capacitive coupling via displacement currents associated with AC vertical electric fields;
2. Inductive coupling via AC magnetic fields; and
3. Resistive coupling via DC space charge fields and AC or DC horizontal electric fields resulting from ground currents.

Coupling can arise from one or more of these modes, especially where large, distributed metallic objects are involved. The energy transferred by these mechanisms appears as static electric charges and currents on the surface of and within the conductive object.

Direct coupling occurs when the biological organism itself is the conductive object. Here, the resulting energy transfer presents a minor shock potential under ideal conditions; more important however, is the alleged possibility of long-term adverse human health impact resulting from chronic exposure to minute currents flowing within the body. This is a controversial subject of considerable public concern, particularly with EHV and HVDC technology. Nonetheless, the existence of such phenomena is still speculative, although being extensively studied. Known biological effects resulting from direct mechanisms and the present research programs are discussed in detail in Chapters III and IV, respectively.

In Chapter I, the predominant coupling hazard to human subjects was characterized as an indirect one: the shock resulting from two-point contact with objects at differing potential (voltage) within the field, such as touching a large, ungrounded, highly conductive object while standing on the ground. In this situation, direct coupling with the biological organism is not the effect of concern; rather, the energy transfer to the large conductive object creates the hazard. The position taken by this report is that this shock hazard represents the only significant known adverse public health and safety effect of high-voltage overhead transmission lines, possibly constituting a safety problem for operators of large agricultural equipment. Such shocks, while not at physiologically harmful levels in the steady-state transmission line environment, are annoying and may cause involuntary muscular reactions with possible adverse secondary effects. This phenomenon is fully described in this chapter.

While coupling effects and their impact on public health and safety are the thrust of this report, there are several other major concerns with the transmission line electrical environment:

1. Contact with an energized conductor, either directly or indirectly with a conductive object, can be lethal.
2. The effects described in this report may also be applicable to wildlife and livestock.
3. Energy transfer via coupling mechanisms can create other environmental problems, such as corrosion and operational interference with other utilities, such as pipelines, railroads and telecommunications.
4. Fuel vapor ignition is theoretically possible in the proximity of both AC and DC transmission lines; however, the risk is low and there is no known instances of this occurring under practical refueling conditions.
5. In addition to the space charge field, corona discharge causes other adverse environmental effects (see Chapter I and Appendix B).

TRANSMISSION LINE FIELD ENVIRONMENT

The following discussion characterizes the three field types in both the AC and DC transmission line environments, cites units of measure, describes coupling mechanisms and provides comparisons with non-transmission line environments. In addition, electric fields are subdivided and discussed in terms of vertical and horizontal components, which display dissimilar effects. This particular classification of fields is not unique, but was selected for its appropriateness to the particular purposes of this report.

For further information on engineering aspects of transmission line design and operation, other environmental effects and mitigative design practices, the reader is referred to Appendix B.

A. Vertical Electric Field. Energizing the phase conductors

(AC) or poles (DC) of an overhead transmission line creates a time-varying or static vertical electric force field, respectively, resulting from the distributed surface charge on the conductor or pole (*Hancock, et al., 1975; Reilly, 1977*), which exists in the space between the conductors or poles and the earth's surface. The AC transmission line vertical electric field gradient is considerably higher--by more than an order of magnitude--than AC electric fields experienced in the home environment, and this field is of primary concern with respect to both long-term biological effects and the shock hazard described earlier. Consequently, much of the remainder of this chapter is concerned with the magnitude of its associated effects and mitigative measures.

The intensity of an electric field is described by the magnitude and direction of the force that would be experienced by a unit charge placed in the field at that point (*Prasad et al., 1976; Kornberg, 1977*) and is usually measured as a voltage gradient in volts per unit length, such as volts per centimeter (V/cm) or kilovolts per meter (kV/m). The gradient is at its maximum at the conductor or pole surface; if it exceeds the dielectric strength of air--approximately 2,500 kV/m--the line is "in corona" with attendant corona-related effects. The gradient then decreases rapidly at distances away from the conductor or pole.

An electric field can be "mapped" by drawing "flow" lines through each point in the field in the direction of the field force existing at that point. Lines perpendicular to the flow lines can also be drawn; these are "equipotential" lines (*Kornberg, 1977*), every point of which is at the same voltage. The presence of a conductive object distorts the field, causing an increase in the density of the flow lines and a compression of the equipotential lines; e.g., an increase in the voltage gradient. The resulting distortion pattern is dependent upon the size, geometry and orientation of the object.

If the object is insulated from ground, it will develop some potential with respect to ground. For example, a small sphere located two meters above ground in a 5-kV/m field will have a potential of 10 kV. This is the so-called "open-circuit" voltage (V_{oc}), although as Shah et al. (1977) properly points out, this term is a misnomer, as "most objects will have some leakage resistance to ground and virtually all have some capacitive impedance to ground. Open-circuit voltage really means 'ungrounded object' voltage."

In the case of an AC electric field, "displacement current," or capacitively-coupled current, flows between the conductor and the earth along the flow lines, representing a small shunt power loss. An object immersed in the field will intercept some of this displacement current. The extent to which this occurs is dependent upon field distortion and the degree to which the object is insulated from ground. This is the "capacitive coupling" phenomenon associated with AC electric fields.

Capacitive coupling is not possible with DC fields. For this reason, as well as the observation that other DC electric field effects are usually masked by the space charge field, it is usual engineering practice to consider the two fields together assessing the composite effect for the DC line environment. This practice is adopted here; consequently, the remainder of the present discussion of vertical electric fields will be limited to the AC line environment.

In the AC transmission line environment, the field is nearly uniform at the earth's surface; e.g., flow lines are approximately vertical. Also, the presence of objects of concern to this analysis will have a negligible effect on the source of the electric field--the conductor voltage--and the resulting surface charge. Thus, from an engineering perspective, field effects can be discussed solely in terms of voltage gradient at ground level (*Anonymous, 1975b*).

Determination of the magnitude and spatial distribution of the ground-level gradient is, however, a complex function of phase voltage, conductor size, separation and clearance. For a single-circuit line, the field gradient is at its maximum midway between towers (point of maximum sag), near or under the outside conductors. From these points, it drops off rapidly in a direction perpendicular to and away from the right-of-way center line. Parallel to the center line, the field decreases with increasing clearance. Thus field strengths approaching the maximum are encountered only over a small percentage of the right-of-way. Field phenomena are well understood theoretically, and field strengths can be estimated from computer models which agree well with actual measurements (*Shah et al., 1977; Anonymous, 1976a*). Figure II-1 portrays these effects in graphical form for typical 345-kV and 500-kV line configurations at various clearances.

One rough rule-of-thumb is that the maximum gradient at ground level is approximately 1.6 kV/m per 100 kV of line-to-line voltage for single-circuit AC lines (*Anonymous, 1976b*). For example, calculated maximum gradients at ground level for two Minnesota lines under construction are:

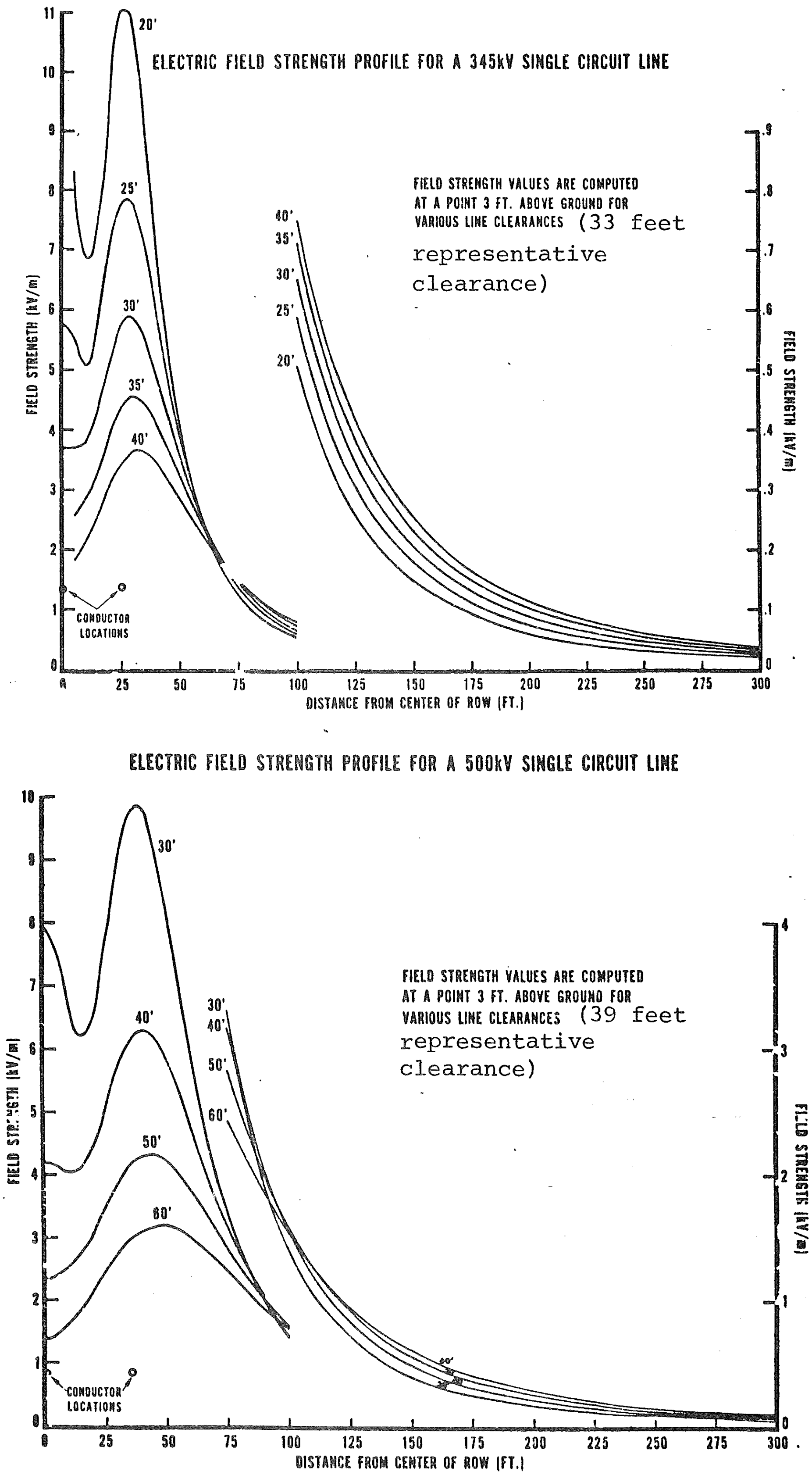


FIGURE II-1

TYPICAL VERTICAL ELECTRIC FIELD GRADIENTS FOR SINGLE CIRCUIT LINES

(Note that two ordinate scales are used, the left for distances less than 100 ft., the right for distances greater than 100 ft.)
Source: Tell et al. (1977)

Project	Nominal Operating Voltage	Maximum Gradient
Delano/Willmarth	345	5.4 kV/m
Twin Cities/Winnipeg	500	7.6 kV/m

This implicit proportionality has been true for lines designed in conformance with conventional practice; however, controlling capacitive coupling effects constrains the ground-level field strength so that this proportionality may not be applicable to the higher operating voltages of the future. To put the above data in better perspective, the threshold of perception is in the range of 10 to 15 kV/m. At this level, discomfort may occur, resulting from erection and/or vibration of body hair (*Barthold et al., 1971; Sheppard and Eisenbud, 1977; Anonymous, 1975b*).

The vertical electric field gradient is often stated at different elevations in different documents; the usual being ground level, or 1.0 or 1.5 meters above the earth's surface. However cited, all are attempts to quantify the intensity at ground level, as a measure of human exposure. Since the gradient increases only slightly with elevation at ground level, any of these measures give a good estimation of the unperturbed field exposure of human subjects standing at ground level.

The earth has a naturally occurring DC electric field, which is described in a report prepared by IIT Research Institute (IITRI) for the U.S. Energy Research and Development Administration (ERDA):

> *The naturally occurring DC electric field of the earth . . . can attain very significant and large transitory values. The typical value cited is 130 V/m, with the earth negative with respect to the ionosphere. The earth and the ionosphere are regarded as two plates of a gigantic capacitor. This capacitor is constantly being charged by the world-wide thunderstorm activity, and constantly being discharged by ions within the air flowing between the earth and the ionosphere giving rise to very small current flow.*

The static electric field can, under certain meteorological conditions, increase to very large values and can also reverse its polarity. In some areas of the world, such as northern West Africa, the Harmattan dust haze caused by winds blowing from the Sahara during the dry season, can cause a negative charge to accumulate in the lower atmosphere. This causes a regular daily polarity reversal of the natural electric field which lasts for several hours and produces field values as high as 1.5 kV/m. Similar field reversals occur beneath thunderclouds with peak field intensities of 3 kV/m or greater. On occasion, the field strength on the ground beneath a thundercloud is sufficiently great to cause visible corona at the tips of blades of grass or at the tops of masts (known as St. Elmo's fire). (Anonymous, 1976a)

Since AC and DC fields are not exactly comparable, relating the above data to the AC transmission line electric field is not entirely satisfactory. Another and frequently comparable measure is the electric field produced by common household appliances. Table II-1 provides representative examples. These field strengths were measured at 30 centimeters (approximately 12 inches) distance, and it is reasonable to expect the gradient to be appreciably higher at the appliance surface. The relatively high electric blanket gradient (250 V/m, or 0.25 kV/m) particularly should be noted.

B. Horizontal Electric Field. There is also a horizontal electric field existing in the earth beneath and in the vicinity of both AC and DC transmission lines, resulting from ground currents. In the case of AC lines, these currents arise from three sources (*Anonymous, 1976a*):

1. Unbalanced, harmonic and fault currents through power system earth counterpoises;
2. Displacement currents collected by the ground from the electric field; and
3. Eddy currents induced in the soil by the magnetic field.

The horizontal field gradient at the ground surface is small, well under 100 millivolts/meter under steady-state operation.

TABLE II-1

60-HERTZ ELECTRIC FIELDS
IN THE VICINITY OF ELECTRICAL APPLIANCES

Appliance	Electric Field Strength (volts/meter)*
Electric Range	4
Toaster	40
Electric Blanket	250
Iron	60
Broiler	130
Hair Dryer	40
Vaporizer	40
Refrigerator	60
Color TV	30
Stereo	90
Coffee Pot	30
Vacuum Cleaner	16
Clock	15
Hand Mixer	50
Incandescent Light Bulb	2
Phonograph	40

*Measured at a distance of 30 cm from the appliance.
Source: Bridges, 1975

Monopolar operation of DC transmission lines also produces ground currents and resulting horizontal electric fields. This current is large: For the Underwood, ND/Delano, MN ±400-kV DC line, the maximum overload current is estimated to be 1,275 amperes, resulting in a maximum ground surface gradient of 5 volts/meter in the vicinity of the ground electrode (*Hancock et al., 1975*).

The hazard with horizontal electric fields is "step potential," the voltage developed between a subject's feet on the earth which is carrying the ground current (*Bridges, 1975*). The gradients cited above indicate that this does not constitute a safety hazard under normal operation.

With a line-to-ground fault (e.g., broken conductor or pole short-circuited to ground), however, large and hazardous horizontal electric field gradients will occur in the immediate vicinity of the fault and at the substation. Protective measures fall into two general categories:

1. Limiting the time duration of the fault (and thus possible public exposure) by high-speed protective relaying which will open circuit breakers in three to five 60-Hz cycles (0.05 to 0.083 seconds) (*Shah et al., 1977*). It should be pointed out that standard recovery practice includes attempts to reenergize the line by reclosing the circuit breakers, typically one to three times. Since this occurs within a matter of approximately one-quarter second, such practice must be considered in evaluating the overall hazard of these fault conditions.

2. Provisions in the National Electrical Safety Code for "extensive grounding grid systems of multiple buried wires and rods and other protective means" in the vicinity of large substations to limit the step potential to safe levels, as well as personnel access restrictions (*Anonymous,*

1977b). Comparable safety precautions at the point of the fault would obviously require fencing a width at least that of the right-of-way, which, considering the extremely low risk of exposure at any point in space and time, seems unduly cautious. This appears particularly true when considered in terms of the obvious disadvantages of fencing to the landowner and community, as well as to the utility itself.

However, restrictions on right-of-way utilization, such as exclusion of some public and private facilities, might be appropriate. To our knowledge, there are no present restrictions of this type, other than whatever policies the owning utility itself imposes. Chapter V includes a recommendation for assessment of the experience of Minnesota electric utilities with respect to transmission line equipment and operational failures of a nature that could impact public safety. Such information would be extremely useful to the State in developing appropriate policy for excluded uses of transmission line right-of-way.

Horizontal electric fields are not considered further herein with respect to public health and safety. This is not to minimize other effects of ground currents. They constitute a significant problem for other utilities with respect to such phenomena as electrolytic corrosion of pipelines, and interference with telephone communications, railway signalling, and between lines sharing a common right-of-way (*Hancock et al., 1975; Anonymous, 1976a*). Additionally, AC transmission systems with grounded transformer neutrals could experience a direct current flow under monopolar operation of a DC line with a nearby ground electrode, possibly resulting in transformer overheating and false operation of ground relays (*Hancock et al., 1975*).

C. Magnetic Field. Current flow in a conductor gives rise to a surrounding magnetic force field. Through inductive coupling, an

AC magnetic field can induce voltages at the open ends of nearby parallel conductive circuits (*Reilly, 1977*). This induction effect is directly proportional to the magnitude of the current flow in the conductor, the length of the conductor and the power system frequency, and is inversely proportional to the lateral distance of the circuit from the conductor (*Hancock et al., 1975*). Since a DC transmission line creates a static magnetic field, induction cannot occur and the field is not of major concern.

For an AC transmission line, the time phasing of the currents in the three conductors causes the vector orientation of the magnetic field at any point to rotate in space at a 60-Hz rate. This vector is proportional to the line current, with a vertical component and components perpendicular and parallel to the right-of-way center line (*Anonymous, 1976a*).

Field strength is described in terms of flux density, usually expressed in units of gauss, although the MKS unit of teslas or webers per square meter (10,000 gauss), is finding its way into the technical literature (*Hancock et al., 1975; Anonymous, 1976a*).

Transmission line magnetic fields are low. An AC transmission line will produce a 60-Hz magnetic field at ground level of one-third gauss or less under steady-state operating conditions (*Anonymous, 1976a*). The Underwood, ND/Delano, MN ±400-kV DC line is estimated to produce a maximum static magnetic field flux density of 0.20 gauss at ground level for bipolar operation and 0.23 gauss for monopolar operation at design levels (*Hancock et al., 1975*). Recommended exposure standards (see Chapter III) are two to three orders of magnitude (100 to 1,000 times) or more greater. By way of further comparison, many common household appliances produce considerably higher 60-Hz magnetic flux densities (see Table II-2). These are highly localized, and the IIT Research Institute notes, "it is possible that the strong fields do interact with substantial portions of the human body, for example, in the case of a portable hair dryer which is carried on a strap and which rests against the chest" (*Anonymous, 1976a*).

The earth itself has its familiar static or DC magnetic field which has a flux density of about one-half gauss. Superimposed on this static density are micropulsations of low frequency (*Anonymous, 1976a*).

Given the relatively low magnetic flux densities in the transmission line environment, long-term deleterious biological effects are not anticipated. Consequently, relatively little discussion is included in Chapter III on this field as an environmental stress on human subjects.

As suggested above, AC inductive coupling with parallel conductors can represent a safety hazard. One reference, for example, cites a value of 0.1 volt per mile per ampere of conductor current, at the ungrounded end of a circuit--such as a telephone line--closely paralleling a transmission line (*Barthold et al., 1973*). This corresponds to a voltage of perhaps 100-300 volts/mile under steady-state operation and as high as nine kilovolts per mile under fault conditions. This is obviously hazardous, requiring stringent occupational safety rules for linemen and others involved in the construction and maintenance of such circuits.

Induction effects in nearby ground-level parallel circuits--such as wire fences--do not create a safety hazard with steady-state operation. However, under certain line-to-ground fault conditions,

TABLE II-2

LOCALIZED 60-HERTZ MAGNETIC FLUX DENSITIES
PRODUCED BY ELECTRICAL APPLIANCES

10 - 25 Gauss

325 Watt Soldering Gun
Magnetic Stirrer
Power Feeder Cable
Hair Dryer

5 - 10 Gauss

Can Opener
140 Watt Soldering Gun
Fluorescent Desk Lamp
Kitchen Range
Electric Shaver

1 - 5 Gauss

Bench Grinder
Arc Welder
Food Mixer
Power Transformer
Induction Motor
Color Television Set
Food Blender
Electric Drill
Portable Heater

0.01 - 1.0 Gauss

Toy Auto Transformer
Garbage Disposal
Clothes Dryer
Black/White Television Set
Vacuum Cleaner
Heating Pad
Electric Toaster
Bell Transformer

0.01 - 0.1 Gauss

Home Electric Service Unit
Kitchen Fluorescent Lamp
Dishwasher
Laundry Washer
Phonograph
Calculator
Electric Iron

0.001 - 0.01 Gauss

Refrigerator

Source: Bridges, 1975 (from Miller, D.A., 1974, "Electric and Magnetic Fields Produced by Commercial Power Systems," Llaurdo, J. G. et al., Biologic and Clinical Effects of Low-Frequency Magnetic and Electric Fields, Charles C. Thomas, Springfield, 1974) extremely high unbalanced currents can occur, reaching perhaps 90,000 amperes (*Shah et al., 1977*). If such a parallel circuit is grounded at only one end, say, and a human subject touches the ungrounded end, the circuit to ground can be completed through the body, with a possibly large resultant current for the duration of the fault. With a sufficiently long fence, the current level and duration can cause severe and possibly lethal shock. The reader is cautioned, however, that this statement only applies to a particular fault condition--an extremely infrequent event in itself--in combination with other low probability circumstances, including one point grounding, which is highly unrealistic. Discussion of mitigative measures is provided in this chapter.

Although interference problems with other utilities were described in conjunction with the transmission line horizontal electric field, inductive coupling produces similar effects. A major problem here is electrolytic corrosion of buried pipelines running parallel to a transmission line. Inductive coupling can also affect parallel telephone and railway signalling circuits. This is a problem that has been dealt with for many years but takes on more importance with increased circuit-miles of higher capacity electric power transmission systems.

D. Space Charge Field. The field produced by an operating DC transmission line consists of two components:

1. The static vertical electric field resulting from energization of the line, as described previously. The term "electrostatic field" correctly describes this field in the absence of an ion current flow (*Anonymous, 1977a*).

The ground-level gradient is greater than that for an AC line operating of the same voltage. For example, the engineering report for the Underwood, ND/Delano, MN ±400-kV DC line indicates that the calculated maximum ground-level field strength will be ±9.6 kV/m for bipolar operation and ±12.7 kV/m for monopolar operation at the point of minimum design conductor clearance (*Hancock et al., 1975*). However, AC and DC fields cannot be compared because of the absence of the capacitive coupling phenomenon in the DC case (*Anonymous, 1977a*). That is, the DC electric field cannot induce a steady-state current in a conductive object although it can slowly charge such an object if well insulated (*Hancock et al., 1975*).

Subjective evaluation of DC vertical electric field sensations have been conducted for human subjects standing on a highly insulated rubber mat. Typical remarks and findings at various unperturbed electrostatic field strengths were:

22 kV/m (400 kV)	*Very slight tingling sensation on the scalp.*
27 kV/m (500 kV)	*Hair stimulation; slight feeling on ears and hair.*
30 kV/m (600 kV)	*Strong tingling sensation on scalp.*
40 kV/m (750 kV)	*Sensation on face and legs.*

With normal footwear, a slight tingling of the scalp and hair stimulation usually occurs at gradients around 30 kV/m. These sensations would be primarily due to the presence of the high intensity field as perturbed by the presence of the subject (Anonymous, 1977a).

2. A "space charge" field unique to DC lines, existing whenever the line is energized to a voltage above that required for corona onset. Application of potential to the poles causes charges of opposite polarity to appear at the pole surface, producing very intense local field gradients. As a result of these gradients, electrons are released from the gaseous molecules of air and accelerate either toward or away from adjacent conductor. Collisions then occur between these electrons and atoms in the air resulting in the formation of ions that are then repelled by the adjacent

conductor, if it is of like charge and drift into the space surrounding the line and eventually to the ground. An ion cloud forms in the space immediately adjacent to the pole conductor and tends to stabilize the voltage gradient in the region and thus keeps the surface gradient near the critical level for corona onset. However, if the wind should cause a removal of ions from this cloud, then the pole will replenish the charge to sustain stability in the ion cloud, creating more corona loss. This process is similar in the AC case, but no space charge field results because the continually changing charge on the conductor surface always attracts oppositely charged ions, and they will not escape from the immediate vicinity of the conductor.

The undirectional DC electrostatic field causes movement of air ions toward the oppositely polarized conductor and to the ground. This is effectively a current flow, similar to the displacement current under AC lines and providing a mechanism for resistive coupling with conductive objects (*Anonymous, 1976a*). Ion currents, however, are relatively small (less than 100 nanoamperes per square meter), and objects found in the proximity of a transmission line cannot collect sufficient current to constitute a source of steady-state shock (*Bracken et al., 1977*).

Another factor unique to DC lines is "ion drift," the movement of air ions away from the line, by the action of wind, allowing charging of highly insulated objects at distances as far as several hundred feet from the right-of-way. It is estimated that about 20% of the air ions migrate away from the line either under the influence of the electrostatic field or air movement (*Shah et al., 1977*). Bracken et al. (1977) note that space charge effects have been reported as far as 10 kilometers downwind from corona sources.

As pointed out previously, usual engineering practice is to consider the two fields in conjunction, describing the composite field as the "DC electric field." At ground level, the composite field gradient will have a maximum positive (negative) value directly under or slightly outside the positive (negative). At some point between the poles, the field strength is zero. Figure II-2 shows this effect, in graph form, utilizing data from the Bonneville Power Administration's test facility. This line operates at higher voltages than Minnesota's two DC lines; however, the effects are similar.

The effect of the space charge field is such as to reduce the resistance of the air space beneath the conductors, decreasing the electrostatic field gradient at the pole and increasing it at the ground surface. For the Celilo-Sylmar ±400-kV DC line with a clearance of 12 meters (39.4 feet), for example, the calculated effect is to increase the electrostatic field gradient from ±7.7 kV/m to ±18.6 kV/m directly under the respective poles with no wind. However, even under low wind conditions, the measured gradients were highly unsymmetrical: -34 kV/m and +13 kV/m, respectively. This asymmetry is due to the lower gradient required for corona onset on the negative pole, as well as the fact that negative corona is less sporadic than positive corona (*Bracken et al., 1977*), and is shown in Figure II-2.

Other possible factors contributing to asymmetry are not completely understood, but may also include differences in the positive and negative ionization phenomena, ion life and mobility, in addition to corona onset differences (*Anonymous, 1977a*). For either pole, however, the gradient experienced is highly dependent upon air temperature, humidity, wind speed and operating voltage.

ELECTRIC SHOCK

The coupling mechanisms associated with each of these fields

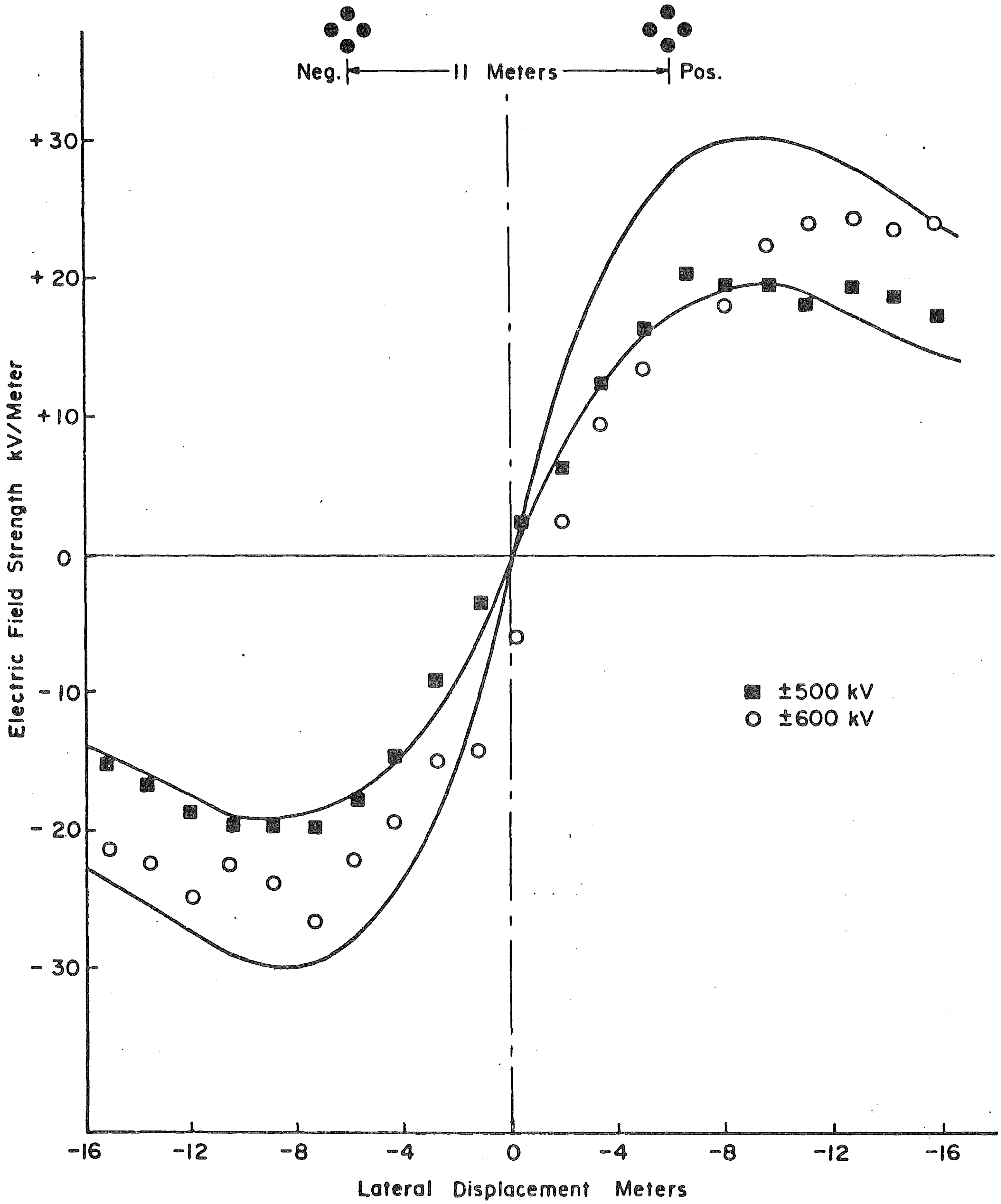


FIGURE II-2. COMPARISON OF CALCULATED AND MEASURED ELECTRIC FIELD GRADIENTS UNDER FOUR 1.2-INCH BUNDLE CONDUCTORS WITH LINE-TO-GROUND CLEARANCE OF 40 FEET.

Source: Anonymous, 1976a

creates potential shock hazards of various degrees of severity; consequently, the physiology of shock must be quantitatively examined to provide a basis for determination of mitigative measures. Electric shock results from the passage of electric current through the body between two points of contact (for example, between the hand and foot) at differing potential, or voltage. A convenient classification of shock current types for discussion of the transmission line environment is:

1. AC steady-state current, resulting from capacitive or inductive coupling, including transients of a few 60-hertz cycles duration.
2. DC steady-state current, resulting from ion current flow.
3. Discharge current, resulting from discharge of capacitively or resistively coupled stored energy.

Shock currents can also be classified in terms of the severity of the shock produced. Both discharge and steady-state currents at sufficiently high levels can cause direct physiological harm. These are termed "primary shock currents" (*Barthold et al., 1971*). Primary shocks can cause death by producing ventricular fibrillation or cardiac arrest, or by arresting lung function and thus blood oxygenation, due to tetanization of the thoracic musculature or inhibition of central nervous musculature control. Both cardiac arrest and respiratory inhibition require higher currents for their initiation than do the ventricular fibrillation and thoracic tetanization processes and are thus masked in the assessment of minimum primary shock currents (*Keesey and Letcher, 1969 and 1970*).

Thoracic tetanization is caused by sustained currents smaller than those required for ventricular fibrillation. In this process, the current produces uncontrollable muscular contraction of the respiratory muscles of the thorax and diaphram. When the subject cannot let go of the current source, death can result from suffocation. Data presented by Keesey and Letcher (1969 and 1970) and Barthold et al. (1971) indicate that this process can be initiated by currents not far in excess of the "let-go threshold," which is defined as the highest current in a hand-to-hand or hand-to-foot pathway from which the subject retains sufficient muscular control to release an energized electrode held in a hand (*Anonymous, 1976b; Keesey and Letcher, 1970*). A conservative posture, therefore, is to consider <u>any</u> current in excess of the let-go threshold as a primary shock current and potentially lethal. Thus as a transmission line performance standard we recommend that the maximum possible steady-state current exposure be limited to the let-go threshold, as also suggested by others (*Barthold et al., 1976*). This posture is taken on the recommendations in Chapter V.

Ventricular fibrillation appears to result from a sufficiently high level of deposition and therefore may be a consequence of exposure to either discharge or steady-state primary shock currents. The process involves incoordinate asynchronous contraction of heart muscle fibers, resulting in immediate arrest of blood circulation (*Keesey and Letcher, 1969 and 1970; Barthold et al., 1977*). Even after the current is removed, the condition rarely reverts back to normal heart beat spontaneously, and prompt medical assistance is necessary. Consequently, current thresholds for ventricular fibrillation are particularly important to safety experts concerned with electrical accidents. Keesey and Letcher (1969) report that 60-hertz currents through the thorax in the 60- to 120-milliampere range for adults and 30 milliamperes for children are probable threshold for ventricular fibrillation. In the transmission line environment, however, coupling effects cannot produce currents of these magnitudes at ground level under normal line operation. In experiments with dogs, Professor Charles F. Dalziel of the University of California developed his empirical "electrocution equation," relating AC currents above these thresholds with time (*Dalziel and Lee, 1968*):

$$i = \frac{k}{\sqrt{t}}$$

where, i = current corresponding to a particular probability of ventricular fibrillation, milliamperes, rms.
t = shock duration, seconds.
k = fibrillation constant depending upon body weight.

Dalziel's work indicates that the fibrillation current for full-grown dogs is in direct proportion to their body weight. Extrapolating this data, he estimated the fibrillation constants for a 50-kilogram (110 pound) human subject as follows (*Dalziel and Lee, 1968*):

k = 116 (0.5% probability)
k = 185 (99.5% probability)

This equation has been found useful in establishing various protective standards, including the provisions in the National Electrical Safety Code relating to substation grounding to limit "step potential" under fault conditions (*Anonymous, 1977b*). As discussed later, it has also been applied to calculation of the fence grounding intervals in Table II-7 for protection of certain AC line-to-ground fault conditions.

Dalziel's electrocution equation was derived from experimental work with 60-hertz currents extending over the range eight milliseconds to five seconds. Although the relationship between current and time implies constant energy deposition, it is not clear that it can be extended to shorter times. In this range--which applies to discharge currents--an energy deposition threshold for ventricular fibrillation is suggested in the 25-50 joule (watt-second) range (*Barthold et al., 1971*). This is orders of magnitude above the capacitive discharge energy expected from conductive objects in the proximity of transmission lines.

Table II-3 indicates the DC current-time relationships do not satisfy the electrocution equation. There is relatively little information on DC steady-state primary shock currents (*Anonymous, 1976a*); fortunately, these do not appear to be realizable in the DC transmission line field environment, with the possible exception of DC fault conditions.

"Secondary shock currents" are those below the let-go threshold. These cannot cause direct physiological harm but may produce involuntary muscular reactions (*Barthold et al., 1971*). If these currents are above the perception level, they may be annoying, painful and if repeated, fatiguing. For these reasons, secondary shocks are sometimes described as "psycho-shocks," an unfortunate term tending to minimize these possible secondary effects. Secondary shocks are of predominant concern in the transmission line environment, and further discussion of these currents is provided in the following paragraphs. Therein, references are made to Table II-3, which is adapted from Barthold et al. (1971). The reader is cautioned that these threshold currents, although widely cited, were originally extracted from an unpublished source. Most of the 60-hertz thresholds appear to have been taken from Dalziel's work and generally agree with other sources, such as Keesey and Letcher (1969 and 1970). However, many of the DC thresholds are not verified. Nor, however, have they been challenged in the literature; hence, the best that can be said is that they are better than none.

The following paragraphs further discuss these discharge and steady-state secondary shock current thresholds with particular reference to the transmission line environment.

A. AC Steady-State Currents. The choice of 60 hertz for power transmission was based partially on the fact that this is about the lowest AC frequency giving the illusion of continuous lightling (no flicker) with incandescent lamps. Unfortunately, the frequency band below 100 hertz has also been found to be the most hazardous in the range between direct current (0 hertz) and broadcast frequencies. Keesey and Letcher (1970) report that "the thresholds for stimulation of nerve, skeletal muscle, and cardiac muscle have all been found experimentally to be minimal near the prevailing alternating current frequencies of 50 and 60 Hz." Figure II-3 exemplifies this phenomenon with the let-go threshold for men; comparison of the AC and DC thresholds in Table II-3 also demonstrates the same effect. As with vertical AC and DC electric field gradients, equal magnitudes of AC and DC electric shock currents do not characterize comparable effects.

Considerable research has been done over the years in terms of the physiological response to electric shock. Table II-3 summarizes representative results. No attempt will be made here to review the literature; rather, the reader is referred to such literature surveys as that of Keesey and Letcher (1969).

TABLE II-3

PHYSIOLOGICAL RESPONSE THRESHOLDS FOR ELECTRIC SHOCK

Effect	Current, Milliamperes: Direct Current, Men	Direct Current, Women	60 Hertz, rms, Men	60 Hertz, rms, Women
1. No sensation on hand. Perception threshold for 0.5% of men tested; extrapolated for women.	1.0	0.7	0.4	0.3
2. Slight tingling. Perception threshold for 50% of men tested and extrapolated for women.	5.2	3.5	1.1	0.7
3. Shock. Not painful and muscular control not lost. Perception threshold for 99.5% of men tested and extrapolated for women.	9.5	6.4	1.8	1.2
4. Painful shock. Let-go threshold for 99.5% of persons tested.	62.0	41.0	9.0	6.0
5. Painful shock. Let-go threshold for 50% of persons tested.	76.1	50.3	16.0	10.5
6. Painful and severe shock muscular contractions, breathing difficult.	90	60	23	15
7. Possible ventricular fibrillation from short shocks:				
a) Shock duration 0.03 sec	1300	1300	670	670
b) Shock duration 3.0 sec	500	500	67	67
8. Certain ventricular fibrillation (if shock duration is over one heart beat interval).	1375	1375	275	275

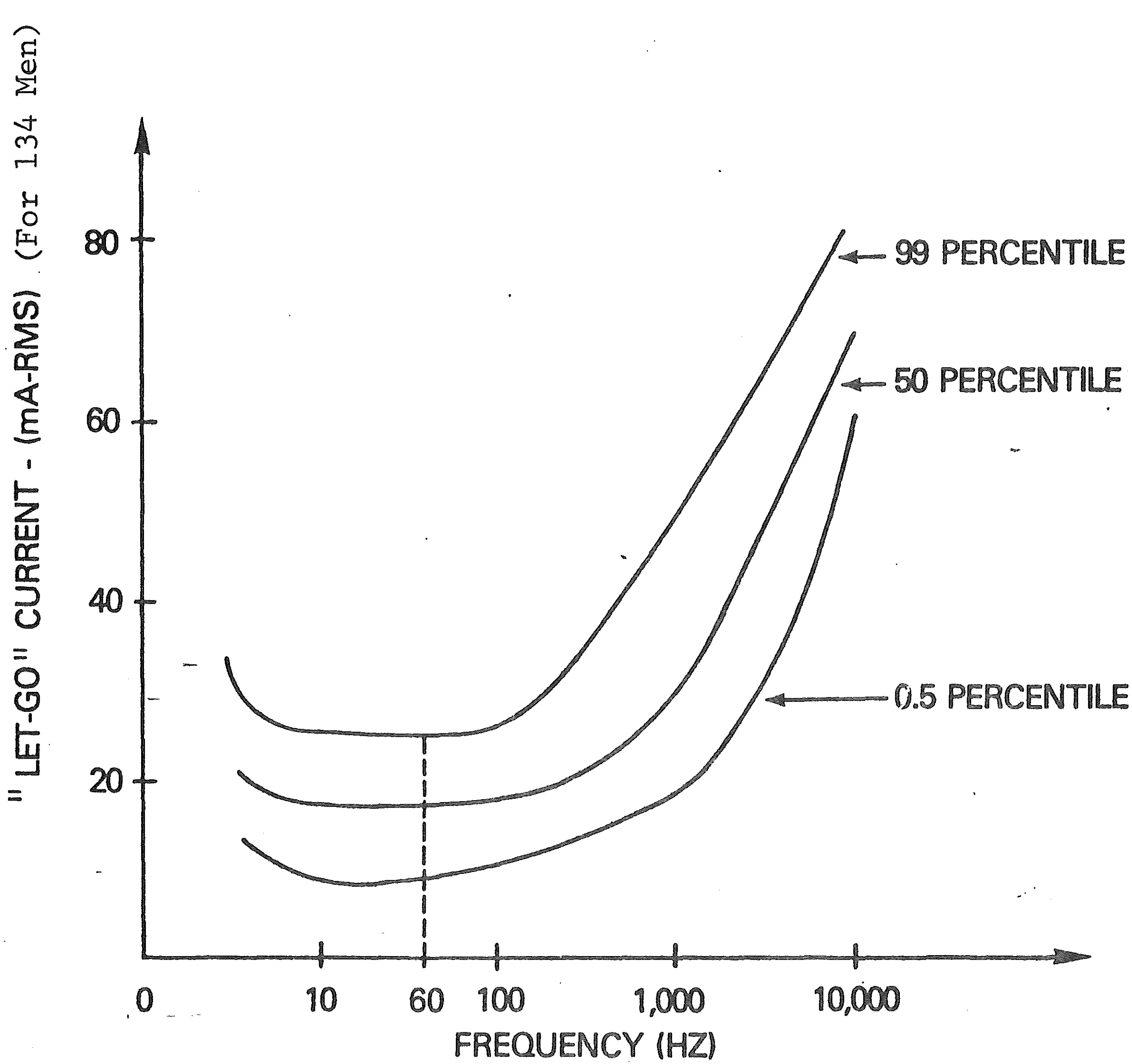
Adapted from Barthold et al., 1971 and Anonymous, 1976a and 1977a. (Data for Effects Nos. 1-5 (AC and DC) and 6 and 7 (AC only) verified and corrected as necessary from Dalziel et al., 1943; Dalziel, 1954; Dalziel and Lee, 1968; and Keesey and Letcher, 1969.)

Based on the recommendations of Barthold et al. (1971), the electric utility industry generally considers one milliampere, rms, as the perception threshold, which the authors define as "the value of current at which a person is just able to detect a slight tingling sensation on his hands or fingers due to current flow." This is at odds with the 0.7 milliampere threshold for women presented in the same paper; a 0.5 milliampere standard for appliance leakage currents; and data presented by Keesey and Letcher (1969). The latter recommend a 0.5 milliampere "general perception" threshold, which based on available data appears proper. However, we accept the one-milliampere criterion for the transmission line environment, because primary shock current is not involved and the probabilistic nature of this environment indicates that the risk of exposure to any maximum possible current criterion is low.

Statistical distributions of let-go currents for men and women are shown in Figure II-4. Note that 99.5% of the men and women tested can release an energized electrode at 9.0 and 6.0 milliamperes, respectively. In its report to ERDA, IIT Research Institute points out that, "the 'let-go' current thresholds were initially developed for a non-power-line industrial equipment situation. The 'let-go' current tests were intended to simulate a barefooted electrical worker firmly grasping an uninsulated saltwater wetted metallic set of pliers connected to a voltage or current source," as an argument that this work is "not directly applicable" to the transmission line environment. As noted earlier, the position is taken herein that any current exposure above the let-go threshold should be considered a primary shock current. In this context, these let-go thresholds are applicable to establishing the maximum possible shock hazard in the transmission line environment.

FIGURE II-3

LET-GO CURRENT THRESHOLD AS A FUNCTION OF FREQUENCY



Source: Dalziel and Lee, 1969

(Adapted from Anonymous, 1976b)

The let-go thresholds have been extrapolated to children, resulting in a generally accepted five-milliampere level. Dalziel has recommended 4.5 milliamperes (derived by taking half of the 9.0 milliampere threshold for men); however, the difference between 4.5 and 5.0 (approximately 10%) is well masked by differences in the size of children, and the distinction appears more academic than real. Keesey and Letcher also accept the five-milliampere standard, although they perceive it as the minimum primary shock current and is thus a "general safety" threshold, which is the posture already adopted herein.

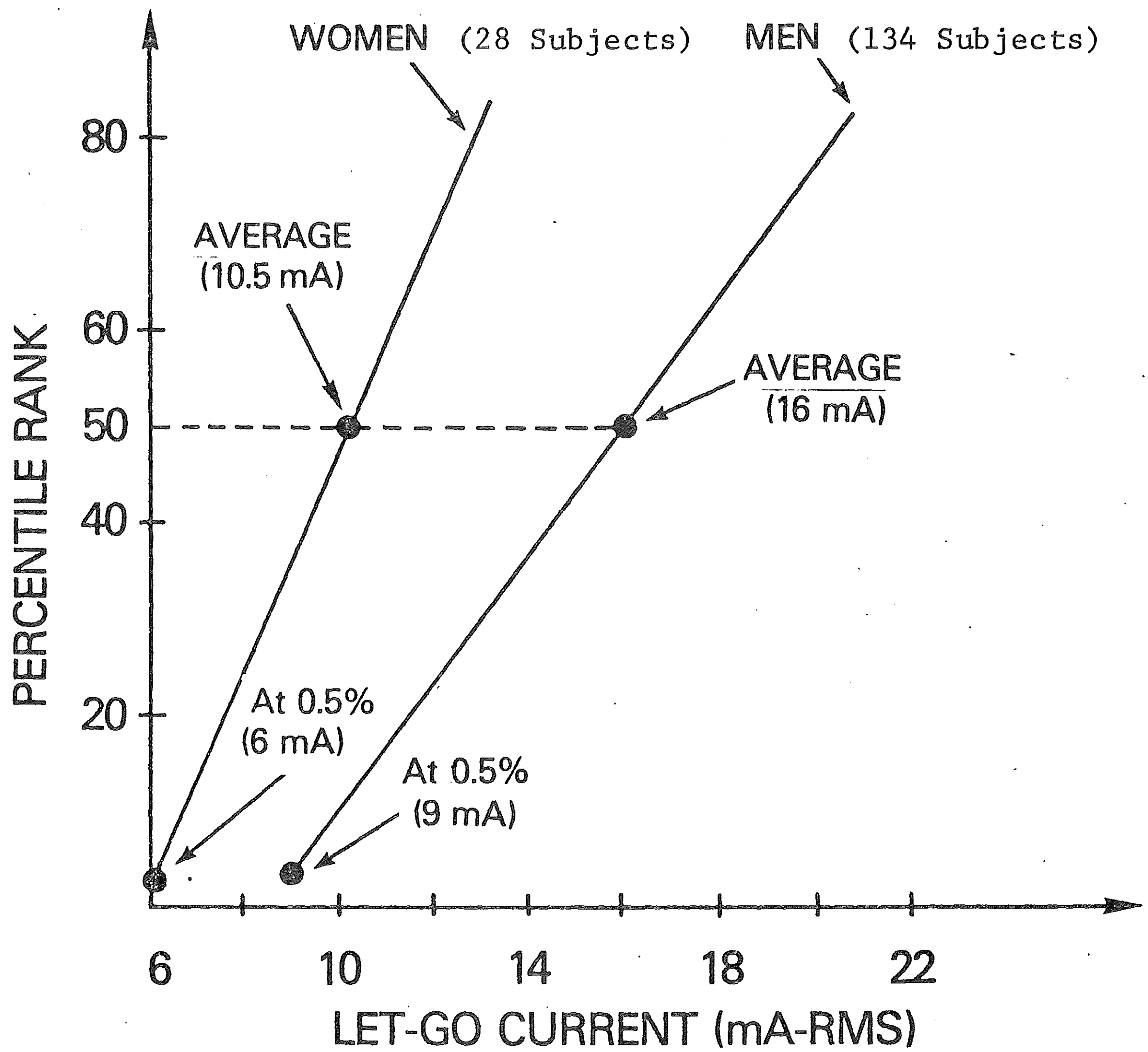
B. DC Steady-State Currents. Recommended perception and let-go thresholds are not available for DC currents. However, using comparable logic to that used for AC current thresholds to extrapolate the data presented in Table II-3, the perception threshold appears to be about 2.4 milliamperes and the let-go threshold, about 31 milliamperes. This is admittedly a risky process; consequently, these are not recommended criteria and their derivation is solely to provide a point of reference for discussion of DC transmission line ion current safety effects hereinafter.

Another approach, implicitly included in the National Electrical Safety Code, is simply use of AC crest voltages for DC criteria. Using this approach, the perception threshold is 1.4 milliamperes and the let-go threshold, 7.1 milliamperes. This may be excessively conservative in view of the sensitivity of the human body to 60-hertz currents, as shown in Figure II-3.

As this discussion indicates, additional research into DC secondary shock currents is clearly warranted.

FIGURE II-4

60-HERTZ LET-GO CURRENT DISTRIBUTION



Source: Dalziel and Lee, 1969

(Adapted from Anonymous, 1976b)

C. Discharge Current. As a grounded human subject comes into contact with an object capacitively coupled to a transmission line, a series of one or more small-arc or spark discharges may occur before firm contact is made. For a DC line, a single discharge may occur, in the AC case, one or more may occur each half cycle. These result from discharge of the stored energy in the object and are of very short duration (less than one millisecond). After firm contact is made, a steady-state current may also flow.

Spark discharges are very similar to a familiar carpet shock. Since the open-circuit voltage in both cases can be in the range of 1,000 volts or more, it is worthwhile repeating IIT Research Institute's findings to put the matter in perspective:

> *During days of low humidity, as a person walks across a rug, a charge accumulates in his body. This can build up to surprisingly large values, sufficient to cause potential differences in the order of 10,000 volts between the body and nearby grounded objects. The static field intensity near the body surface, will range between 10 to 15 kilovolts per meter. Near the finger tips just before arc-over, this field intensity obviously must surpass 2500 kilovolts per meter--the voltage breakdown of air. The peak current flowing during arc-over may rise to a few tens of amperes. The energy content can be in excess of 10^{-3} watt seconds or joules. These discharges via humans have caused reliability problems during the manufacture of transistors, and have caused explosions in hospitals during anesthesia where combustible gases are present. As a result of such naturally occurring problems, various mitigation techniques have been developed which are also roughly applicable to the power-line situation. These include the use of partially conductive soles on shoes and conducting asphalt floors and a variety of grounding techniques. Discharge currents can also be reduced by using insulated gloves or clothing materials. (Anonymous, 1976a)*

There has been relatively little research done in human response to spark discharge in the range of concern in the transmission line environment. Dalziel has reported a threshold for "unpleasant" shock energy of 250 millijoules (one joule equals one watt-second of electrical energy) for single pulse discharges from capacitors (*Anonymous, 1975b*). Utilizing another source, IIT Research Institute finds the same value as the "involuntary reaction" threshold (*Anonymous, 1976a*). In the absence of better data, we recommend use of this value as the maximum discharge energy to be experienced under DC transmission lines; however, its applicability to the AC environment--where one or more spark discharges can occur each half cycle--is questionable.

Limited work at Project UHV in the AC environment suggests a perception threshold of 0.12 millijoule for adult males. Barthold et al. (1976) suggest an annoyance threshold of two millijoules, again for adult males. Without recommending use of these values as performance standards, they are used for discussion purposes later in this chapter.

Transmission-line-associated-spark discharges are secondary shocks and, like their steady-state counterparts, can be annoying, painful and fatiguing. The limited research to date strongly suggests the need for further characterization of this phenomenon, particularly in the AC transmission line environment. The recommendation in Chapter V for "psycho-shock" research is intended to include, and probably emphasize, discharge current effects on human subjects.

AC SAFETY CRITERIA

The limiting safety criterion for AC overhead transmission line electric fields occurs in the situation where a grounded individual comes in contact with a large conductive object located in the field which is fully or partially insulated from ground, such as a vehicle, wire fence or a structure with large metal components. Unless deliberately grounded, these objects can be conceptualized as one plate of a large capacitor, the other plate being the ground surface. The "equivalent area" and "effective height" above ground of this conceptual plate are both functions of the size and geometry of the object (*Anonymous, 1975b*). In any realistic situation, the plate will have some leakage resistance to ground, created by the carbon content of tires, contact with blades of grass, etc. (*Anonymous, 1975b; 1976a*).

Immersed in an AC transmission line electric field, the object will develop a potential with respect to ground, the aforementioned "open-circuit voltage," V_{oc}, and thus will be oppositely charged each half-cycle (1/120 second). When a connection to ground is made, a steady-state, "short-circuit-to-ground" current, I_{sc}, will flow resulting from capacitively coupled energy transfer from the line to the object.

IIT Research Institute divides these effects into "voltage dominant" and "current dominant" hazards to human subjects. V_{oc}, in the absence of a leakage resistance to ground, can reach values of several thousand volts; however, the stored energy even in this idealized case is small. The effect on a grounded human subject just prior to making firm contact with the object can be one or more spark discharges (*Anonymous, 1975b and 1976a*), resulting from discharge current flow.

Current dominant effects occur after firm contact with the object is made. In this situation, a steady-state current will flow through the body from the point of contact to ground. The body resistance is relatively low compared to the source impedance, and the actual current experienced can approach the theoretical I_{sc}. Therefore, as a limiting safety criterion, specification of the maximum allowable short-circuit-to-ground current is appropriate.

Vehicles, in contrast to fences and structures, present the greatest hazard due to difficulty in obtaining a satisfactory ground. In their report for Northern States Power Company, Barthold et al. (1976) analyzed several vehicles with respect to both stored energy and I_{sc} criteria at "perception," "annoyance" and "safety" thresholds, as shown in Table II-4.

As mentioned, we find the 25-joule safety threshold in Table II-4 is quite inappropriate; however, the five-milliampere (let-go threshold) level is reasonable and is also specified in the new edition of the National Electrical Safety Code (*Anonymous, 1977b*). Thus, this table indicates that if the Minnesota Environmental Quality Board maintains its 8-kV/m maximum vertical electric field gradient standard as a criterion for <u>both</u> public health and safety reasons (and a recommendation to this effect is included in Chapter V), the only vehicles not meeting NESC requirements are buses and trailer trucks. Such vehicles can reasonably be expected to be located only on roads; thus, if the maximum gradient for AC overhead transmission lines is limited to 6 kV/m at public road crossings and on the road surface where the right-of-way is adjacent to and parallels such roads (which is also recommended), NESC safety requirements will be met. Note that this approach specifies the vertical maximum electric field gradient--which is both readily calculatable and measurable--as an implicit safety performance standard, rather than explicit specification of I_{sc}, which is considerably more difficult to measure and thus enforce.

TABLE II-4

LIMITING GRADIENTS FOR SPECIFIED CRITERIA

		Automobiles, Pickup Trucks	Crop Wagons	Farm Vehicles	Buses, Trailer Trucks
Dimensions					
	Length (ft.)	20	20	25	50
	Overall				
	Height (ft.)	8	13.0	13.5	13.5
	Width (ft.)	6	7	8	8
Effect	Current Dominant/ Voltage Dominant Criteria	Limiting Gradients (kV/m)			
Safety	5 milliamperes/	22.32	11.62	10.86	6.33
	25 joules	259.00	167.00	159.00	106.50
Annoyance	2 milliamperes/	8.92	4.65	4.35	2.50
	2 millijoules	2.37	1.47	1.41	0.95
Perception	1.1 milliamperes/	4.91	2.56	2.39	1.39
	0.12 millijoules	0.58	0.36	0.35	0.23

Source: Barthold et al. (1976)

The reader is cautioned at this point that actual exposure to a five-milliampere current is highly unlikely. A I_{sc} of this magnitude requires a well-insulated vehicle and a well-grounded human subject, which in most practical situations are contradictory requirements. Further, the vehicle must be located parallel to and directly underneath an outer phase conductor at midspan and under conditions of maximum conductor sag. The probability of simultaneous occurrence of all these conditions is extremely low. Nonetheless, this standard does ensure no possible exposure to primary shock currents.

One exception to this overall strategy is, however, recommended in Chapter V. Loading and unloading of students into and from school buses should not occur on a right-of-way if at all possible. In the situation where this is not possible, as when the right-of-way parallels a road, bus stops should be located at points where the field strength will induce a shock at the perception threshold or less; e.g., 1.2 kV/m, as extrapolated from Table II-4. This recommendation is in recognition of the relatively large size of a school bus, the number of individuals involved, the fact that they as a group, are considerably smaller than adults, and the real possibility of dissimilar surfaces (e.g., pavement and shoulder) for the vehicle and the subject.

Improperly grounded fences can also represent a shock hazard. For example, an ideally insulated wire fence one meter above ground and 150 meters long will produce a I_{sc} of five milliamperes in an 11-kV/m vertical electric field, with a maximum discharge energy of 60 millijoules (*Anonymous, 1975b and 1976a*). The Rural Electrification Administration has done an extensive theoretical analysis, confirmed by field experience, of both fence and structure grounding requirements for protection from "electrostatic (E/S)" effects (*Anonymous, 1976b*). For AC lines of 230 kV and below, the REA concludes that "as a general rule, E/S effects should not be a problem on typical rural system transmission lines," but for lines 345 kV and above, fence and structure grounding should be utilized, with recommended requirements shown in Tables II-5 and II-6, respectively. With regard to these requirements, the REA states:

> *Fences, Non-Electric - Recommended ground intervals for non-electric fences parallel to transmission lines are specified in (Table II-5) for line voltages of 345, 500 and 765 kV. For non-electric fences that cross the transmission line right-of-way (ROW) at right or oblique angles, it is recommended that the fence be grounded at the edges of the ROW.*
>
> *Fences, Electric - In conjunction with the grounding intervals specified in (Table II-5), it is recommended that the electric fence charger be an Underwriter's Laboratory approved capacitive discharge type, coupled with the installation of separate 60 Hz series filters at the grounding locations. This procedure permits proper operation of the electric fence while reducing the 60 Hz E/S induced voltages from overhead transmission lines to acceptable levels. For electric fences that cross the transmission line ROW at right or oblique angles, it is recommended that the fence be grounded and 60 Hz series filters be located at the edges of the ROW.*
>
> *Buildings, Roofs and Gutters - The grounding criteria in (Table II-6) is recommended for metallic surfaces near 345, 500 and 765 kV transmission lines. This grounding also pertains to all buildings with metal components including roofs, gutters, and downspouts. (Anonymous, 1976b)*

Generally, the REA recommendations have been adopted by the State in recent construction permits. Table II-5 specifies fence grounding intervals to achieve a I_{sc} of both one and five milliamperes. Since stationary objects are readily grounded, it is recommended that the one-milliampere short-circuit-to-ground intervals continue to be utilized, to limit current exposure to approximately the perception threshold.

TABLE II-5

FENCE GROUNDING INTERVALS FOR LINE VOLTAGES 345 kV AND ABOVE
(Capacitive Coupling Protection)

LINE VOLTAGE (kV)	FENCE LATERAL DISTANCE FROM CENTER OF ROW (FEET)	FENCE GROUNDING INTERVAL FOR I_{sc} = 1 mA* (FEET)	FENCE GROUNDING INTERVAL FOR I_{sc} = 5 mA** (FEET)
345	Within 75	200	1,000
500	Within 125	150	750
500	Between 125 and 250 (Min.)	200	1,000
765	Within 175	125	625
765	Between 175 and 375 (Min.)	200	1,000

* = Perception Threshold Current

** = "Let-Go" Threshold Current

Source: Anonymous, 1976b

TABLE II-6

METALLIC OBJECT GROUNDING CRITERIA FOR LINE VOLTAGES 345 kV AND ABOVE
(Capacitive Coupling Protection)

LINE VOLTAGE (kV)	OBJECT HORIZONTAL DISTANCE FROM OUTSIDE PHASE CONDUCTOR (FEET)	MINIMUM AREA OF METALLIC SURFACE REQUIRING GROUNDING (SQUARE FEET)	MINIMUM LENGTH OF GUTTER REQUIRING GROUNDING (FEET)
345	Within 75	*	*
345	Between 75 and 100 (Min.)	2,000	150
500	Within 100	*	*
500	Between 100 and 150 (Min.)	2,000	150
765	Within 130	*	*
765	Between 130 and 215 (Min.)	2,000	150

* = No minimums are specified. Consideration should be given to grounding of any insulated metallic object.

Source: Anonymous, 1976b

As noted previously, certain AC transmission line fault conditions can, through inductive coupling, produce potentially hazardous current dominant effects for the duration of the fault in long, parallel, improperly grounded, conductive objects. The objects of particular concern herein are wire fences in the proximity of the transmission line right-of-way. Using Dalziel's electrocution equation, the REA has also developed recommended fence grounding intervals for protection of 50-kg (110 pound) subjects from ventricular fibrillation (Table II-7). This analysis does not limit current exposure to five milliamperes; however, it will provide adequate protection in this unlikely combination of events. The footnote to Table II-7 indicates that the grounding intervals assume a three 60-hertz cycle clearing time. In any application of the REA's analysis, fault clearing time must be considered, as well as possibly the number of attempts at re-energization (reclosures) since these occur in a small number of cycles. This latter point, particularly, may need further laboratory investigation. Dependent upon the line voltage, line configuration and anticipated fault currents and clearing time, fence grounding requirements will be determined by the intervals specified in Table II-5 or in Table II-7.

The REA analysis is well done; however, it would be worthwhile to confirm its analysis both theoretically and experimentally, extended to include inspection and maintenance requirements for grounds. These are not power grounds (*Shah et al., 1977*); thus, maintenance and inspection need not be as stringent as those required for transmission line and substation grounds. However, there has been no known effort as yet to determine the extent to

TABLE II-7

FENCE GROUNDING INTERVALS
FENCE GROUNDING INTERVAL FOR A SINGLE LINE-TO-GROUND FAULT, FEET
(Inductive Coupling Protection)

FAULT CURRENT AMPERES	69 kV	115 kV to 230 kV	345 kV*
1,000	5,000	7,000	10,000
5,000	1,000	1,400	2,000
10,000	500	700	1,000
20,000	250	350	500
30,000	170	235	335
40,000	125	175	250
50,000	100	140	200

*For similar parameters such as a three cycle fault clearing time, these grounding intervals are considered adequate for voltages between 345 and 765 kV. If the fault clearing time is different than three cycles, the grounding intervals should be modified.

Source: Anonymous, 1976b

which this should be done for fence and structure grounds. A recommendation incorporating this point is included in Chapter V.

In view of the extensive research of physiological responses of the human body to 60-hertz currents, it is not surprising to find contemporary standards established in terms of current dominant criteria. Further, as the field strength is increased, as shown by Table II-4, the five-milliampere let-go threshold is reached long before the 25-joule ventricular fibrillation threshold; hence, it is a proper safety standard.

However, the same table demonstrates that perception and annoyance for voltage dominant effects are reached in considerably lower gradient fields than are equivalent current dominant effects. In too much of the technical literature concerned with electric field phenomena, voltage dominant effects on human subjects are dismissed as "harmless" spark discharges. While it is true that these are physiologically "harmless," this attitude nonetheless masks proper concern for possible secondary effects.

Numerous complaints were received in response to our notice (Appendix D) from Minnesota farmers regarding shock experience with agricultural equipment in the proximity of 345-kV AC overhead transmission lines. In all likelihood, these complaints were concerned with spark discharges, rather than steady-state currents; however, this remains to be assessed. Nonetheless, we find these complaints to be reasonable and legitimate, suggesting a possible problem for agricultural workers that should be investigated, particularly when considered in the context of the higher electric field gradients anticipated in the future. Consequently, Chapter V suggests further assessment of the magnitude and extent of this problem and effectiveness of current mitigative measures utilizing funds available under the Power Plant Siting Act.

IITRI, in its recommendations to ERDA, suggests a similar study (*Anonymous, 1976a*). It is possible that if the State were to adequately scope the problem and design and propose a comprehensive research program for mitigative measures, Federal funding might be available for further work. Such a project would require comprehensive analysis of human response to various levels of secondary shock current, in addition to analysis in the agricultural environment. For the latter, variables include such factors as soil resistivity, contact resistance, crop and equipment types, equipment component bonding, leakage resistance, etc.

DC SAFETY CRITERIA

Corona-induced ion currents are the predominant effect of concern with DC overhead transmission lines. Ion currents are somewhat analogous to AC displacement currents in that both serve as the coupling mechanism between the conductors (poles) and a conductive object located in the proximity of the line. In contrast to AC coupling effects, however, DC coupling mechanisms are not as yet well quantified (*Anonymous, 1976b*). DC electric field strengths and ion current densities are highly variable due to changing atmospheric conditions, and long-term statistical data is needed for quantitative analysis of these dependent variables (*Anonymous, 1977a*).

Nonetheless, the extremely low current densities encountered, combined with higher perception and let-go thresholds for DC current, indicate that voltage dominant effects predominate. This is in marked contrast to the AC environment where both voltage dominant and current dominant effects must be evaluated.

Voltage dominant effects consist of the same spark discharge phenomena discussed with respect to AC lines, with several significant differences (*Anonymous, 1976b*):

1. Slow charging rate.
2. Finite resistance of any normal insulation, which is able to leak off and thus limit the charge.
3. Infrequent discharge, not every 1/120-second as is the case with AC capacitive coupling.

The net effect is that any reasonable object is not able to collect a sufficient charge to constitute a significant hazard to a grounded human subject coming in contact with it. While we acknowledge that systematic characterization of ion currents has not been done, a few examples will verify the reasonableness of this position, even in the absence of such research (*Anonymous, 1977a*):

1. Using analytical techniques, a normally grounded individual coming in contact with a large vehicle having a high, but not infinite, resistance to ground, and intercepting 1,000 microamperes of ion current, will receive an estimated 5 millijoules of stored energy, a perceptible "carpet shock." Once contact is made, the steady-state current experienced is limited to the intercepted ion current (1.0 milliamperes), which is less than the estimated 2.4 milliampere perception threshold.

   Tests on a 14 meter x 2.4 meter x 4 meter trailer truck showed that the DC steady-state current did not exceed 300 microamperes, which is almost an order of magnitude less than the estimated perception threshold. The test was performed under a $\pm$600-kV line on a misty morning with a clearance of less than 2.5 meters between the top of the truck and the poles.

2. Tests were conducted on a series of wire fences parallel to the right-of-way center line for a $\pm$600-kV line with an average line-to-ground clearance of 13 meters.

Each fence was 61 meters in length, with untreated Douglas fir posts at approximately 6 meter intervals; e.g., 11 posts per fence. Each fence consisted of a single 4-point, 2-strand, 12½-gauge barbed wire one meter above ground. Posts were 1.8 meters long, 0.6 meter of which was in the earth.

The closest fences (4.6 meters laterally outside a point directly under the nearest pole) had a short-circuit-to-ground current exceeding 0.2 milliamperes only one percent of the time. Extrapolating these results, a 730-meter (approximately 0.45 mile) fence would produce a current exceeding the estimated 2.4 milliampere perception threshold approximately one percent of the time. Similarly, to develop the estimated 31-milliampere let-go threshold, an ungrounded fence at the edge of the right-of-way would have to be 15 kilometers (9.4 miles) in length.

Voltage dominant effects are achieved with shorter fences. The closest fence will achieve the 0.25-joule "uncomfortable shock" level when the fence reaches 1,500 meters; however, the threshold of perception is reached at only 20 meters.

This fence is well within the right-of-way. At 17 meters laterally outside from a point under a pole, which would correspond to a typical edge-of-right-of-way, perception is not reached until the fence is 600 meters in length.

3. A simulated shed roof 6 meters by 3 meters, was located 30 meters from the positive pole of the aforementioned line, supported by the same posts. Studies indicate that the intercepted current was less than 4 microamperes (which is equivalent to an ion current density of 220 nanoamperes per square meter) 99 percent of the time. For the short-circuit-to-ground current to exceed the estimated 2.4 milliampere perception threshold, the panel would have 10,800 square meters (116,000 square feet). An ungrounded surface of this size will not be found anywhere near a transmission line.

These examples, while demonstrating the relatively low shock hazard of objects in the proximity of DC lines, nonetheless still indicate that metallic grounding is required, although fence grounding intervals can be considerably relaxed relative to AC requirements. However, since it appears that stationary objects are unable to collect a sufficient charge to constitute more than an annoyance and since a theoretical and/or experimental basis is not yet available upon which to base grounding intervals, we do not recommend that the Minnesota Environmental Quality Board develop and promulgate grounding standards for DC lines at this time. Rather, it should ensure that the utilities operating DC lines promptly install adequate grounds in response to legitimate landowner, tenant or public complaint of shock experience.

The U.S. Energy Research and Development Administration has recently issued a contract for measurement and characterization of ion currents (see Chapter IV). When this work is complete, the Board should reassess the need for and its ability to specify reasonable fence and structure grounding standards in the proximity of DC lines. A recommendation in Chapter V incorporates this position.

REGULATORY CONTROLS

Within the State of Minnesota, the public safety of high-voltage overhead transmission lines is ensured by provisions of both the Minnesota Electrical Act and the Power Plant Siting Act.

The Minnesota Electrical Act specifies "the then most recently published edition" of the National Electrical Safety Code (NESC) as "prima facie evidence of accepted standards of construction for safety to life and property" (Minn. Stat. § 326.243 (1976)), but exempts from inspection those "installations, materials, or equipment,"

> *. . . owned or leased, and operated and maintained by any electric, communications or railway utility in the exercise of its utility function; and*
>
> *(i) are used in connection with the generations, transformation, distribution, transmission, or metering of electric current, or the operation of railway signals, or the transmission of intelligence, and do not have as a principal function the consumption or use of electric current by or for the benefit of any person other than such utility; and*
>
> *(ii) are generally accessible only to the employees of such utility or persons acting under its control or direction (Minn. Stat. § 326.244, Subd. 5(2)(1976)).*

Pursuant to this language, the State Board of Electricity inspects only those transmission lines owned and operated by non-utilities (*Joriman, 1977*).

Paragraph (ii) can be interpreted otherwise, as mandating inspection of those electric utility facilities accessible to the general public, which includes most of the transmission line circuit-mileage within the State. Such inspection could include both formal engineering plan review prior to construction and periodic or spot-check inspections in the field. With respect to plan review particularly, it is not clear to the extent to which the State can or should involve itself, because of (1) the level and specificity of engineering expertise required for transmission line design in conformance with the NESC and the commitment of such expertise to the electric utility industry; and (2) lack of information as to the extent to which Minnesota utilities voluntarily conform to all of the NESC's provisions, although there is no indication that they do not. Nonetheless, a recommendation to explore the necessity for and feasibility of plan review and inspection is included in Chapter V.

The Power Plant Siting Act mandates State jurisdiction over the routing and licensing of all high-voltage transmission lines rated at 200 kV or higher nominal line-to-line voltage and associated facilities. Minnesota Statute § 116C.57 (1976) and Minnesota Regulation MEQC 73(c)(6) (1974) require issuance of a construction permit specifying the route and other appropriate conditions. In all of the construction permits issued thus far, the Minnesota Environmental Quality Board has specified electrical performance standards and other conditions supplementing those contained in the NESC to further protect public health and safety and to address other environmental concerns.

Thus far, these construction permit conditions have been applied on a largely case-by-case basis. A recommendation is included in Chapter V for the Minnesota Environmental Quality Board or other appropriate State agency to promulgate by rule technical standards of this type, which would assure future procedural fairness, completeness, and uniformity of application. Additionally, the the rule-making process could properly evaluate and balance all of the various engineering, environmental, economic and risk factors involved.

A. National Electrical Safety Code. Safeguards for potential safety hazards associated with high-voltage overhead transmission lines are specified by the American National Standard, National Electrical Safety Code, C2. The standard's abstract summarizes its purpose:

> *This standard covers basic provisions for safeguarding of persons from hazards arising from the installation, operation, or maintenance of 1) conductors and equipment in electric-supply stations, and 2) overhead and underground, electric-supply and communication lines. It also includes work rules for the construction, maintenance and operation of electric-supply and communication lines and equipment.*

The standard is applicable to the systems and equipment operated by utilities, or similar systems and equipment, of an industrial establishment or complex under the control of qualified persons.

This standard consists of the definitions, grounding rules, and Parts 1, 2, 3 and 4 of the 1977 edition of the National Electrical Safety Code. (Anonymous, 1977b)

Adoption as an American Standard "implies a consensus of those substantially concerned with its scope and provisions . . . (and) . . . is intended as a guide to aid the manufacturer, the consumer and the general public." Additionally, the forward to the Code itself states:

The code as written is a voluntary standard. However, some editions and some parts of the code have been adopted, with and without changes, by some state and local jurisdictional authorities. To determine the legal status of the National Electrical Safety Code in any particular state or locality within a state, the authority having jurisdiction should be contacted.

The NESC has been adopted or is used as a guide by at least 31 states (*Anonymous, 1975a*).

Ware (1974) observes, "The NESC is a safety code and not a design manual. Therefore, it should specify minimum but safe values and should not be concerned with combinations of contingencies that each designer considers in arriving at a practical design." This is a recurring theme or commentary regarding the NESC and is at odds with the previously quoted language from the Minnesota Electrical Act recognizing construction in conformance with the NESC as "prima facie evidence of accepted standards of construction . . . ." Consequently, we are somewhat concerned about the possibility of excessively literal application of the code.

Principal concern in this report is with ANSI C2.2-1976, which includes NESC Section 9, "Grounding Methods for Electrical Supply and Communication Facilities," and Part 2, "Safety Rules for the

Installation and Maintenance of Electric Supply and Communication Lines." This standard was adopted on September 16, 1976 as the Seventh Edition of the NESC and incorporating a Part 2--which is directly applicable to transmission lines--revised for first time in 16 years and finally reflecting some consideration of EHV transmission technology.

NESC Part 2 specifies standards related to the design and construction of transmission line structures and conductors, horizontal and vertical clearance, and line insulators. With respect to this study, minimum clearance requirements determine field effects. The NESC recognizes eight land uses which conductors could cross:

> *1. Track rails of railroads (except electrified railroads using over-head trolley conductors);*
>
> *2. Roads, streets, alleys, parking lots subject to truck traffic;*
>
> *3. Residential driveways and commercial areas not subject to truck traffic;*
>
> *4. Other land traversed by vehicles such as cultivated, grazing, forest, orchard, etc.;*
>
> *5. Spaces or ways accessible to pedestrians only;*
>
> *6. Water areas not suitable for sailboating or where sailboating is prohibited;*
>
> *7. Water areas suitable for sailboating including lakes, ponds, reservoirs, tidal waves, rivers, streams and canals with an unobstructed surface area of:*
> *(a) Less than 20 acres*
> *(b) 20 to 200 acres*
> *(c) Over 200 acres; and*
>
> *8. Public or posted private land and water areas for rigging or launching sailboats. (Anonymous, 1977b)*

Of particular concern are the clearances for Item 4 which are "for land cultivated or traversed by vehicles and equipment whose overall operating height is less than 14 feet" (*Anonymous, 1977b*). This may well be inadequate for Minnesota farming operations, and a survey of agricultural equipment operating heights is recommended in Chapter V.

To these basic clearances are added increments for line-to-ground voltage, elevation above sea level, span length and maximum conductor temperature. The resulting clearance is primarily set to prevent flashover, which has been the predominant safety concern with respect to vertical clearance in earlier NESC editions. It should be noted that the concern in earlier editions was exclusively with AC transmission. In the new edition, language is added stating that the computed clearance is "applicable to both alternating and direct current circuits. For direct current circuits, the clearance requirements shall be the same as those for alternating current circuits having the same crest voltage to ground."

The edition also recognizes electrostatic effects for the first time, with language specifying that "clearances shall be increased or the electric field shall be reduced by other names, as required, to limit the current due to electrostatic effects to 5.0 milliamperes, rms, if the largest anticipated truck, vehicle, or equipment under the line were short-circuited to ground." This is based on the AC let-go threshold. A comparable DC value (7.1 milliamperes) could reasonably be argued to be applicable to DC lines, although as noted previously this may be excessively cautious.

This language requires specification of such "truck, vehicle or equipment" (*Shah, 1977*), which the State is not presently doing. However, the recommended practice of specifying the maximum vertical electric field gradient as a performance standard will implicitly assure meeting NESC requirements. The NESC itself does not as yet contain any restrictions on discharge energy which would provide protection from spark discharges.

Section 9 on grounding applies only to the transmission line facilities and does not cover non-utility-owned wire fences, structures with large metal components, etc. located on or near the right-of-way, nor bonding and grounding standards for equipment used in the vicinity of the right-of-way. Generally, utilities have established their own grounding policies for fences and structures (*Shah et al., 1977*).

The National Electrical Safety Code is an industry code and is updated cautiously, lagging technology advancements by years. For example, in the 16 years between the sixth and seventh editions, commercial transmission voltages more than doubled. Further, during this same period, there was considerable recognition throughout the industry that electrical effects other than flashover must be considered from a safety perspective. Nonetheless, the only provision in the new (seventh) edition directly relating to these phenomena is the five-milliampere standard cited above. One can only conclude that code revision is inherently a reactive process and is thus an inappropriate forum for adequate debate and consideration of public health and safety standards.

In spite of these limitations, the NESC is widely respected, accepted and utilized. It would appear to be the appropriate ultimate repository for both safety standards and any eventual field strength and/or exposure duration standards, as these appear consistent with the philosophy of the NESC as a safety code.

B. Construction Permits. As mentioned, the Minnesota Environmental Quality Board has included provisions in its transmission line construction permits extending standards contained in the National Electrical Safety Code. The most recent permit, issued to Minnesota Power and Light Company (Docket No. MP&L-TR-1A), specifies the following conditions relative to public health and safety.

1.13) Prior to the signing of an individual easement, MP&L shall provide the affected landowner and tenants with:

(a) A copy of this construction permit; and
(b) A brochure informing the public of safety precautions to be observed when under or near the HVTL. This brochure shall also be available upon request to members of the public.

1.18) Where the HVTL crosses or runs adjacent to cultivated lands, a sign shall be posted on each tower structure warning farm equipment operators not to refuel their equipment in the vicinity of the HVTL right-of-way.

1.19) MP&L must promptly report to the MEQC any complaint received about construction, operation and maintenance of the line during the entire period of the line's existence. Reporting procedures established by the MEQC are described in Attachment I of this permit.

1.20) MP&L shall make available to the MEQC, for informational purposes only, its plan for inspection of the HVTL and associated facilities as required by the 1977 Edition of the National Electrical Safety Code (NESC) Rule 214-A-2.

2.1) The HVTL shall be designed, constructed, and operated in such a manner that the maximum steady state short-circuit current shall be limited to 5 milliamperes rms ac and the maximum capacitive discharge energy shall be limited to 25 joules between the ground and any non-stationary object within the HVTL right-of-way including, but not limited to, large motor vehicles, agricultural equipment and implements or irrigation devices.

MP&L shall, at its expense, ground all stationary objects to meet the following standards:

(a) Non-electric metal fences paralleling or crossing the right-of-way shall be grounded by the applicant in such a manner so that the short-circuit current to ground, under steady state conditions, will not exceed 1 milliampere rms.
(b) Electric fences parallel or crossing the right-of-way shall be grounded by the applicant by the installation of 60 Hz filter devices so that the short-circuit 60 Hz current, under steady state conditions, will not exceed 1 milliampere rms. Existing chargers shall be replaced at the applicant's expense if necessary to meet this requirement. Chargers shall be a compatible Underwriters Laboratory approved type.
(c) All metal structures or metal parts of structures in the right-of-way of the HVTL shall be grounded by the applicant in such a manner so that the short-circuit to ground, under steady state conditions, will not exceed 1 milliampere rms.

2.2) The above requirements notwithstanding, the applicant shall also ground any fence or stationary object on or off the right-of-way so the short-circuit current to ground, under steady state conditions shall not exceed 1 milliampere rms when:

(a) Prior to initial operation, where the calculated shock would exceed 1 milliampere rms.
(b) On a continuing basis in response to a legitimate complaint or request by a landowner or tenant.

2.3) The HVTL shall be designed, constructed and operated so that:

(a) The electric field measured one meter above ground level shall not exceed 8.0 kV/m rms.
(b) It complies with Minn. Reg. Noise Pollution Control NPC-2. The provisions of NPC-1(c) and Minn. Reg. MPCA-6 shall govern any request for a variance therefrom.
(c) The ground level concentrations of ozone and oxides of nitrogen attributable to the HVTL shall not exceed MPCA Ambient Air Quality Standards.

Several of these conditions (Nos. 1.18, 1.20, the portions of 2.1 dealing with stationary objects, and 2.2) are a direct consequence of this study. Nonetheless, there are still inadequacies in these provisions that need attention:

1. (Condition 1.13) The brochure "informing the public of safety precautions" presumably will address bonding and grounding requirements for agricultural equipment. This may be an inappropriate requirement to levy on the applicant without an independent assessment of the secondary shock problems associated with the usage of agricultural equipment in the vicinity of transmission lines, followed by development of any necessary rules.

2. (Condition 1.19) The complaint reporting mechanism is not oriented toward data requirements to fully assess the safety hazard associated with transmission lines. An adequate reporting mechanism for both operational problems creating hazards and accidents should be established.

3. (Condition 2.1) The 25-joule capacitive discharge energy standard is inappropriate, inasmuch as a single pulse discharge of this magnitude is at the calculated threshold range for ventricular fibrillation in human subjects.

As discussed previously, a more appropriate value is 0.25 joule. While short-circuit requirements are the limiting criteria with AC lines, this standard will limit DC line design and should be incorporated in all future construction permits for such lines.

4. (Condition 2.1) Provisions for periodic inspection and maintenance of wire fence and structure grounds after installation should be included.

Recommendations addressing each of these issues are included in Chapter V.

SUMMARY AND CONCLUSIONS

The electric, magnetic and space charge fields existing in the proximity of energized AC and DC overhead transmission lines provide "coupling" mechanisms whereby small amounts of electrical energy are transferred to conductive objects within the fields. Such objects include vehicles and other non-stationary equipment, wire fences and structures, as well as biological organisms.

These coupling mechanisms differ significantly for AC and DC transmission line environments. For AC lines the vertical steady-state electric field and the transient magnetic field are of principal concern. These can, however, be decoupled and considered as independent phenomena. Corona effects are completely separate and do not enter into any analysis of field effects.

In contrast, for the DC case, consideration must not only be given to the electrostatic field, but also to corona effects--in terms of the space charge field--to describe the composite vertical electric field effect; in fact, it can be reasonably be argued that the space charge field--from a public health and safety perspective--is the dominant DC effect.

As with AC, DC steady-state magnetic fields do not appear to be of concern; unfortunately, there is little analysis to indicate whether transient magnetic fields can create a safety problem. This should be investigated, and a recommendation to this effect is included in Chapter V.

In summary, one major conclusion of this report is that equal AC and DC field magnitudes do not characterize comparable proximity effects. This distinction must be recognized in transmission line regulatory proceedings, as noted in Chapter V.

The energy transferred to biological organisms--including human subjects--via the coupling mechanisms associated with these fields can occur either directly or indirectly. Direct exposure has been a matter of considerable public concern. In fact, this was the original impetus for this study and is discussed in considerable detail in Chapter III.

Indirect exposure occurs where some other conductive object, wholly or partially insulated from ground, is the collector of the transferred energy. In this situation, this is the coupling effect of concern, and the hazard occurs when a grounded human subject comes into contact with the object. The subject is then exposed to the passage of electrical energy through the body, including possibly both a discharge current and a steady-state current. Most conductive objects usually found in the proximity of transmission lines are not capable of collecting sufficient energy to constitute a primary shock hazard, although very large vehicles in the proximity of AC transmission lines can be somewhat above the let-go threshold; as a result, greater clearances should be maintained in the proximity of public roads where necessary.

Electric and non-electric wire fences and other stationary structures can be readily grounded to the level of perception of shock current. This is a reasonable requirement to be imposed on Minnesota electric utilities and Chapter V recommends that standards for installation, inspection and maintenance of metallic fence grounds be developed, promulgated and enforced by the State.

Vehicles and other non-stationary equipment are not as readily grounded and therefore can present a secondary shock hazard. Such shocks, while not physiologically harmful, can be annoying, painful and if occurring frequently, fatiguing. In addition, secondary shocks can cause involuntary muscular reactions, which can be hazardous if the subject is working near machinery or loses his/her balance.

Several complaints have been received from Minnesota farmers complaining of this problem while operating agricultural equipment in the vicinity of 345-kV AC lines. While it is not known whether the concern is over discharge current prior to contact or the steady-state current after contact, these complaints are theoretically reasonable, and therefore, we have every reason to believe they are legitimate. It is also not known what expertise the owning utilities have to mitigate such shock problems, nor what incentive they have to do so. The Minnesota Environmental Quality Board Power Plant Siting Staff has a complaint reporting procedure which should be utilized to ensure prompt application of effective mitigative measures. In addition, these complaints should be further analyzed by measurement of the discharge energy and/or short-circuit-to-ground current under the field conditions causing the shock. There is limited information available here, and such data would greatly assist scoping the magnitude and extent of this problem.

Finally, overhead transmission line performance standards adequate to protect the public safety can be specified in terms directly interpretable by the design engineer. For AC lines, specification of the maximum electric field gradient constrains both capacitive discharge energy and steady-state current. Comparable DC parameters include the composite electric and space charge field gradient and ion current density. These quantities can be readily measured with portable instrumentation for monitoring and enforcement. This is noted in contrast to attempting to locate the "largest anticipated truck, vehicle or equipment" (*Anonymous, 1977b*), positioning it on insulated pads at a point midway between support structures and outside one of the outer conductors under conditions of maximum sag, and finally, measuring the short-circuit-to-ground current. Consequently, we recommend use of the aforementioned parameters as performance standards.

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III. BIOLOGICAL EFFECTS

The spectre of possible long-term, adverse human health effects from exposure to the transmission line field environment has caused some public anxiety in recent years. As reported in Appendix C, much of this concern is based on reports from Russia where studies of worker exposure to electric fields in the AC switchyard environment suggests various nonspecific central nervous system disorders. The only similar research in the United States was a nine-year study of ten linemen which found no adverse health effects. While these findings appear superficially contradictory, there are significant differences in the work environments for the two groups of workers as well as study design deficiencies in both studies, making comparisons, as well as definitive conclusions, difficult. These studies, along with representative examples of other human and animal research, are described and critiqued in this chapter together with a summary of proposed and existing standards for electric and magnetic field exposure. This review is primarily concerned with biological effects of AC electric fields, although effects of AC magnetic fields and DC electric fields are also briefly discussed.

In evaluating this material, several factors must be appreciated (*Reilly, 1977*):

1. Both the Russian and United States studies of utility workers are deficient in terms of experimental protocol and reporting of results. In the case of the Russian switchyard workers particularly, other environmental stresses may also be involved.
2. Unshielded switchyard workers and linemen experience higher field strengths than the public on the right-of-way, exposed at ground level. This point obviously may not apply to agricultural workers operating equipment in elevated positions.

3. The maximum electric field strengths cited for the transmission line environment in Chapter II assume maximum conductor sag, which occurs only at high ambient temperatures and maximum current flow. Actual peak gradients will generally be less than these calculated maximums.

4. Exposure to peak gradients occurs only under the outer conductors at the point of maximum sag. Average field strengths on and off the right-of-way are considerably less.

5. Exposure duration (chronic versus intermittent) varies significantly for switchyard workers, linemen and the general public.

It is not anticipated that transmission line AC magnetic fields (see Chapter II) will have deleterious effects. Magnetic field effects are well documented and as a general statement, observed effects occur at field strengths much higher than those encountered under transmission lines.

Recommended standards for exposure (discussed later in detail) are two to three orders of magnitude greater than transmission line magnetic fields. However, these standards are not based on good biological data (*McCall, 1975*), and evidence from recent human and animal experiments suggests that there may be biological effects of uncertain significance at fields as low as one gauss (*Sheppard, 1977*). The significance of this data to the still lower AC transmission line magnetic field remains to be demonstrated.

Little research to date has been done on the possible biological effects associated with DC transmission lines, probably because of the newness of this technology in the United States. The only mechanism for low-intensity DC electric fields to induce current flow in exposed biosystems is by means of conductive coupling. Research is limited by a lack of suitable instruments to measure those fields. Generally, no documented hazardous effects have been reported in experimental work involving DC electric fields.

One of the more important electrical phenomena associated with DC lines is the ion current associated with the space-charge field (see Chapter II). Air ions are a controversial matter, with experimental work yielding conflicting results. The presence of the right kind of ions is believed to cause beneficial effects while the wrong type of ions have been suggested to produce such effects as fatigue and irritability (*Bridges, 1975*). The ion concentration in air has been associated with changes in the development of experimentally induced influenza in mice. However, other investigators have concluded that biological effects of air ions if they do exist, are weak (*Krueger, 1972*). Because of these implications, air ions cannot be ignored and further investigation is indicated.

The possible biological effects due to AC electric fields have been investigated more fully than for DC fields; as a result, the possible electric field effects on man and animals resulting from exposure to AC transmission line electric fields can be discussed more fully in the remainder of this chapter.

POSSIBLE MECHANISMS OF ACTION

In order for electric field effects to be observed the field must interact with the organism at some level, be it the whole organism, at the cellular level, or at some intermediate level. The possible mechanisms of action of AC electric fields are as follows (*Bridges, 1975; Kornberg*):

1. Induced external fields on the surface of the organism. For electric fields under transmission lines the only known surface effect is a mechanical effect on hairs of exposed skin. This effect is related to displacement current surface density and proportional to frequency (*Schmitt, 1977*). In a 60-Hz field the threshold of perception of this effect is about 10 kV/m.

2. Induced displacement currents in exposed biomaterial. The displacement current running through an organism will be on the order of 100-200 microamperes. This is well below the threshold of perception (*Cabanes, 1976*).

3. Induced angular vibration at power-line frequencies in susceptible macromolecules and colloids containing dipoles. Occurrence of any biologic effect requires an interaction of the induced body currents or exterior surface field with some part of the body.

The distribution of internal electric fields in a biological system is influenced by the shape, orientation and inhomogeneities in the conductivity of the system. Thus, internal current densities in long thin conductive objects will be greater than for flat objects. At the microscopic level all living tissue is inhomogeneous, some being more conducting than others (*Carstensen*). Although biological material is more conductive than air, the body provides natural internal shielding from electric fields (*Schmitt, 1977*). Electric fields under transmission lines are not strong enough to cause nerve stimulation or tissue heating. The transfer of energy from these fields to exposed biologic systems is so small and biological functions so complex and intertwined that recognition of true biological effects caused by electric fields is very difficult (*Kornberg*).

HUMAN STUDIES

Extensive human studies, both epidemiological and experimental, have not been conducted. Heightened interest in biological effects of transmission line electric fields originated with reports from Russia in 1972 on the health status of high-voltage switchyard workers. Studies of electric field effects on humans have been carried out in the USSR since 1962. T. E. Sazanova and A. I. Rakov

(1967) conducted a physiological assessment of persons working in 500-kV AC open switchyards. Two groups of workers were compared: operating personnal not working under electric field exposure for more than 2 hours/day (29 persons); and maintenance personnel not exposed less than 5 hours/day (25 persons). Various tests were conducted daily for six days on both groups before and after work. Parameters measured included temperature, pulse, blood pressure, reaction time, quantitative error, critical flicker frequency, and reaction of the adductor muscle of the thumb to electrical stimulation. A number of physiological differences were observed between the two groups. It should be noted that these differences do not necessarily indicate abnormalities. The observed differences must be cautiously considered in light of the fact that no reported attempt was made to control either group on age, sex, physical condition or the general work environment before comparison of the various parameters was made. Possible uncontrolled switchyard environmental factors include small-arc discharges, high-level 100-hertz acoustical noise arising from magnetostriction in power transformers, vapors from transformer oils and oxidants produced from corona. Thus, factors other than electric field exposure could well have caused the effects reported for Soviet switchyard workers. However, to totally dismiss their findings on this argument requires an extremely cavalier posture toward Russian scientific competence, which is completely unwarranted.

A paper by Krivova (1975) describes a Soviet study in which medical and physiological tests were performed on 319 attending personnel during and after work in 220-, 330- and 500-kV AC switchyards. Non-specific disturbances in the functioning of the central nervous system and cardiovascular system were attributed to exposure to electric fields. The implication that the electric field was the only contributing factor in these disturbances is not supported by additional tests which were conducted in the laboratory by the Russians on bald men. Bald subjects were used because the current experienced in the neck and head of such men was three to six times greater than that experienced by non-bald subjects in the same field.

T. P. Asanova and A. I. Rakov (1966) reported on the state of health of persons working in the electric field of outdoor 400-kV and 500-kV AC switchyards. Medical examinations were carried out on 45 persons (41 men and 4 women). The workers were 30-40 years old and had less than five years experience in an electric substation. This group was classified by exposure duration: "maintenance personnel" (average exposure of 5 hours/day); "attending personnel" (average exposure of 2 hours/day); and "secondary personnel" (no prolonged exposure). The workers were exposed to 50-Hz fields with intensities from 2 to 26 kV/m. The report described various disorders among the workers. Subjective neurologic disorders were highest in frequency of complaint (41 of 45 persons). These included headache, sluggishness, fatigue, sleepiness. Twenty-six persons were reported to have moderate autonomic disfunctions such as pulse and arterial pressure instability and fine tremors of the extended hand. Various other ailments were also reported.

The conclusion drawn was that "high voltage electric fields of commercial frequency have an adverse influence on the working person. . . . manifested by disorders of the functional state of the nervous and cardiovascular systems." No quantitative data is given to support this statement. More importantly, no comparison is made of the incidence of these reported disorders in a control population (i.e., a group identical to the exposed group except for exposure to the field). Because of these limitations, this report can only be regarded as a characterization of physical disorders of a population of workers exposed to electric fields, and no inferences can properly be drawn from the information provided.

These Soviet studies on their own do not indicate that the observed disorders are necessarily directly related to electric fields. They do, however, strongly suggest the need for further investigation. Nonetheless, as a result of these and other studies, the Russians now allow unlimited exposure to fields less than 5 kV/m and limited exposure to higher intensity fields. These are occupational standards, and are discussed hereinafter in detail.

Recent Russian reports (*Lyskov et al., 1975*) indicate that reported effects disappear when workers are assigned to jobs outside a high electric field environment. The only study thus far to report similar disturbances as the Russian studies is a report from Spain (*Fole, 1972*) on eight or nine 450-kV AC switchyard workers who complained of vertigo, nausea, fatigue and headaches. Here again, reports do not discuss environmental influences which could cause similar symptoms.

The only similar American study was in the 1960's on linemen who performed live-line maintenance on 345-kV lines (*Kouwenhoven, 1967, 1973*), sponsored by the American Electric Power Service Corporation. In this study 10 healthy linemen doing maintenance work were each given a series of complete laboratory, medical and psychological examinations over a period of 42 months. No significant changes were observed. A follow-up study was conducted in June, 1972. It was concluded from the study that the health of the linemen was not affected by their exposure to EHV lines. Linemen conducting both hot-stick and barehand maintenance were involved, however, the latter were protected by conductive clothing and gloves. For these linemen exposure was presumably low. This problem, combined with small number of subjects and lack of controls, limits the study's utility.

The contradictory reports on health effects of occupational exposure to electric fields may be explained by noting that the American study is not exactly comparable to the Soviet study. The Soviet switchyard workers were exposed to relatively intense fields for four to five hours daily, while the American linemen were exposed to more intense fields for a shorter daily duration. Also the work environments were different. The Soviet and Spanish studies report on results from exposure in a complex switchyard environment, whereas the American study involved a transmission line environment.

Nonoccupational exposure to the transmission line field environment was studied by Strumza of France (*Bridges, 1975; Kornberg*). Medical records of two groups of people of the same social level were analyzed, one group living within 25 meters of 200- to 400-kV AC lines and the other group living greater than 125 meters from these lines. Statistical analysis showed no difference between the two groups regarding costs of medical care and drugs as well as the number of medical examinations. This is only a rough, indirect estimate of the health status of the groups and does not necessarily reflect lack of electric field effects. No actual physiological comparisons were made between the two groups.

Only limited human experimentation has been done. German investigators, G. Hauf and R. Hauf (*Bridges, 1975; Hauf, 1976*) independently conducted a series of experiments where humans were exposed to 1-kV/m, 15-kV/m and 20-kV/m electric fields at a frequency of 50 Hz. The exposure time was up to three hours, enough time to demonstrate acute, but not chronic, effects. These experiments were carefully designed to exclude factors other than the electric field which might influence the results, including interference from clinical and medical errors. The field strengths simulated actual conditions under transmission lines. The human subjects were men and women of average age 25, determined before experimentation to be in good physical health. Exposed subjects were compared to controls who were treated in an identical manner except for exposure to electric fields. Excellent experimental protocol was employed. The results of this study indicate no observed change in electrocardiogram, electroencephalogram, blood pressure, pulse rate, hematology or pathology. The researchers conclude that "in the given test conditions and considering the studied parameters, besides the slight, nonspecific and completely physiological excitation effects in an electric field, the observed electric and magnetic field did not exert any detrimental influence nor any harmful effects." The "slight excitation effects" may not have been observed by Kouwenhoven (1967) in his linemen study because of their rapid dissipation when removed from the electric field.

A Swedish study was conducted by R. Johansson (*Bridges, 1975*). It measured the influence of a 50-Hz field, intensity of 100 kV/m, on the psychological test performance of a test group compared to a control group. No statistically significant differences were observed in the performance or the subjective well-being between the two groups.

S. Koeppen (1964) conducted laboratory experiments on humans, exposing them to electric fields simulating conditions under a 380-kV AC transmission line. Measurements of ECG were taken before and after 15- to 30-minute exposures to 7.5-, 12.5-, and 27-kV/m. Nothing abnormal was observed, which is supported by the work of R. Hauf (1973). Other human experimental studies have demonstrated effects of low-level electric fields but at frequencies of 12 Hz or less. These include alteration of circadian rhythums (*Wever, 1975*) and changes in human reaction time (*Adey, 1977*).

ANIMAL MODEL STUDIES

The potential biological effects of electric fields have also been investigated using animal experiments. A review of current scientific literature reveals that the majority of experimental results do not indicate detrimental effects for electric fields at intensities observed under transmission lines. However, some biological changes have been observed experimentally. The mechanism of action and significance of these responses are not known.

Following is a summary of experiments which may be of interest and concern. It is not intended to be detailed and comprehensive but rather a critique spotlighting items that raise attention and indicate areas where additional research is needed.

Frequently cited in reports on the biological effects of electric fields is the pioneering work of G. G. Knickerbocker and W. B. Kouwenhoven (1967). In this experiment 22 male mice were exposed to a 160-kV/m, 60-Hz electric field over a period of 10.5 months. No observable changes were noted in the primary group of exposed males, but male progeny of the exposed mice showed a slower growth rate than the control group. The authors, however, consider these results inconclusive, suggesting that body heat loss due to exposure of animals to a window and not allowing ad-lib access to drinking water may account for the variation.

Studies by Meda (1974) of guinea pigs and rats exposed to 100-kV/m fields for 18 hours per day show temporary transitory changes in electroencephalogram and electrocardiogram. Silney (1976) reports similar changes for rats and cats. Changes in blood chemistry and pulse were also noted. Although these changes are statistically significant, they are within normal physiological limits of variability and do not represent pathological changes. Fischer (1976) reports a significant drop in heart frequency for rats exposed for up to 50 days to a 50-Hz field with strengths of .5 kV/m and 5.3 kV/m. The intensity and temporal development of the influence were dependent upon field strength and length of application. Fischer attributes a strong drop in frequency after 15 minutes in the 5.3-kV/m field to a stress effect, resulting in the development of a biological reaction over time. Hematological modifications have been noted by other researchers for animals exposed to both AC and DC fields (*Marino, 1974; Cerretelli, 1976; LeBars, 1976*). Natural variability may account for observed changes. Confirmation of findings with close attention paid to experimental conditions and statistical analysis is necessary to validate these findings and to determine their practical significance.

In work by LeBars (1976) the post-infection recovery capacity was demonstrated to be inferior for rabbits exposed chronically, i.e., eight hours per day for 30-100 days to 50-kV/m fields as compared to controls. This was true both for animals during exposure and for animals exposed two months previously. Cerretelli (1976) at the University of Milan, reports that the resistance of mice to experimental infection is being investigated.

Operant behavior and reaction time response rate have been investigated for non-human primates exposed to electric and magnetic fields. DeLorge (1973) reports no changes in operant behavior, blood chemistry or reaction time for rhesus monkeys exposed to both electric and magnetic fields. However, Gavalis-Medici (1976) reports a statistically significant reduction in reaction time for Macaca nemestrina monkeys exposed to 56-V/m, 75-Hz electric fields. Conditions for these experiments were vastly different, which may explain conflicting results.

Genetic effects have only been investigated sparsely, again revealing conflicting results. No modification in mutation rate was observed for bacteria cells exposed to 50-Hz, 10- to 200-kV/m fields as compared to controls (*Riviere, 1976*). In contrast a fourfold increase in the number of chromosomal aberrations was observed by Marino (1974), for tumor cells which had been innoculated into rats subsequently exposed to 8- to 16-kV/m vertical DC electric fields. The mechanism and significance of this effect are not known.

Marino (1974) also reports secondary glaucoma being observed in 16% of rats exposed to vertical DC electric fields while none of the control rats or rats exposed to horizontal fields exhibited this condition. However, these results are not conclusive as the rats were not examined ophthalmologically before the experiment. Also secondary glaucoma is a complication of uveitis, an inflammation of the inner eye, which is normally present in 1-2% of the laboratory animals. Striking as these results are, verification with careful control of experimental design is necessary.

In summary, research to date on the biological effects of the transmission line field environment is inconclusive. The majority of experimental results are negative for adverse effects; however, biological changes have been reported. Absence of a clearly defined picture may be due to variations in experimental parameters in separate experiments such as frequency, voltage gradient, duration of exposure, experimental animal and type of assay employed. Additional research is needed to confirm findings and to determine the mechanisms of action associated with the observed effects.

Experimental design also needs to be refined. Extraordinary measures must be taken to avoid attributing an observed effect to the electric field when it is in fact due to some extraneous variable. For example, rats exposed to 50-kV/m AC fields will experience hair stimulation, which generally causes increased activity. This might wrongly be attributed to increased metabolic rate due to field exposure (*Kornberg*). Once the cause of observed effects are determined, those attributable to fields must be realistically examined to determine their significance for exposed human subjects.

STANDARDS

A. Magnetic Fields. Safety standards for magnetic field exposure have been recommended by the Stanford Linear Accelerator Center (SLAC), as follows (*McCall, 1975*):

	Extended Periods of Exposure (Hours)	*Short Periods of Exposure (Minutes)*
Whole Body or Head	*200 Gauss*	*2,000 Gauss*
Arms and Hands	*2,000 Gauss*	*20,000 Gauss*

R. C. McCall (1975), SLAC Health Physics, offers the following comments on these standards: "We do not feel that they are firmly based on good biological data. They are limits we felt we could live with without severe penalties in terms of cost and convenience. I suggest that they be classified as better than none." Nonetheless, it should be noted that the most stringent of these standards is 100 to 1,000 times the magnetic field intensity experienced under transmission lines.

B. <u>Electric Fields.</u> No standards or regulations for exposure to 60-Hz electric fields have been developed at the Federal level in the United States; however, the U.S. Environmental Protection Agency is currently investigating the need for such standards. The major industry standard concerned with transmission lines, the National Electrical Safety Code, likewise specifies no explicit field strength standards, although the five-milliampere short-circuit-to-ground standard (see Chapter II) implicitly limits maximum electric field strength.

As a result of the Russian switchyard worker studies, the Soviet Union has promulgated "Rules and Regulations on Labor Protection at 400, 500 and 750 kV AC Substation and Overhead Lines of Industrial Frequency," as follows:

Number	*Maximum Permissible Electric Field Intensity Without Protection (kV/m)*	*Permissible Duration of Exposure in 24 Hours (Minutes)*
1	*5*	*unlimited*
*2**	*10*	*180 minutes*
*3**	*15*	*90*
*4**	*20*	*10*
*5**	*25*	*5*

**The regulations are valid if: (1) all the remaining time the person is in areas less than or equal to 5 kV/m or (2) the possibility of electrical discharge is eliminated.*

These standards apply only to maintenance personnel working on electrical installations. As of February 1975, standards for the local population and agricultural workers were only in the development stage. The Soviet position with regard to transient incidental exposure was reported at a joint U.S.-Soviet meeting in a paper presented by Yu. I. Lyskov, et al. (1975) which states, "In designing the overhead 750- to 1,150-kV line, considering that cumulative effect of the field due to an infrequent and non-systematic exposure of the local population and agricultural workers can practically be disregarded. As permissible magnitudes of the field intensity the following higher standards were accepted: 20 kV/m for difficult terrain, 15-20 kV/m for non-populated regions, 10-12 kV/m for road crossings."

Both Driscoll (1976) and Young argue that the Russian field strength standards require conversion factors for application in the United States, as a result of two separate technical considerations:

1. The Russian power frequency is 50 Hz, and coupling effects are directly proportional to frequency. Thus, Russian standards must be multiplied by a factor of $\frac{50}{60}$ (0.833) for application to the 60-Hz electric field environment in the United States.
2. The Russian standards are based on use of specific instrumentation and a measurement methodology which results in measurement of a more perturbed field--and thus a higher gradient--than do American techniques. Driscoll contends that the Russian measurements will average 1.3 to 1.5 times higher, while Young found a factor of 1.6.

The first factor is defensible on a theoretical basis and should be applied; the second, however, assumes a degree of incompetence in calibration of the Russian instrumentation that does not appear warranted in the face of the limited information available.

Within the United States, several state regulatory agencies have investigated the need for electric field strength standards. The most prominant of these is the on-going common record hearing before the New York Public Service Commission (see Appendix C). At this proceeding, staff witness Dr. Andrew A. Marino in his direct testimony proposed a tentative "safety level" of .15 kV/m (150 V/m) at the edge of the right-of-way. This figure was based mainly on a literature review and experiments on rats performed by him (*Marino, 1976*), derived by applying a 100 to 1 safety factor to the 15-kV/m electric field gradient exposure that produced the reported biological effects in his experiments.

During direct testimony, Marino was questioned as to the basis of his 100 to 1 safety factor, to which he responded in part as follows:

> *In evaluating the safe-in-use of food additives, a safety factor of 100 has been explicitly chosen by the Federal government. The Federal rule seeks to balance the desire of a manufacturer to gain an economic advantage with the desire of the government to protect the public health. The numerical value of 100, was chosen as the appropriate balance point, and it is therefore significant as a precedent when a similar balance must be struck. I am not urging that the safety factor for food additives be adopted, but rather that the policy considerations underlying the adoption of a safety factor of 100 for food additives are also present in connection with involuntary exposure of the general population to power line electric fields, and therefore that the same numerical value should be adopted. (Tr:7241)*

In addition to challenging this argument, the applicants provided witnesses who testified that Marino's experiments are invalid, citing defective experimental protocol and unorthodox and inconsistent statistical analysis as reasons for rejecting his work as the basis of a human health and safety standard. By way of comparison, several common household appliances (Table II-1) produce electric fields of the same order of magnitude. Specifically, the 0.25-kV/m electric blanket field strength should be noted. The use of such blankets by the general public--at distances closer than the 12-inch point of measurement without apparent ill effect--suggests that Marino has proposed a safe level for chronic exposure, although additional research is clearly justified to insure such a stringent standard is in fact warranted.

The New York Public Service Commission staff in its initial brief of August 30, 1977 used a somewhat similar argument to arrive at a proposed 0.4-kV/m maximum field strength at the edge of the right-of-way. Based on its position that

> *the 765 kV transmission line will probably cause biological effects in humans exposed to them on a chronic basis,*

the staff then argued in its brief:

> *. . . Once we accept the hypothesis that there may be some risk associated with exposure to electric fields, we must determine what measures are appropriate to protect the public. It is our opinion that residents living in proximity to the ROW should have the option of selling their house or having it moved if the electric field strength at the residence exceeds a value that can be judged as safe based on the evidence in the record.*
>
> *Staff believes that a safety factor is appropriate since the scientific research strongly suggests that the biological effects may be adverse. A safety factor is necessary especially when the exact probability of hazard and the extent of hazards to individuals is unknown. The concept of safety factor is routinely applied by the government for the protection of the public under such circumstances. The safety factor is applied to a suitable field level based on the most relevant experimental data.*

In this case we see no compelling reason to accept the safety factor of 100 recommended by Dr. Marino. We believe that any safety factor between 10 and 100 could represent a reasonable choice. Dr. Marino has noted that a safety factor of 10 is generally applied for occupational exposure. In those situations the health status of the exposed individuals is known or they are assumed to be healthy, and exposure can be controlled accordingly. Here where we have an undefined population, e.g., the old, the young, the sick, persons whose health status may vary considerably and whose exposure cannot be controlled, it is appropriate to utilize a safety factor in excess of 10. We have determined that the appropriate safety factor for 765 kV lines is 25. This factor will provide a significant amount of protection to exposed individuals and at the same time should not cause extraordinary economic penalties to the utilities through the option to buy or relocation programs. If research results provide a more precise understanding of the nature of biological effects in humans and the field strengths and circumstances for which they occur, it may be appropriate to alter the safety factor either upward or downward.

which resulted in the following recommendation:

There is a need to inform individuals living in proximity to the lines of this hazard, and require the utilities to relocate residences or offer to purchase houses when the electric field strength exceeds .4 kV/m.

Significantly, while the staff essentially recommended an edge of right-of-way standard to avoid chronic exposure, it did not recommend either a maximum vertical electric field strength standard, nor any restrictions on right-of-way access and utilization. In this sense, the staff's proposal does not parallel the Russian standards. The Commission itself has not as yet acted on the staff's recommendations which are among several submitted by the various parties.

The State of Minnesota is currently applying only maximum vertical electric field strength standards under the Environmental Quality Board's transmission line routing program. In the case of the construction permit issued to Cooperative Power and United Power Associations on June 3, 1976 (Docket No. CU-TR-1), the Board required that the applicants design, construct and operate their proposed transmission lines in such a manner that the electric field measured at one meter above ground shall not exceed 8 kV/m, rms, for 345-kV AC line operation and 12 kV/m measured at ground level for ±400-kV DC line operation. The Board has also applied the 8-kV/m, rms, standard to all three segments of Northern States Power and Minnesota Power and Light Companies' WTC 500 Project, which includes approximately 350 miles of 500-kV AC transmission line within the State.

To our knowledge, the 12-kV/m standard is the only such standard extant nationwide for DC lines. It is based on the crest field strength in an 8-kV/m, rms, AC field. As emphasized in Chapter II, extrapolations from AC to DC are inappropriate, and this standard may or may not be valid.

SUMMARY AND CONCLUSIONS

Adverse health effects resulting from exposure to the high-voltage overhead transmission line field environment are a matter of considerable public concern. Although it is not possible to say that there is no risk, thus far both epidemiological and laboratory studies have failed--for various reasons--to indict transmission lines as a health hazard. As yet, there is no evidence whatsoever suggesting any effect on health or a sense of well-being from the intermittent exposure experienced in the transmission line environment. Nor has a theoretical basis for the presumption of effects been postulated. This is a particularly important point, for it forces research into the biological effects of power frequency fields to be exploratory or observational, rather than rigorous experimental studies designed to accept or reject specific hypotheses.

AC electric fields are the environmental stress of greatest--although, not exclusive--concern. While these fields are not strong enough to cause tissue heating or nerve stimulation, the possibility of more insidious effects has prompted research in this area. Human and animal studies on the biological effects of AC electric fields have generally yielded conflicting results. One major reason for discrepancies is differing experimental exposure parameters (i.e., frequency, gradient and exposure duration) between studies. Another problem is that many of the experiments conducted thus far have not paid close attention to experimental design, and control of extraneous, interfering variables and statistical analysis of experimental data. Biological effects, if they exist, are likely to be subtle; recognition of true effects demands investigation utilizing a systematic, interdisciplinary approach to assure well-designed, closely controlled research.

Taken in total, this body of research does not provide an adequate basis for even responsible assessment of the need for, let alone specification of, meaningful standards in terms of either field strength or exposure duration. Consequently, there is no basis to question the Minnesota Environmental Quality Board's present 8-kV/m, rms, maximum vertical electric field gradient standard for AC transmission lines. Even when the Russian studies are given the full benefit of the doubt, to include the aforementioned statement by Lyskov et al. (1975), a more stringent standard is not warranted for the transmission line environment.

Nonetheless, the Russian studies, particularly when viewed in the context of the trend toward higher operating voltages, also strongly support the need for continued research. The ground-level electric field gradient in both the transmission line and switchyard environments is approximately proportional to the line's operating voltage; thus in the progression from 345 kV to 765 kV, say, the exposure more than doubles. An argument can be advanced that voltages in the relatively intense switchyard environment, could have recently reached the point where "biological thresholds may be passed, activating processes that did not take place at all at lower voltages" (*Young and Young, 1974*), explaining why effects had not been reported earlier. Given this posture, the Soviet studies cannot be dismissed simply because of technical shortcomings in research procedures, for Russian operating voltage trends are comparable to those in this country. Problems in the Russian switchyard environment could conceivably portend future difficulties in the United States transmission line environment as transmission voltages rise into the UHV range, given comparable exposure durations.

The above comments are solely speculative and are no basis for alarm; they must be interpreted simply as an argument advocating prudence and timely completion of appropriate research. This is particularly true when contemplating the additional circuit-mile growth anticipated in the future, providing greatly increased opportunity for public exposure. In this regard, Mr. Allan H. Frey in his direct testimony before the New York Public Service Commission, made the following recommendation:

> *To establish whether these (765-kV) transmission lines present a hazard from the neural or behavioral standpoint, multiple years of experimental investigation are necessary. I would suggest, for the Commission's consideration, that*

> *it allow the 765 kV transmission lines but with a right-of-way of such width that the field strength to which the general public could be exposed on both a short- or long-term basis, is no higher than that which exists with present lines. Note that there is implicit within this suggestion the assumption that present lines do not have subtle adverse neural and behavioral effects. It is possible that they do have such effects, but they also are unrecognized due to the lack of appropriate testing to determine if this is the case. (Tr:9994)*

This is an empirical approach, based on prudence, and has a great deal of merit. In effect, it suggests adoption of an edge of right-of-way standard--possibly, in addition to a maximum standard--to limit chronic exposure. We recommend adoption of this strategy, using 345-kV AC transmission technology as a base to establish a temporary "holding position" until completion of necessary research. The 345-kV base is utilized because of the extensive commercial utilization of this technology across the United States over the past 25 years. Chapter V details this recommendation.

As a final comment on AC transmission, we would note that the transmission line controversy in other states is not over HVDC lines, but 765-kV AC lines. The ground-level field strength (approximately 10 kV/m) for such lines is in fact at the threshold for one known effect--albeit, non-biological--perception, apparently by erection or vibration of body hair (*Sheppard and Eisenbud, 1977*). Minnesota is fortunate that no 765-kV lines are currently planned, providing it with time to take advantage of research and experience gained elsewhere in establishing appropriate regulatory controls.

With regard to HVDC transmission, insufficient research and experience exists to propose any meaningful performance standards, whether empirically based or otherwise, that have an objective of protecting the public health. As a general observation, there does not seem to be as much concern among the scientific community over DC electric fields. However, this position appears to be based on extremely limited information. In particular, the whole issue of the space charge field needs investigation and clarification. For example, air ions have been suggested as responsible for both adverse and beneficial effects. The subject is controversial and considerable further research is unquestionably warranted.

The research programs described in the next chapter are intended to address many of the unknowns in both the AC and DC transmission line environments. The animal model studies, in particular, appear to correct many of the experimental difficulties described herein and should greatly assist in clarifying the entire biological effects issue.

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IV. RESEARCH PROGRAMS

As suggested by the two previous chapters, there are numerous unanswered questions concerning the potential public health and safety implications of high-voltage overhead transmission lines, requiring significant research efforts to provide answers.

The position of the Federal government on the matter is reflected in a recent letter to Congressman Bruce F. Vento from the U.S. Energy Research and Development Administration (ERDA):

> *The electric utilities have, until a few years ago, maintained a hands off attitude about the possible biological effects of high voltage transmission. This, of course, cannot be tolerated. It is the responsibility of industry and the government to prove that no hazard to the public exists under high-voltage lines, either those in operation or those contemplated for the future. This can be done with well-organized and controlled experiments both in the laboratory and under operating lines. We cannot afford to build 1200 kV transmission lines and fence in the right of way as we do interstate highways. The overhead transmission lines of the future can be designed so that field strengths on the ground are at levels that are safe, presenting no danger, seen or unseen, to human, animal or plant life. (Flugum, 1977)*

Generally speaking, this is a valid criticism of both the electric utility industry and government, although the study of linemen sponsored by the American Electric Power Service Corporation (see Chapter III) is clearly an exception. In fairness, though, it should be pointed out that until the Russian studies were reported in the West (1972) there was no apparent reason for concern.

It appears that both sectors are now willing to accept their responsibility "to prove that no hazard to the public exists under high-voltage lines," as stated above. This is the thrust of several new research programs into the biological effects of the transmission line environment, sponsored by the electric utility industry through its research and development arm, the Electric Power Research Institute, and by the Federal government primarily through the U.S. Energy Research and Development Administration and the Bonneville Power Administration. While separately funded, all of these programs are coordinated. Contracts awarded to date exceed $4.3 million.

The major research projects under these various programs are described in this chapter. Of particular interest are two animal model studies which will address the technical limitations of earlier experimental work. Nonetheless, they will undoubtedly be criticized--with some justification--because of incentives, funding sources and the close collaborative working relationship between the Federal government and the electric utility industry. For example, as the above quote suggests, ERDA's research is part of its overall 1,200-kV technology development support program, for which commercial introduction is planned for the 1980's. In terms of credibility, more disinterested sponsorship would have been desirable.

In spite of these shortcomings, the animal model studies are being conducted by a highly competent research house utilizing excellent experimental protocol. Further, to our knowledge, these are the only major research programs directed toward the transmission line environment, for such studies are extremely expensive. Our review of available experimental plans indicates quality research, and thus our concern lies more in the evaluation and interpretation of their eventual findings. Here, we may well find honest differences of opinion dependent upon perspective. ERDA has invited us to participate in the program review meetings with the animal model studies research contractor (*Feero, 1977b*). On-site visibility and discussions of this work would increase our confidence and ability to evaluate and interpret findings. A recommendation for such participation is included in Chapter V.

A summary of the major research programs is provided in this chapter, with an evaluation of their adequacy to address the public health issues of transmission lines. Selected major studies--including the animal model studies--are described in detail to illustrate the nature and scope of these programs. To aid in developing a cohesive picture of this research, an explanation of funding sources is also included. In reviewing this work, the reader is again cautioned that in spite of ERDA's goal, neither government nor industry nor anyone else can absolutely "prove that no hazard to the public exists:" such is a logical impossibility. The best we can achieve is a greatly improved confidence--but still less than 100% certainty--that such exists.

FUNDING SOURCES

The major research being conducted in the United States on the biological effects of high-voltage transmission lines is sponsored by the three organizations mentioned above, each of which is briefly described below. Additional work is being conducted by various other Federal agencies, universities, private utilities, the Institute of Electrical and Electronics Engineers (IEEE) through its committees, subcommittees and working groups, and CIGRE (International Conference on Large High Tension Electric Systems) which provides an international forum.

The Electric Power Research Institute (Palo Alto, California) was organized in 1972, but its roots can be traced back to 1964 when the Electric Research Council was organized to encourage all sectors of the utility industry to join in cooperative sponsorship and management of electric energy research. A Research and Development Goals and Task Force was set up in 1969; in 1971 it requested a nationwide commitment of $1.12 billion per year by the utility industry, the Federal government and electric equipment manufacturers for research and development through the year 2000. The Electric Power Research Institute was organized to manage the utilities' participation and is supported by all segments of the utility industry including investor-owned companies, publicly owned utilities, rural cooperatives, the Tennessee Valley Authority and the U.S. Department of the Interior.

The primary areas of EPRI's research are fossil fuel and advanced systems, nuclear power, electrical systems and energy analysis and environment. Its total 1977 research and development budget is $180 million making it second only to the Federal government in total research and development expenditures. Research areas are determined and priorities evaluated in terms of magnitude of impact, probability of success, probable timing of impact, cost, need, etc. (*Anonymous, 1977*). The Electric Power Research Institute does not in itself conduct research and development, but awards and monitors research contracts. The research described herein is sponsored by EPRI's Environmental Assessment Department, Energy Analysis and Environment Division.

The United States Energy Research and Development Administration (Washington, D.C.) is a Federal agency established by the Energy Reorganization Act of 1974 (88 Stat. 1234; 42 USC 5811) and activated on January 19, 1975 by Executive Order 11834 of January 15, 1975. The purpose of ERDA is to reorganize and consolidate Federal activities relating to research and development on the various sources of energy. Included among its research and development goals are those of restoring, protecting and enhancing environmental quality, and to assure public health and safety.

ERDA is required to utilize the facilities and capabilities of other Federal agencies, national laboratories, universities, nonprofit organizations, industrial and other non-Federal entities for energy research and development and demonstration projects. ERDA also encourages international cooperation in energy and related environmental research and development (*Anonymous, 1976a*). Research concerning the biological effects of high-voltage overhead transmission lines is sponsored by ERDA's Division of Electric Energy Systems, Office of Conservation.

The Bonneville Power Administration (Portland, Oregon) was created pursuant to the act of August 20, 1937 (50 Stat. 731, as amended; 16 U.S.C. 832 et seq.). It markets electric power and energy from Federal hydroelectric projects in the Pacific Northwest, constructed and operated by the Corps of Engineers and the Bureau of Reclamation, and participates in interregional exchanges of power. It seeks to assure an adequate and reliable supply of power for the region's future energy needs with maximum attention to the importance of preserving environmental quality. The Bonneville Power Administration conducts power marketing programs and with other private and government agencies, participates in planning for the development of the region's potential energy resources (*Anonymous, 1976a*).

With creation of the Federal Department of Energy, there may be some realignment of responsibilities. However, it is too early to determine the implications--if any--on the respective research programs, of this reorganization which took effect October 1, 1977.

RESEARCH PROGRAM

A well-conceived, overall research strategy is needed both to assess the biological and safety effects of the current transmission line environment and to determine to what extent field strengths can be safely increased--if at all--to allow use of higher transmission voltages. Such a program plan was developed in 1975 for EPRI by the IIT Research Institute (IITRI), Chicago, Illinois. At a workshop held at IITRI on April 7 and 8, 1975, 30 experts from research centers, universities, government and industry met to discuss biological effects of high-voltage electric fields. From this workshop general agreement was reached on the following:

1. *The direct (conductive) shock problem has been well researched, as evidenced by the abundant references.*
2. *Research efforts should emphasize whole organisms, populations, and ecosystems.*
3. *Planned research should be of the highest quality with careful consideration given to dosimetry and biological protocol. Quick-look "pilot" programs yield misleading results and should be avoided.*
4. *The coexisting magnetic field near high voltage lines induces a different kind of internal current distribution in humans than the electric fields.*
5. *The small-arc self-discharge problem may be one of the limiting environmental influences. (Bridges, 1975)*

At a later meeting on May 1 and 2, 1975, discussions involved specific details of possible programs including biological protocol, selection of subjects and dosimetry support. From these meetings, supplemented by a literature review involving some 2,300 references and personal discussions, a state-of-the-art review incorporating approximately 800 citations and a program plan emerged.

The program plan is divided into four main project categories: existing environments, simulated environments, medical devices, and dosimetry and support. In selecting possible programs the highest priority was given to areas in which risk to humans is likely or there may be significant agricultural or ecological impact. Tables IV-1 through IV-4 summarize the programs specified in this plan, the rationale for setting priorities and their objectives.

TABLE IV-1. EXISTING TRANSMISSION LINE ENVIRONMENT

PROGRAM	RATIONALE	OBJECTIVE
MEDICAL RECORD COMPARISONS	Identification and elimination of risks to humans is of primary importance in these studies. Comparison of medical records provides a quantitative measure of any possible long-term effects.	Confirm safety of existing HVAC lines for intermittent high and low-level exposures.
HUMAN PERCEPTION of HVAC Fields and Arcs	Preliminary data are available. These should be augmented and mitigation procedures against prolonged stress should be developed.	Develop design criteria regarding perception thresholds for HVAC fields and arcs under a variety of meteorological conditions.
AGRICULTURAL	Agricultural animals are economically critical. Controlled studies in actual field environments of agricultural animals is needed to confirm present HVAC line design. Biochemical analysis of milk is a convenient non-invasive measurement.	Determine if field from HVAC line has any practical effect on milk production and on agricultural animals in general.
INSECTS	Agricultural importance of bees (pollination) requires that they be considered over other insects. The highly developed social structure and rapid reproduction pattern are characteristics of the honeybee which provide the basis to investigate fundamental biological concerns, such as genetics, reproduction and communication.	Confirm observed effect and develop distance thresholds
BIRDS	Birds employ magnetic fields as cues for navigation. It is believed that birds follow power lines much as they do other visual cues, but the extent to which the fields created by these lines affect the natural migration paths of birds is an important ecological concern.	Determine if EHV lines significantly affect the ability of birds to migrate.
CROPS Corn and Soybeans	Economic importance of these crops requires confirmation of field intensities of current HVAC lines.	Identify possible effects and thresholds
ECOSYSTEMS	It is ecologically important to determine the impact of fields on plants and interdependent biota within and beyond rights-of-way. Radioisotopes provide a convenient quantitative measurement.	Determine impact of fields within and beyond right-of-way

Source: Bridges 1975

TABLE IV-2. CONTROLLED SIMULATED ENVIRONMENTS

	PROGRAM	RATIONALE	OBJECTIVE
Psycho-Physiological Aspects CNS/Reproduction	RODENT	Results from Eastern Europe have suggested that HVAC electric fields affect the CNS. This is not confirmed by careful laboratory tests in Western Europe and USA on humans and other animals.	Determine threshold where hazardous effects may occur in terms of physiological functions with emphasis on CNS and reproduction in smaller animals pure fields, collateral and cofactor environments considered.
	PIG	Same as above.	Same as above.
	NONHUMAN PRIMATE	Same as above.	Same as above.
Special Objective Programs	PIG Small-arc discharge	The small-arc, self-discharge is considered to be a limiting factor by both Soviet and Western researchers.	Determine threshold for transitory and possible long term effects in terms of field intensity.
	RODENT/ SMALL PRIMATE Seizure latency	Seizure Latency is an alternative, rapid and possible confirming approach to study side effects, if any, from electric fields	Measure seizure latency to develop thresholds to electric fields and collateral and cofactor environments
	HUMAN Behavioral/ Physiological (as appropriate)	See item one.	See item one.
	*VEGETATION Acute Damage	Leaf-tip damage to plants has been observed in high fields. Design criteria for large plants geometries and field strengths needed.	Develop design criteria thresholds for acute corona damage to plants as a function of size and height.

*In this area, some work is currently being done for EPRI. Additional work is needed.

Source: Bridges 1975

TABLE IV-3. MEDICAL DEVICES

PROGRAM	RATIONALE	OBJECTIVE
ELECTRONIC CARDIAC PACEMAKERS	Some 100,000 patients rely on pacemakers; threshold for interaction for magnetic fields has been established; comparable study for electric field and conduction effects needed.	Determine threshold for electric field interaction and threshold for possible serious effects at higher levels. Establish inter-industry solutions if required.
MEDICAL DEVICES	Medical devices, other than pacemakers may have some susceptibility to HVAC fields. Gradual proliferation and use of such devices is anticipated.	Determine approximate thresholds, using these data, working with device manufacturers, physicians and government agencies to develop long-range solutions.
METALLIC IMPLANTS	Metallic implants can collect and enhance internal current concentrations induced by power line fields long-term effects need to be assessed.	Determine if long-term effects exist and thresholds. Develop remedial actions if needed.

Source: Bridges 1975

TABLE IV-4. DOSIMETRY AND SUPPORT

PROGRAM	RATIONALE	OBJECTIVE
PEER REVIEW AND ENVIRONMENTAL VERIFICATION	Past results have been inconclusive because of improper biological procedures or unknown environmental influences.	Minimize the risks of invalid research by peer review and independent certification of test environments.
DATA BANK AND INFORMATION EXCHANGE	Several thousand references have been identified as pertinent but many are difficult to obtain or are in a foreign language. Meetings on the subject of biological aspects of power-line fields have to be extensively conducted.	Maintain data bank of reference material, develop translations, conduct workshops and seminars.
RELATING OTHER BIOLOGICAL DATA	Environments comparable to two of the three primary powerline environments have been extensively considered in terms of Project Sanguine. Other test results on tissue and organ cultures exist. These data can be related by means of developing internal current densities and other techniques <u>for immediate and timely use</u>.	Relate results of complementary past and ongoing programs to the power-line environment. This includes relating aquatic system and subsoil life beneath lines and developing, by <u>in vivo</u> measurement, internal voltage and currents on laboratory animals.
COLLATERAL ENVIRONMENTS Field measurements	The disparity between Soviet and Western results may be explained by the presence of other environments such as air ions, acoustical noise, arc-discharges, and ozone. The levels of these environments must be developed for use in laboratory animal programs and to assess research results.	Measure collateral and primary environments at a variety of transmission and switchyard sites for different meteorological conditions.
EXPOSURE PROFILES	The disparity between Soviet and Western results may also be partially explained by differences in intensity and duration of exposures. These data on workers and animals near power lines are a key input to the laboratory animal programs and to interpret results of epidemological studies.	Develop the range of actual exposure profiles of workers and animals for primary and collateral environments.
LABORATORY INSTRUMENTATION	Past laboratory research has often been inconclusive because the fields--intensity and divergence--as well as the collateral and cofactor environments were not measured; because instrumentation was not available commercially or details published in readily available literature.	Identify source or develop details such that biologists can obtain necessary supporting instruments for electric, magnetic fields and divergence, ozone, acoustical noise, small arc-discharge.

Source: Bridges 1975

Initial projects address biological considerations associated with electric fields from EHV transmission lines. HVDC transmission line fields were also of concern, but financial contraints prohibit simultaneous implementations of full-fledged efforts in both areas, and the plan calls for HVDC studies to be integrated into relevant EHV programs at a later date. This strategy was selected because of the relatively few miles of HVDC lines in the United States.

This plan, entitled, "Biological Effects of High Voltage Electric Fields: State-of-the-Art Review and Program Plan" (*Bridges, 1975*) (herein, "Biological Effects Plan"), is well documented and appears to be well received in the technical community. However, it is unclear to what extent it is actually being implemented. EPRI and ERDA are both sponsoring some of the research specified by it; unfortunately, the documentation available for these individual research projects does not readily relate to the overall plan.

A companion plan, "Coupling and Corona Effects Research Plan for EHV Transmission Lines" (*Anonymous, 1976c*) (herein, "Coupling and Corona Effects Plan"), was also prepared by IITRI Research Institute under ERDA sponsorship. Drawing heavily upon and using a comparable approach to the EPRI's Biological Effects Plan, the ERDA plan is also based on a state-of-the-art literature review and a workshop, involving some 40 scientists and engineers held on October 15 and 16, 1975. The literature review was concerned with four areas: electromagnetic interference, acoustic noise, generation of gaseous effluents, and safety considerations of induced voltages and currents (*Anonymous, 1976c*).

The Coupling and Corona Effects Plan identifies and recommends 20 short-term projects (see Table IV-5), described in the plan

TABLE IV-5

PROJECTS SUITABLE FOR EARLY INITIATION

Corona Effect

Acoustical Noise

** Acceptable Operating Condition Survey

** Psychoacoustical Response

Improved Prediction of AN for lines above 1000 kV

Radio Interference/Television Interference

** TVI Measurement Instrumentation

* TVI from HVDC Lines

HVDC and HVAC Subjective Responses to RI

* Prediction of VHF-UHF and Microwave Interference

Reradiation and Propagation

Ozone

* Summary and Perspective

Coupling Effects

** Fuel Ignition

* Technology Trends in Perspective

* Subjective Responses to Non-Hazardous Currents and Discharges

* "Let-go" and Discharge Safety Criteria

** Basic Understanding of HVDC Line Phenomena

* Experimental Coupling Studies for HVDC Lines

** Instrumentation for HVDC Lines

Multidiscipline Programs

Measurement Van for AN and RI/TVI

Advance Techniques to Reduce Corona Effects

Transmission Line Environmental Effects Tradeoff

Reliability/Maintainability

(** indicates highest priority, * priority)

Source: Anonymous 1976c

as follows:

> *In the case of the corona effects, a number of programs were recommended for acoustic noise and electromagnetic interference to delineate improved power line design criteria in terms of social, meteorological, geographical and cost constraints. Only one project is recommended in the case of ozone generation, because the results of comprehensive analyses, laboratory studies and field measurements have demonstrated that power lines do not contribute significant quantitities of ozone. In the case of the coupling effects, a number of programs are recommended for HVAC transmission lines to improve the theoretically developed design guidelines by considering practical constraints. For HVDC transmission lines, programs are suggested to engender a better theoretical understanding and practical measurements capability for the coupling mechanisms of the DC electric and magnetic field with nearby objects. (Anonymous, 1976c)*

Portions of this plan relating to HVDC transmission are found in work sponsored by ERDA. Overall, however, it is not being implemented because of apparent funding limitations. This is unfortunate, for some of coupling effects projects proposed would relate directly to the shock problem outlined in Chapter II.

Tables IV-6 and IV-7 provide a fairly current summary of current research projects sponsored by EPRI and the Federal government, respectively. A notable omission in Table IV-7 is ERDA's aforementioned work on HVDC transmission, which is a recent contract, but is described in this chapter.

EPRI-SPONSORED RESEARCH

A review of EPRI research projects reveal that those projects proposed by the Biological Effects Plan which are likely to rapidly detect subtle biological changes or investigate areas of major impact are being implemented.

An investigation of honeybees which will rapidly address fundamental biological issues such as genetics and reproduction is underway (RP129, RP934). The feasibility study is complete, and

TABLE IV-6

EPRI-SPONSORED RESEARCH ON BIOLOGICAL EFFECTS OF HIGH-VOLTAGE OVERHEAD TRANSMISSION LINES

November, 1976

Number	Title, Contractor	Funding/Duration	Summary & Status
RP129	Ecological Influence of Electric Fields; J.W. Bankoske, Westinghouse Electric Corp.	$376,000 5/22/74-3/21/77	<u>Objectives:</u> Investigate the effects of electric fields at powerline frequencies on voles, trees & plants, and chicken embryos at the Waltz Mill HV test facility. <u>Status:</u> - Defined and simulated electric field environment under powerlines. - Chicks exposed to 40-80 kv/m during incubation show temporary increased growth rate. - Plants with pointed leaves show tip damage during ~the first week of exposure. - No effect on plant germination of 50 kv/m. - Voles exposed to 50 kv/m showed temporary slower growth rate. No other effects. - No effect on egg hatchability or embryo activity at 50 kv/m. Due to increase in project cost, an RIPC is being put before the November Board meeting which would carry this work through March, 1977. A follow-up project is under consideration.
RP679	Effect of 60-Herz Electric & Magnetic Fields on Patients with Implanted Cardiac Pacemakers; J.E. Bridges, IITRI	$110,000 9/10/75-12/31/76	<u>Objectives:</u> Investigate the effect of 60Hz high voltage electric fields on cardiac pacemakers implanted in baboons and establish relationships for translating any effects to the human case. <u>Status:</u> HV fields have been found to effect one type of pacemaker, but the significance to the wearer has not been demonstrated.

RP799	Electric Field Effects on Large Animals; R.D. Phillips, BNWL	$1,200,000 3/1/76-2/28/78	Objectives: Investigation of effects of chronic exposure of Hanford Miniature swine to HV electric fields. Test animals will be exposed from conception to project end to field levels greater than those found under powerlines, but below perception levels. Constant clinical assays will be taken in an attempt to identify even very subtle effects. Status: - Exposure facility site was located, obtained & prepared for construction. - Electrode exposure system was designed & constructed and testing is underway. - Operating procedure and safety rules for exposure system were written and approved. - Swine exposure stalls and housing prototypes are constructed & under testing. - Breeding protocols for 2 generations of animals to be used has been designed.
RP857	Biological Effects of Electric Fields - General Support Study; J.E. Bridges, IITRI	$130,000 8/1/76-7/31/77	Objectives: The contractor will update the state of the art study initiated by RP381, abstract foreign literature and translate key documents, provide technical support for the EPRI HV effects program, determine the applicability of various Sanguine data to powerline environments, and study internal currents and dosimetry associated with HV fields. Status: - Foreign literature review and abstract translation is near completion. Translation of key documents is underway. - Domestic literative review is underway. - A November meeting of EPRI HV effects contractors is being organized.

RP934	Field Evaluation of Effects of HV Powerlines; B. Greenberg	$122,000 8/15/76-12/31/78	Objectives: Investigate the effects of exposure of honeybees to maximum fields under a 765 kV line. Will study honey and wax production, reproductive success, hive health, activity and behavior as indicators of neurological effects. Status: - Feasibility study completed and hives established under contract TPS76-630. - Contract for RP934 under negotiation.
SOA76-323	Basic Introduction to Electrical Effects of HV Power Lines; J.E. Bridges, IITRI	$20,000 5/20/76-10/31/76	Objectives: Prepare a primer to educate the public on facts relating to effects of electric fields Status: Rough draft under preparation.
TPS76-639	Feasibility Study: Epidemiology of Linemen and Switchyard Workers; M. Utidjian, Equitable Environmental Health, Inc.	$17,000 4/1/76-9/30/76	Objectives: Assess the feasibility of conducting epidemiological studies on workers routinely exposed to HV fields. Status: Preliminary report to be reviewed at ACBEEF meeting, November 3-4, 1976.
	Total	$1,975,000	

Under Consideration:

- International Workshop on Biological Effects of Electric Fields
- Development of Personal Dosimeter

TABLE IV-7

FEDERAL GOVERNMENT-SPONSORED RESEARCH ON
BIOLOGICAL EFFECTS OF HIGH-VOLTAGE OVERHEAD TRANSMISSION LINES

(1) Project Title: Electric Field Instrumentation and Calibration

Contractor: National Bureau of Standards, Electricity Division

Funding Unit	Duration	Starting Date	Obligation
ERDA/EES	12 mos.	July 1, 1975	$126,000

Scope of Work

Over the last decade a number of different types of instruments have been developed for the measurement of electric field strength under high voltage transmission lines. While a few in situ tests have been made to compare these instruments under identical conditions, there has been no calibration method and facility for both a.c. and d.c. electric field measurements. It will also develop factors for comparing and equating readings from these different meters, and guide lines for determining the perturbating effect of the meter on the field.

(2) Project Title: State-of-the-Art Review and Research Plan for Corona and Corona Induced Effects from HV Transmission

Contractor: Illinois Institute of Technology Research Institute

Funding Unit	Duration	Starting Date	Obligation
ERDA/EES	9 mos.	June 1, 1975	$40,000

Scope of Work

A considerable amount of work has been done by the industry on corona produced noise from HV lines, particularly in the area of radio noise. There are, however, a number of other effects which have had much less attention and this project identifies those, discusses the state-of-knowledge and provides recommendations for further research. Corona effects are subdivided into three separate areas, acoustical noise, electromagnetic interference, and ozone generation. Coupling induced effects will cover both HVAC and HVDC. A full bibliography will be included with the final report.

(3) Project Title: Psycho-Acoustic Response to Noise in the Audible Spectrum for HV Transmission Lines

Contractor: National Bureau of Standards, Sound Division

Funding Unit	Duration	Starting Date	Obligation
ERDA/EES	33 mos.	January 15, 1976	$422,000

Scope of Work

Although the level of noise in the audible spectrum generated by corona during foul weather is of relatively low level (usually 60 dba), it may be an annoyance in nearby areas. This project is an attempt to apply modern psychological study techniques by using tapes of transmission line noises in controlled experiments where subjects are given alternate choices of audible stimulae. A pilot study with relatively few subjects will be completed within 6 months. If the technique is proved feasible, more experiments will be conducted.

(4) Project Title: Biological Effects of High Strength Electric Fields on Small Laboratory Animals.

Contractor: Battelle Pacfic NW Laboratories

Funding Unit	Duration	Starting Date	Obligation
ERDA/EES	27 mos.	January 15, 1976	$1,200,000

Scope of Work

There has been relatively little meaningful data available from laboratory studies with humans or animals exposed to electric fields. This study is designed to establish an improved data base by which safe human exposure limits may be better defined. Laboratory studies on small animals will be made to screen for effects using a wide variety of biological tests over a broad range of electric field strengths. The results of these studies should provide a better basis for evaluating potential hazards of exposure to 60 Hz electric fields and help define parameters to be studied in clinical evaluations on humans.

(5) Project Title: Effect of Electric Fields on Fruit Flies

Contractor: Battelle NW

Funding Unit	Duration	Starting Date	Obligation
EPA/ERDA/DBER	24 mos.	September, 1975	$50,000 (approx).

Scope of Work

The fruit fly is an insect frequently used for preliminary biological tests and in this study is being subjected to low level fields and monitored using the standard assessments for such studies.

(6) Project Title: Synthesis of Data and Information Received in Response to EPA Federal Register Notice of March 18, 1975.

Contractor: Competitive Bidding Underway

Funding Unit	Duration	Starting Date	Obligation
EPA/ERDA/EES	6 mos.	Est. Aug, 1976	$20,000

Scope of Work

The Federal Register of March 18, 1975 carried a notice submitted by EPA asking for data and information from EHV transmission lines. This data, following a preliminary review on environmental effects did not reveal any evidence of undesirable effects. A detailed comprehensive review of this data base is required, however, in order to properly assess its meaning and render it useful to researchers. This project will be awarded by competitive process to an outside contractor.

(7) Project Title: Effects of 60 Hz Fields on Mammalian Control Nervous System

Contractor: W. Ross Adey, Md. University of CA. Los Angeles

Funding Unit	Duration	Starting Date	Obligation
EPA/DHEW/ONR	1 year	August, 1975	$100,000

Scope of Work

In this contract, effects of electromagnetic fields on the central nervous system of mammals will be investigated in conditions simulating those near high voltage transmission lines. The effects and behavior will be studied and correlated with measured changes on brain rhythm and neuronal membrane conditions.

(8) Project Title: Environmental Effects of BPA 1100 kV Test Transmission Line

Contractor: Battelle Pacific NW Labs

Funding Unit	Duration	Starting Date	Obligation
DOI/BPA	31 mos.	May, 1976	$197,650

Scope of Work

Bonneville Power Administration is building an 1100 kV test line to study electrical design parameters for this voltage level. The site will be energized for several years at this voltage and thus provides an excellent field test site for study of effects from electric fields in the area. Field work has already begun monitoring vegetation, wildlife and domestic animals under and adjacent to the line.

(9) Project Title: Investigation Into Environmental Effects of HVDC Transmission

Contractor: Western Interstate Commission for Higher Education (WICHE)

Funding Unit	Duration	Starting Date	Obligation
DOI/BPA	12 mos.	May, 1976	$20,000

(9) Project Title: Investigation Into Environmental Effects of HVDC Transmission (Con't)

Scope of Work

The West Coast ± 400 kV Transmission Line has been in service between Oregon and Los Angeles for over seven years. A second line from Oregon to Phoenix is planned for construction within the next ten years. BPA has begun a one year project to study possible effects from the present line. This study will determine by field observation if plants, wildlife, and domestic animals are affected by an operating dc line and identify the possible significance of any observed effects. BPA personnel are involved in planning and preliminary field work.

(10) Project Title: Investigation of Ground Level Electric Field and Ions from HVDC Lines

Contractor: In-House

Funding Unit	Duration	Starting Date	Obligation
DOI/BPA	36 mos.	May, 1976	$150,000

Scope of Work

This contract is an in house effort to quantify the ground level electric fields, ion densities, and ion currents associated with high voltage dc transmission lines. Predictive models for these effects will be developed and verified by field measurement under operating lines.

Total $2,326,000

the entire project is scheduled for completion by December 1978. Additionally several projects are being conducted on the ecological influence of HVTLs (RP129, RP855).

In the past year EPRI supported a feasibility study on conducting an epidemiological survey on high-voltage electric field effects on linemen (TPS 76-639). If this work is carried out it will help clarify the issues raised by earlier Soviet and Spanish reports; however, it is unclear at this point what EPRI's further plans are. The influence of 60-Hz electric and magnetic fields on patients with implanted cardiac pacemakers was investigated using baboons as the experimental animal. High-strength electric fields were found to affect one type of pacemaker. The significance to humans has not been demonstrated; however, the relationships for translating effects to the human case are being investigated.

Effects due to long-term exposure to electric fields are, of course, the area of greatest uncertainty. Battelle Pacific Northwest Laboratories (Richland, Washington) is conducting major animal research in this area for both EPRI and ERDA. Battelle Memorial Institute is the world's largest nonprofit scientific institute. It operates three other major research complexes--at its headquarters in Columbus, Ohio; Geneva, Switzerland; Frankfurt, West Germany--in addition to its Richland facility. It employs more than 5,000 scientists, engineers, economists and supporting personnel to conduct research (*Anonymous, 1976b*).

In 1976 Battelle completed a feasibility study for EPRI, "The Effects of Electric Fields on Large Animals" (*Kornberg, 1976*), which is guiding a major $1.2 million investigation of effects of chronic exposure of Hanford Miniature Swine (HMS) to high-intensity power frequency electric fields. Choice of experimental animal was critical. Hanford Miniature Swine are bred as a research model for humans, having comparable body and skeletal mass. Whether effects reported at the cellular level, in vitro systems and in rodents are detectable and significant in animals closer to man should be answered by this work.

Other characteristics of HMS that make them a useful experimental model are that they are hardy, free of disease and congenital abnormalities, have a gestation period of 110 days and are capable of successful pen breeding, and that their diseases of old age are well known. Also, HMS do not perspire much, eliminating the shielding perspiration might offer, and they do not stand erect which could cause greater field perturbations. This latter factor may cause some difficulty extrapolating experimental results to the erect human body orientation; however, this problem is recognized and will be addressed through supplementary research.

The experimental design in this study closely controls possible interfering factors in detecting biological effects of electric fields, a problem that has plagued earlier research. In the feasibility study, limits on field strength were established that would not produce corona (hence, ozone) on or near the animal or minishocks or hair stimulation which could cause effects that might inappropriately be attributed to the electric field. The maximum vertical field strength meeting these criteria is 30 kV/m and is the choice for this study. Control animals will be shielded to avoid exposure to this field, but otherwise maintained in the same environment.

The exposure system and operating procedures have been designed from an analysis of several designs to produce the desired fields for long-term exposure. Supplying drinking water to experimental animals without causing shocks has been a problem, and the system for this study will prevent shock from the watering device and minimize current flow to the swine when it drinks. Dosimetry studies which are essential to establish human exposure limits are included in this research.

To investigate the Russian reports of nonspecific disturbances of the central nervous system in switchyard workers, experimental animals that have been exposed to the electric field from conception through at least one breeding cycle, will periodically be given a wide variety of physiological and behavioral tests to determine if there is any difference between results of the same tests of control animals. A long-term study will involve following HMS exposed to electric fields and control animals through two generations. Research parameters will be identified by a parallel study sponsored by ERDA on small experimental animals (see below).

FEDERAL GOVERNMENT-SPONSORED RESEARCH

ERDA and other Federal government-sponsored research projects on health and environmental effects of high-voltage overhead transmission lines initiated in 1975 and 1976 total more than $2.3 million. They cover topics of both a technical and biological nature including electric field and instrumentation calibration, corona and corona-induced effects, psycho-acoustic response to audible noise generated by corona, environmental effects of 1,100-kV AC and a ±400-kV DC transmission, ground-level fields and ion currents from HVDC lines.

Preliminary biological tests are being investigated with fruit flies. Potential effects on the central nervous system of mammals are being investigated by measuring changes in brain rythms and conditions on the neuronal membrane.

Of particular interest is the study, "Biological Effects of High Strength Electric Fields on Small Laboratory Animals," also conducted by Battelle Pacific Northwest Laboratories for ERDA (*Phillips, 1976*).

The main purpose of this study is to determine, through an integrated series of experiments covering a broad range of organ systems, whether exposure to electric fields have any biological effects. It also will help narrow research areas for EPRI's HMS study.

Exposure systems for the Small Animal Study are designed to avoid attributing effects such as field perception, arc discharges, shocks or hair stimulation, to actual field exposure. Care is also necessary in the feeding and care of exposed animals and controls to avoid the pitfalls that befell much early research on biological effects. Animal shape and orientation are considered as important variables in determining the dose received as opposed to the "uniform" field strength to which they are exposed, especially when extrapolation of results to humans is intended.

The engineering design aspects of the housing and exposure system for this study have been completed, and biological screening tests are scheduled to begin in 1977 and continue for approximately 2½ years. These will cover the following areas: hematology and serum chemistry, immunology, metabolism and growth, cardiovascular function, endocrinology, pathology, reproduction, growth and development, male reproduction, central nervous system structure and function, neurophysiology and animal behavior. The Small Animal Study should effectively screen for biological effects of electric fields, narrowing the field of experimentation and provide a good basis for evaluating potential hazards from exposure to 60-Hz electric fields.

The Federal government is now also involved in HVDC research. Projects sponsored by ERDA and the Bonneville Power Administration are underway. Work for ERDA will be performed at General Electric's Project UHV, Pittsfield, Massachusetts. Initial tasks involve construction of HVDC test facilities, development of practical techniques to measure HVDC electric fields, ion currents and ion charge densities and determining the relationship between transmission line parameters and the generated electric fields and ion currents for different weather conditions. The following electric and space-charge field parameters and effects will be investigated as follows:

> 1. *Ion currents shall be continuously monitored . . . providing statistical data for a variety of voltage and weather conditions.*
> 2. *Voltages and currents induced on object of different shapes shall be measured for different controlled impedances to ground . . . . Further attention to practical situations shall be given in the form of short-duration tests involving vehicles and people in a variety of weather and ground conditions.*
> 3. *The rate of ion inhalation with a specially prepared mannequin with aspirating equipment to simulate a person's normal breathing activity, and monitoring the quantity and type of ions inhaled.*
> 4. *Corona on objects close to ground: To investigate this phenomenon objects of simple shape, such as vertical cylinders, shall be positioned under the test line.*
> 5. *The amount of shielding afforded by support structures associated with the DC line and by trees in the vicinity shall be assessed through field mappings over the entire area of the DC line.*
> 6. *In order to determine the levels of perception and annoyance and the physical factors influencing these levels a program shall be conducted.* (Feero, 1977a)

The results of this work will be compared to EHV research conducted for EPRI to provide an indication of the relative importance of the problem. This will be useful in evaluating the HVDC question and serve as a guide for development of standards.

The Bonneville Power Administration is conducting biological studies on the right-of-way of the Celilo-Sylmar $\pm$400-kV DC transmission line from The Dalles, Oregon to Los Angeles, California. This study includes assessment of effects on natural vegetation, crops, wildlife and domestic animals. Since energization of the Celilo-Sylmar line in 1970, BPA indicates there have been no reports of adverse effects to plants, animals or humans. However, systematic collection of data has not been done as yet and is the purpose of its study.

SUMMARY AND CONCLUSIONS

The lack of definitive, replicable effects from electric and magnetic fields creates major difficulties in designing a responsive, effective research program. As Sheppard and Eisenbud (1977) note:

> *The whole subject would be greatly simplified if the kinds to be expected could be identified from theoretical considerations. However, . . . this is difficult in the present state of knowledge. The absence of a rationale for the assumption of effects is a serious impediment to the design of productive biological experiments.*

For this reason, studies like the Small Animal Study funded by ERDA, and the Hanford Miniature Swine Study funded by EPRI, are absolutely essential in providing a sound basis for determining what biological effects do in fact exist and for evaluating their importance.

Cost and convenience require the use of small animals in initial screening tests to detect biological effects over a broad range of organ systems. If biological effects are detected it is important to have an understanding of the mechanisms of action for these effects. Importantly, dosimetry investigations will be conducted to complement the animal studies. The Small Animal Study will also help narrow research areas for the HMS Study.

The HMS Study will employ an experimental animal bred as a research model for humans. This study will investigate effects due to long-term exposure to electric fields, an area of great uncertainty. This study is carefully designed to control extraneous factors, which might interfere with evaluation and interpretation of experimental results. Dosimetry studies, essential for determining human exposure limits, are also included.

While such animal studies are necessary to develop working hypotheses for human effects, there is ultimately no substitute for human epidemiological studies (*Sheppard and Eisenbud, 1977*). Unfortunately, well-designed epidemiological studies are expensive and difficult to conduct. However, the Soviet reports have raised questions which need to be answered, and a comprehensive occupational study should be undertaken as soon as possible, of linemen, switchyard workers and/or others working in strong electric and magnetic fields, supplementing the limited work done to date.

If the animal studies do indicate biological effects, a general population epidemiological study might be warranted, particularly if impact on risk populations--the young, elderly, infirm or fetuses--is suggested. This point must be stressed because such populations are not represented in an occupational study.

It must be emphasized that all of the biological effects laboratory research projects described in this chapter are concerned with 60 Hz vertical electric fields as the environmental stress. Other than BPA's right-of-way study, there are no biological effects DC projects currently underway.

From a nationwide perspective this situation is understandable, for the overall trend is toward increased circuit-miles of higher

AC operating voltages. Unfortunately, Minnesota and North Dakota are also faced with HVDC technology; they contain the second and third HVDC lines in the United States.

As Chapter II suggests, relatively little is known about the spatial and temporal distribution of the DC electric field, particularly with regard to the space charge component. Project UHV's research project to characterize these effects is a necessary preliminary step. It is critically important that this work be carefully monitored, for it will define the characteristics of the environmental stresses to be studied in follow-on biological studies.

The latter work is included in the Biological Effects Plan, and both ERDA and EPRI have expressed their interest in supporting research. Nonetheless, no funding has as yet been provided. This is not a critical observation; funding at this time would be premature. This point is stressed, however, because of the unique importance of the HVDC transmission line environment to Minnesota, and the State must ensure that an adequate research program is undertaken at the proper time.

The posture taken by this report is maximum reliance on industry- and Federal government-sponsorship of biological effects research. The hazards of this strategy are appreciated: it is difficult for any investigator to reach conclusions contrary to the interests of his sponsor. Unfortunately, the costs of such research are too great to be borne otherwise. However, both ERDA and EPRI are at least somewhat removed from direct interest; research planning has been thorough; and competent research houses are being utilized. In addition, ERDA has strongly encouraged our participation in the joint-review sessions with Battelle for both the ERDA- and EPRI-sponsored research. Participation would provide considerable visibility into the design, progress and findings of the animal model studies. This would greatly facilitate our ability to evaluate this research and provide recommendations for additional research, and we strongly recommend acceptance of this invitation.

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V. RECOMMENDATIONS

This chapter contains a list of specific recommendations for consideration of the Minnesota Department of Health and the Minnesota Environmental Quality Board. In some cases, funding will be required; however, as yet possible sources have not been investigated. The Department and the MEQB Power Plant Siting Staff intend to seek appropriate funding and prepare a definitive plan in cooperation with the MEQB Technical Committee, for necessary approval.

Regretfully, these recommendations are primarily concerned with AC transmission lines. The concern over the possible effects associated with the Underwood, ND/Delano, MN $\pm$400-kV DC transmission line is recognized; unfortunately, there is neither sufficient experience nor research with HVDC field effects on which to base meaningful recommendations. In addition, given Recommendation 1 (below), extrapolations from AC are meaningless and are not attempted.

GENERAL

1. The coupling mechanisms for electric and magnetic fields are completely different for AC and DC transmission lines; effects for either cannot be extrapolated to the other. In future transmission line matters, the Board should carefully distinguish between the two sets of fields and their associated effects. In the case of DC lines, the space charge field, particularly, should be examined.

2. Although the Board's resolution of September 14, 1976 contained a clause stating,

> *THAT the MEQB reaffirms its intent to hold generic public hearings on the health effects associated with extra-high-voltage (EHV) transmission lines,*

such a hearing should be deferred until significant new research findings are available. This recommendation is based on (1) the fact that detrimental effects have not been demonstrated for either the AC or DC transmission line environment and that a theoretical basis has not yet been postulated which would provide a reasonable rationale for assuming the existence of effects; (2) the currentness and exhaustiveness of the New York Public Service Commission common record hearings on the same subject; (3) the observation that hearings through administrative agency processes are not a productive vehicle to address uncertain scientific issues; and (4) the fact that appropriate research programs directly oriented toward both the AC and DC transmission line field environments are underway, which will be monitored by the State if these recommendations are implemented (see Recommendations 6 and 7, below).

3. The Department and the Board should jointly consider the U.S. Energy Research and Development Administration's (ERDA) proposal to joint-venture a contract for comprehensive analysis of the material received in response to the official State Register notice (Appendix D), provided a mutually beneficial work product would result. This contract would be through ERDA's Division of Environmental Control Technology which provides an environmental check on ERDA's energy technology development.

BIOLOGICAL EFFECTS

4. The Board has utilized a 8-kV/m, rms, maximum vertical electric field gradient, measured at one meter above ground, performance standard in all recent construction permits it has issued for AC transmission lines. Since (1) this field strength is equivalent to the latest known Russian position on the transmission line environ-

ment; (2) a working hypothesis has not yet been postulated which would provide a reasonable rationale for assuming the existence of effects; (3) the maximum field strength occurs only over a small portion of the right-of-way and at maximum overvoltage and conductor sag; and (4) most importantly, public exposure is intermittent, this standard is reasonable.

5. The Board should adopt an edge of right-of-way vertical electric field strength standard for AC transmission lines. This standard should not exceed that of existing 345-kV lines and will probably lie in the 0.5- to 1.0-kV/m range. The precise value cannot be determined without a survey of right-of-way widths of existing 345-kV lines, as edge of right-of-way field strengths are not generally reported in the literature.

In addition to this standard, the Board should condition its construction permits for <u>all</u> transmission lines so as to preclude residences, private or otherwise, and associated yards from the right-of-way.

Both Recommendations 4 and 5 are intended to remain in effect until completion of necessary research and establishment of responsive performance and/or exposure limitation standards.

6. The Department should accept the invitation of ERDA's Division of Electric Energy Systems to participate in the program review meetings for the animal model research conducted by Battelle Pacific Northwest Laboratories, Richland, Washington, for ERDA and the Electric Power Research Institute (EPRI), respectively. This would assist these projects by providing a third party, public-health-oriented review and critique and would greatly increase our ability to interpret and evaluate the findings and conclusions from this research.

In addition, either the Department or the MEQB Power Plant Siting Staff should arrange to participate in the comparable review meetings for other relevant, ERDA-sponsored projects, in particular, the contract to Project UHV for characterization of HVDC ion currents.

7. Until a comprehensive human subject study is undertaken, the questions raised by the Russian studies will not be satisfactorily answered. Therefore, the Department should actively encourage EPRI to initiate its epidemiological study of linemen and others routinely exposed to high-strength electric fields as soon as possible. The problems of industry sponsorship are acknowledged, and more disinterested sponsorship is preferred. However, with its feasibility study complete, EPRI is in an excellent position to get such an investigation underway at an early date.

As with the Battelle animal model studies, the Department should to the extent possible, actively monitor this research, evaluating study protocol, findings and conclusions.

PUBLIC SAFETY

8. In its two most recent construction permits (Docket Nos. CU-TR-2 and MP&L-TR-1A), the Board has applied the following performance standards for control of AC capacitive-coupling: (1) five-milliamperes, rms, maximum short-circuit-to-ground, steady-state current induced in the largest non-stationary equipment expected to be in the proximity of the line; (2) one-milliampere, rms, maximum short-circuit-to-ground, steady-state current for stationary conductive objects (wire fences, structures, etc.); and (3) 25-joules maximum capacitive discharge energy. With the caveats noted in the following

recommendations, the first two of these standards are reasonable for AC transmission lines.

The 25-joule standard, however, should be altered. This is a large value, at the lower end of the calculated range to cause ventricular fibrillation from a single-pulse capacitive discharge. This is at best a marginally safe level. A conservative standard is 0.25 joule which is considered at the threshold of involuntary reaction and is thus a rough counterpart of the one-milliampere standard. This standard would be the limiting criterion for DC lines and should be adopted for all future contruction permits for such lines.

9. The five-milliampere standard described in Recommendation 8 is also incorporated in the new edition of the National Electrical Safety Code and, therefore, does not need to be explicitly cited in construction permits. For AC transmission lines, the Board should consider the possibility of meeting this standard through specification of the maximum vertical electric field gradient. The 8-kV/m gradient (Recommendation 4) will limit the shock hazard from non-stationary equipment to the five-milliampere standard for all land uses except public road crossings and where the right-of-way is parallel and adjacent to such roads. Here, the maximum gradient should be restricted to 6 kV/m on the roadway surface and shoulders. This restriction will limit capacitively coupled AC currents from buses and trailer trucks to the five-milliampere standard.

10. The Board should condition future construction permits for AC transmission lines to require coordination with local school districts to avoid school bus stops on the right-of-way, if possible. Otherwise these stops should be located at points where the vertical

electric field gradient is less than 1.2 kV/m.

11. In the absence of specific recommendations for DC lines, the MEQB Power Plant Siting Staff should utilize its complaint reporting mechanism to insure prompt application of mitigative measures for the $\pm$400-kV DC line.

These complaints should be further investigated with an objective of gathering sufficient data to develop eventual performance and/or grounding standard to ensure public safety.

12. For non-stationary objects, the principal possible problem appears to be with farm equipment operated in the proximity of AC transmission lines. Several complaints have been made by Minnesota farmers with 345-kV AC lines crossing or adjacent to their property, with none by other sectors of the public, supporting a recommendation specifically oriented toward agricultural equipment operators. The Board or other appropriate State agency should sponsor a study assessing shock hazards associated with farm equipment usage in the vicinity of the AC transmission line right-of-way, to better assess their nature and degree of risk. If this pilot study determines the need for further study a research proposal for a "psycho-shock" study should be prepared and appropriate funding sought. The ultimate result would be performance standards and a complementary safety program, consisting of equipment component bonding and grounding standards, safety instructions (booklet and/or training program) and some form of program evaluation.

13. An associated study of agricultural equipment should also be initiated under the same sponsorship. The current edition of the National Electrical Safety Code recognizes a class of land "traversed by vehicles, such as cultivated, grazing, forest, orchard, etc.," but

in specifying the minimum clearance for such land, it assumes a maximum equipment height of only 14 feet. Present equipment heights and trends should be analyzed, so that appropriate minimum clearances as a function of land use can be recommended. As an alternative, however, applicants could be required to survey equipment usage on their proposed right-of-way prior to submission of a construction permit application.

14. For stationary conductive objects, such as wire fences and structures with large metal components, protection from shock due to AC capacitive coupling can be achieved through proper grounding practice. The one-milliampere standard described in Recommendation 8 also appears to provide adequate protection from AC inductive coupling under fault conditions; however, this should be confirmed.

To guide the development and enforcement of appropriate standards, the Board or other appropriate State agency should sponsor an independent analysis of REA Bulletin 62-4 to confirm the recommended standards for AC lines therein with respect to fence and structure grounding, including field verification. The objective would be (1) to develop a set of nomographs specifying fence grounding intervals and structure grounding and bonding requirements as a function of appropriate transmission line parameters; and (2) recommended inspection and maintenance requirements to assure continued adequacy of grounds over the operational life of the transmission line.

This work should be extended to the DC environment at an appropriate time. It is recognized that much research remains to be done in the area of ion current effects on conductive objects, and attempts to establish reasonable mitigative standards for DC electric field effects may be premature. However, DC transient phenomena can be studied analytically, and it appears feasible at this time to assess this effect as a safety hazard and to develop any necessary grounding standards.

15. The Board should study the experience of Minnesota electric utilities with respect to (1) equipment or operational failure experience thay may endanger the public safety; and (2) accident reports of serious injury or death to employees, contractors or the general public, attributable in any way to the electrical effects associated with transmission line installation, operation or maintenance. Such information would provide a basis for determining any appropriate constraints on right-of-way utilization--such as limitations on certain types of public facilities or activity--that may be appropriate to impose.

16. As part of an overall inspection program, a computer-based mathematical model to compute ground-level field strengths, should be purchased or developed by the State. Such a model should be carefully field checked, then used to verify applicants' analyses.

17. Although Minn. Stat. § 326.243 (1976) adopts by reference the most recently published editions of the National Electrical Safety Code, there is no formal engineering plan review or inspection to insure compliance. This does not appear consistent with the intent of Minn. Stat. § 326.244, Subd. 5(2)(ii) (1976), and the Board or other appropriate State agency, should assess the need for and feasibility of, such plan review and promulgate appropriate rules as necessary.

18. When Recommendations 12-17 have been completed, the Board

or other appropriate State agency should adopt by rule the standards developed by these studies, to supplement provisions of the National Electrical Safety Code.

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B. ENGINEERING ASPECTS

To better evaluate the material in the body of this report, some tutorial background information is necessary on overhead transmission line design considerations and economic trade-offs that may influence environmental effects. This appendix overviews these subjects, with emphasis on the electrical environmental phenomena associated with both EHV and HVDC transmission line operation not discussed elsewhere. Chapter II provides a comprehensive review of the electric, magnetic and space-charge fields and the reader is referred there for technical information. The other general class of environmental effects--those related to corona discharge--is not the subject of this report, and this appendix emphasizes corona-related environmental effects such as radio and television interference, oxidant production, audible noise and shunt-power losses. The interaction of major engineering and economic factors in aggravating or mitigating these effects is also discussed to provide some background for consideration of future appropriate performance (as distinct from design) standards, as necessary.

GENERAL DESCRIPTION OF AC AND DC TRANSMISSION SYSTEMS

There are two systems for the transmission of electric power; alternating current (AC) and direct current (DC). By far the most predominant, best documented and most researched is the alternating-current system. Since AC voltages can be readily stepped up and down and AC is the mode in which electricity is used in our homes and businesses, it has also been the logical choice for electric transmission. Recently, however, with the advent of certain technological developments in terminal switching equipment, DC has begun to become a feasible alternative for long-distance electric power transmission. DC transmission, although contemplated for years because of certain advantages and used on a limited basis overseas, was not thought to be practical because of the costly, unreliable terminal switching equipment required to convert the direct current back to alternating current for distribution and consumption. This emerging interest in DC is due to several technical and economic advantages that DC enjoys over AC, including the fact that it employs one less conductor than AC thereby presenting the opportunity for a considerable capital savings, especially over long distances. There is also an added advantage to DC transmission, that being the environmental effects are not as great--especially in foul weather--as are the effects from AC.

The physical appearance and component parts of both transmission systems are quite similar and to the layman, all but identical. The environmental effects produced by each system are also similar and are influenced by the same factors, i.e., rain, humidity, etc., but not always in the same ways. These differences are spelled out in more detail below with examination of each particular environmental effect and its relationship with each of the transmission systems.

As mentioned before, the physical components--towers, insulators, conductors and shield wires for both AC and DC transmission lines are basically the same. The most significant difference in the appearance of the two types of transmission lines is the number of conductors used for each--three for AC and two for DC. At the present time AC transmission utilizes three phases with each phase utilizing a conductor. The typical DC transmission line has a bipolar transmission configuration and thus requires two conductors, one each for the positive and negative poles.

ENVIRONMENTAL EFFECTS

There are many factors to consider when discussing electric power transmission systems; such as stability requirements, insulation design, etc., but for the purpose of this summary we will concentrate on the environmental effects caused by the operation of HVTLs and how these effects relate to the line's design. As mentioned, environmental effects can be broadly categorized in two general areas: (1) corona effects; and (2) field effects, which are discussed in Chapter II. In the following section, corona effects are further examined as to their relationship to and interaction with the existing environment along a HVTL and their variability in magnitude and duration when subjected to external stimuli such as foul-weather conditions.

Corona is a luminous discharge occurring when the electric field strength at the conductor surface exceeds a certain critical value; namely, the breakdown strength of the surrounding air. This breakdown strength is highly variable, dependent on a number of atmospheric and climatic conditions. Among these are air pressure, relative humidity, presence of water vapor, incident photoionization and wind.

From calculations, it has been determined that corona begins at a conductor surface voltage gradient of 29.8 kilovolts per centimeter (kV/cm). However, under actual operating conditions it has been found that corona discharge usually begins when the voltage gradient at the conductor's surface is approximately 14-15 kV/cm. This is due in part to the variable breakdown strength of air, as mentioned earlier, but mainly to the irregularities on a conductor surface serving to concentrate the surface gradient and thus raise it above the breakdown threshold of the surrounding air. It must be noted that even though conductor surface irregularities and variations in the air's breakdown strength make corona formation possible at voltage gradients lower than the theoretical value required, the operating voltage of the line must be in the EHV range, e.g., 345 kV or above, for corona discharge to occur at all.

Corona discharge manifests itself in a number of different forms; flashes of light, audible noise, radio and television interference, formation of ozone and oxides of nitrogen, and dissipation of energy commonly referred to as "corona loss." The question of the level of ozone concentration produced by a transmission line "in corona" has been one of some concern and controversy. In an attempt to quantify the actual amount of ozone produced and to compare that level to the background ozone concentration in the same area before the line is built and operating, a condition of the construction permit for the Minnesota portion of the ±400-kV DC line from Underwood, North Dakota to Delano, Minnesota requires the applicants to contract for the construction and operation of a number of monitoring stations to measure "before" and "after" ozone concentrations. We feel, because of this project and other HVTL related ozone research, the ozone question is being adequately addressed at this time and therefore is not examined further in this study.

One very important characteristic of corona formation is that the magnitude of the corona-induced environmental effects are highly weather dependent. The magnitude of the difference between fair- and foul-weather (foul weather refers to heavy rain or an equally wet condition) corona effects varies depending on the type of resultant effect, e.g., audible noise, energy dissipation, etc., and also on whether AC or DC transmission is involved. Corona discharge from AC lines during foul-weather conditions is significantly larger than the corona discharge from the same line during fair-weather conditions, but for the DC case foul-weather corona effects will either slightly decrease or remain about the same as fair-weather effects. One of the reasons for the increased corona discharge from AC lines during foul or rainy weather is that raindrops and snowflakes that pass close to the conductors initiate a discharge from conductor to particle. Also, raindrops that collect on the surface of conductors serve as concentration points that allow surface voltage gradients to build above the corona onset voltage gradient, thereby producing more corona discharge. It is this highly variable, weather-dependent nature of corona formation that makes it all but impossible for the transmission engineer to design an economically feasible system that will totally eliminate any corona effects.

A. Corona Loss. The first effect of corona discharge we will look at is the energy loss occurring along a HVTL that has "gone into corona." This particular environmental effect is more commonly referred to as corona loss. This is electric energy loss along the length of a HVTL that will not reach the load. This must be supplied by generation, and therefore it is in the best economic interest of the utility to minimize corona losses. For AC transmission the magnitude of foul-weather induced corona loss can be as much as 50 times greater than that of fair-weather corona loss. During fair-weather conditions energy loss frequently will be negligible for a given segment of the HVTL but over the length of the line might average approximately 3-6 kilowatts per circuit mile.

Fair-weather DC corona loss will be approximately the same magnitude as comparable AC loss, but the DC foul-weather loss will be only about 10 times as great as DC fair-weather loss as opposed to the much higher differential for AC. One explanation for the relatively lower DC foul-weather corona loss is that for DC transmission there is a counteracting effect from unipolar space charges which tend to reduce corona formation, particularly in wet weather.

Wind effects are another corona loss factor unique to DC transmission. Corona formation creates an ion cloud around the conductor, producing a stable atmosphere around the conductor that suppresses further ion formation. Wind disperses this ion cloud, creating an unstable charge condition that is compensated for by the conductor forming more ions through increased corona formation. Therefore, as wind velocities increase and the ion cloud is dispersed even more, corona loss will also increase porportionately.

B. Radio Interference. Radio interference (RI) is an aspect of transmission-line operation with which most people are familiar. Much of the radio noise that the public encounters is caused by discharges from insulators on lower voltage distribution and transmission lines. The portion of RI that is of interest here is that caused by the radiating electromagnetic field created by corona discharge.

Because of its subjective nature, it is difficult to assess the environmental impact of RI. The level of adverse effects due to corona-induced radio interference will vary depending on the location of the receiving device in relation to its distance from the HVTL, the strength of the broadcast signal at the receiving location and on each individual listener's tolerance limit as to the amount of interference they personally can accept without being an annoyance to them.

Although RI may theoretically interfere with any radio frequency communication, it is most noticeable in the AM broadcast band. Rather than using the absolute value of radio noise field strength for rating interference, it is more logical to use a relative measure such as "signal to noise ratio" (SNR) which compares the level of radio noise at a position adjacent to the HVTL to the strength of the broadcast signal at that same location. By using the SNR, the actual amount of interference for a particular broadcasting station can be adequately assessed, and if need be, changes in the design or operation of the line can be made to reduce the RI to acceptable levels.

Foul weather will greatly increase the amount of RI an AC line will produce. Also RI is a function of the line voltage: the higher the surface voltage gradient, which comes from higher operating voltages, the more radio interference.

DC radio interference is very similar to that described above for the AC case. It is caused by the same electrical phenomenon, and its interference level is also measured by the signal-to-noise-ratio method. The only significant difference is that DC RI levels are decreased by rain or wet snow and increased by the wind.

C. Television Interference. Although television interference (TVI) has been identified as an environmental effect of corona discharge for years, very little research has been conducted in this area. One possible reason for this lack of research is that the problem is relatively new in comparison with radio interferences, and its impact has been quite limited so far. Therefore, it is difficult to adequately assess the magnitude of this particular corona effect and whether it will be a problem for HVTL design and operation.

Tolerance criteria for TVI is based on the same signal-to-noise-ratio technique that is used for measuring radio interference because it is of the same subjective nature. Because of the lack of research most of the TVI empirical models have been derived from RI criteria rather than actual TVI measurements.

In addition to the line-radiated TVI that is similar to AC television interference, television antennas located near a DC transmission line operating above the corona-onset voltage gradient, may pick up ion currents that will produce the same type of interference. It should be noted though, that from field measurements conducted to determine the range of the ion-current TVI, it was found that the TVI would be of little or no concern off the right-of-way. It was also found that interference due to ion currents could be reduced to acceptable levels by shielding the tips of the TV antenna.

D. Audible Noise. It has been predicted that for AC transmission lines with a nominal operating voltage of 500 kV and above, corona-induced audible noise may become the limiting design factor. For AC lines operating at less than 500 kV, acceptable audible noise levels are achieved if radio noise design criteria were met. Because of the increasing concern with all types of noise, audible noise emitted by HVTLs will take on increasing significance in design practice.

There are two basic components of AC transmission line audible noise; (1) broadband noise, commonly described as a crackling, frying or hissing sound; and (2) pure-tone components (hum) at frequencies of 120 Hz and multiples thereof. The broadband noise which is the most annoying, is caused by random-corona discharge into the air at the surface of the conductor. The positive-polarity streamer is the largest contributor of the corona discharges that generate this type of audible noise. Not all corona discharges create broadband noise and hum in the same proportions; therefore, depending on various weather conditions that might produce dissimilar discharges, the relative magnitude of random noise and hum can differ considerably.

Foul-weather conditions, particularly heavy rain or similar wet conditions that saturate the conductor, will greatly increase AC audible noise levels over comparable fair-weather levels. This is caused by the water drops on the conductor serving as point sources of corona discharge, which will in turn greatly increase the audible noise emitted. The fact that audible noise from AC transmission lines is loudest during foul weather makes the matter of determining annoyance levels even more difficult because of the higher background noise level.

The source of audible noise from DC transmission lines is corona discharge mainly from the positive polarity conductor. The most obvious and annoying component of DC audible noise is the impulsive, random positive-polarity streamer that is distinguished by its "popping" sound.

As in the AC case, DC audible noise levels are a function of line voltage and/or maximum conductor surface gradient for all voltage gradients above corona onset. For DC transmission, rainy weather will actually cause a slight decrease in audible noise levels compared to fair-weather levels.

AC and DC audible noise rapidly decreases as the listener moves away from the right-of-way center line. It has been determined from field measurements that AC audible noise will typically have high levels for a short duration, while DC audible noise will be of a lower level but more consistent in nature.

Due to the subjective nature of what constitutes a tolerable level of audible noise, transmission line designers have done considerable research into determining criteria for rating noise. Since the frequency of the audible noise more closely relates to the dB(A) scale of noise level measurements, it is used in developing actual noise criteria. Subjective studies have been made rating the level of audible noise that individuals consider annoying. From these studies design limits have been formulated to attempt to keep audible noise from HVTLs "in corona" at tolerable levels below the annoyance range. This is possible to a certain degree, because like the other corona effects audible noise is a function of the surface voltage gradient of the conductor, and therefore, the designer can employ measures to minimize that surface gradient.

MITIGATING DESIGN FACTORS

In discussing design factors that may mitigate overhead transmission line environmental effects, we will begin with those factors that limit corona-induced effects. It was discussed earlier that when a HVTL goes "into corona," the resulting effects will be numerous, e.g., audible noise, radio interference, etc., so that by designing a line to limit corona, a number of environmental effects will in turn be limited. It should be pointed out that electric power transmission is a complex operation and that a line design change that might possibly mitigate an environmental effect might have an adverse effect on some other component of the system, thus making tradeoffs difficult to the utility from both technical and economic standpoints.

The largest single mitigating design factor in limiting corona is the bundle-conductor design concept. A bundled conductor is a group of several subconductors placed in various arrangements with respect to each other, that collectively act as one conductor, but that are physically separated by spacers. Conductor bundling effectively increases the electrical diameter compared to any single conductor in the bundle. Bundled conductors are able to limit corona formation by maintaining the surface voltage gradient for a given operating voltage at a level below that for corona onset. Naturally the higher the operating voltage, the higher the corresponding surface voltage gradient and thus the greater the need for bundled conductors to minimize the amount of corona.

Increasing the number and size of subconductors has the greatest effect on how well a conductor-bundle mitigates corona. For a given line voltage, phase or pole spacing and height of the conductor above ground have very little effect on the corona reducing performance of a conductor-bundle. The economic and technical limitations to increasing the number and size of subconductors are the added expense of more material required and also added conductor-oscillation, ice-loading and line-stringing problems.

The aging or weathering of a conductor in actual operation has been found to help reduce the amount of corona discharge. The aging process smooths out conductor surface irregularities that serve as corona sources and helps draw up water drops into the strands of the conductor so that they will not act as corona sources either. Sandblasting the conductors before stringing will duplicate the aging process and eliminate the time that is required for natural aging to take place.

Also entering the picture of conductor-bundle design is the variability of the weather. The conductor-bundle can be designed through theoretical calculations to virtually eliminate fair-weather corona, but when foul-weather corona is considered, the design becomes much more subjective. It is apparently economically unfeasible to design the conductor-bundle for the worst possible weather conditions and perhaps unnecessary because of high background noise levels. Thus the designer must set subjective limits on reasonable design criteria in relation to foul-weather occurrence and how often design limits will be exceeded.

The other area over which the HVTL designer has some control is the magnitude of the vertical electric field beneath the conductors. A change in any one of the following five design parameters will effect a change in the field strength: Line voltage; conductor type (bundle or single); phase configuration; phase or pole spacing; and conductor height above ground.

It is evident that decreasing line voltage will decrease the electric field strength, but with the need for greater amounts of power to be transmitted over individual HVTLs, it is not a practical solution to reduce line voltages to attain reductions in electric field strengths. Although bundle-conductors are used to limit corona effects by increasing the effective conductor radius, bundle-conductors also increase a line's capacitance to objects in its vicinity, thus inducing larger voltages on objects than would a single conductor. For technical and economic reasons most transmission lines have horizontal phase configurations, but the triangular phase configuration will induce less current in objects, especially as the conductive object's lateral distance from the line increases, in comparison to the horizontal phase configuration. Increasing the phase or pole spacing will help reduce corona, but it will in turn increase the magnitude of currents induced in objects close to the line.

The design parameter which has the greatest influence on ground-level electric fields is conductor height. It is also at this time the only practical parameter change that will effectively reduce electric fields. The other parameters, as has been previously discussed, are heavily constrained by other considerations. But as operating voltages move into the "ultra-high-voltage" (UHV) range, the conductor heights necessary to limit induced currents will be so great as to make them all but physically impractical and economically highly unattractive.

Although not presently in use, auxiliary shield wires can effectively reduce electric field strengths by approximately 25%. Shield wires are simply grounded conductive cables strung under or close to the conductors to minimize the ground-level electric field strength. The height of the shield wires may be much less than the conductors so that they may pose clearance problems in certain areas. The additional cost of stringing the shield wires is the principal impediment to their use at the present time.

In view of the inherent problems of most of the electric field mitigating measures, one proposed solution is to limit the access to the HVTL right-of-way by fencing or other measures. This would mean that only vehicles that are properly grounded would be permitted on the right-of-way. Although this would help mitigate electric field-oriented problems, it would open the door to a myriad of associated land-use problems and would also be in conflict with the principle of corridor sharing. For these reasons, such an approach would be highly undesirable to the majority of the parties involved.

C. STUDY BACKGROUND

Recently there has been heightened interest in segments of both the general public and the scientific community concerning the alleged health hazards associated with operation of high-voltage overhead transmission lines (HVTLs). This heightened interest in possible biological effects was initiated by Russian reports. There, studies of occupational exposure to switchyard electric fields have been carried out since 1962, involving medical and physiological studies of 220-, 330- and 500-kV switchyard workers. The conclusion reached by Russian researchers is that electric fields cause unfavorable nonspecific disturbances in the central nervous system (CNS) and functional changes in the cardiovascular system.

The only similar study in the United States was sponsored in the 1960's by the American Electric Power Service Corporation. Frequently cited is the study by W. B. Kouwenhoven and associates on 10 linemen engaged in live-line maintenance work on 345-kV lines. Medical evaluations on these men over a period of 42 months by a team of physicians at Johns Hopkins Hospital revealed no significant changes in their health status due to exposure to the high-voltage lines. At the same time to hasten obtaining information on possible long-term effects, studies were conducted by G. G. Knickerbocker and colleagues on mice exposed to strong AC electric fields. The results showed no effect on exposed mice, but male progeny of exposed males exhibited decreased growth rates. However, the results were not conclusive and need validation, as the researchers themselves observe (see Chapter III).

In 1967 the U.S. Navy instituted an environmental compatibility program to study the effects of its Project Sanguine. Sanguine (now, Seafarer) is a proposed communication system that would radiate energy in the extremely-low-frequency (ELF) range (less than 100 Hz), producing low-intensity electric and magnetic fields. The studies conducted have generally involved lower voltage gradients (10-20 v/m) and higher magnetic fields (2-3 gauss) than those experienced under HVTLs. Investigations of the biological effects of these fields have been inconclusive and have not revealed adverse effects for frequencies and intensities comparable to those produced by HVTLs.

Public concern started rising with the nationwide transmission line construction boom of the 1960's. In 1969, a 765-kV line was routed near the town of Laurel, Ohio. The series of events that followed in citizen opposition formed the basis for Louise B. Young's book, Power Over People. Published in 1973, Ms. Young's graphic, disturbing book aroused the public, created controversy and generally enhanced awareness of the HVTL issue.

In March 1975, the U.S. Environmental Protection Agency (EPA) issued a notice (Federal Register, 40(53): 12312, March 18, 1975) requesting data on the health and environmental effects associated with the operation of EHV overhead transmission lines. As of March 1976, over 50 responses totaling more than 6,000 pages had been received, providing extensive technical background information.

The public was made aware of the EPA investigation and dramatically aroused over the Russian studies by an article in the National Enquirer, February 10, 1976, where headlines read, "Scientists Discover . . . Ultrahigh Voltage Power Lines Cause Organ, Blood and Nerve Damage."

In addition to public interest, transmission line questions have attracted worldwide professional attention for some time. International meetings and symposiums have been held discussing worldwide experimental and epidemiological findings on this topic. The International Conference on Large High Tension Electric Systems Study Committee (CIGRE) has been following and investigating these findings for the last eight years.

Potential health hazards of electrical fields at power frequencies first became an issue of regulatory concern in the United States in proceedings before the New York Public Service Commission. In September 1973, the Power Authority of the State of New York (PASNY) filed with the Commission an application for a Certificate of Environmental Compatibility and Public Need, which would authorize the construction of 155 miles of 765-kV transmission line, connecting the Authority's system with Hydro-Quebec. Public hearings commenced in December 1973 and continued through February 1975, during which period 28 witnesses presented evidence and a 6,000-page record was compiled on the routing and land-use impact of the proposed facilities.

In November 1974, motions were filed by the Public Service Commission staff and by the Department of Environmental Conservation, joined by the Attorney General, the Department of Health and the Department of Agriculture and Markets, requesting an independent investigation of alleged health and safety hazards of 765-kV transmission lines. In response, the Commission directed the merger of the Authority case with that of Niagara Mohawk Power Corporation and Rochester Gas and Electric Corporation, who had jointly filed for permission to construct a 66.5-mile 765-kV transmission line. The purpose of the merger was to place investigation of the alleged health and safety effects on a common record. This ruling gave rise to what now appears to be the most extensive investigation in a public forum to date of the health and safety effects of extra-high-voltage overhead transmission lines.

The effects specified to be the subject of the common record hearing were:

1. Ozone
2. Audible Noise
3. Induced Current Shocks
4. Biological Effects of Electric and Magnetic Fields
5. Pacemakers

The hearings commenced in February 1975 and by June 1976, direct testimony from 26 scientists and engineers was in evidence, more than 90 exhibits had been introduced, and a more than 10,000-page record of direct testimony and cross-examination had been compiled.

It is significant to note that the five-member Commission with one dissent, issued its "Opinion and Order Authorizing Erection of Support Structures and Conductors" on June 30, 1976, based solely on the record developed from direct testimony and cross-examination. The Commission concluded that "prompt construction of the facilities proposed by PASNY, as modified, is needed to serve the public interest, convenience and necessity, and that further delay is not needed to ensure that the facilities will have the minimum adverse environmental impact, considering the state of available technology and the nature and economics of all of the various alternatives."

Importantly, the Commission reserved the right--at the conclusion of its hearings--to require the Authority, as a condition of operation, to take such protective measures as the Commission deems necessary to protect the public health and safety. These

> *. . . may include, but shall not be limited to, the acquisition, by fee simple or easements, of a substantially wider right-of-way or protective zone than proposed by applicant; measures to limit use of, or access to, the right-of-way or protective zone, including offers by PASNY to purchase structures within a period of time to be specified or to acquire development rights; educational programs by PASNY relating to permitted or prohibited uses of the right-of-way or protective zone or to conditions caused by the facilities' operation; posting of signs; construction of fences or other barriers; landscaping and planting programs; and the undertaking of programs outside the right-of-way to assure adequate grounding and bonding to prevent or minimize effects from induced shocks. PASNY also may be required to conduct, or contribute to, any research programs which the Commission, as a result of the present hearings, find necessary with respect to the health or safety issues involved in this proceeding.*

Additionally, the Commission reserved the right,

> *. . . at any time during the existence of the certified facilities, to impose such reasonable restrictions on the operation of the line--including but not limited to its operating voltage and loading--as may be necessary to protect the health or safety of the public and any other protective measures, as a condition to the line's continued operation, that the Commission determines, after hearing, necessary as a result of further research which it may require or which may be brought to its attention.*

In essence, the Commission concluded that based on the record, adequate mitigative measures to protect the public safety and health could be taken without design modification of the structures and conductors. While this is undoubtedly true, an excessively wide right-of-way with possible access limitations and/or uneconomic operating constraints could well be the result, a point well made by the dissenting commissioner.

In spite of the issuance of this opinion, the matter was far from closed. Rebuttal testimony was scheduled for submission on November 24, 1976; motions to strike this testimony, on December 8; and replies to motions on December 21. Cross-examination of rebuttal testimony for seven witnesses began on January 13, 1977 and continued through July 12, adding 3,626 pages to the record. As of the latter date the hearing was finally closed. The two administrative law judges received "initial briefs" on August 30 from the Public Service Commission staff, the Department of Environmental Conservation, and from each of the three applicant utilities, as well as an amicus curiae brief from Dr. Andrew A. Marino. "Reply briefs," responding to the initial briefs were submitted on September 23. Findings and recommendations from the judges to the Commission are expected in mid-November, and a final determination by the Commission is anticipated by March of next year.

The initial and reply briefs are only the respective parties' recommendations to the administrative law judges. This point is particularly applicable to the Commission staff, which acted as a party itself throughout the proceeding. Consequently, the New York Times September 18 headline, "P.S.C. Finds 'Biological Effects' caused by High-Voltage Conduits," was misleading to a number of Minnesotans. Nonetheless the staff's recommendations are worthwhile reporting:

> *The Staff believes that the evidence in this record establishes that:*
>
> 1. *The 765 kV transmission line will probably cause biological effects in humans exposed to them on a chronic basis.*
> 2. *There is a need to inform individuals living in proximity to the lines of this hazard, and require the utilities to relocate residences or offer to purchase houses when the electric field strength exceeds .4 kV/m.*
> 3. *There is a need for a comprehensive research program to determine if specific adverse biological effects will be induced in humans exposed to the lines.*
> 4. *Some individuals will be aroused from sleep or prevented from sleeping by the noise produced by these lines during inclement weather.*
> 5. *The utilities should be required to reduce the noise produced by the line, or to purchase or relocate residences within 325 feet of the center-line of 765 kV lines.*

6. *The utilities should be required to design 765 kV lines under a set of circumstances specified herein so that shocks from fixed objects are limited to 1.0 milliamperes and 4.5 milliamperes for vehicles and movable objects.*

7. *The companies should be required to supply drag chains at the request of adjacent landowners who operate vehicles on the right-of-way.*

8. *The utilities should ground all fixed objects which would yield a shock current in excess of 1 mA.*

9. *The utilities should ground electrical fences and maintain their effectiveness or safe operation if either condition is affected by the line.*

10. *The utilities should notify residents adjacent to the line of the potential shock hazard, and inform these people that the utility will attempt to ameliorate this problem. Also adjacent landowners should be notified that refueling of vehicles should not be done on the right-of-way.*

11. *The companies should notify school districts that buses should not pick up or discharge passengers under overhead transmission lines.*

12. *The utilities should be required to notify pacemaker manufacturers and cardiologists of the line's potential for interfering with the operation of pacers.*

13. *The ozone produced by the line will not cause effects in humans, animals or plants.*

The Commission's common record hearing has provided an excellent "state-of-the-knowledge" review of the health and safety effects of HVTLs. Public Service Commission staff witnesses, Andrew A. Marino, Ph.D., J.D., and Robert O. Becker, M.D., both of the Veterans Administration Hospital, Syracuse, New York; and Mr. Allan H. Frey, Randomline, Incorporated, provided direct testimony on the biological effects of the electric and magnetic fields which raised much controversy. Their testimony indicates that biological effects might occur from HVTL electric and magnetic fields.

The Power Authority presented four witnesses, Herman P. Schwan, Dr. Phil. Nat., Professor in the College of Engineering and Applied

Science and in the School of Medicine, University of Pennsylvania; and Solomon Michaelson, D.V.M., Professor of Radiation Biology and Biophysics and Associate Professor of Medicine; Morton W. Miller, Ph.D., Associate Professor of Radiation Biology and Biophysics and Assistant Director of the Department of Radiation Biology and Biophysics; and Edwin L. Carstensen, Professor of Electrical Engineering and Director of Biomedical Engineering, all of the University of Rochester, who testified and concluded that there will be no significant biological effects from exposure to the electric and magnetic fields of the proposed 765-kV lines.

The research of Drs. Becker and Marino is concerned with the electrical control systems utilized by organisms to direct certain basic life functions such as growth, healing and biological cycles. Presently, their work is being used to stimulate the healing of non-united fractures and to treat certain types of infectious processes by the application of small electrical currents to simulate those which occur naturally.

The doctors had been invited by the Commission to review the evidence submitted and to testify themselves with regard to the biological effects of ELF electric fields. Their testimony discussed the medical and biological significance of exposure to ELF electrical and magnetic fields, the medical ethics of such exposure, a proposed maximum field strength standard of 1.5 volts/cm, and a recommendation that the 765-kV lines as designed not be built. These recommendations were based on the conclusions reached from two studies conducted by them relating to the health effects on rats and mice exposed to electric fields at 60 Hz, similar to those that would be produced by the 765-kV transmission lines and from a comprehensive analysis of the scientific literature concerned with studies in the area of biological effects of electric fields and related phenomena.

Dr. Marino, a biophysicist, conducted the actual experiments, the statistical analysis of the data, and formulated the general hypothesis that exposure to ELF electric fields will produce biological effects in test animals. Dr. Becker, a medical doctor, then carried it further and concluded from their studies and the current scientific literature that there is possible medical significance to the continuous exposure of humans to such fields. Under cross-examination, neither doctor would testify as to any specific effects that electric fields might have on humans, nor did they know or were willing to estimate exposure time or field strength they would consider unsafe. The strongest statement either doctor would make is that they believe there is a biological effect caused by exposure to ELF electrical fields and that further study of this area is definitely needed to ascertain any specific effects these fields might have on humans. Additionally they pointed out that their position is only applicable to AC electric fields and that it could not be extrapolated to DC fields.

Based upon our review of the NYPSC common record hearing transcript, Marino's conclusion that transmission lines are unsafe cannot be strongly considered. Unorthodox data handling techniques and a lack of critical consideration of quality and applicability of research reported in the literature, limit the weight that can be attached to his recommendations. Biological effects if present are apparently subtle, requiring extremely carefully designed experimental protocols and biostatistical analyses.

The Minnesota Department of Health became formally involved in the HVTL issue last year. On September 14, 1976, the Minnesota Environmental Quality Board adopted a resolution, denying a petition of Counties United for a Rural Environment, Inc. to "modify, revoke or suspend" the Construction Permit issued by the Board to Cooperative Power and United Power Associations for construction of the Minnesota portion of a ±400-kV DC high-voltage transmission line and associated facilities from Underwood, North Dakota to Dickinson, Wright County, Minnesota. The basis of CURE's motion was that this HVTL "would be dangerous to the public health and the environment," citing the direct testimony of Drs. Becker and Marino before the New York Public Service Commission. The Board's resolution concluded that the doctors' "direct testimony taken with subsequent cross-examination provides no substantive basis for modification, revocation or suspension of said construction permit."

However, the same resolution, at the recommendation of the Minnesota Department of Health, included the following provision which provides the mandate for the present study:

> *THAT the MEQB requests the Minnesota Department of Health, with the assistance of the MEQB Power Plant Siting Staff, to prepare a staff report on the state of knowledge of the human health effects associated with EHV transmission lines; such report to be presented at the January 1977 MEQB meeting and to include but not necessarily limited to:*
>
> - *A bibliography and an evaluation of the scientific literature on biological effects of electrical fields as it pertains to human populations;*
> - *A summary of current research including objectives, status, findings to date, and schedule;*
> - *Identification of the additional review necessary to determine research needs for establishing performance standards for EHV transmission lines; and*
> - *Recommendations as to the scope, purpose and timing of the MEQB's generic public hearing taking into consideration the outcome of the New York State proceedings.*

The January 1977 date was not met for several reasons, primarily due to difficulties in information gathering generally and delays in the New York Public Service Commission common record hearing schedule specifically. This report does comprise the response to the Board's original request.

It is instructive to compare the New York proceeding with this ("Minnesota") study. The NYPSC was concerned solely with 765-kV AC transmission, whereas the Minnesota study dealt more broadly with EHV transmission and importantly, also with HVDC transmission. On the other hand, the NYSPC dealt with the entire range of environmental effects, while the scope herein was limited to field effects.

Looking at the Commission's 13 recommended findings (Page C-), Recommendations 1-3 are encompassed by the Minnesota study. While we find that the research to date does not support Recommendation 1, a counterpart to Recommendation 2 is discussed in Chapter III and included in Chapter V, and Recommendation 3 is considered in some detail in Chapter IV.

Recommendations 4 and 5 are concerned with corona-induced audible noise, which is not within the scope of this study. However, the Minnesota Pollution Control Agency has considerable regulatory authority with respect to this issue.

Recommendations 6 through 11 deal with shock hazards and are very similar to those outlined in Chapters II and V herein. One important distinction, however, is that the Minnesota study recommends limiting induced shocks implicitly through specification of the maximum electric field gradient, and not explicitly by specification of maximum short-circuit-to-ground current.

Recommendation 12 deals with pacemakers. This is a known potential problem, well recognized by the medical instrumentation industry and extensively studied in conjunction with Project Seafarer. The New York recommendation is non-operative, as it would provide manufacturers and cardiologists with no additional information. We lack the electronic expertise to evaluate this issue, but prefer to recommend that pacemaker users individually consult with their physicians with regard to risk.

Recommendation 13 appears to be generally supported by all parties in the New York proceeding. Ozone production, as a corona-related effect, was not considered by the Minnesota study. Here, as with audible noise, the Minnesota Pollution Control Agency has regulatory control to limit ambient photochemical oxidant concentrations.

D. <u>STATE REGISTER</u> NOTICE RESPONSE

This appendix consists of the following report:

Banks, R. S., et al., 1977, "Information Received on the Health and Safety Effects of High-Voltage Overhead Transmission Lines," Minnesota Department of Health, Minneapolis, June 7, 1977 (56 pages).

However, because of its length and expected limited interest, it is not included herein.

The report itemizes the 129 responses received in response to the Minnesota Department of Health's official notice appearing in the December 27, 1976 issue of the Minnesota State Register (1 S.R. 960). It consists of three listings:

1. Individual respondents ordered by date of receipt, consisting of name and address, a short description of the subject matter and/or material received and a sequential file number as an identifier to allowing cross-referencing by respondent.
2. Citations for all technical documents received, including abstract where available. The citation includes the file number of each respondent providing the same material. In some instances, several respondents provided the same document, in which case the citation references all such respondents.
3. A list of concerns expressed by the public that extended beyond the scope of the notice, referenced by file number. These were generally short quotes expressing the nature--but not necessarily a summary--of the issues raised.

This report can be obtained through the Minnesota Department of Health.