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Coupling and Corona Effects Research Plan for Transmission Lines

Final Report

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ABSTRACT

Concern has arisen over the possible effects of electric and magnetic fields produced by EHV-UHV transmission lines. Past and ongoing research concerning the electric and magnetic field effects from EHV-UHV transmission lines was reviewed as it pertains to the following areas: 1) Electromagnetic Interference, 2) Acoustic Noise, 3) Generation of Gaseous Effluents, 4) Safety Considerations of Induced Voltages and Currents. The intent of this review was to identify the short and long range research projects required to address these areas.

The research plan identifies and gives priority to twenty programs in corona and coupling effects. 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 quantities 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. The interrelationship of the programs and their role in a long-term research plan is also discussed.

ACKNOWLEDGEMENT

The assistance of many workers in the electric power industry must be acknowledged, particularly in their support and contributions to the Ad Hoc Workshop that was held on October 15-16, 1975. Special thanks should go to Mr. N. Kolico, Chairman of the IEEE Subcommittee on Radio Noise and Corona Effects from Transmission Lines, and Mr. E. G. Lambert, Chairman of the IEEE Working Group on E/S and E/M Effects of Transmission Lines, who enlisted the aid of their groups and contributed greatly to the success of the Ad Hoc Workshop. The experience and recommendations of these groups were instrumental in developing the programs presented in this report.

We are especially indebted to Prof. Charles Dalziel for his discussions on let-go consideration and electric shock hazards.

The participants of the Ad Hoc Workshop contributed their combined experience in most useful and constructive ways. The list of speakers and participants is presented in Appendix A.

The principal investigator for this program was Mr. J. Bridges, who received major support from Mr. V. Formanek who was project engineer, Mr. A. Valentino, Dr. E. Brueschke, Dr. M. Henry, Mr. W. Able, Mr. R. Brabets, Dr. R. Norman, Dr. H. Wakely, and Mr. R. Kaminecki, all of IIT Research Institute. Contributing as consultants were Dr. S. Sebo of Ohio State University, and Dr. W. Janischewskyj of the University of Toronto. Mr. Robert Flugum and William E. Feero of ERDA were the program managers. Ms. C. A. Damberger of IITRI edited this report and provided recommendations on format.

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COUPLING AND CORONA EFFECTS RESEARCH PLAN FOR UHV TRANSMISSION LINES

1. OVERVIEW

1.1 Introduction

1.1.1 Background

There has been a significant increase in recent years in the public concern for the environment and the effect of man's projects upon it. The environmental considerations for high voltage overhead power transmission lines can be classified into the following categories:

1. Coupling and corona effects of electric and magnetic fields,
2. Biological effects of electric and magnetic fields, and
3. Asthetic aspects of the physical design of the power line.

While considerable research results are available in the above areas, there is still need for additional data, especially for fields from overhead transmission lines operating at voltages in excess of one million volts, which will become increasingly important in the context of future technology. Developing this data can be difficult and costly, since many complex phenomena and human value judgments are involved. To minimize these difficulties, a well planned research program is necessary.

In response to this need, this report identifies the overall research necessary to address the problems initiated by the electric and magnetic fields acting on non-living materials, such as air or metal. This interaction creates side-effects which in turn may have some social or biological significance. Examples of these interactions include the formation of corona, with attendent acoustical and radio noise, or induction of a potential on a vehicle, with the possibility of shock.

On the other hand, the effects of electric and magnetic fields from transmission lines acting directly on life-forms, such as animals and plants, have been considered on a companion program. This program, sponsored by EPRI, considered the long-term research needed to address these direct biological effects of fields from transmission lines. Included in that program were effects on patients with implanted cardiac pacemakers.

1.1.2 Summary of the Project Effort

A state-of-the-art review was conducted in order to avoid duplication of effort and to assure proper assignment of priorities. Under the sponsorship of the Energy Research and Development Administration, as part of this contract, a workshop was held at IIT Research Institute on October 15 and 16, 1975. During these two days, engineers and scientists who have expertise in the appropriate fields of interest provided information for the state-of-the-art review, for the assignment of priorities and for the development of the recommended program plan. Appendix A lists the participants of this workshop who generously supplied their aid.

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1. A review of past and ongoing programs,

2. The workshop at which approximately forty experts from research centers, universities, government and industry participated, and

3. Steering committee meetings and discussions with participating working groups.

1.2 Summary of the State-of-the-Art Appraisal

The nonbiological effects of overhead transmission lines are divided into two major categories: corona effects and coupling effects. Corona effects are further subdivided into acoustical noise (AN), electromagnetic interference effects and ozone. The coupling effects of High Voltage Alternating Current (HVAC) lines are not identical with those of High Voltage Direct Current (HVDC) lines; consequently, these effects are each discussed separately. Each of the subdivisions of nonbiological effects of overhead transmission lines and, in some cases, certain aspects of each subdivision represents a highly specialized and sometimes thoroughly developed scientific or engineering discipline. Acoustics and radio noise are two of the more prominent examples of such specialized disciplines.

Due to the large number of disciplines and the maturity of many of these technologies, the review of the literature and ongoing research was largely confined to references that emphasize the point of view of power engineering. The literature search was completed in the Spring of 1975, and relied heavily on the material identified on the companion EPRI

Major consideration was given to the nonbiological effects of electric and magnetic fields from HVAC and HVDC overhead lines, especially in the context of future designs--which would operate above one million volts. Highlighted for discussion were acoustical noise, explosion/fire hazards and ozone. Other related areas, such as electromagnetic interference, are also considered for completeness. Intentionally deleted from consideration are coupling problems with other utilities, advanced energy storage systems, power line transient effects, ground return corrosion problems, rights-of-way sharing considerations, and future transmission systems.

In developing possible programs, the highest priority has been given to areas in which risks or disturbances to humans are likely, or where there might be a significant economic impact. The scarcity of reliable information in the particular area of concern was also a factor in determining the level of program priority.

1.1.3 Objectives of the Overall Research Plan

The overall objective of the suggested long-term research plan is to develop a sufficient understanding of the coupling and corona effects of overhead high voltage power line fields to determine safe and compatible design criteria.

1.1.4 Basis for the Recommended Program

The recommended program was developed from data developed during the state-of-the-art review in three major areas:

sponsored program mentioned in section 1.1.1. Only the more recent publications were considered--especially summary and review articles and articles that were originally written in English.

Unlike the case with several fields of endeavor, most of the present research activity is confined to a few major centers, since such research requires substantial continuing support and access to costly equipment. Typically, this research cuts across disciplinary lines, with its unifying element being the development of overhead transmission line design data at high operating voltages.

The detailed appraisals of the state-of-the-art in sections 2, 3, 4 and 5 of this document consider each major discipline--ozone, acoustical noise, radio noise and electric/magnetic field coupling--as separate and complete sections. Each section has its own reference and illustration numbering system, and its own bibliography (except section 4, for the reasons cited therein) which includes the references cited in the body of the text plus abstracts of the articles. Following the appraisal of the state-of-the-art in each section are the projects recommended for ongoing and future work in that area. Section 6 discusses multipurpose programs, which cut across these disciplinary lines, that are also recommended projects.

1.2.1 Acoustical Noise

Acoustical noise from high voltage overhead lines arises from several sources, the most important of which are the random sequences of corona pulses and, in the case of HVAC lines, the spatial modulations of corona region by the line voltage. Such noise is generally of significance only near the power line. HVAC noise is greater in foul weather; HVDC noise is greater in fair weather.

While it has been recognized for some time that audible noise is generated from corona sources associated with transmission lines, the expansion of EHV and UHV Systems has caused increased focus on the effects. Prediction techniques and measurement methods have been developed to a point where reasonable agreement exists between analytical and experimental results for representative fair and foul weather conditions. However, major problems remain in establishing a relationship between the human responses to power-line noise and the human responses to other ambient acoustical noise sources. The magnitude and spectra from both types of noise sources can fluctuate over wide ranges as a function of weather, terrain and human activity. Consequently, the human responses to varying mixes of ambient and power-line noise become an important consideration in transmission line design.

1.2.2 <u>Radio and Television Interference</u>

Radio interference from transmission lines arises from discrete source impulsive corona discharges. The interference effects are confined to the immediate vicinity of the power line. The physical nature of the corona sources are such that HVAC RI is a foul weather phenomenon whereas HVDC RI is a fair weather effect. These phenomena have been studied extensively for several decades, so reliable prediction methods are available for RI (Radio Interference) from HVAC lines, and to a lesser extent, TVI (Television Interference) from HVAC lines, and RI from HVDC lines. A major problem area remains in the measurement of TVI, and prediction of the higher frequency interference, especially for HVDC lines.

1.2.3 Electric and Magnetic Coupling Effects

High level electric and magnetic field environments are also confined to the immediate vicinity of the power line. Rigorous analytical techniques confirmed by measurements are available to predict the field from HVAC lines. On the other hand, only tentative, inexact methods are available for HVDC lines.

Coupling from HVAC lines can arise from three basic mechanisms: 1) capacitance, 2) inductance, and 3) conductance. By these coupling mechanisms, the fields in the immediate vicinity of the power line are converted into currents and voltages by conducting objects.

These currents and voltages may be perceived by animals or humans, or may cause certain involuntary reflexes, under unlikely circumstances. Such voltages, under highly improbable circumstances, could cause fuel ignition.
While the theoretical aspects of HVAC coupling are well understood, a major area of uncertainty exists in how this coupling is affected by practical factors--such as weather,

terrain, or obscure details of the field collector. An area needing further refinement is how humans react to these voltages and currents psychologically, physically and physiologically. Further work is also needed to understand concretely the phenomena associated with the possibility of fuel ignition.

Instrumentation to measure HVAC line fields and resulting currents or voltages is satisfactory.

In the case of HVDC lines, coupling arises largely from air ion conduction currents. In general, the effects are somewhat similar to coupling in HVAC lines except for the drift of air ions. These effects can be observed over a greater area around the HVDC lines than the effects around HVAC lines. As was the case in the prediction of fields, the understanding of coupling phenomena and measurement instrumentation for HVDC lines is embryonic compared with HVAC lines.

1.2.4 Ozone

Interest in ozone generation by transmission lines is prompted more by an acute awareness of the air pollution problems in general rather than by realistic appraisal of the scientific data available. Although ozone generation is generally associated with electrical discharges, laboratory studies and analyses have demonstrated that power lines do not generate significant quantities of ozone. These results have been confirmed in six field measurement programs in which no measurable increase in the ozone concentration near power lines was found. Instrumentation for ozone measurement is adequate if properly used and maintained.

1.3 Summary of Projects Suitable for Immediate Initiation

The short term plan identifies some twenty (20) programs which could be implemented within the next two years. These programs are listed with brief titles in Table 1, and are described in detail in their respective sections. The short term programs are divided roughly into two major categories: (1) corona effects, and (2) electric and magnetic coupling effects.

In the case of corona effects, the only need in the ozone area is to place the past work in perspective. In the case of acoustical noise, the human response to power line noise received major emphasis along with prediction techniques appropriate for power lines operating above one million volts. Recommended for electromagnetic interference are measurement techniques and evaluation methods emphasizing the higher frequency and television interference aspects oriented toward the higher frequency problems.

In the case of electromagnetic coupling, the programs are divided into those associated with HVAC and those associated with HVDC lines. This division is necessary owing to the very large amount of data already available concerning coupling effects from HVAC lines and relatively sparse data available for HVDC lines. In the case of HVAC lines, the programs focus on certain potentially hazardous

TABLE 1

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) conditions. In the case of HVDC lines, the recommended programs emphasized the development of basic understanding of the electrification phenomena along with the development of the supporting instrumentation.

For reasons of economy and convenience, programs combining several disciplines appear especially desirable in the case of corona-related effects.

1.4 Long Term Plan

1.4.1 General Approach

The separation of nonbiological effects into corona and E&M coupling categories provides the basis for the long-term overall plan. Figure 1 illustrates how these general considerations could lead to a long-term research plan. For both general categories, the priority programs are initiated first. In the case of HVDC programs, phenomenology, coupling and instrumentation studies should be largely completed before initiating additional HVDC research on an extensive basis. Specific programs concerning HVDC hazards and psychobiological effects remain to be identified as part of the basic HVDC theory, coupling and instrumentation studies. Toward the end of the plan, consideration can be given to possible effects associated with future transmission line systems, rights-of-way sharing, or line induced transients.

1.4.2 Milestones

Owing to the relatively advanced state-of-the-art concerning HVAC nonbiological effects, very few program inter-

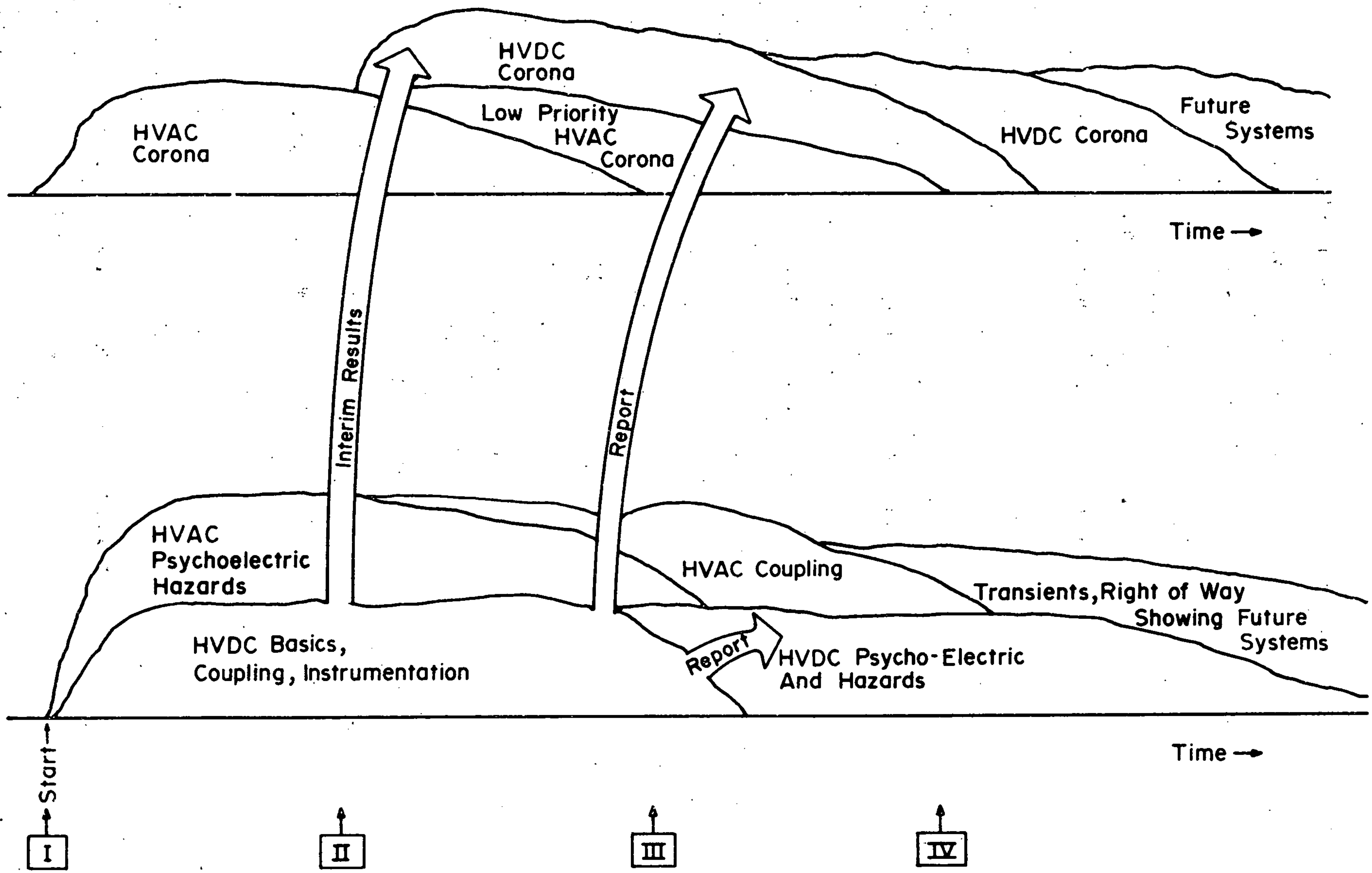

Fig. I PLAN FOR CORONA AND COUPLING RESEARCH dependencies exist. Therefore, any milestones associated with this effort are to be developed largely on the basis of individual priorities with due consideration to time, funding and personnel limitations.

Assuming timely initiation and reasonable resources, the following milestones seem reasonable:

1st Action	The priority ac corona effects, priority ac hazard/psychological effects, and HVDC phenomena, coupling, and instrumentation studies are initiated.
2nd Action	Interim results of the HVDC basic coupling and instrumentation study will be made available, and then the priority HVDC corona effects studies will be initiated.
3rd Action	Priority HVAC corona effects and the priority HVAC hazards and psychological effects will be completed. Lower priority HVAC programs concerning corona effects and hazards and psychological effects can be initiated. Potential problems regarding hazards and psychological effects with HVDC lines will be identified and used as the basis for HVDC psychological and hazards analysis studies.
4th Action	All low priority HVAC corona and coupling problems work will be completed. During this fourth period, consideration can be given to initiate relevant research concerning future systems, power line transients effects and other areas.

1.4.3 Limitations

The plan recommends a comprehensive series of projects which are felt to be the most cost-effective and defensible way to develop the necessary environmental design criteria for overhead high voltage power lines. It is also recognized that other time phasings or priorities can be set which may be more appropriate. This document delineates the basic framework from which a modified plan can be developed.

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2. CORONA EFFECTS--ACOUSTICAL NOISE

2.1 Introduction

2.1.1 Units of Measure

The basic unit used to measure sound is newtons per square meter (N/m^2). Since human beings can sense sounds over a large dynamic range, sound levels are usually expressed in terms of decibels (dB) relative to $2x10^{-5}$ N/m^2, which is considered to be the threshold of hearing. The sound level in dB (S.L.) may be determined by:

$$S.L. = 20 \log_{10} (\text{Sound Pressure in } N/m^2 / 20x10^{-6} \ N/m^2)$$

The human ear does not have a consistent response over the audio frequency range for a given sound pressure; consequently, there are certain weighting factors to take into account the variations in response. A human being also responds differently to different kinds of sounds, and there are rating schemes to handle these variations as well. Some of the more common weighting and rating factors are presented in the following sections.

2.1.2 Weighting Networks

The weighting networks specified by the American Standards Association constitute the prevailing mode of frequency specification in this country. These networks approximate the varying perceived loudness that the human auditory system attributes to sound pressures of different frequencies. Typical frequency-response curves of weighting networks that meet the limits specified by reference 1 are shown in Fig. 1 (as curves A, B, and C). Readings taken with A or B networks are not strictly sound pressure levels because of the weighting; they are therefore termed sound levels.

As shown in Fig. 1, the C network discriminates only against very low and very high frequencies, and is flat between 20 and 4000 Hz.

The A scale is used most frequently to represent the response of the human ear to ordinary noise sources. It is the standard reference for occupational noise exposure and many derived, statistical units.

<u>Octave Bands</u>

Another method of classifying the frequency composition of a noise consists of dividing the frequency spectrum into various octave bands, an octave being the band between any two frequencies having a ratio of 2:1.

Two sets of standard octave bands are currently in use. The newer and more commonly used set of standard octaves is defined by center frequencies as follows: 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16,000 Hz.

Octave bands are satisfactory from the viewpoint of specification but are too wide for practical work in noise control. A complex noise source often has individual sources producing more than one frequency of noise within a particular octave. A narrower frequency bandwidth is required to provide adequate definition of the noise produced.

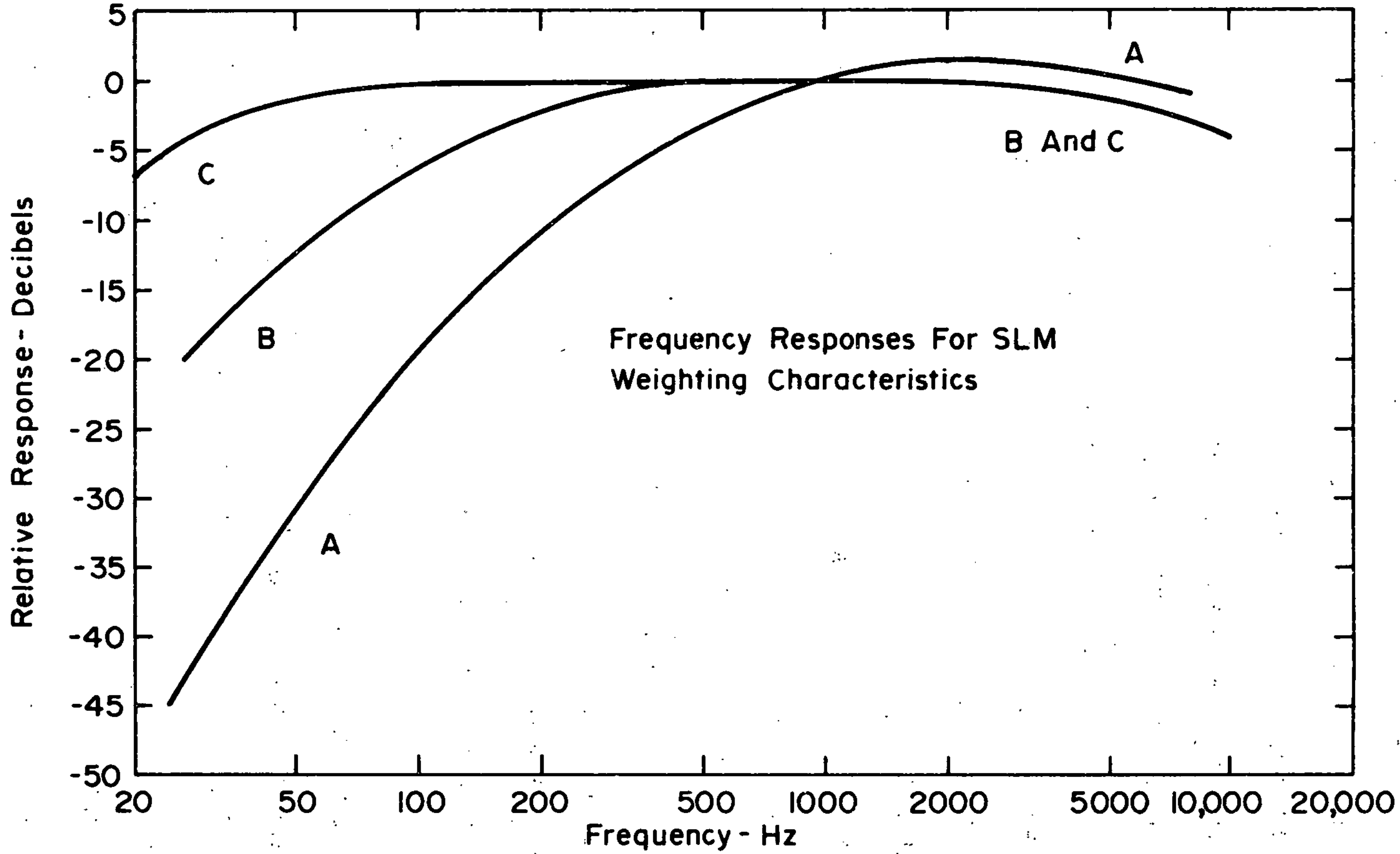

Fig. I FREQUENCY-RESPONSE CHARACTERISTICS IN THE AMERICAN NATIONAL STANDARD SPECIFICATION FOR SOUND-LEVEL METER, ANSI-S1.4-1971

One-Third Octave Bands

This mode of frequency analysis is a practical and effective compromise between the rapid but inadequate octave-band analysis and the time-consuming but precise narrow-band analysis. The frequency spectrum is divided into one-third octave bands in which the ratio of the limiting frequencies is $2^{1/3}$ or 1.2599.

Standard bands which are essentially one-third octaves, have also been developed to provide for the repetition of bands by multiples of 10. The ratio of limiting frequencies for bandwidths in this series is $10^{0.1}$ or 1.2589.

One-third octaves are also designated by their geometric mean frequencies, e.g., a 63, 80, or 100-Hz one-third octave. Standard values for geometric mean frequencies are those numbers whose mantissae of their common logarithms are multiples of 0.1.

A one-third octave is sufficiently narrow to define the noise source adequately for most noise control work. Rotating equipment characteristically produces noise at multiples of the rotational frequency. Two prominent sources in the equipment seldom produce noise within the same one-third octave. Recorded spectrograms of one-third octaves are usually the same length as octave spectrograms. For these reasons, the one-third octave bandwidth is ideally suited for most specification purposes.

Narrow Bands

Instrumentation is available for analysis of frequency bands considerably smaller than an octave in width. Narrow bands have either a constant bandwidth or, more frequently, a constant-percentage bandwidth. With constant-percentage bandwidths, each successive frequency band is larger than the preceding band. Constant-percentage bandwidths have a width which is a specified percentage (such as 5 or 8 percent) of the geometric mean frequency of the band.

2.1.3 Other Rating Indices Used to Evaluate Environmental Noise

Several indices have been developed to evaluate the effective "noisiness" of different community environments. These indices range from simple dBA short-duration readings to 24-hour statistical averages. Several of the indices were developed to categorize aircraft noise effects. The following guide is presented as a concise listing of the major rating techniques.[2]

A-weighted Sound Level (L_A or dBA)

$$L_A = 10 \log_{10} (p_A^2/p_o^2) \qquad \text{(dB)}$$

where p_A^2 is the mean square A-weighted sound pressure and p_o is the reference sound pressure; $p_o = 2 \times 10^{-5}$ N/m^2. A-weighted levels are identified by the letter A following the decibel symbol dBA. When the dBA value varies with time, L_{10}, L_{50} and L_{90} are sometimes used. These numbers denote the dBA level which is exceeded 10, 50, and 90 percent of the measuring time.

Equivalent Level (L_{eq})

$$L_{eq} = 10 \log_{10} \left\{ \int_{t_1}^{t_2} p_A^2 dt \Big/ \left[p_0^2 (t_2 - t_1) \right] \right\} \text{(dB)}$$

where t_1 and t_2 define the time period of integration.

Day-Night Average Level (L_{dn})

$$L_{dn} = 10 \log_{10} \left\{ \left[\int_{0700}^{2200} p_A^2 dt + 10 \int_{2200}^{0700} p_A^2 dt \right] \Big/ \left[24\, p_0^2 \right] \right\} \text{(dB)}$$

where time is measured in hours and the limits specify day and night.

Community Noise Equivalent Level

CNEL is similar to L_{dn} but evening energy (1900 to 2200 hours) is given a weight of 3 instead of 1.

Loudness Level

The loudness level of a sound is numerically equal to the sound-pressure level in decibels of the 1000-cycle pure tone judged by listeners to be equivalent in loudness. It is calculated by complex but standard procedures (see PNL). The unit is the phon.

Perceived Noise Level (PNL)

A measure of the "noisiness" of a complex sound is given by the PNL which, for its calculation from physical data, is based on several standardized properties of the human hearing system, such as the equal-noisiness contours and a band-summation formula, determined by psychoacoustic methods. PNL is expressed in PNdB. It is closely related to the loudness level. PNL_{max} is the highest level of a transient noise attained during any 0.5-second time period. For typical noise spectra, PNL $\simeq L_A + 13$.

Composite Noise Rating for Aircraft Noise (CNR)

$$CNR = PNL_{max} + 10 \log_{10}(N_d + 16.7\ N_n) - 12 \qquad (dB)$$

where N_d is the number of noisy events during the day (7 a.m. to 10 p.m.) and N_n the number during the night.

Noise and Number Index (NNI)

NNI is similar to CNR apart from the coefficient of the second term, which is 15 instead of 10. Hence NNI is more strongly dependent on the number of events that is required by energy averaging.

Effective Perceived Noise Level (EPNL)

EPNL is the maximum value of PNL during a noisy event weighted to take account of the event's duration and, where necessary, the presence of a prominent pure tone. It is expressed in EPNdB.

Noise Exposure Forecast (NEF)

$$NEF = EPNL + 10 \log_{10}(N_d + 16.7\ N_n) - 88 \qquad (dB)$$

Since L_{dn}, CNEL, NEF, CNR and NNI all vary at least approximately as log(energy) and incorporate broadly similar day-night weighting, the following approximations can be used for comparison purposes:

$$L_{dn} \simeq CNEL \simeq (NEF+35) \simeq (CNR-35) \simeq (NNI+25)$$

2.1.4 Ambient Non-Power-Line Environments

The natural sources of acoustic noise in the environment are myriad. There is some noise associated with all movement or mechanical stressing of materials, and in the normal environment surrounding transmission lines, the major noise source is wind acting upon fixed objects. Some additional noise will be from animals or insects, but this contribution may be small. The background noise will, of course, be highly unpredictable since it is dependent upon many variables, such as weather conditions. Therefore, the natural background noise may vary from a minimum under still, calm conditions to a maximum under conditions of a thunderstorm or windstorm where there is thunder, heavy rain, and high winds. The extreme variability of these conditions makes statistical prediction of the background noise at any particular location an extremely complicated matter.

In addition, the man-made environment also contributes to the background noise levels. All sorts of operating vehicles have intense noise associated with them. Manufacturing facilities can produce high levels of noise in the surrounding area. There are also background noises--people shouting or talking--and noise sources associated with residential areas, such as power mowers or radios. Table 1 and Figure 2 show the range of the sound levels normally encountered in common environments. Sound levels greater

TABLE 1--LEVELS OF SOME COMMON SOUNDS

SOUND POWER, WATTS	SOUND POWER LEVEL dB re 10^{-12} WATT	SOUND PRESSURE, N/m^2	SOUND PRESSURE LEVEL dB re $2 \times 10^{-5} N/m^2$	SOUND SOURCE
3,000,000.0	200	1 atmosphere	194	Saturn rocket.
	185	20000.0	180	
	175		170	
30,000.0	165	2000.0	160	Ram jet.
	155		150	Turbo jet.
300.0	145	200.0	140	Propeller aircraft.
			135	Threshold of pain.
	135		130	Pipe organ.
3.0	125	20.0	120	Riveter, chipper.
	115		110	Punchpress.
0.03	105	2.0	100	Passing truck.
	95		90	Factory.
0.0003	85	0.2	80	Noisy Office.
	75		70	
0.000003	65	0.02	60	Conversational speech.
	55		50	Private office.
0.00000003	45	0.002	40	Average residence.
	35		30	Recording studio.
0.0000000003	25	0.0002	20	Rustle of leaves.
	15		10	Threshold of good hearing.
0.000000000003	5	0.00002	0	Threshold of excellent youthful hearing.

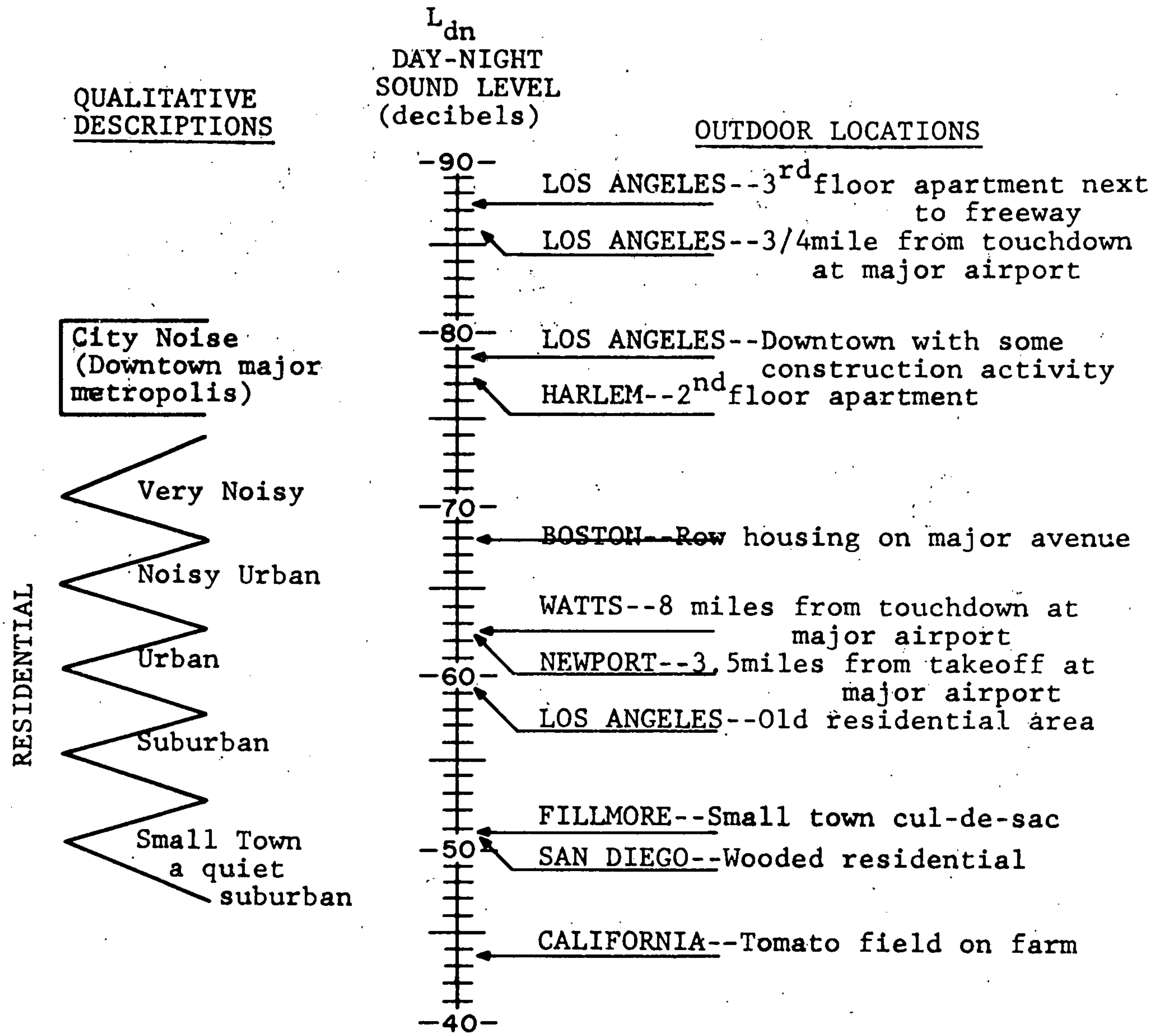

Fig. 2 OUTDOOR DAY-NIGHT SOUND LEVEL IN dB (re 20 micropascals) AT VARIOUS LOCATIONS (Ref. 3)

than 55 dB (re 20×10^{-6} N/m^2) are very common, and large populations are exposed to noise that is over 70 dB (re 20×10^{-6} N/m^2).

2.1.5 Biological and Social Aspects of Noise

At very high levels (>125 dB), noise can effect the whole human body. The effects of lower noise levels range from hearing damage to annoyance.

The Federal EPA has chosen L_{eq} and L_{dn} to define noise levels for the protection of the public.[3] In Table 2, these levels are defined for hearing loss effects, outdoor activity annoyance, and indoor activity annoyance. $L_{eq(24)}$ represents the equivalent A-weighted sound level over a 24-hr period, while L_{dn} represents the L_{eq} with a 10 dB nighttime weighting. The EPA has determined that virtually the entire U. S. population will be protected against hearing loss if $L_{eq(24)}$ is less than 70 dB.

Table 2

SUMMARY OF NOISE LEVELS IDENTIFIED AS REQUISITE TO PROTECT PUBLIC HEALTH AND WELFARE WITH AN ADEQUATE MARGIN OF SAFETY (REF. 3)

EFFECT	LEVEL	AREA
Hearing Loss	$L_{eq(24)} \leq 70$ dB	All areas
Outdoor activity interference and annoyance	$L_{dn} \leq 55$ dB	Outdoors in residential areas and farms and other outdoor areas where people spend widely varying amounts of time and other places in which quiet is a basis for use.
	$L_{eq(24)} \leq 55$ dB	Outdoor areas where people spend limited amounts of time, such as school yards, playgrounds, etc.
Indoor activity interference and annoyance	$L_{dn} \leq 45$ dB	Indoor residential areas
	$L_{eq(24)} \leq 45$ dB	Other indoor areas with human activities such as schools, etc.

Actual environmental noise levels vary considerably from these EPA recommendations. In Fig. 2, L_{dn} levels were presented for several urban and residential locations. Values of the L_{dn} between 80 and 90 are possible near major freeways or airports. Note that the "small town" or "quiet suburban" location must be reached to achieve an L_{dn} of 55 or less. For indoor locations, a broad range of L_{eq} values are shown in Table 3. Again it is necessary to be in a rather quiet environment (e.g. normal speech at 10 feet) in order to meet the EPA criteria of $L_{eq(24)} \leq 55$ dB.

Table 3

EQUIVALENT SOUND LEVELS IN DECIBELS
NORMALLY OCCURRING INDOORS (REF. 3)

SPACE	L_{eq}
Small Store (1-5 clerks)	60
Large Store (more than 5 clerks)	65
Small Office (1-2 desks)	58
Medium Office (3-10 desks)	63
Large Office (more than 10 desks)	67
Miscellaneous Business	63
Residences	
Typical movement of people-no TV or radio	40-45
Speech at 10 feet, normal voice	55
TV listening at 10 feet, no other activity	55-60
Stereo music	50-70

The EPA has estimated the number of people exposed to various noise levels throughout the country. Approximately one percent of the U. S. population is exposed to L_{dn} levels over 75 dB. Finally, Table 4 shows a more detailed break-down of the percentage of urban population which is exposed to average L_{dn} values from 50 to 70 dB.

Table 4

ESTIMATED PERCENTAGE OF URBAN POPULATION (134 MILLION) RESIDING IN AREAS WITH VARIOUS DAY-NIGHT NOISE LEVELS TOGETHER WITH CUSTOMARY QUALITATIVE DESCRIPTION OF THE AREA (REF. 3)

Description	Typical Range L_{dn} in dB	Average L_{dn} in dB	Estimated Percentage of Urban Population	Average Census Tract Population Density, Number of People Per Square Mile
Quiet Suburban Residential	48-52	50	12	630
Normal Suburban Residential	53-57	55	21	2,000
Urban Residential	58-62	60	28	6,300
Noisy Urban Residential	63-67	65	19	20,000
Very Noisy Urban Residential	68-72	70	7	63,000

During inclement weather under the center conductor, the noise level produced by some transmission lines may reach an L_{max} of 60 dB(A); so by EPA standards, the only possible effect that could be caused by the acoustical noise from these transmission lines is annoyance.

2.2 Appraisal of State-of-the-Art

2.2.1 Introduction

Acoustic noise is considered to be the limiting design parameter for the design of transmission lines for voltages of 500 kV or over.[5] The electric power companies and appropriate groups of the IEEE have recognized the problems and have sponsored and performed work in this area. Examples of this concern are: The Panel on Acoustic Noise in New York during 1971; the Power Apparatus and Systems Group of the IEEE Committee Report of May and June, 1972; the Task Force Report on Acoustic Noise from Power Lines, given in New York during 1975; and the Electric Power Research Institute's (EPRI) Funded Research on HVAC Transmission Lines during 1974.

The work to date has been generally in the area of "hard data"; that is, noise level measurements on the dBA scale, octave band measurement or single frequency measurement at 120 Hz and its harmonics.

2.2.2 Noise Generation Mechanisms

The generation of acoustic noise from transmission lines is related to corona loss. EHV transmission lines are designed to be essentially corona-free under fair weather conditions. It is only when the surface gradient is increased by rain, insects, or conductor damage that corona becomes important.[6]

For EHVAC lines and above, there are three generation mechanisms which produce audible noise. The first mechanism gives rise to the "crackle" or high frequency, broadband noise produced by random sequences of pulses of positive polarity at the conductor surface. These pulses occur when the surface gradient is increased by some foreign matter on the conductor. Second, a "hum" is produced by the modulation of corona development at line conductors by the ac line voltage. Since the sound pressure level is considerably higher from positive corona than from negative corona, the hum is composed of 120 Hz and its multiples. The third mechanism occurs when conductors vibrate and produce 2-5 Hz modulation of audible noise. The first two mechanisms are the primary sources of audible noise for HVAC systems. For HVDC systems, the "hum" is not present, only the broadband "crackle" and low frequency modulation.[7]

2.2.3 Environmental Effects

A goal for any transmission line might be that the line be less noisy than the background noise conditions. This would be especially true if reducing the noise from this transmission line was not at the expense of other factors, such as aesthetics or economics. Since both the background noise and transmission line noise are variable, it is important to consider their effects in perspective. It is not clear if the line should, under all conditions, be less noisy than the background.

Audible noise from EHVAC lines is primarily a foul weather problem. The noise mechanisms are present when water drops form on a conductor and corona is induced. Therefore, EHVAC lines emit audible noise during rain or fog conditions and immediately after a rain when the lines are still wet. The background noise levels associated with weather conditions then play a significant role in assessing the impact of HVAC audible noise. High ambient noise levels would be associated with a heavy, windy rainstorm. A gentle, light rain would be relatively quiet. Atmospheric attenuation of higher frequencies increases under fog conditions. Wind conditions are especially important in making accurate noise level measurements. The post-rain condition is especially significant since rain and wind noise may be completely eliminated. Then, HVAC audible noise must be compared against typical background noise levels. In a rural environment, typical nighttime levels range from 30-35 dBA. The relative impact of HVAC fair weather audible noise must then be evaluated in this quiet environment. Conversely, significant HVAC line audible noise over ambient noise will occur only for short periods after a rain. Fig. 3 shows a typical transmission line noise profile.

The conditions necessary to produce significant EHVDC audible noise over ambient noise are different. Dry-type projections on conductors, rather than water drops, are the major source for HVDC audible noise. Therefore, HVDC noise is a fair weather problem. Audible noise levels from

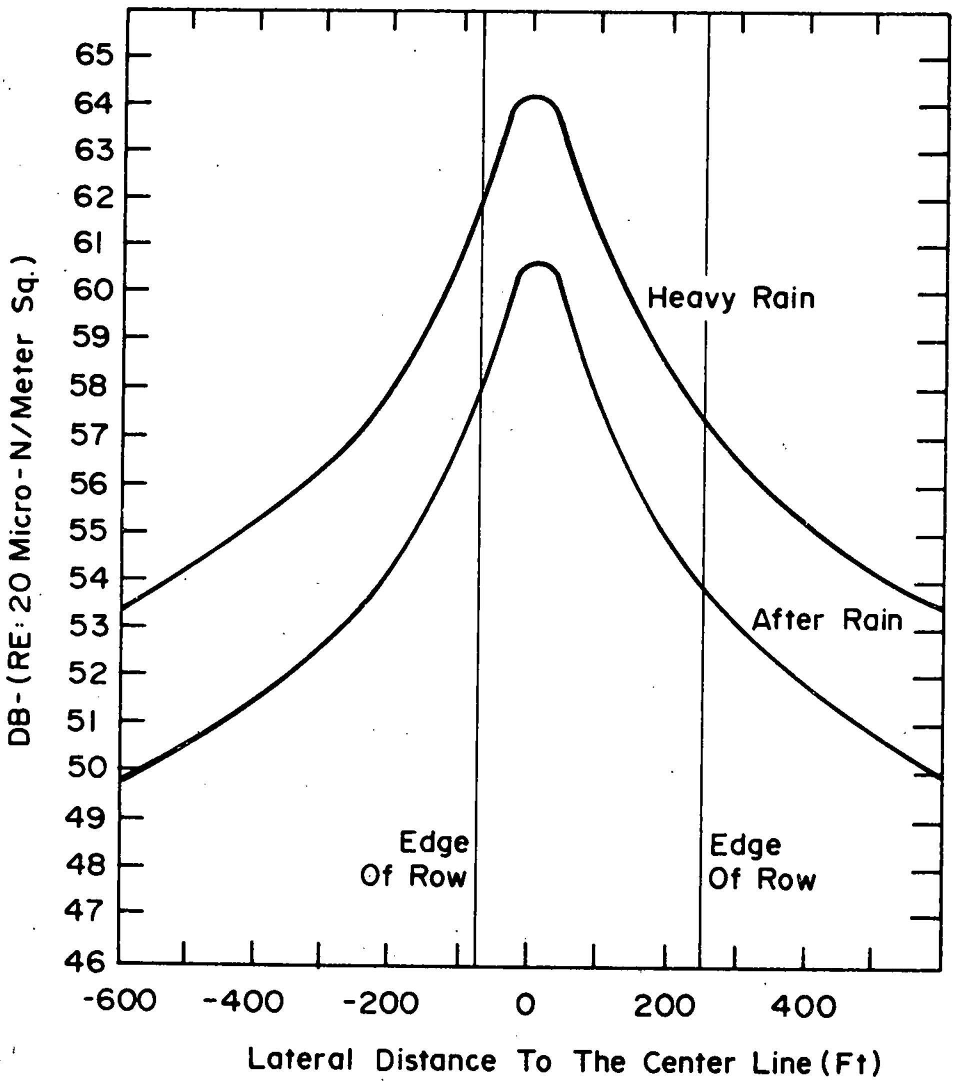

Fig. 3 HEAVY RAIN AND AFTER RAIN AUDIBILE NOISE PROFILE OF 500KV LINE (REF. 4)

HVDC systems under a spectrum of weather conditions is less well documented than that from HVAC systems under comparable conditions. The absence of a "hum" component of the noise generated by EHVDC line makes comparison of the EHVAC lines difficult. It has been stated that some people react differently to both types of noise.[8]

2.2.4 Review of Literature

2.2.4.1 Introduction and Historical Review

The American literature regarding acoustic noise from transmission lines is reviewed here to supply a context for and historical insight to the development of the proposed research plans. This review was not meant to be exhaustive but only to identify areas for future work.

While there exists a considerable body of literature regarding corona losses on power lines and a large amount of literature on the problems regarding ozone generated by power lines, the amount of literature in the area of acoustic noise from power lines is more limited. The number of current programs in this area are also limited at present. These projects are represented by General Electric's Project UHV sponsored by EPRI, Westinghouse's Apple Grove Project, partially sponsored by American Electric Power Corp. (AEP), and Bonneville Power Administration (BPA) The Dalles Project (EHVDC) also sponsored by EPRI. Other measurements and analyses are being conducted on behalf of Project UHV and various parties to the New York State Public Service Commission Hearing concerning a proposed EHVAC line. The Institute de Recherch de l'Hydro Québec (IREQ) has also been active in this area. University studies exclusively concerned with acoustical noise have been funded at Oregon State University and Massachusetts Institute of Technology. The OSU study was funded by the Department of the Interior (BPA) and had S. A. Annestrand and L. N. Stone as principal investigators. This project was funded during 1973 and 1974 and no reference from this project in the literature could be found. A 1974-1975 MIT study under Dr. Wilson was sponsored by AEP.[9]

These studies have approached the problem of acoustic noise in a semiempirical manner. First, the problem was identified during the course of research into other corona effects, then mechanisms were identified and studied, methods to predict noise levels were confirmed and, lastly, data were gathered on operational line configurations.

Because most of the AN studies were offshoots of other investigations, it is difficult to divide the programs into subheadings. For this reason, and because there are relatively few articles available, the literature review is organized chronologically.

2.2.4.2 Acoustic Measurements on Transmission Lines

One of the first groups to report on acoustical noise from transmission lines was Taylor, Chartier and Rice.[10] These investigators conducted tests on the EHV corona performance of lines and had considered some acoustic noise generation effects. The major emphasis of this work was

RI and corona loss. Some consideration was given to reducing all corona effects by increasing the number of conductors and the individual conductor diameters. Bundles of 6 conductors and subconductor diameters to 2.5 in. were considered.

Acoustical noise effects continued to be the concern of only those researchers working in the EHV corona effects area. Those that were most active were some General Electric engineers working on what was to become Project UHV. Juette and Zaffanella[11,12] published some data from Project UHV in 1970. This article gave RI and AN measurements on some four conductor test cage measurements under various weather conditions and voltage gradients. In these articles, Juette and Zaffanella postulate an experimental relationship between RI and acoustic noise levels.

Later in 1973 Comber and Zaffanella[13,14] presented a semiempirical method of predicting the acoustic noise generated by transmission lines. These papers used data gathered on test cages and test lines to predict the acoustic performance of transmission lines as a function of subconductor electric field gradient. These papers indicated that the acoustic noise performance of a three-phase line could be predicted by using single phase test cage data, and they laid the foundation for use of the concept of "generation quantity" for prediction of acoustical noise. The generation quantity concept states that a subconductor generates a certain acoustic noise power per unit length as a unique function of average voltage gradient at the conductor. Thus the contribution from all the phases may be added using the laws of acoustics to find the acoustic noise at a point removed from the line. This concept of "generation quantities" had been first used to calculate the radio noise from power lines.

This procedure was refined and extended by Comber and Zaffanella[4] in their work that was published in Chapter six of the Transmission Line Reference Book 345 kV and Above, which dealt with audible noise. This work was published in 1975 and includes a section which deals with audible noise generation as a function of subconductor voltage gradient, conductor condition (wet or dry), weather conditions and angle at which rain strikes the subconductor. This procedure and the curves provide calculation of the acoustic noise performance of any transmission line. The authors also give data on the 120 Hertz components. This work also contains some tentative annoyance evaluations on the rating of transmission line noise. The authors present a guideline which was first presented by Perry[15] of BPA on the relationship of subscriber complaints to the level of acoustic noise in dB(A). They also found that B scale weighting gave the best correlation to the subjective reaction of the observer and that the modulation of the noise by conductor vibration was unimportant to subjective responses. The authors noted that the annoyance engendered by the noise was dependant not only on the absolute value of the AN but also on the ambient conditions, for example, AN was most annoying under light rain or fog conditions. In order to evaluate the impact of AN more realistically, the authors present an audible noise weather model and weather statistics for the country.

While work was being done at Project UHV, work was being carried out at Apple Grove by Westinghouse Electric with the aid of the American Electric Power Service Corporation. The work at Apple Grove was more operations-oriented than the work at Project UHV. Kolcio et al.[16] report the acoustic noise results for the three test lines available there, i.e., line A (4 x 1.382 in), line B (4 x 1.96 in), and line C (4 x 1.00 in). The paper cites that 26,400 out of 200,000 all-weather records were used to develop AN performance curves for test lines A, B, and C. This represents a large amount of data on the particular lines involved. The data derived from those tests can be used to design lines having similar configurations. The authors also show valuable AN statistics on the test lines involved.

Work on EHV and UHVDC lines was being carried out on the Dalles Project in Oregon under the sponsorship of the Bonneville Power Authority and EPRI. The first AN tests were begun on the 5 mile DC test line in the fall of 1968[17] on a single conductor at $\pm$400 kV. Some foul weather tests were done but detailed reports are not yet available. The conclusion from these tests was that the dc line noise is so low (less than 43 dB(A) for a bundled conductor under a hard rain worst-case for a dc line) that it would not be annoying. As attention became focused on subjective effects, more work was done in this area during 1974. In these short studies, observers were exposed to AN from a 4 x 1.2 inch bundle and 2 x 1.8 bundle for 350, 400, 450, 500, 550, and 600 kV bipolar dc transmission lines.[8,18] These observers ranked the noise from very quiet to intolerably noisy. The results of this study tended to show that because the dc noise was unfamiliar it was more annoying. New techniques seem to be required in order to evaluate fully the nuisance value of the dc noise.

A major report is expected from BPA and EPRI during the summer of 1976 that will contain new data on HVDC power line noise.

2.2.4.3 Psychoacoustics

As research continued into the AN aspects of EHV and UHV transmission, it became apparent that the general public responds to the acoustic noise from EHV transmission lines in a different manner than to other common man-made noises like traffic and airplanes.[19,20,21,22]

This problem is even more severe in the case of UHVDC lines--data are lacking because a very limited population has been exposed to these lines.

A possible explanation is that annoyance due to AN from power lines is not measured very well by using the sound rating systems presently in common use.[19] These systems include the dB(A) scale which was originally intended to measure intelligibility in voice systems, the dB(B) scale, and special purpose rating scales like the noise pollution level (NPL) or traffic noise index (TNI).

In order to try to resolve these questions the Radio Noise and Corona Subcommittee of the IEEE Power Engineering Society's Transmission and Distribution Committee held a July 17, 1974 Workshop on Psychoacoustics. This workshop is the major source of literature dealing with the subjective effects of transmission line acoustical noise. Although the proceedings of this workshop represent a fine basis to evaluate subjective effects, there are still questions that must be answered.

Pearsons,[21] in his article for this workshop, discusses some research approaches that may be utilized to assess the impact of AN from transmission lines. He suggests laboratory and survey studies to evaluate the annoyance potential of this noise relative to other commonly encountered noises such as traffic noises or office noises. He conjectures that using detectability or recognizability as a measurement criterion may lead to better measurement of annoyance.

Wells[19] does a detailed comparison of different sound level measurements (dB(A), dB(B), PNL, etc.) to an arbitrary juror scale. The results are given in Table 5. This data indicates that dB(B) best correlates to annoyance, but it must be noted that the subjects were tested in an anechoic environment and the direct application of this conclusion to a real-life situation is a matter of conjecture.

Table 5 Correlation of Juror Ratings with Sound Levels at 120 and 240 Hertz, Various Sound Level Meter Readings, Computed Perceived Noise Level (PNL), Tone Corrected Perceived Noise Level (PNLT), and Annoyance Level (ANL) (Ref. 19)

Measure	Std. Dev (dB)	Range (dB)	Correl Coeff	Slope of Line
120~	4.26	16.7	0.803	0.904
240~	3.62	16.8	0.863	0.978
dB(C)	1.39	5.2	0.976	0.991
dB(B)	0.80	3.4	0.993	1.041
dB(A)	1.22	6.0	0.986	1.128
dB(D)	1.03	4.8	0.990	1.132
PNL	1.00	5.2	0.990	1.126
PNLT	0.90	4.7	0.992	1.144
ANL	0.86	3.7	0.993	1.147

Wells also considers the basic differences between AN and other more normally considered environmental noise. These include differences in time variation, in frequency, and in statistics of the noise. Among his conclusions are:

1. The value of a reasonably precise basic measure lies in the fact that if limits are set using a poor measure, a transmission line that exceeds the specified limit may actually be rated by listeners as much as 10 dB, or more, less objectionable than one which does not exceed the limit.

2. According to one study of UHV noise, sound level A, dB(A), is only a fair measure for this purpose. This study suggests that dB(B) would be a somewhat better choice.

3. As far as actual human reaction to this type of noise is concerned, the analysis of the subjective effects of time variability is expected to be more critical than the actual choice of a basic measure.

4. Two measure variants, traffic noise index (TNI) and noise pollution level (NPL) are shown to be poor choices as a means

of rating time variability, because the numerical value of these quantities cannot be well correlated with human response.

5. Another possible measure, noise complaint rating (NCR), shows some promise. However, it is recognized that this also may not be fully satisfactory.
6. It is suggested that a definitive research effort be undertaken to determine the optimum method of rating the time variability of such noise. (Ref. 19)

Bragdon and Miller review the salient characteristics of power line noise and compare the dB(A) levels of AN to other environmental noise levels. Their conclusions are:

1. The intensity of corona noise relative to other environmental noise sources is relatively minor.
2. Currently the linear mileage exposure to high voltage lines (500 kV and above) compared to other environmental noise sources constitutes a small degree of exposure.
3. Corona audible noise is generally audible only during rain or fog, a condition which greatly reduces its environmental impact.
4. Compared to other environmental sources, corona audible noise maintains relatively stable high frequency responses, in contrast to other sources, which experience a decrease in response above 2-5 kHz. At low frequencies, the response is similar to other environmental sources.
5. Theoretically, corona audible noise functions as a line source. The fluctuating temporal characteristics (during rain) also result in spatial variations.
6. The fluctuations (L_{10} - L_{90}) of corona audible noise are greater than most environmental noise sources. In addition, corona noise is characterized by

a rapid rate of change of fluctuations, while other noise source variations are "slow" with respect to the response time of the human ear.

Although the present acoustical impact of power transmission lines appears to be minor, as the consumer demand for electrical energy increases, there will be a greater requirement for high voltage power lines. This demand will potentially increase population and land use exposure, which may result in a greater community impact. (Ref. 22)

Interest to resolve the psychoacoustic area is mounting, as evidenced by the interaction of at least five major programs. The first, sponsored by ERA, is with the National Bureau of Standards. The planned programs are expected to be initiated soon by EPRI.

2.2.4.4 Conclusions and Consolidation of the State-of-the-Art

At this time, there is a reasonably-sized body of data on the acoustic performance of EHV/UHV transmission lines. There are also fairly good methods existing to predict the noise level from these lines. The data from Project UHV, Apple Grove and l'Hydro-Quebec bear this out.

However, data on and methodologies for dc lines need to be developed to assure that the lines annoy the general public as little as practicable. Minimizing annoyance is one of the major problems in AN technology today.

Both EHVAC and EHVDC audible noise have unique characteristics relative to other commonly encountered environmental noise. Simple measurements of dBA or octave bands which are usually used for regulatory purposes do not adequately predict the impact of transmission line noise. Other human feelings such as apprehension, anger, security, or disinterest may influence an individual's reaction to audible noise.

The exchange of information at the Workshop* pertinent to the acoustic noise aspects of transmission lines supported the conclusions obtained by the literature search.

It was decided that transmission line acoustic measurements and theory are deficient in the following areas:

1. The relationship between pure tones and broadband noise relative to overall annoyance is not known.

2. The influence of the background noise on annoyance is not known. For example, if the background is 20 dBA and the line is 35 dBA, will the line noise be annoying compared with an ambient of 45 dBA and a noise level of 60 dBA?

3. Precise correlation of acoustic noise with weather conditions is not known, e.g., AN with rain intensity, fog, snow, and humidity.

4. The influence of load current on fair and foul weather acoustic noise is not known. A better statistical base should be constructed.

The amount of information in the area of the acoustic noise from HVDC lines is much less than that available for HVAC lines. There has been very little published in the way of data regarding the effects of voltage, altitude, and line

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*Identified in Section 1 of this report.

and conductor configuration. There is little information available on the annoyance potential of a HVDC line versus a HVAC line.

2.3 Research Program Plans for Acoustical Noise

Transmission lines, as presently designed, emanate significant acoustic noise over ambient noisee only during periods of fog, rain or snow. Under these conditions, the noise levels in the line right-of-way may be as high as 60 dBA. Usually, when the line noise is high, the ambient noise is also high, as in the case of thunderstorms or heavy rain. However, there can be exceptions--the line noise can be high and the ambient low, as for certain fogs or snowfalls. These conditions will tend to make the line-related noise less annoying than other noises of the same amplitude but having more of a temporal variation.

It is with these considerations in mind that the acoustic noise from transmission lines must be evaluated. Some of the questions that must be answered are:

How does this noise annoy the general public? What, if any, changes in activity patterns are necessitated by the presence of the noise? What regulations must be written to protect both the public and the power companies?

2.3.1 Social Responses to Acoustic Noise from Transmission Lines

Background

This program would be an effort to develop better insights into human social responses to acoustic noise from transmission lines and, ultimately, to determine a method for evaluating the annoyance potential. The response to and attitude of people living near existing power lines should be surveyed. A major problem exists, however, in developing unbiased information in this manner.

Objective

The objective of this effort would be to obtain the subjective responses of workers and people living near power lines in an unbiased fashion.

Tasks

The initial phase of the program would be to explore the feasibility of accomplishing this survey in an objective way. Once this aspect has been completed, then the survey should be undertaken. Consideration should be given to methods of comparing the annoyance due to the UHVAC and UHVDC line noise to other high level man-made sources, such as planes, traffic, radios, etc. Special care should be taken so the effect of unrelated cofactors are eliminated. An example of such a cofactor is the increased irritability of some people during periods of low barometric pressure occurring during storms. During these periods, it is possible that these people would be more annoyed by any source of noise.

As an example to accomplish this task, a transmission line that may be turned off during low load conditions could be selected. This line will also run through representative urban and rural areas. Homes, offices, and other spaces near this line would be selected as locations to monitor the ambient noise levels during normal and foul weather. To assure proper base line data, measurements would be taken with the transmission line turned on and off whenever possible. Acoustical transmission characteristics of buildings and building materials should be considered.

The survey would be supported by measurements of the acoustical noise over a variety of meteorological conditions from power lines located near the interview area.

As the procedures and methods for the evaluation of the subjective responses become accepted, these methods may then be extended to other operating voltages as well as to dc lines.

2.3.2 Psychoacoustical Responses Program

Background

The basic human responses to transmission line noises are still unknown, especially in relation to the responses to other noises. Furthermore, the present sound rating methods are not adequate to measure annoyance due to AN from power lines.

Objective

The objective of this program would be to quantize human annoyance potential for transmission lines in relation to other ambient man-made noises. More specifically, several questions should be addressed, such as the following.

How important is single frequency noise with respect to overall annoyance?

What is the correlation between the AN measured in dB(A), dB(B), etc. and actual annoyance?

What influence does background noise have on annoyance?

What influence do single frequency components have on annoyance?

What is the optimum balance between "hum" and "crackle" noise components in terms of human annoyance, speech interference and sleep disturbance?

What is the relative noise impact of direct versus alternating current UHV transmission lines for equivalent power capacity?

Tasks

Two separate activities would be required to quantify the effects of power-line noise on human behavior. First, a series of experiments in which all independent and dependent variables are well controlled and quantified will be used to identify the threshold for human response for annoyance, speech interference, and sleep disturbance. Included in these activities should be a field survey to verify the persistence of these effects under conditions of conventional exposure. Secondly, a rating system for realistic assessments of noise effects would be developed and used to compare transmission line noise to other types of environmental noise.

In the initial experimental program, a test protocol should be established by searching out and organizing any data on how human behavior has been demonstrated to be effected by environmental stresses. The independent variables will include noise profiles and exposure patterns. The dependent variables will include: risk-taking propensities; frequency, magnitude and type of social interactions; decision making effectiveness; and efficiency at performing complex time-shared psychomotor tasks.

This information should be obtained from subjects representing the general population with an adequately designed sampling and experimental protocol.

The results of the experiment would provide empirical evidence of the noise profiles which can affect human behavior and responsiveness. By determining the threshold for these effects in the manner described, we would have reliable evidence which defines the conditions under which noise affects behavior. This evidence should be compared to the results of field surveys to determine whether uncontrolled variables were affecting the survey results.

The results of the initial phase will be used to develop a quantitative rating system for environmental noise that may be used to rank all types of noises. The rating scale will be used to make a comparison of responses to high voltage transmission line audible noise and more common noises to which people are presently subjected. This should provide information on levels acceptable for the higher voltage lines of the future.

The methods formulated in the initial phases will also be used to determine the relative tolerance to various noise levels for annoyance, speech interference and sleep disturbance. The noise from comparable sources will be measured and these should include railroad lines, highways, airports, and factories in both urban and rural settings. The noise from operating transmission lines (ac and dc) in a variety of operating and meteorological conditions will similarly be recorded. These recordings would be used to simulate, on a laboratory basis, the various noise levels to obtain relative acceptable and tolerance ratings regarding transmission line noise relative to other noise sources developed.

2.3.3 Prediction of Acoustical Noise for Transmission Lines Above 800 kV

Background

As the operating voltages of power lines are increased, improved methods of predicting the acoustical noise appear to be highly desirable. For example, refinements of currently used techniques, such as the incorporation of wind conditions and the drop-size distributions for light-rains or fogs, might permit a more rational basis for correlating power-line noise than is presently possible by extension of cage measurements. A more detailed development of noise outputs in terms of a wider range of weather conditions could permit a more valid statistical prediction of AN where statistics of local weather conditions are employed.

Objective

It would be the objective of this effort to consider improved methods of predicting the acoustical noise on both ac and dc high voltage lines, particularly as operating voltages are increased above 800 kV.

Tasks

The tasks would include measurements on operating lines and test lines; as well as the evaluation and validation of high voltage ac cage and high voltage dc test line results.

Better methods to consider the effects of precipitation--either rain or wet snow--would also be considered. The prediction methods would also include geometry, and the conductor design and compacting. The effect of conductor temperature on minimizing the onset of acoustical noise or postponing it should also be considered.

The specific tasks required for this program would be:

a. an evaluation of the different analytical and empirical techniques for calculating the AN performance of transmission lines, with the aim of providing reliable and easy to use methods for design engineers;

b. a comprehensive theory to describe the noise generation mechanisms for both the "hum" and "crackle" components of transmission line audible noise should be formulated. Theoretical hypotheses must be tested against these data, so that extrapolations can be made with confidence for future operating configurations.

c. The relative importance of the modulation effect and space charge effect in the generation of the second harmonic noise should be studied.

d. The possibilities of other noise generation mechanisms should be considered, such as conductor vibrations.

e. The problem of standing wave formation on the annoyance potential of transmission lines should be studied.

f. Better statistical relations between acoustical noise and the weather at particular locations should be found.

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ABSTRACT: This paper presents the special problems associated with audible noise from corona on high voltage power lines. Human response to this noise source is examined in the context of requirements for special noise measuring methods and instrumentation and considering existing and proposed legislation for noise control in various countries. The need for a new and more realistic evaluation by regulatory bodies and utilities, of transmission line noise--and its effects on individuals and communities--is stressed.

Audible Noise Task Force of the Radio Noise Subcommittee of the IEEE T & D Committee. "A Guide for the Measurement of Audible Noise from Transmission Lines." IEEE Transactions on Power Apparatus and Systems PAS-91, no. 3 (May/June 1972), 853-856.

ABSTRACT: In 1969 the Radio Noise Subcommittee appointed a task force to develop a guideline for the measurement of transmission line audible noise. This report is the result of the experience of the task force members and a two-day investigation conducted at Project UHV. Also, existing standards for the measurement of sound pressure levels were freely used by the task force.

Beranek, L. L. "Noise Rating Using Stevens' Mark VII Method and Robinson's Noise Pollution Level." A paper presented at the Second Arden House Workshop on Noise Control Engineering (January 1972).

Beranek, L. L. Noise and Vibration Control. New York: McGraw-Hill, 1971.

Bragdon, C. R. and Miller, R. K. "Comparisons Between Corona Audible Noise and Other Sources," in Psychoacoustics: Proceedings of a Workshop. New York: Institute of Electrical and Electronics Engineers, Inc., 1974.

ABSTRACT: Audible noise due to a transmission line conductor corona has not received the same public recognition that transportation and industrial noise problems have. The emphasis on this potential noise problem in the scientific community, however, has been significant. This is primarily due to the anticipated energy demands which will result in the need for higher capacity lines, the multi-million dollar expenditure for the design and installation of these lines, and the desire of public utilities to achieve environmental compatability.

To understand the characteristics of corona audible noise, it should be compared to other more common environmental noise sources. Comparison can be made using five sound attributors:

1. Intensity
2. Exposure
3. Spectrum
4. Spatial Variation
5. Temporal Variation

Bragdon, C. R. "Municipal Noise Ordinances." Sound and Vibration 7, no. 12 (December 1973), 16.

Cocquard, A. and Gary, C. "Audible Noise Produced by Electrical Power Transmission Lines at Very High Voltage." Paper no. 36-03 presented at CIGRE International Conference on Large High Tension Electric Systems in Paris, France (August 28-September 8, 1972).

Comber, M. G. and Cortina, R. "Audible Noise Generation of Individual Subconductors of Transmission Line Conductor Bundles." A paper presented at the IEEE Power Engineering Society Summer Meeting in San Francisco, California (July 20-25, 1975).

ABSTRACT: Audible noise due to corona on high-voltage transmission line conductors can be reduced by introducing an asymmetry into the conductor bundle geometry. Predetermination of the optimum arrangement of conductors can be extremely involved and is best investigated by analyzing the performance of individual subconductors in the bundle. An experimental technique used for the determination of individual subconductor foul-weather noise generation is described. The results obtained allow one to compute the noise performance of any bundle configuration. Calculations are compared to the measured performances for two different bundle arrangements.

Comber, M. G. and Nigbor, R. J. "Audible Noise Performance of the First Three-Phase Ultra-High Voltage Transmission Line Test at EPRI's Project UHV." A paper presented at the IEEE Power Engineering Society Winter Meeting in New York (January 25-30, 1976).

ABSTRACT: A three-phase ultra-high voltage transmission test line at EPRI's Project UHV was energized in January 1975. Analyses of the audible noise performance of the first six-months of energization are presented. The result of long-term energization during foul-weather are reported in terms of cumulative frequency distributions, lateral profiles and frequency spectra. Audible noise variations with voltage in rain and fair weather are also presented. Results are compared with calculations made on the basis of single-phase tests. Good agreement between measured and calculated performances is demonstrated.

Comber, M. G. and Zaffenella, L. E. "Audible-Noise Reduction by Bundle Geometry Optimization." IEEE Transactions on Power Apparatus and Systems PAS-92, no. 5 (September/October 1973), 1782-1791.

ABSTRACT: Audible noise due to foul-weather corona on multiconductor bundles for EHV and UHV transmission can be reduced by proper choice of the bundle geometry. Laboratory tests have been carried out to determine the noise generation of individual subconductors in a bundle. Based on the results of these tests, the relative audible-noise performance of several different configurations of 4-, 6-, and 8-conductor bundles are determined. A comparison is made between computed and measured performances for a 6-conductor bundle.

Daniel, T. N. and Whittaker, E. B. "The Reduction of Audible Corona Discharges on AC Transmission Lines." Second International Conference on Gas Discharges, Conference Records (September 1972), 197-199.

ABSTRACT: The most important factors influencing corona discharges are the electric field at the conductor surface (E) and the rate of divergence of the electric fieldwidth distance away from the conductor. The latter is largely fixed by the diameter of the conductor and its height above the ground plane whilst the former is considerably influenced by local geometry. Elimination of these corona discharges can be best achieved by reduction of the surface gradients. This may be accomplished for a fixed voltage by either increasing the conductor diameter or by using multi-conductor bundles. The latter course is often followed but alternative means of suppressing these discharges are desirable. This paper describes some methods which have been tried, and the measurements made of their effectiveness.

DiPolvere, E. J. "Noise Regulations in the State of New Jersey," in *Psychoacoustics: Proceedings of a Workshop*. New York: Institute of Electrical and Electronics Engineers, Inc., 1974.

ABSTRACT: The State Noise Control Act of 1971 was signed into law by Governor Cahill in January 1972. It mandated that the Department of Environmental Protection should ensure an environment free from noise which unnecessarily degrades the quality of life; that the levels of noise in the community have reached such a degree as to endanger the health, safety and welfare of the people of this State as well as the integrity of the environment; and that this threat can be abated by the adoption and enforcement of noise standards embodied in regulations. The definition of health herein used is as interpreted by the World Health Organization as being, "not merely the absence of disease and infirmity, but rather a sense of well-being."

The act goes on further to indicate that regulations promulgated under the act be "reasonable" but does not require economic or technical surveys be made of various forms of noise prior to regulations. The emphasis is on the protection of the community, not on what is in the interest of the pollutors. In spite of this, the department has a policy of not promulgating unreasonable regulations-we seldom go to court and even less frequently lose. This is because we make our regulations reasonable and, in addition, administrative procedures allow for a compliance schedule.

Djuric, S. V. "Comparative Outdoor Tests of Measurement Microphones," in *Psychoacoustics: Proceedings of a Workshop*. New York: Institute of Electrical and Electronics Engineers, Inc., 1974.

ABSTRACT: The measurements described in this paper are a continuation of a series of tests done on ceramic microphones. This time we investigated the influence of the outdoor environment on two other types of measurement microphones (electret condenser microphones and conventional air condenser microphones) and compared them to ceramic microphones.

The microphones were located on the roof of the General Radio Company building in Concord, Massachusetts. The weather pattern around Concord represents rather well different climatic zones in the United States. The winters are long with a good average snowfall and a few weeks of artic frost. Closeness to the ocean is responsible for a fair amount of rain during the remaining three seasons. Every summer brings in several weeks of very hot and humid subtropical weather.

Driscoll, D. A. and Haag, F. G. "Prevention and Control of Environmental Noise Pollution in New York State," in Psychoacoustics: Proceedings of a Workshop. New York: Institute of Electrical and Electronics Engineers, Inc., 1974.

ABSTRACT: Noise produced by 765-kV transmission lines during fog conditions (Apple Grove data) is analyzed to determine the degree of interference with human activities, and the distances within which the New York State proposed noise level standards would be exceeded. Within about 400 feet of the line, some speech interference can be expected; sleep interference will extend to about 950 feet. The proposed noise level standards for commercial areas and for residential areas during the day are exceeded within 300 to 400 feet of the line. The proposed nighttime noise level standards for residential areas are exceeded within about 950 feet.

Griffiths, I. E. and Langdon, F. J. "Subjective Responses to Road Traffic Noise." Journal of Sound and Vibrations. 8, (1968), 1.

"Guide for the Measurement of Audible Noise from Transmission Lines." IEEE Transactions on Power Apparatus and Systems PAS-91 (May/June 1972), 853-856.

Heroux, P. and Trinh, N. G. "A Statistical Study of Electrical and Acoustical Characteristics of Pulsative Corona." A paper presented at the IEEE Power Engineering Society Winter Meeting in New York (January 25-30, 1976).

ABSTRACT: With the growing interest concerning audible noise generated by corona discharges, a systematic study has been carried out at IREQ to determine and correlate the electrical and acoustical characteristics of pulsative corona at single discharge sites. Small protrusions of both spherical and conical shapes were placed on a 12-cm sphere, in a point-to-plane test arrangement.

The shapes of current and sound pressure pulses were investigated. Also, the statistical distributions of deadtime between consecutive pulses and pulse amplitude were established automatically using a multichannel analyzer. The results obtained show that:

- typical wave shapes can be defined for both the current and sound pressure pulses for each polarity of the discharge;
- a correlation exists between the amplitudes of the electrical and acoustical pulses;

- the pulse successions that constitute a corona regime can be described by a three-dimensional "evacuation diagram" correlating the amplitude of the current pulses and the associated dead time;
- the frequency spectrum of the audible noise generated from a single discharge source can be evaluated from the Fourier transform of the acoustical pulse and a spectral repartition derived from the evacuation diagram of the corona regime.

Hoburg, J. F. and Melcher, J. R. "Current-Driven, Corona-Terminated Water Jets as Sources of Charged Droplets and Audible Noise." Paper C-73-165-8 presented at the IEEE PES Winter Meeting in New York (January 1973).

Howes, W. L. "Loudness, How a Human Judgment is Quantified." NASA Lewis Research Center Report, February 1973.

Ianna, F., Wilson, G. L. and Bosack, D. J. "Spectral Characteristics of Acoustic Noise from Metallic Protrusions and Water Droplets in High Electric Fields." Paper C-73-164-1 presented at the IEEE PES Winter Meeting in New York (January 1973).

Kolcio, N. "Audible Noise," in EHV Transmission Line Corona Effects. (Tutorial Course Text 72 CH0644-5 PWR). New York: Institute of Electrical and Electronics Engineers, Inc., 1972.

Morgan, M. "EHV and the Environment: The Tip of the Iceberg." Electric Light and Power (August 1974).

Pearsons, K. S. "Determining the Effects of Power Line Noise on People," in Psychoacoustics: Proceedings of a Workshop. New York: Institute of Electrical and Electronics Engineers, Inc., 1974.

ABSTRACT: This paper discusses research approaches which could be employed to assess the impact of power line noise. The approaches have been used successfully in research involving the evaluation of other types of noise. A method for determining the detectability of power line noise is also presented.

Perry, D. E. "Corona Noise Measurements in the Field--Methods and Results," in Psychoacoustics: Proceedings of a Workshop. New York: Institute of Electrical and Electronics Engineers, Inc., 1974.

ABSTRACT: The design of EHV transmission lines is such that under certain weather conditions corona discharges occur on the conductor surface. Both electromagnetic and acoustic energy are emitted resulting in radio and television interference and audible noise. This presentation is concerned with the acoustic emission of the energy spectrum referred to as transmission line audible noise. Included is a discussion of methods of noise measurement as related in particular to the measurement of transmission line noise and a discussion of measured noise levels from operating EHV transmission lines.

Pirotte, P. "Audible Noise Produced by Corona Effect on AC and DC Overhead Lines." Paper no. 36-02 presented at CIGRE International Conference in Paris, France (1972).

Sawada, Y., et al. "A Laboratory Study on RI, TVI and AN of Insulator Strings Under Contaminated Conditions." IEEE Transactions (May 1, 1973), paper no. T73 415-7.

Schneider, A. J. "Instrumentation for Power Line Noise Measurement and Evaluation," in Psychoacoustics: Proceedings of a Workshop. New York: Institute of Electrical and Electronics Engineers, Inc., 1974.

ABSTRACT: This paper reviews the requirements for measuring power line noise and shows the capability of state-of-the-art instruments to reliably perform these difficult measurements. The paper also shows the latest techniques for evaluating noise amplitude distribution.

Sforzini, M., et al. "Acoustic Noise by AC Corona on Conductors: Results of an Experimental Investigation in the Anechoic Chamber." Paper T74 402-4 presented at the IEEE PES Summer Meeting and Energy Resources Conference in Anaheim, California (June 14-19, 1974).

Sforzini, M. "Results of Audible Noise Field Measurements Carried Out on HV and EHV Lines." A paper presented at the IEEE Symposium on Audible Noise from HV Transmission Lines in Dallas, Texas (June 1969).

Shankle, D. F. "RI, Audible Noise, and Electrostatic Induction Problems." A paper presented at the Westinghouse 1972 Electric Utility Engineering Conference (April 1972).

Shaw, E. A. G. "Noise Pollution-What Can Be Done," Physics Today 28, no. 1 (January 1975).

Strong, N. G., Davis, N. E. and Melville, D. R. G. "Visual, Ultraviolet and Ultrasonic Display of Corona Fields in Air." Proceedings of the Institute of Electrical Engineers (London) 117, no. 7 (July 1970), 1453-1459.

ABSTRACT: Photographic techniques were devised to assist in examining flashover behavior of insulators, and these were developed to display the electric-field pattern by photographing, in daylight, the ultraviolet portion of the corona spectrum. Later, a special television camera was used to enable the field phenomena to be observed continuously. These techniques give more information than can be obtained by normal methods of field analysis or by visual observation in darkness. The ultraviolet discharge is accompanied by ultrasonic noise, which has been detected, and the characteristic ultrasonic patterns for various gap geometries have been recorded. Both the ultraviolet and ultrasonic techniques may be used to determine corona inception in daylight, and both are more sensitive and reliable than visual observation in darkness.

Taylor, E. R., Chartier, V. L. and Rice, D. N. "Audible Noise and Visual Corona from HV and EHV Transmission Lines and Substation Conductors--Laboratory Tests." IEEE Transactions on Power Apparatus and Systems PAS-88, no. 5 (May 1969), 666-679.

ABSTRACT: The results of laboratory studies and preliminary field test exploring the effects of conductor size and bundling on audible and visual phenomena associated with corona in wet weather are presented. Tubular conductors in five diameters of 1.063 to 2.375 inches were tested.

Tong, D. W., Wilson, G. L. and Johansen, I. "Effects of Surface Wettability on Audible Noise and Capillary Absorption as a Noise Reduction Scheme." A paper presented at the IEEE Power Engineering Society Summer Meeting in San Francisco, California (July 20-25, 1975).

ABSTRACT: The effect of surface wettability on foul weather audible noise generation is experimentally investigated. Droplet formation is discussed in terms of the contact angle description. Hysteresis of contact angle is used to explain the observation that droplet formation on a particular surface depends on the fluid deposition process. An experimental conductor is described which is capable of absorbing surface droplets into its interior and test results are given which shows a noise improvement of better than 10dbs.

Trinh, N. G. "Analysis of the Second Harmonic (120 Hz) Audible Noise Generated by Line Coronas." A paper presented at the Power Engineering Society Summer Meeting in San Francisco, California (July 20-25, 1975).

Trinh, N. G. and Maruvada, P. S. "A Semi-Empirical Formula for Evaluation of Audible Noise from Line Corona." Proceedings of the IEEE Canadian Communications and EHV Conference in Montreal (November 9-10, 1972), 166-167.

U. S. Environmental Protection Agency. Effects of Noise on People. Washington, D. C.: USEPA, December 31, 1971.

U. S. Environmental Protection Agency. Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety. EPA document no. 550/9-74-004. March 1974.

U. S. Environmental Protection Agency. Measurement of Effects of Noise on Man. Fundamentals of Noise: Measurement, Rating Schemes and Standards. Washington D. C.: USEPA, December 31, 1971.

Wardlaw, R. L., Cooper, K. R. and Scanlan, R. H. "Observations on the Problem of Subspan Oscillation of Bundled Power Conductors." Paper no. 323 presented at the International Symposium on Vibration Problems in Industry in Keswick, England (April 10-12, 1973).

ABSTRACT: Experimental and analytical investigations into the problem of the aerodynamically induced oscillations of bundled power conductors are described. The mean aerodynamic forces on the conductors have been measured in wind tunnels for 2, 4, 6 and 8 conductor bundles using two-dimensional full scale models. Dynamic response studies have been made using spring-mounted two-dimensional full-scale models and reduced scale aeroelastic models. The physical causes of the vertical aerodynamic force and the effects of terrain on the forces and the instability are discussed.

Wells, R. J. "Noise Complaint Potential: Ambient Noise Versus Intrusive Noise." Paper no. 20-N-6 presented at the Seventh International Congress on Acoustics in Budapest, Hungary (August 1971).

Wells, R. J. "Subjective Analysis of the Noise from High Voltage Transmission Lines," in Psychacoustics: Proceedings of a Workshop. New York: Institute of Electrical and Electronics Engineers, Inc., 1974.

ABSTRACT: This paper discusses the relative merits of basic sound measures such as dB(A), dB(B), etc., when used to rate subjective response to the noise of high voltage transmission lines. It also considers the aspect of time variability of such noises and the relative merits of three different measure variants which may be employed to rate the subjective effect of this variability.

Wilson, G. "The Mechanism for Audible Noise on EHV Transmission Lines." A report presented to CIGRE 31 in London (1972).

Winants, V. and Riez, M. "Conductor Galloping on Overhead Lines." Paper 22-06 presented at the CIGRE Conference in Paris, France (August 24-September 2, 1970).

ABSTRACT: The investigation is concerned with the classification of conductor galloping according to the various observed forms of oscillations, explanation of this phenomenon, major disadvantages resulting from its appearance, influence of the various factors affecting it, as dependent on the environment, and design characteristics of the lines. The measures to be taken against galloping are reviewed along with a new design of overhead lines with the sole purpose of avoiding two-phase short-circuits caused by galloping.

3. CORONA EFFECTS--RADIO AND TELEVISION INTERFERENCE

3.1 Introduction

3.1.1 Units of Measure

The electromagnetic interference field is measured in volts per meter. However, since most radio frequency fields are quite weak, the reference level used is microvolts rather than volts or kilovolts. In the case of continuous wave sinusoidal signals, the measured levels are independent of the bandwidth of the receiver, assuming proper initial tuning. On the other hand, in the case of naturally wide-band generated interference and some man-made interference, the receiver's response in amplitude is proportional to the square root of the operating bandwidth. In the case of impulsive noise, the amplitude response over limited frequency regions can be proportional to the bandwidth. Usually for convenience, most of the natural and man-made interference is generally related to the square root of the bandwidth.

3.1.2 Ambient Non-Power-Line Environments

Interference from all sources can be classified as either active or passive. In the case of active interference, a signal source separate from that of the desired signal produces an interfering waveform. In the case of passive interference, only the desired signal source is involved, but the propagation path is modified. A typical example of passive interference is the "ghost" generated from rescattering of TV signals from high-rise buildings.

Figure 1 presents[1,2] some typical levels of naturally occurring radio frequency interference. Below approximately 10 megahertz, the main source of naturally occurring interference arises from the impulsive radiated fields from lightening discharges throughout the world. These are propagated by ionospheric reflection.

Man-made sources of interference may even be authorized radiations, but are generally of a spurious nature. Impulsive interference from automobile ignition systems, switching circuits, electric typewriters, and brush-type commutators can also be radiated over wide areas.

The level of the ambient interference, either man-made or natural, varies with location and is typically much greater in metropolitan areas where considerable man-made noise is present as opposed to the more quiet rural areas. Some assessment of these ambient levels in metropolitan and rural areas can be developed by noting the recommended field intensity levels[3] for radio broadcast signals necessary for reliable service in different regions. These are as follows: 1) a major metropolitan business area, 80 to 94 dB above a microvolt per meter; 2) a residential district of the city, 66 to 80 dB above a microvolt per meter; and 3) a rural area, 40 to 54 dB above a microvolt per meter.

The ambient noise levels can be inferred from the required signal-to-noise ratios to produce acceptable annoying or almost unintelligible listening. Guidelines[4] for such signal/noise ratios are presented in Table 1. Using a 20 dB

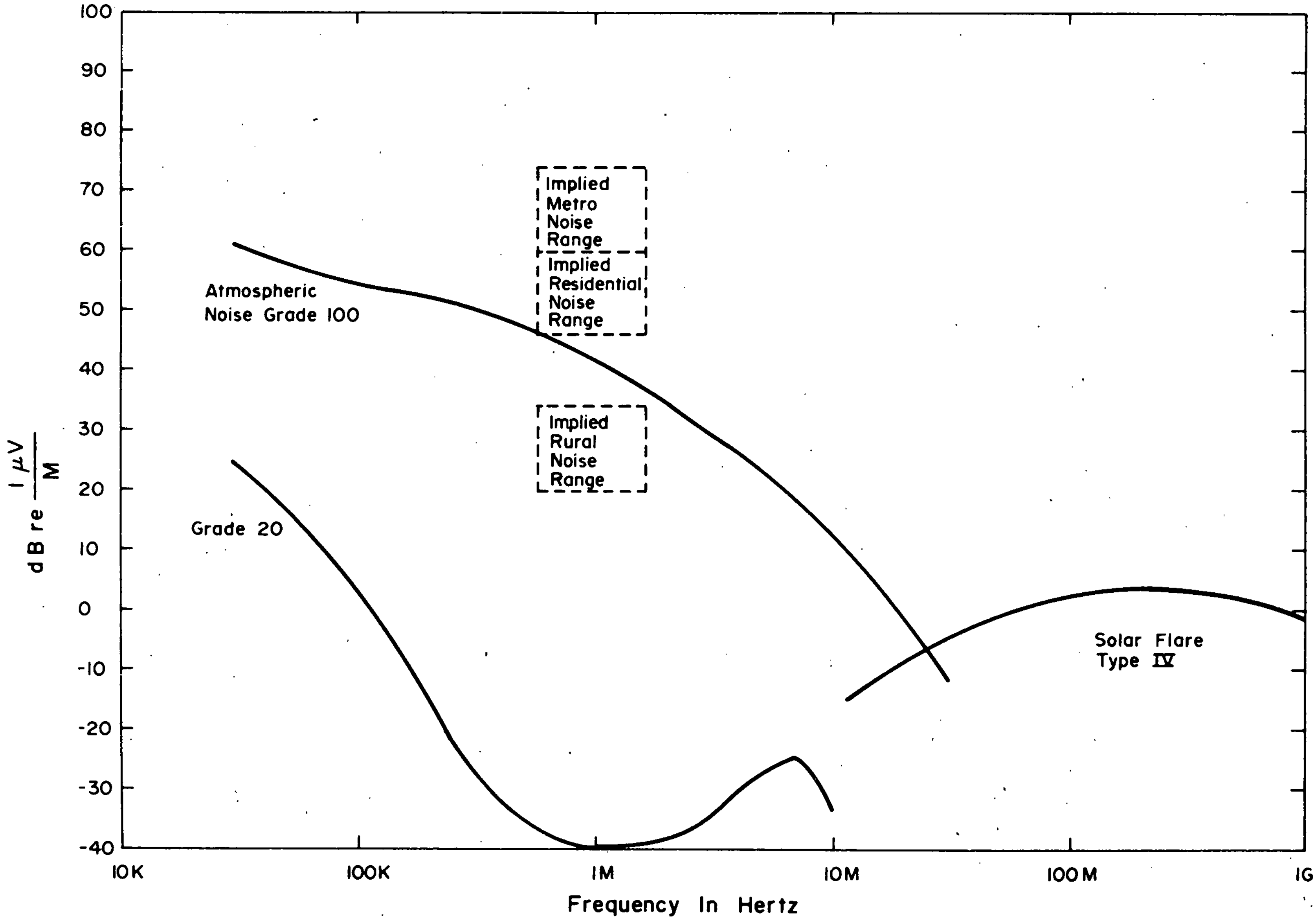

Fig. 1 NATURAL AND NON-POWERLINE RADIATED ELECTROMAGNETIC ENVIRONMENTS (BANDWIDTH 9 KHZ)

signal-to-noise ratio, an upper bound for typical ambient man-made noise levels in metropolitan, suburban and rural areas can be established and these values are also plotted in Figure 1.

Table 1

SUBJECTIVE RESPONSES TO THE AUDIBLE OUTPUT FROM A RADIO BROADCAST RECEIVER FOR VARYING INPUT SIGNAL-TO-NOISE RATIOS[4]

Signal/noise ratio Scales Logarithmic (dB)	Linear	Code	Reception quality Subjective Impression
30	32	5	Interference not audible.
24	16	4	Interference just perceptible.
18	8	3	Interference audible but speech perfectly received.
12	4	2	Unacceptable for music but speech intelligible.
6	2	1	Speech understandable only with great concentration.
0	1	0	Spoken work unintelligible: noise swamps speech totally.

3.1.3 Historical Appraisal

Radio noise and television interference are a corona-induced phenomena and corona has been the subject of detailed study since the early 1920's. However, the problems associated with radio interference and later on television interference were not seriously addressed until the late 1940's with the advent of operating voltages in excess of 250 kilovolts.[4] As the operating voltages increased, the interference became an important factor in the design of the transmission line and the choice of the route as well. The state-of-the-art of radio interference from power lines is now quite advanced, particularly in the areas of AM broadcasting and lower shortwave bands. Considerable information is available on the generation mechanism for this interference, methods of measurement, and the line design requirements for limiting this interference to acceptable levels. The Transmission Line Reference Book, 345 Kilovolts and Above[3] and Interferences Produced by Corona Effects of Electric Systems[4] contain extensive bibliographies summarizing the present state-of-the-art. The reader is referred to those sources, which are sufficiently comprehensive to eliminate the need for a bibliography on the topics in this document.

3.2 Interference Effects From High Voltage AC Lines

Interference effects from high voltage ac lines can also be both active and passive. The active interference is generated by impulsive kinds of corona discharges or the so-called "gap discharges" which also generate impulsive currents, both of which lead to interference. Passive interference is generated by transmission lines by the rescattering of television signals causing ghosting.

In the case of passive interference, that is, rescattering of incident energy by the power line or its towers, and the resulting ghosting or multipath problems, the basic phenomena is well understood and analytical techniques of varying reliability have been applied to predict this effect. Unfortunately, no solution has been found to prevent reflections from many high buildings, towers and high voltage lines for a given siting. Some options do exist in the case of new lines wherein the routing and orientation of the lines may be made in ways to prevent either high level initial illumination or rescattering into populous regions.

Most of the complaints arise from viewers whose homes are on the transmitter side of the line.[4] In this case, a typical solution is the use of high gain antennas with a high front to back ratio, such that the direct pickup from the transmitter is enhanced while suppressing the rescattered energy from the line.

The interference problems are treated in two major areas, the first is generally referred to as RI, meaning radio interference applicable to frequencies below 10 megahertz. The second category is referred to as TVI and is applicable to interference generated above 30 megahertz (and upwards into the lower microwave band).

3.2.1 HVAC RI

Interference Generation Mechanisms

Below approximately 10 megahertz, the impulsive corona discharges are responsible for generating the bulk of the interference. The general nature of such pulses and the related interference spectra are well understood. As with all corona effects, the surface imperfections on the conductor constitute a decisive working factor--the onset of corona is much lower in actual lines than would be predicted for idealized conductors. Similarly, atmospheric conditions also play a leading part by the introduction of imperfections on the conductor--in the form of water droplets.

According to one viewpoint, each site of the corona impulsive discharge along each conductor provides an incremental source generator which causes the interference to propagate along the power line. The total interference as seen at any particular point will, therefore, consist of contributions from many impulsive sources which probably extend over some tens of kilometers. The basic modes of propagation along polyphase lines can be treated in matrix form.[4] Since the radio interference is strongly dependent on the meteorological conditions as well as the surface treatment of the conductors, statistical accumulation of radio interference data is often required. The reference meteorological conditions are of two categories, heavy rain and fair weather.

The spectral content of the corona-induced pulses is such that the high frequency content tends to fall off quite rapidly above approximately 1 megahertz. This fall-off is reflected in the spectral content of the measured radio noise as shown in Figure 2.[4]

Spectral components below about 10 megahertz are not efficiently radiated from the power line. This occurs because the vertical dimensions, conductor separations, and the size of discontinuities (such as drop-wires) are small compared with the wavelength. Where an antenna is electrically short (small compared with a wavelength), efficient radiation is not possible. Since all vertically polarized antenna like radiators on a transmission are electrically short, the high intensity noise fields are confined to the immediate vicinity of the line. Figure 3 presents a typical lateral profile of the distribution of radio noise for a horizontal conductor line.[4]

Prediction Methods for RI

Both semiempirical and the quasi-analytical methods have been perfected sufficiently that satisfactory predictions of the radio interference levels for transmission lines from 22 to 800 kilovolts are possible. The semiempirical method emphasizes data developed on the basis of long-term recordings under a variety of weather conditions, whereas the quasi-analytical methods employ empirical test results developed on small conductor bundles. These

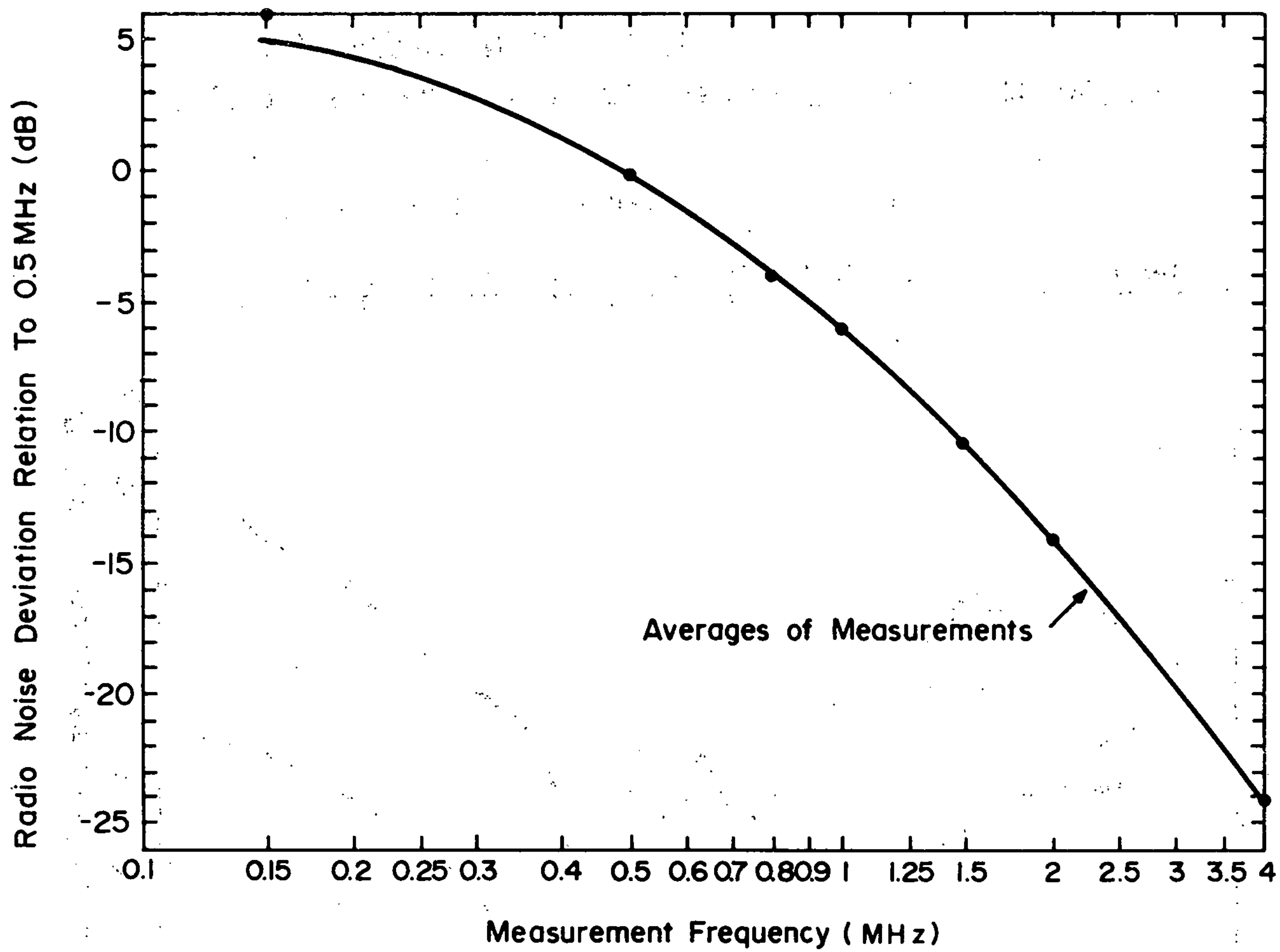

Fig. 2 TYPICAL FREQUENCY SPECTRA REFERENCE 0.5 MHz
FOR A HORIZONTAL LINE (9 KHz BW)
USING A QUASI-PEAK FIELD INTENSITY METER

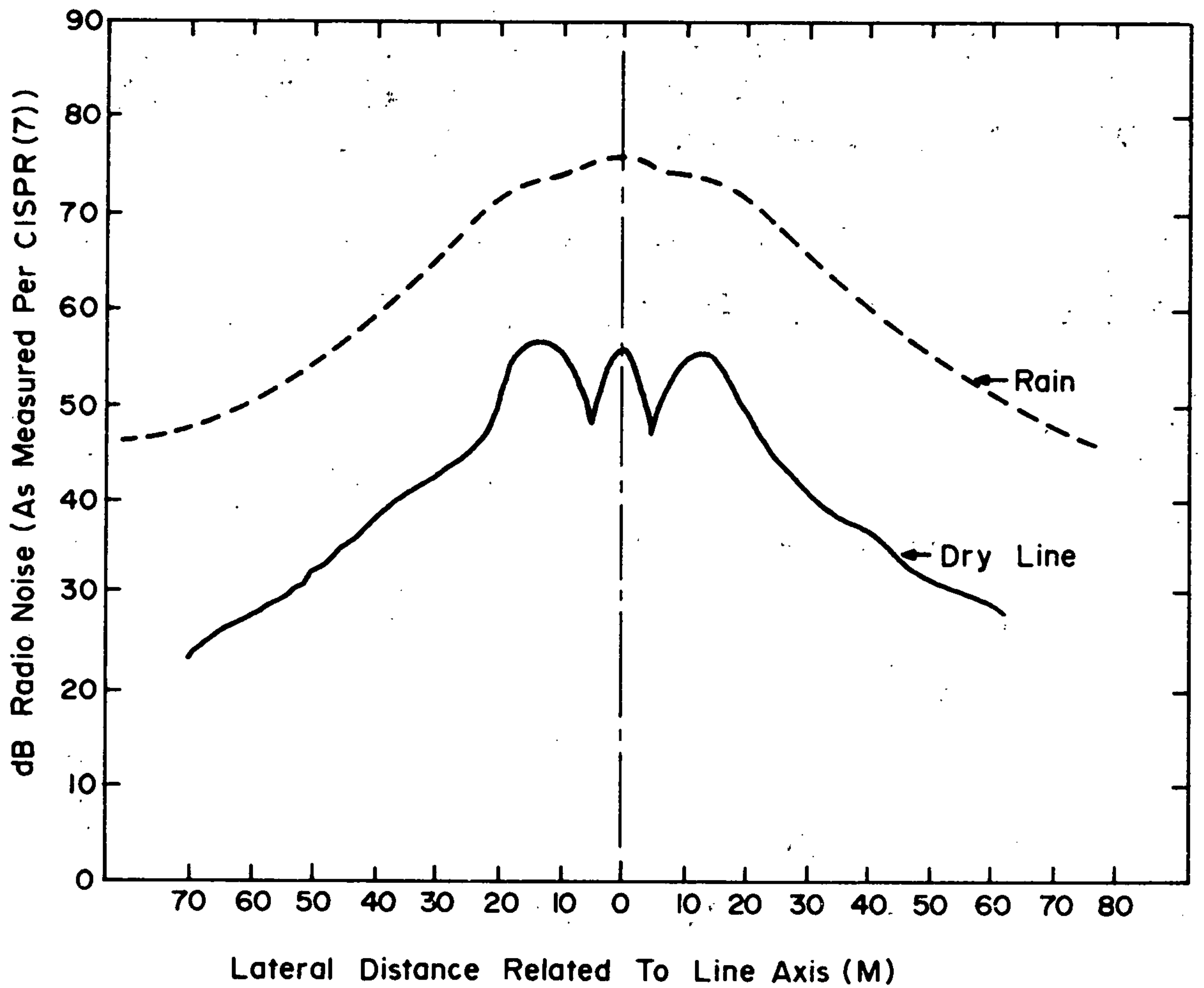

Fig. 3 EXAMPLES OF LATERAL PROFILES FOR AN ACTUAL 380 KV HORIZONTAL LINE

empirical small-line-segment results are then employed using rigorous analyses to predict the interference levels. There are, however, some areas which need additional resolution. These include a better understanding of the relationship between long line, short line and cage measurements.

Measurement Techniques for RI

Measurement equipment and methods have been refined to a point where standards have been published by ANSI, CISPR and IEEE.[5,6,7]

3.2.2 TVI and Microwave Interference

Interference caused by overhead high voltage ac lines in the FM and TV broadcast bands, and possibly in the lower microwave band, has two aspects. The first aspect is active interference which is produced by electrical discharges on all parts of the line and the other is passive interference introduced by rescattering which causes ghosting.

TVI Generation Mechanisms

In this particular band, interference is caused both by the impulsive corona effects, which have spectral contents "spilling over" into the TV and lower microwave band, and by gap discharges. "Gap discharge" is a collective term for the electrical breakdown of insulation between two charged surfaces, e.g., sparks between two metal parts of hardware items or smaller sparks between a metal part and an electrically charged insulating surface.

TVI Prediction Methods

A general lack of refinement exists for TVI relative to RI. This lack of development may be traced, in part, to the apparent absence of problems in correctly designed and maintained overhead lines. It has been stated that

> when an overhead line has been correctly designed to prevent radio interference in the frequency range or range around one megahertz, interference problems above 30 megahertz will be accidental. If interference happens, it will, in most cases, be caused by sparks on insulators and hardware, and seldom by microsparks or corona. (Ref. 4)

This statement may be applicable for <u>typical</u> receiving conditions in the vicinity of a high voltage transmission line. However, special situations may occur where a very highly sensitive receiver is to be located near a high voltage transmission line.[8]

To a limited extent, the methods developed for RI can be extended to the TVI region. With decreasing reliability, the predictive method may also be applied to the upper microwave region.

Measurement Techniques

While standard radio frequency instrumentation is available[9] which can make both narrow-band and broad-band field intensity measurements in the television and lower microwave bands, correlation of these measurements to the subjective responses of viewers of television displays is difficult. This arises because very little has been done to date to develop this correlation. In addition, the subjective response of the viewer to the types of noise generated by a transmission line is another unknown. This latter aspect however, is being addressed by the IEEE Working Group on Corona and Radio Interference.[10]

3.3 <u>Interference Effects From High Voltage DC Lines</u>

The many factors appearing in the HVAC line discussion are equally applicable to HVDC lines. There are, however, some noticeable exceptions. First of all, owing to slightly different RI generation phenomenology, the foul weather radio noise is usually lower than fair weather radio interference.[4] Also, there is little statistical data regarding measurements from actual working lines, and most of the prediction techniques are based on extensions of the methods employed for ac lines. Thirdly, perhaps owing to the absence of modulation by the 60 Hertz frequency and its harmonics, radio noise originating from HVDC lines is considerably less annoying to the average listener than noise from HVAC lines of the same electric field intensity. While the conductor voltage gradient is still a useful criterion to estimate corona effects in the dc case, some of the corona effects are influenced by air ions, wind and humidity more evidently than in the case of high voltage ac.

Little definitive information is available about the TVI interference from HVDC lines. This lack of interest, may, in part, be caused by the fewer circuit miles of HVDC lines, and also because these lines are generally located in nonpopulous areas. Similarly, little has been done regarding the prediction of television interference from HVDC lines.

3.4 Conclusion and Consolidation of the State-of-the-Art

Both the state-of-the-art review and the discussions at the workshop* clearly indicated that relatively little additional research is required to resolve future problem areas concerning radio interference. The exception to this is the resolution of the subjective aspects of HVAC generated RI versus HVDC generated RI.

The power line represents a special case for RI inasmuch as the interference levels associated with the line are confined largely to the rights-of-way area. On the other hand, other major sources of interference associated with non-power-line situations are such that this interference can be radiated over a wide area and cause disruption of many types of services. To control radiated interference over wide areas, limits on the amount of radiation permissible for such interference sources are sometimes necessary.

On the other hand, in the case of power lines, owing to the very restricted region where some interference may be a problem, issues more complex than just a choice between simple interference or no interference must be considered. As is noted in Table 1 and Figure 1, various levels of desired

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* Identified in Section 1 of this report.

signal as well as non-power-line noise signals occur at varying levels depending on the location and the nature of the services.

In addition to the foregoing technical factors, such human factors as density of the population in the areas crossed by the lines may also be important from an economic point of view. For example, where the power lines are run in very sparsely populated areas, interference problems will be rare, but could occur if the receiving site were located next to the right-of-way. In this case, it makes far more economic sense to relocate the antennas for this one receiver rather than to increase the cost of the transmission line to a point where interference is negligible.

As indicated in the state-of-the-art review, and as similarly discussed in the workshop, some additional work is required to determine the active and passive interference components in the television and microwave bands. A prime need is a measurement instrument having a meter indication that correlates well with the human subjective responses to power-line interference and television displays. More complete and thorough measurements of TVI from high voltage dc lines, both test and operating, are needed.

Programs to resolve any misgivings about long line, test and cage measurements were topics of discussion at the workshop. However, such considerations are better addressed within the context of a more general transmission line design program. These considerations still can be an important consideration for the operating companies.

Specific problems associated with the TVI generated by hardware items were also discussed at the workshop. These could best be dealt with as parts of a general program for improving reliability.

3.5 Research Program Plans for Radio and TV Interference

3.5.1 TVI Measurement Instrumentation

Background

Because there is a lack of correlation between the measurement indications of existing equipment and the subjective responses of television viewers, present measurements of the amount of TVI from power lines are unsatisfactory. Part of the problem lies in the basic design differences between the television sets and radio frequency measurement instrumentation which generally relies on quasi-peak measurements for the impulse noise generated in the TV Band. The IEEE working group is attempting to obtain a subjective rating factor by means of video tapes taken of television pictures with interference generated from power lines. This information may be used for the design of an alternate instrumentation which considers the subjective factors.

Objective

The objective of the proposed effort would be to develop measurement instrumentation having meter indication readings that correlate well with the human subjective responses to power-line interference in television displays for both HVAC and HVDC transmission lines.

Tasks

The first task would consider the development of an objective criterion of picture quality for under HVAC and HVDC TVI noise conditions. This criterion would be used to quantify viewer subjective responses on a statistical basis. Existing television tapes and other data will be employed.

The second task would consist of development of a prototype instrument. This will measure a quantity which is as closely related as possible to the objective criterion developed in the first task.

3.5.2 TVI From HVDC Lines

Background

Television, UHF, and microwave interference from HVAC lines are important considerations; and it appears that comparable interference generation from HVDC lines may also occur. As of this date, extensive measurements of television, UHF, and microwave interference from high voltage dc lines have not been made with suitable equipment, under a variety of meteorological and geographical conditions.

Objective

It will be the objective of this effort to measure the TVI, UHF, and microwave interference from high voltage dc lines under a variety of operating conditions for as many conductor geometries and geographical locations as appropriate.

Tasks

Various mechanisms which generate TVI and related interference would be experimentally studied and supported by analyses where appropriate. Equipment would be assembled and used to locate faults which may cause the generation of TVI in hardware items. If the same mechanisms are not evident for HVDC as they are for HVAC, then these various mechanisms will also have to be experimentally identified. Measurement techniques suitable to measure TVI from HVDC lines will be developed based on HVAC TVI measurement instrumentation program results. Measurement data on test operating lines would be documented.

3.5.3 Prediction of VHF-UHF Microwave Interference For HVAC and HVDC Transmission Lines

Background

Many important equipments designed for space, military or civilian purposes may be located near power lines. These equipments may be sensitive to unintentional interference from the power lines in the VHF, UHF, and microwave bands.

To a limited degree, techniques developed for RI, can be extended into the TV, UHF, and microwave bands. The existing measurement data also appear inadequate to provide a prediction of interference in these bands, expecially for lines operating above one million volts. Often, this type of interference is generated by hardware, and is a function of the maintenance on the line. A major prediction problem is that each line may well be unique.

Objective

The objective of this effort will be to determine the feasibility of a program to improve the reliability of prediction for VHF, UHF, and microwave power line interference, especially for lines above one million volts.

Tasks

Semiempirical and quasi-analytical prediction methods of measuring interference in these bands would be considered. Initial emphasis would be for HVAC lines. Commonalities in hardware design and maintenance methods would be studied. Based on the results of the feasibility study, a program would be recommended to improve the prediction of the VHF, UHF, and microwave interference from HVAC power lines and, if appropriate HVDC lines as well. This would consider line designs necessary to obtain power transmission between 1 and 2 megavolts.

3.5.4 Subjective Responses to HVDC and HVAC RI

Background

The audio output of radios experiencing radio frequency interference from HVDC is different than the audio output from comparable radio sets experiencing radio frequency interference from HVAC power lines. Preliminary evaluations of the subjective responses indicate a preference for the HVDC noise for otherwise comparable situations. The differences may be partly attributed to the 120 or 60-Hertz components present in a radio interference from HVAC power line.

Objective

The objective of this effort will be to correlate the subjective responses of the degradation in the quality of AM radio reception due to RI from HVDC and HVAC power lines.

Tasks

Data would be developed which can be used as a basis for comparing the radio noise generation of either HVAC or HVDC power line system designs. The subjective responses under varying EMI conditions would be taken with and without radio signals of various types, such as speech patterns, rock through classical music, and various types of programming, from variety shows through newscasting.

3.5.5 Reradiation and Propagation

Background

Incremental radio, television, and UHF corona noise sources excite transmission lines phase-to-phase and phase-to-ground in unique manners. The manner in which the excitation takes place controls the way that the radio energy propagates along the line and the way it is subsequently reradiated.

As the operating voltage of a transmission line increases, the tower heights will increase similarly. The presence of these higher towers also affects the way in which energy is propagated and reradiated along the line.

Rescattering of energy in the TV band can introduce additional ghosting; and radio frequency radiation patterns can also be distorted by situating a power line near a broadcast station. Where a line changes direction or where discontinuities occur, such as for drop lines to transformers, radiation can also take place.

Analytical techniques can be refined to characterize TVI noise propagating along the line. Advances in scattering theory and computation methods could be applied to provide a more reliable analysis. Similarly, while some material has been published on passive interference, further refinement can be accomplished by using recent advances in numerical integration digital computation to include actual tower and conductor geometry in calculations.

Objective

The objective of this effort would be to apply advanced techniques to predict the radiation, rescattering, and propagation characteristics of power lines.

Tasks

Several major areas of endeavor are envisioned, and these include: 1) rescattering of energy in the broadcast band; 2) rescattering of energy in the TV and microwave bands, either by the power line or the tower, as appropriate; 3) the propagation of radio energy along the power line as affected by the conductor arrangement, tower design, changes of direction, and drop wires to transformers. UHF or microwave broadband RF, 100 to 1 scale model measurements would be used to supplement the analytical study. Measurement of reflection from existing full size structures would be made to validate the results. If appropriate, the results of these measurements would be enlarged for use in handbooks.

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4. CORONA EFFECTS--OZONE

4.1 Introduction

4.1.1 Sources of Ozone and Related Oxidants

There are at least three categories of ozone formation which are of interest: (1) photochemical formation in the stratosphere; (2) photochemical production near the earth; and (3) ozone generation associated with electrical discharges.

Ozone is formed in the upper atmosphere when solar ultraviolet light causes the disassociation of the oxygen molecules.[1] Originally, it was believed that such a process does not contribute substantially to the ozone concentrations found near the ground; however, more recent data indicates that this may not be true.[2,3]

Significant amounts of ozone are believed to be formed near the ground by the action of ultraviolet radiation with the gaseous emissions of combustion processes, such as automobile exhaust gases.[1] Contributions may also arise from hydrocarbons emitted from natural sources.[3] In this process, the ozone concentrations tend to be much greater during periods of intense sunlight that are coincident with meteorological conditions which allow accumulation of industrial and automotive industrial waste gases, such as during an inversion.

It has been known for many years that electrical arcs and corona discharges from electrical apparatus can create ozone and, to a minor extent, other gases such as oxides of nitrogen. The process is quite complex and is generally rather inefficient in terms of total energy required during actual process versus theoretical limit.

Production of nitrogen oxides is more difficult electrically in the corona discharge, since higher electron energies are required. Thus, the yield of NO_x is substantially less than the yield of ozone.

Since ozone is one of the most reactive compounds known, its concentration will continually decrease unless additional ozone is generated or transported to the area. The presence of oxides of nitrogen, some spray can propellants, carbon tetrachloride and other sources of chlorine and bromine can accelerate the recombination of ozone both near and well above the earth's surface.[4] Near the earth's surface, vegetation and other material can act to reduce the concentration.

Thus, the ozone concentration in any given area is a delicate balance between the ozone formed or transported and the destruction of ozone in that area. The decay rate of ozone, and the factors which affect the rate, are of interest in predicting ozone buildups near transmission lines.

4.1.2 Distribution and Concentration

Ozone has been recognized as a significant air pollutant in urban areas, but it has not been until recently that good comparative measurements over wide areas have been developed over a year's time. Recent papers by Stasiuk and Coffey[2,3] discuss measurements in both urban and rural sites. These show a daily variation of the ozone concentrations in the urban areas which, surprisingly, do not occur in the rural areas. The diurnal variations in the metropolitan areas suggest the presence of some element which accelerates the recombination process during nighttime. Typical ozone concentrations measured on rural mountain top locations during the late summer months range from 30 ppb to 102 ppb. In the urban areas, the maximum hourly average ozone concentration ranged from 30 ppb to 124 ppb. Note that the maximum values in both the rural (in this case, two mountain tops) and urban areas exceeded the air quality standard of 80 ppb.[5] It is suggested that the higher rural ozone levels are not primarily due to the transport of ozone and ozone precursors from other urban areas, but could be due to naturally occuring phenomena, such as photochemical generation from non-man-made precursors or the transport of ozone from the stratosphere to the troposphere. These results raise questions about the current strategy of controlling the ozone levels in urban areas by limiting automotive and industrial gaseous emissions.

4.1.3 Biological Importance

There are two major biological reasons why ozone is of concern: (1) the destruction of ozone in the stratosphere with the possible health consequences associated with increased ultraviolet light (such as skin cancer) near the earth's surface, and (2) the biological effects of abnormal concentration of ozone near the earth's surface. Only the latter is of interest in discussing power line effects. The effects of ozone and similar oxidants on humans, animals and vegetation has been presented in detail.[6] This forms the basis for the National Primary Air Quality Standard for photochemical oxidants of an 80 ppb maximum one-hour arithmetic mean concentration not to be exceeded once a year.

4.1.4 Power-Line Implications

It has been known for a long time that ozone is generated from electrical corona and arc discharges. This property has been utilized for commercial ozone generators and ozonizers. The fact that transmission lines might generate ozone was considered in 1956 for the first time in conjunction with radio and TV interference tests on transmission lines in a publication by Newell and Warburton.[7] Liao, Keen and Powell[8] investigated corona and radio influence phenomena of thin wires in cylindrical cages and noted that ozone had to be removed by the continuous introduction of fresh air.

In the design of the early EHV lines, the ozone generation was not considered to be a major problem.[1] While ozone is usually noticeable by smell in high-voltage laboratories during repetitive testing, it was not noticed near some of the early high voltage lines and stations since a typical person can detect the smell of ozone in concentrations as low as 20 to 50 ppb. This provided fairly good evidence that the overhead transmission lines would not create an environmental ozone problem. This conclusion was supported by simple analyses during the preliminary design for some early EHV transmission lines.[1]

Unfortunately, various episodes associated with air pollution in general occurred in 1948 at Donora, Pennsylvania, and in 1952 in London. Although the problems were air pollution from sources clearly not associated with power lines, these episodes and others have created an acute awareness of the air pollution problems. Consequently, the question of generation of any pollutant, and ozone in particular, by EHV transmission lines, has been raised as a small part of this general environmental issue. As a result, a number of power companies, particularly American Electric Power Service Corporation,[1] began to undertake a comprehensive analytical and laboratory field measurement program to provide a more detailed analysis of the problem.

4.2 Appraisal of the State-of-the-Art

While considerable literature exists regarding corona losses on power lines, there are only approximately two dozen papers which deal directly with the generation, prediction and measurement of ozone from EHV power lines. In addition, a number of current programs in this area are fairly restricted. Typical of such programs is the one being conducted by Johns Hopkins for the State of Maryland. Other measurements and analyses are being conducted on the part of Project UHV for HVAC lines and by Institute de Recherche de l'Hydro for HVDC lines. Parties to the New York State Public Service Commission Hearing concerning proposed EHV transmission lines are conducting limited investigations as well.

Past studies have approached the development of the concentration of ozone near transmission lines in a sequential manner involving laboratory studies and analyses, which are then confirmed by means of field measurements. The corona losses associated with transmission lines are determined and then efficiency with which ozone and other oxide gases are generated is determined. Once the amount of gas near the conductor is determined in terms of the conductor geometry and operating voltages, the atmospheric diffusion characteristics and ozone decay properties are investigated to determine the possible ground-level concentrations. Hopefully, the final result would be confirmed by a series of field tests. Following the sequence of this scheme, the papers are reviewed in terms of three major areas:

1. laborabory measurements;
2. prediction;
3. field measurements.

4.2.1 <u>Laboratory Measurements</u>

Laboratory measurements of the production of ozone as a function of corona loss expressed in terms of the conductor voltage gradient, conductor geometries, operating voltages, and meteorological parameters have been reported in a series of six papers. The most comprehensive study was that reported by Scherer, Ware and Shih.[1] This paper reported the results of a comprehensive program involving laboratory prediction and field measurements. The laboratory work was conducted by Ion Physics Corporation, American Electric Power at Canton, Ohio and Westinghouse Electric Corporation. Preliminary results of a detailed laboratory study are reported by Sebo, Sweeney, Heibel, and Frydman[9] on a program conducted for American Electric Power by the staff at Ohio State. Roach, Chartier and Deitrich[10] summarize extensive laboratory and analytical work conducted by Westinghouse. Frydman, and Shih[11] report additional studies on the effects of the environment on ozone production which are based on tests conducted at American Electric Power Service Corporation's Canton laboratory. The more recent paper by Sebo, Heibel, and Frydman and Shih,[12] provides a comprehensive summary of the recent laboratory work conducted at Ohio State University on ozone production rates for a variety of conductor geometries and weather conditions. Whitemore[13] investigated wind and humidity effects and presented results comparable to those reported by Scherer.[5]

The above laboratory studies established the ozone production rate as a function of conductor geometry, operating voltages and simulated weather conditions. The following general conclusions were noted:

1. The ozone production rate is a function of the air flow rate, is relatively insensitive to air temperature, but is strongly dependent on the humidity.
2. The humidity has an adverse effect on the ozone production rate.
3. The ratio of corona loss to ozone production is constant only over a limited voltage region and is different for specific conductor geometries.
4. For otherwise identical situations, the production rate decreases with an increase in conductor diameter.
5. The ozone production rate is a strong function of the conductor voltage gradient and, over certain regions, increases as a square of the conductor gradient.
6. Ozone production is maximized during heavy rain.
7. The half-life of ozone was observed, on one experiment, to be approximately 10 minutes. Under more carefully controlled conditions, the half-life was 45 minutes and, under conditions of a water spray, was 27 minutes.
8. Once ozone is formed, it has a tendency to diffuse upward, possibly from convection currents introduced by local conductor heating.
9. The nitrogen oxide production rate is considerably less than that for the ozone, roughly 1/10th that for ozone.

4.2.2 Analytical Prediction

Based on laboratory measurements, the analytical prediction of ozone concentrations near high voltage transmission lines has been considered in two papers--the first by Scherer, Ware and Shih[1] and the second by Roach, Chartier and Deitrich.[10] Essentially, the experimentally determined ozone production rates over an incremental section of the overhead conductors is then used in diffusion studies to determine how the ozone diffuses or propagates to regions near the ground. Air diffusion models which have been developed over the last half century are used. However, to use these models for ozone diffusion from extended transmission lines, some unrealistic assumptions must be made, such as a very low velocity wind prevailing in one fixed and arbitrary direction over very long periods of time during inclement weather. In addition, the recombination rate of the ozone is also important, particularly during precipitation, but is not known. Existing calculations have not considered decay rates.

Two limiting cases are considered, that is, where the wind is perpendicular to the transmission line, and where the wind blows parallel to the transmission lines. It is evident that in the latter case, for very low non-turbulent wind conditions blowing parallel to the transmission line, a progressive accumulation along the line might occur under certain idealized and hypothetical conditions. Even under idealized conditions, certain data necessary for a precise calculation is missing, such as the recombination time of ozone under conditions of precipitation. Further, the hypothetical case in which the wind blows in a constant direction with an invariant very low velocity parallel to the line under conditions of heavy precipitation seldom, if ever, occurs. (The ozone generation at the conductor is maximum during heavy rain.) The actual variations of these meteorological parameters must be considered before a realistic assessment or calculation can be made.

A sample calculation for ozone concentrations, based on hypothetical weather conditions, is presented in Scherer.[1] The calculation is based on an assumed corona loss level and production efficiency of the effluents, incorporated with the EHV transmission line configurations. The key parameters are:

Operating Voltage:	765 kV rms line-line
Line Height:	75 feet average (22.86 m)
Total Line Length:	Transverse wind, infinite longitudinal wind, 2.5 miles (4 km)
Production rate of Total Oxidant:	0.08 oz/kWh (2.27 g/kWh)
Foul-weather corona loss:	(1) 79 kW/mi-3 phase (49 kW/km-3 phase) (2) 135 kW/mi-3 phase (83.7 kW/km-3 phase)

The results of the maximum ground level concentrations of the total oxidants are summarized as follows:

TABLE 1

CALCULATED MAXIMUM GROUND-LEVEL CONCENTRATIONS

Transverse Wind Speed (mph)	Maximum Concentration (ppm)	
	(1)	(2)
1	0.0007	0.0012
2	0.0003	0.0006
4	0.0002	0.0003
10	0.001	0.0001
Longitudinal Wind Speed (mph)	**Maximum Concentration (ppm)**	
	(1)	(2)
1	0.0113	0.0193
2	0.0057	0.0097
4	0.0028	0.0049
10	0.0011	0.0019

The authors state that the maximum concentrations for the longitudinal wind case should probably be reduced by a factor of 4, since the diffusion calculations for the parallel wind conditions are sensitive to the length of the line (or the constancy of direction of the wind). The reduction of ozone concentration due to recombination was not included in this analysis.

A. Whitemore[13] has made rough analytical estimates of the ozone contributed by power lines, and reports that transmission lines appear to contribute only minimally to local ozone levels in areas where transmission lines exist.

The plume dispersion theory and lab development of ozone production rates have been used to estimate the ozone concentrations near transmission lines. The more accurate estimates are for the wind perpendicular to the transmission line. Unfortunately, the most important case is the one in which ozone can be progressively concentrated by a wind blowing parallel to the transmission line. In this instance, the inaccuracies embedded in assumptions are cumulative as well, and generally tend to increase calculated values. As a consequence, parallel wind calculations made to date may be regarded as plausible upper bounds subject to downward revision.

Major uncertainties or data yet to be considered include the following: 1) recombination rates of ozone during precipitation, especially heavy rainfall; 2) statistical variations in the wind velocity and direction during various classes of precipitation and the use of these data in calculations; 3) dispersive characteristics introduced by actual terrain, vegetation and towers; 4) the tendancy of ozone to rise; 5) the probability of certain weather conditions favorable to high ozone production and concentration being considered in detail during the evaluation; 6) the presence of other pollutants which could accelerate the recombination during inversions or stagnations.

4.2.3 Field Measurements

Results of six measurement programs concerning the field measurement of ozone from overhead EHV lines are summarized in Table 2. In general, all measurements were capable of resolving concentrations on the order of 2 ppb to 5 ppb out of an ambient which generally ranged from 20 to 60 ppb. Also note that these represent the measurements of five separate groups, three of which were not connected with or sponsored by the power industry. Some of the measurements were conducted over at least a two year period of time at fixed locations, whereas others were conducted in a variety of locations over shorter intervals. A typical procedure is to determine the ambient levels by locating measurement sites well away from or upwind of the power line, and then comparing these results for locations near to and downwind from the line. The conclusions of all of these studies were that the power line had no significant effect on the ozone concentration in the area. During one preliminary study, only one measurement indicated a higher ozone concentration and this could not be repeated.

4.2.4 Measurement Methods

Until about five years ago, ozone monitoring instruments depended on the reaction of ozone with an aqueous potassium iodide solution. The potassium iodide solution would also react with other oxidants to record a total oxidant concentration. Certain other gases, i.e., sulfur dioxide, could negatively affect the indicated ozone concentration. Within the past five years, other instruments have been developed which measure ozone in terms of certain of its unique properties. Two gases, nitrogen oxide (NO)

TABLE 2

SUMMARY OF PUBLISHED OZONE MEASUREMENTS MADE NEAR AN EHV LINE

Investigator/ Sponsor	Line Voltage	Measurement Period	Measurement Locations	Conclusions
Research Triangle Institute/ Environmental Protection Agency[14]	230 kV	March 1971	Upwind, downwind, beneath line, at ground level	Power line had no significant effect on ozone concentration in area
Research Triangle Institute/ Environmental Protection Agency[15]	500 kV	Aug-Sept 1972	5 ground level locations, upwind, downwind, beneath line	No significant variation introduced by line
American Electric Power and Battelle/American Electric Power[16]	765 kV	10/18/70 to 10/21/71, but shorter intervals at any given location	20 locations	No ozone formation attributed to power line for variety of terrain and weather
IITRI/ Commonwealth Edison[17]	138 kV, 345 kV and 765 kV	4/1/71 to 11/15/72, periods of 6 months to 1 year	4 locations, urban and rural	High voltage transmission lines up to 765 kV do not generate measurable ozone above ambient under any weather condition
Ohio State University/ American Electric Power[18]	765 kV	7 month continuous in one location before and after line energization	Up and downwind in one general area	No measurable quantity of ozone within 2 ppb could be detected due to EHV line, either short or long term
Oak Ridge National Laboratory[19]	500 kV	4/6/72 to 5/16/72	Approx. dozen locations near and distant	No increase in ozone concentration near line with one exception which was not repeatable

and ethylene (C_2H_4) react with ozone to emit light in proportion to the amount of ozone reacting. This chemiluminescence principle is the basis for a number of instruments currently being manufactured. Ozone absorbs a specific band of ultraviolet light. This characteristic has been developed into another technique for measuring ozone in a 1 or 2 ppb range.

Currently, there are at least ten manufacturers constructing ozone monitoring equipment based on the above principles. Each particular instrument will have certain advantages and disadvantages. None can be considered perfect. All are subject to interference by other gases or particulate matter to some degree. Suggested maintenance and servicing vary with the instruments, sensing components, and the sampling system. Accuracies of $\pm$ 2 ppb are claimed by the manufacturers, but only under ideal conditions such as might be obtained in the laboratory. Field experience has shown that instrument "A" does not always read the same as instrument "B"; it might read higher or lower depending on atmospheric conditions. Studies have been made to provide "correction factors" for certain instruments compared to the so-called prime standard. Yet these correction factors may not always be applicable to field measurements made at low ozone levels (10 - 80 ppb), because the instruments themselves can vary up to 8 ppb, when sampling a constant ozone supply.

Thus, short term studies of ozone concentrations near HV lines must be viewed with caution unless the instrument calibration and servicing record is fully documented. Composite studies, using several instruments of the same manufacturer, are valid and currently provide the only method of obtaining pertinent information. But because of these instrument inadequacies, values obtained in one study should not be considered absolute and compared with the so-called absolute values of another study.

4.3 Conclusions and Consolidation of the State-of-the-Art

It should be noted that the values predicted by both Scherer[1] and Roach[10] based on the laboratory measurements and diffusion analyses are in the order of 1 ppb or less for the transverse wind. Since the best measurement accuracy for the conducted field tests was in the order of 2 ppb, the more accurate theoretical predictions and measurement results to date are self-consistent.

During the workshop,* the question was raised as to whether additional measurements, such as exemplified in Table 2, should be made. The conclusion was that a repeat of past measurements would not provide any significantly new data. However, in lieu of such measurements, a program was necessary to place in perspective all factors relevant to ozone production by EHV lines. This program would examine existing data on ozone from all sources, specifically

*Identified in Section 1.0 of this report.

in terms of power-line generation. Secondly, it would consider the needs for refining the analytical procedures in terms of the unknowns previously discussed; and thirdly, it would identify the experimental and analytical program needed to resolve this area further both for existing and future transmission lines.

The question of improving existing measurement instrumentation was also raised during the workshop. It was concluded that no effort should be recommended for this program plan, since the problems with existing instruments are not unique to the power transmission area. What problems remain, however, could be better addressed in the context of the overall air pollution oxidant problem.

It should be noted that no published material was identified concerning ozone production for existing HVDC lines. Corona losses on ac transmission lines are usually expressed as a function of conductor surface voltage gradient.[20] Such a procedure, in addition to being convenient, seems justified in the case of HVAC lines because the air ions are confined to the immediate vicinity of the conductor. On the other hand, in the case of HVDC bipolar lines, the air ions may fill the interelectrode region around the lines. Consequently, it is not possible to characterize HVDC line corona losses, as is the case for HVAC, by the conductor surface voltage gradient alone[20] without inclusion of other parameters, such as line height and especially pole spacing.

Data presented by Sarma[20] shows that, for the same conductor voltage gradient, the corona loss is a strong function of pole spacing. The concentrations of the air ions are also influenced by the wind, and, consequently the corona losses and ozone production rates.

4.4 Research Program Plans for Ozone

4.4.1 Background

Environmentalists have long been concerned about the effects of high concentrations of ozone arising from various sources. These fears have been automatically extended into the power-line area without due consideration of the scientific basis for this extension or for published data. Some nonspecialists consider the present published data, which show that power lines do not generate measurable amounts of ozone, to be inadequate. However, a considerable amount of published data is available which shows that the power lines, as presently designed, do not make a significant contribution of ozone to the environment near ground levels. Consideration could be given to conducting additional measurements under a variety of meteorological conditions at different locations. This approach, however, would probably not allay the fears of the nonspecialists, since it would undoubtedly repeat results found for previous tests. What is needed is a program which examines existing data on ozone, both generally (from all sources) and specifically, in terms of power-line generation, and which places all pertinent factors in perspective.

4.4.2 Objective

The objective of this program will be to place in perspective all pertinent factors concerning the ozone generation mechanisms from non-power-line sources, as well as the possible ozone generation by power lines, and to delineate future work as required.

4.4.3 Tasks

This study would summarize past studies and measurements for power lines and, as well, the ozone generation and recombination data pertinent to non-power-line ozone situations. The reliability of existing data and scientific information on ozone sources, recombination rates, and meteorological factors would be carefully reviewed to determine where additional measurement studies or research should be conducted. Consideration should be given to the need for developing additional baseline data by means of routine or specially designed measurements of ozone on nearby existing power lines. The measurements associated with any special conditions which are pertinent either to validating conclusions developed during the study or to allaying the environmentalists' fears should also be considered.

Special problems, if any, associated with HVAC lines over one million volts, should be addressed. Field measurement problems and laboratory test and prediction techniques pertinent to HVDC lines would be considered, especially for HVDC lines for both bipolar and monopolar line designs.

Consideration would also be given to sources of ozone other than the conductors, such as from small gaps, on the basis of a preliminary problem definition.

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[16]M. Frydman, A. Levy and S. E. Miller, "Oxidant Measurements in the Vicinity of Energized 765 kV Lines." IEEE Trans. on Power Apparatus and Systems, 92 (May 1973), 1141-1148.

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ABSTRACT: This paper discusses some parameters governing the amount of the ozone generation in both positive and negative corona discharge. Under idealized test conditions with fixed wire size, etc., tests have shown that the negative polarity generally produces between 5 to 8 times as much ozone as the positive. However, exceptions to this do occur, particularly when the wire is dusty or nicked. It is shown that heating the corona wire will result in a reduction in the ozone generation per unit corona current irrespective of the polarity. A physical explanation is presented to explain the higher ozone generation normally found in the negative case compared to the positive. The presence of sharp nicks at the corona wire surface results in an appreciable increase in the ozone generation per unit corona current in positive corona but a decrease in the negative corona. In all these cases, it is found that the character of the discharge and the voltage drop in the vicinity of the discharge electrode are the major parameters governing the ozone formation in both positive and negative polarity.

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ABSTRACT: In late spring and continuing throughout the summer, concentrations of ozone in excess of 0.08 ppm are commonly found in rural areas of New York State. Widely separated rural sites measure similar ozone concentrations with very slight diurnal fluctuations. During episodes of high rural ozone concentrations, urban areas also experience high ozone peak concentrations, typically in the early afternoon. A transport and mixing hypothesis is made which interprets these urban ozone peak concentrations as primarily the result of the high background level of ozone and not local photochemical generation.

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Fern, W. J. and Brabets, R. I. "Field Investigation of Ozone Adjacent to High Voltage Transmission Lines." IEEE Transactions on Power Apparatus and Systems 93, no. 5 (September 1974), 1269-1281.

ABSTRACT: This paper describes a 19 month field investigation made during 1971 and 1972 by the IIT Research Institute for the Commonwealth Edison Company to determine if high voltage transmission lines generate measurable quantities of ozone.

Continuous ozone measurements made adjacent to a 345 kV switchyard with a high concentration of 345 kV and 138 kV transmission lines and adjacent to a 765 kV line were compared with continuous ambient measurements made at locations in the same areas but remote from the transmission line.

It is concluded from this investigation that high voltage transmission lines have no measurable effect on the ozone present in the atmosphere at ground level adjacent to the lines.

Frydman, M. "Production of Ozone from Energized Conductors." American Electric Power Report CL-92, 1972.

Frydman, M., Levy, A. and Miller, S. E. "Oxidant Measurements in the Vicinity of Energized 765 kV Lines." IEEE Transactions on Power Apparatus and Systems 92 (May 1973), 1141-1148.

ABSTRACT: This paper covers American Electric Power Service Corporation's extensive field-test program of detection of oxidants in the vicinity of energized 765 kV lines. As part of a program studying the production of oxidant in corona, tests were conducted in a variety of terrain configurations and climatic conditions. Oxidant-measuring techniques and criteria for selection of test locations are also described. Under the conditions of these tests, no measurable amounts of oxidants attributable to the presence and operation of the high-voltage installations were detected.

Frydman, M. and Shih, C. H. "Effects of the Environment on Oxidants Production in AC Corona." IEEE Transactions on Power Apparatus and Systems PAS-93 (January/February 1974), 436-443.

ABSTRACT: This paper discusses American Electric Power Service Corporation's laboratory and analytical work on the production of oxidants in AC corona. The test program was oriented toward determination of the production rates of oxidants (mainly ozone) in a broad range of temperatures and humidities, and at a variety of surface gradients.

The test results clearly show that the production rate of oxidants generation is in the neighborhood of 2 g/kWh (1 lb/227 kWh) under standard laboratory conditions, and decreases consistently with the increase of temperature and humidity.

Finally a series of equations was derived which describes the oxidants production rates as a function of temperature and humidity.

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ABSTRACT: With the development of EHV systems, research was necessary to identify and measure the amounts of ozone which potentially could emanate from the corona discharges of EHV transmission lines. The paper reviews the laboratory measurements performed in two high voltage laboratories.

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ABSTRACT: The generation of ozone from the corona wires used in various applications where electric charging is necessary (such as in: electrostatic precipitators, electrophotography, mineral separation, etc.), can be excessive and an attempt has been made to reduce the ozone concentration using a heated corona wire. The study was carried out for positive corona which is normally used in indoor applications where the ozone levels must be kept within safe limits. By operating the positive corona wire at temperatures to 600 degrees k it was observed that the ozone concentration was reduced by 80% from the ambient case for the same corona current. It was similarly observed that the corona discharge processes commenced at a reduced onset voltage with a heated corona wire.

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ABSTRACT: A seven-week program of field measurements was carried out between August 4 and September 25, 1972 to investigate the source of high ozone concentration in the vicinity of Garrett County, Maryland and Preston County, West Virginia. Approximately 11 percent of the hourly ozone concentrations measured at the Garrett County Maryland Airport exceeded the 0.08 ppm National Air Quality Standard. In one episode of high ozone concentration, the Standard was exceeded for 26 consecutive hours. The mean hourly ozone concentration for the study period was 0.057 ppm and the maximum hourly concentration was 0.119 ppm. High ozone concentrations persisted through the night; the nighttime mean was 0.055 ppm. Nitrogen dioxide and nonmethane hydrocarbon concentrations were at or near background levels throughout the study period. It was concluded that local photochemical synthesis could not account for the observed high ozone concentrations in the study area. Analysis of meteorological data indicated that the high ozone concentrations were associated with air masses arriving in the study area after passing over urban-industrial regions.

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ABSTRACT: This paper presents wind-tunnel measurements of ozone and NO_x production rates for single and bundle transmission line conductors in dry and wet corona. Ozone production rates reported in the literature for transmission line and fine wire corona, together with the authors' results are summarized as a function of the maximum surface gradient factor. Numerical calculations estimating the ozone levels near actual 775 kV test transmission lines at the Apple Grove 750 kV Project are presented. It is concluded that pollutant concentrations generated by conductor corona on present EHV transmission lines are too low to be deleterious to the environment.

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ABSTRACT: The generation of gaseous effluents as a result of corona activity on EHV transmission lines has been raised as an environmental issue. This paper discusses analytical, laboratory and field measurement work performed by and for the American Electric Power Service Corporation that clearly shows that no environmental problem exists. A companion paper discusses the field measurement program in greater detail.

Sebo, S. A., et al. "Examination of Ozone Emanating from EHV Transmission Line Corona Discharges." Paper no. F75 510-8 presented at the IEEE PES Summer Meeting in San Francisco, California (June 20-25, 1975).

ABSTRACT: With the development of EHV transmission systems, research was necessary to measure the amounts of ozone which could potentially emanate from the corona discharges of EHV transmission lines under dry conditions and in the presence of light or heavy rain.

The paper reviews experiments performed in two high voltage laboratories. Three cages and seven conductors (solid and stranded, single and bundle arrangements) were used for dry and wet experiments. About 1300 test points were obtained encompassing a wide range of voltage gradient and corona loss values. Qualitative and quantitative analyses were conducted. Measuring equipment and experience were discussed.

Investigations show that the overall average ratio of corona loss to ozone production was about 0.52 kWh/g of O_3 (235 kWh/lb of O_3), based on all of the experiments.

Long-term field tests were conducted and an experimental measurement program extending several months before and after energization of a 765 kV line was carried out.

All of the laboratory and field examinations confirmed that the ozone levels and production rates within the actual operating voltage gradient and corona loss retion were very low, and the ground level ozone concentrations due to EHV transmission line corona were indistinguishable from ambient ozone concentrations.

Sebo, S. A. *et al.* "Measurements of Effluents Due to EHV Transmission Line Corona, II--Laboratory Tests." *Conference Record of the Canadian Communications and EHV Conference of the IEEE* 72-CHO-698-1 (November 1972), 164-165.

ABSTRACT: With the development of EHV systems, research was necessary to identify and measure the amounts of ozone which potentially could emenate from the corona discharges of EHV transmission lines. The paper reviews the laboratory measurements performed in two high voltage laboratories.

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ABSTRACT: High ozone concentrations, often in excess of the national ambient air quality standard for photochemical oxidants, have been measured simultaneously in urban and rural areas of New York State. Average daily rural ozone concentrations were found to correlate well with daily maximum urban ozone concentrations suggesting a common source. Estimations of the quantity of ozone advectively transported into New York State are more than an order of magnitude greater than estimations of the potential photochemical generation of ozone from hydrocarbon emissions within New York State. It is suggested that the high rural ozone levels are not primarily due to the transport of ozone and ozone precursors from other urban areas, but are rather due to natural phenomena such as photochemical generation from naturally occurring precursors or transport of ozone from the stratosphere to the troposphere. The effectiveness of a hydrocarbon control strategy for New York State to meet the ambient air quality standard for photochemical oxidants when background levels themselves may be above the standard is questioned.

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Whitmore, F. C. and Durfee, R. L. "Determination of Corona Ozone Production by High Voltage Power Lines." U. S. Environmental Protection Agency Report PB-229 994/9, November 1973.

ABSTRACT: A sub-scale simulation of a high-voltage transmission line was constructed and operated in a chamber roughly 1.5 meters long by 0.5 meter in diameter to determine ozone production characteristics. Effects of voltage and corona power, conductor size and surface condition, air temperature, relative humidity, and air flow rate (wind velocity) on ozone yield were determined. Of these, corona power (voltage), relative humidity, and air flow rate exhibited significant effects on ozone yield. Average yield values ranged from about 3 gm/kw-hr at high humidity (75-80 percent) to about 7 gm/kw-hr at low humidity (25-30 percent).

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5. ELECTRIC AND MAGNETIC FIELD COUPLING EFFECTS

5.1 Introduction

This appraisal of the state-of-the-art begins with a discussion of the more general considerations pertinent to both HVAC and HVDC lines. These considerations include the non-power-line and power-line electric and magnetic environments, future transmission systems, conversion of electric and magnetic fields into voltages and currents, and safe levels for such voltages, currents or discharges. This discussion is followed by separate sections which treat the factors unique to: 1) HVAC electric field effects, 2) HVAC magnetic field and earth current effects, and 3) HVDC electric field effects. The appraisals are then followed by a summary discussion and the programs recommended for these areas.

5.1.1 Units of Measure

The magnetic and electric fields from transmission lines are considered as separate and variably related entities, since the near, nonpropagating fields are dominant. The term "electromagnetic" is used here in its more common meaning which encompasses all electric and magnetic field phenomena--static electric and magnetic fields, interrelated ac fields and propagating waves. The electric fields, either dc (static) or ac (time-varying) are discussed in terms of the electric field intensity or voltage gradient in volts per meter (V/m) or kilovolts per meter (kV/m). The magnetic fields, either dc (static) or ac (time-varying), are discussed in terms of the flux density, usually stated in the familiar and still widely used term, gauss; however, the MKS units will be employed jointly for graphs. The magnetic field intensity in air that is necessary to produce one gauss is measured as one oersted or about 80 amperes/meters in the MKS unit system. To convert gauss to Webers/m^2 or Teslas, multiply gauss by 10^{-4}. For more details on the usage of terms, reference to any number of modern textbooks[1] on electromagnetic theory is suggested.

5.1.2 Ambient Non-Power-Line Environments

The most familiar naturally occurring field is the earth's steady-state or direct current magnetic field, which has a value of about 1/2 gauss. Superimposed on this field are much smaller low-frequency variations called micropulsations.[2]

The naturally occurring dc electric field of the earth is less well known, but can attain very significant and large transitory values.[2] 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).

The static dc fields are greatly affected by the presence of air ions. These are, therefore, of importance when considering fields from HVDC lines. Natural sources of air ionization near the ground are from nuclear radiations from radon and thoron gases.[2] At higher altitudes, the ionization arises from the ultraviolet and shorter wavelength radiations from the sun.

Another non-transmission line, static-type ambient environment is the small-arc discharge or "carpet shock". This is important to place in perspective some of the electric field effects from transmission lines. 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.[3] 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,[4] and have caused explosions in hospitals during anesthesia where combustible gases are present.[5,6] 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.

In the case of power-line frequencies, the non-power-line, man-made sources make the more significant substantial contributions to the 50/60 Hertz electric and magnetic field environment either in the home or industrial areas. Table 1 summarizes some measurements made of the electric field intensity near household appliances.[7]

TABLE 1

60 Hz ELECTRIC FIELDS
IN THE VICINITY OF ELECTRICAL APPLIANCES
(The measurements were made at a distance of 30 cm from appliances.)

Appliance	Electric Field (volt/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

Note that field intensities in the order of 250 V/m occur at some 30 centimeters distance from the electric blanket. The field intensity exposures are probably greater next to the blanket itself. The man-made 60 Hertz magnetic field environments are summarized in Table 2.[7]

TABLE 2

LOCALIZED 60 Hz MAGNETIC FLUX DENSITIES
PRODUCED BY SOME 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

0.01-1.0 Gauss

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

5-10 Gauss

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

0.01-0.1 Gauss

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

0.001-0.01 Gauss

Refrigerator

Note that the strong fields greater than 1 gauss only occur close to typical household appliances. However, 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.

In industrial situations, both the electric and magnetic field can exceed the intensities shown in Tables 2 and 1 in the working areas, although the strongest fields occur only in the immediate vicinity of the source equipment. Typical high level sources, such as buses, cables, transformers, and machinery, are found where large amounts of electrical energy are transferred (such as substations) or are consumed (such as an aluminum reduction plant).

5.1.3 Transmission Line Electric and Magnetic Field Environments

5.1.3.1 HVAC Lines

The electromagnetic fields produced near and within the ground by the HVAC lines are discussed in terms of the three primary environments: 1) vertical electric fields, 2) magnetic field, and 3) horizontal electric field. These environments are considered, and typical electromagnetic field values are given, in the sections below.

HVAC Vertical Electric Fields

Voltages applied to the phase wires of the overhead transmission line creates a time-varying charge distribution on the conductors. The presence of these charges creates an electric field which influences the position of charges on nearby conductors. The vertical electric fields produced by HVAC overhead transmission lines at and near the surface of the earth have been measured as well as calculated for various line heights and line voltages. Generalized methods are available[8] which allow this vertical electric field to be calculated for several common transmission line configurations. Computer assisted calculations based on rigorous field theory which agree well with actual measurements have also been made. Such approaches can include line sag, tower and ground conductivity effects.[9] While actual fields are a complex function of line geometry--height, size and separation of conductors--only a few examples of fields from HVAC lines will be given, since this area is well understood.

Figures 1, 2 and 3 give the measured vertical electric fields under a 60 Hz, 765 kV, and a 345 kV power transmission line. These figures are adopted from a recent project[10] at IITRI.

In the single circuit transmission lines of these figures, it is seen that the maximum value of vertical electric fields occurs in the region midway between the towers, near or under the outside phase wires of the lines. For the measured fields under the 765 kV lines, this maximum field was approximately 8.5 kV/m.

HVAC Magnetic Field

The currents flowing in the phase wires generate a magnetic field; and, because of phase difference in the respective currents, the orientation at the magnetic field, rotates in space. This magnetic field vector at a point near a three-phase transmission line is proportional to the line current and rotates in space at a 60 Hz rate. As the vector rotates, the amplitude of the magnetic field in a given direction changes. The 60 Hz magnetic fields measured under a 765 kV and a 345 kV line at a height of approximately 1.5 meters above the ground are shown in Figure 4 and 5.[10] In these figures, the "vert" refers to the vertical magnetic field component in a direction perpendicular to the transmission line, and "B horz. par." is the horizontal magnetic field component which is parallel to the direction of the transmission line.

ELECTRIC FIELD MEASURED UNDER 765KV TRANSMISSION LINE

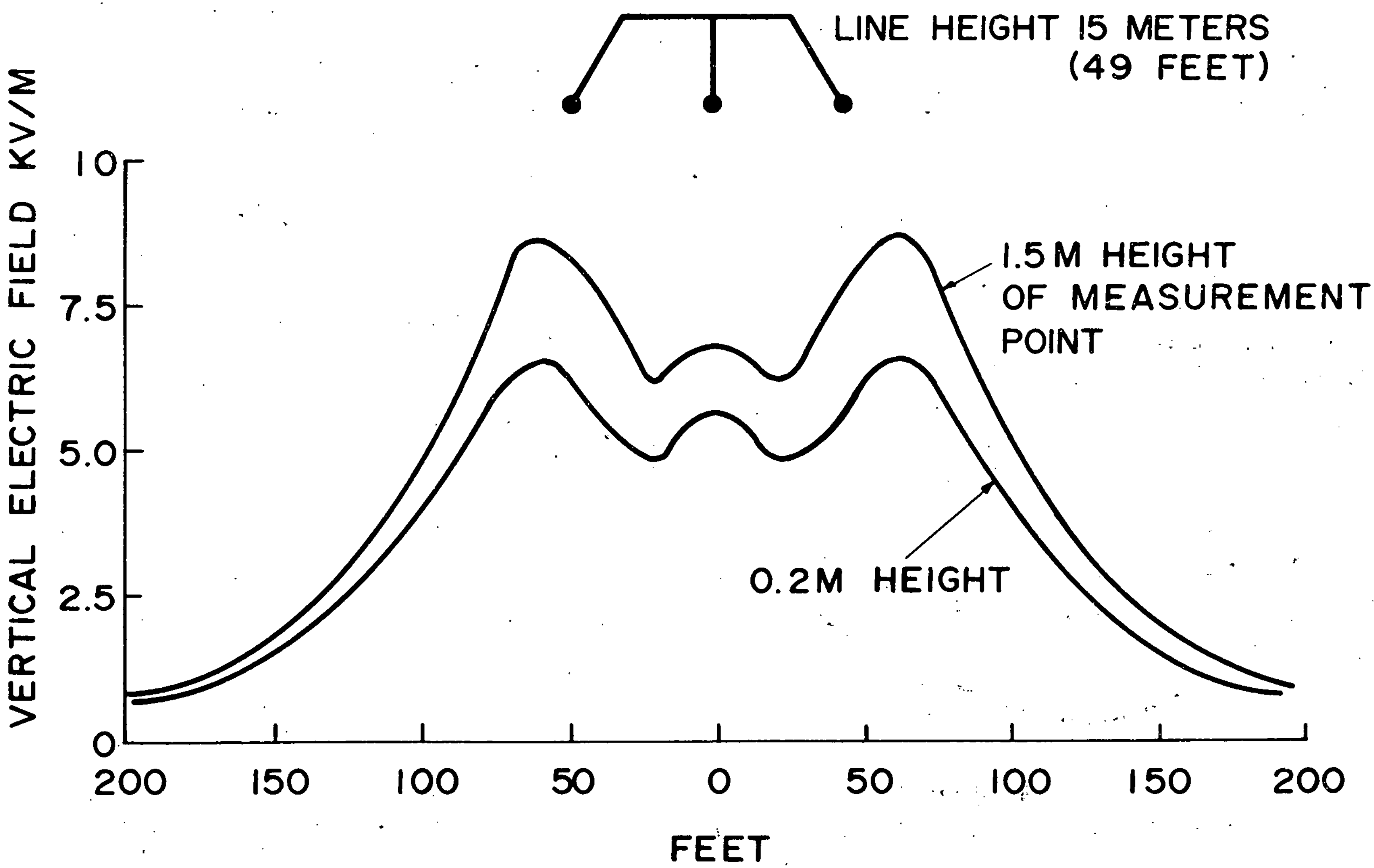

Fig. 1

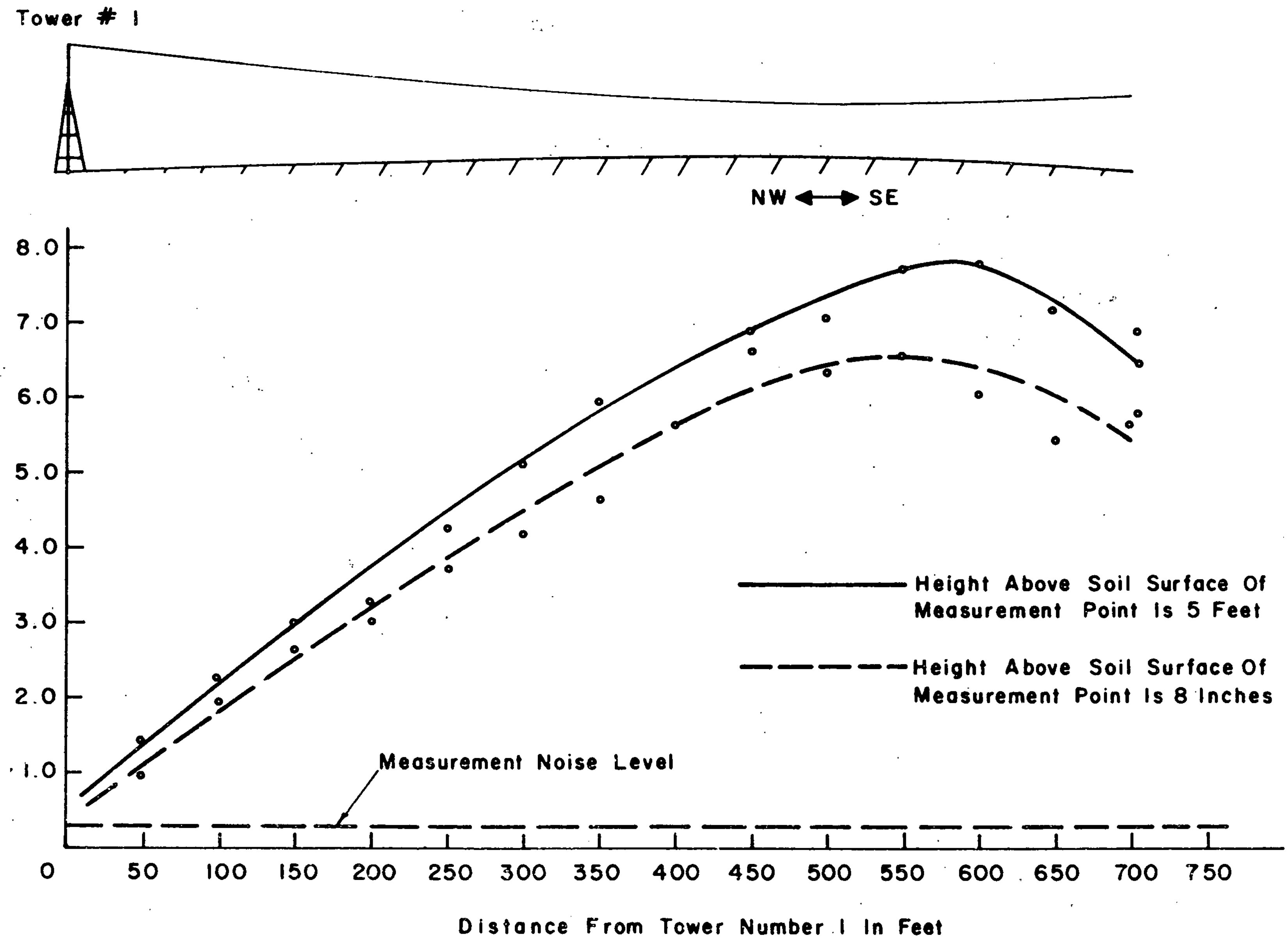

Fig. 2 VERTICAL E FIELD UNDER CENTER PHASE OF 765 kV LINE

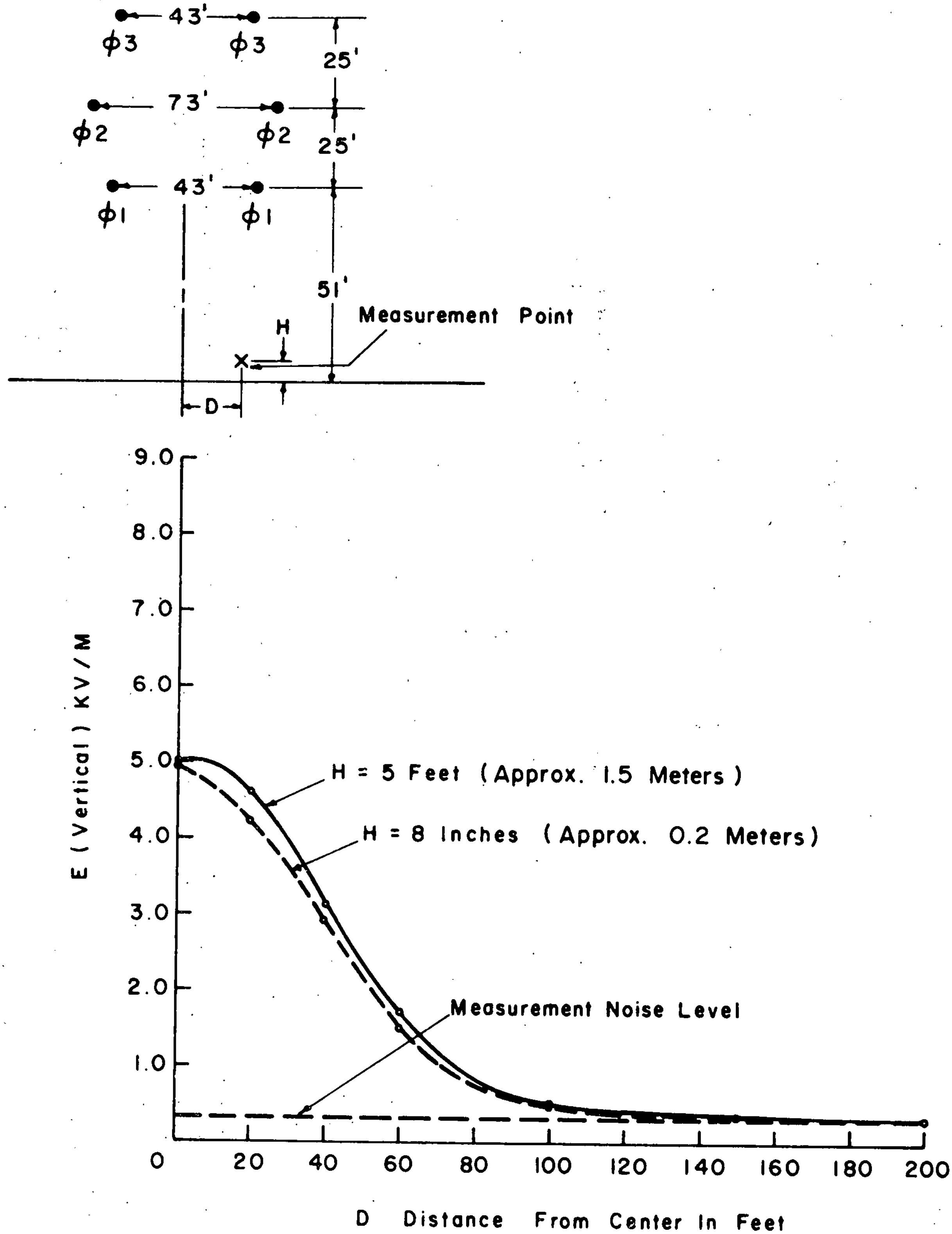

Fig.3 VERTICAL ELECTRIC FIELD MEASURED UNDER A 345 KV DOUBLE CIRCUIT LINE.

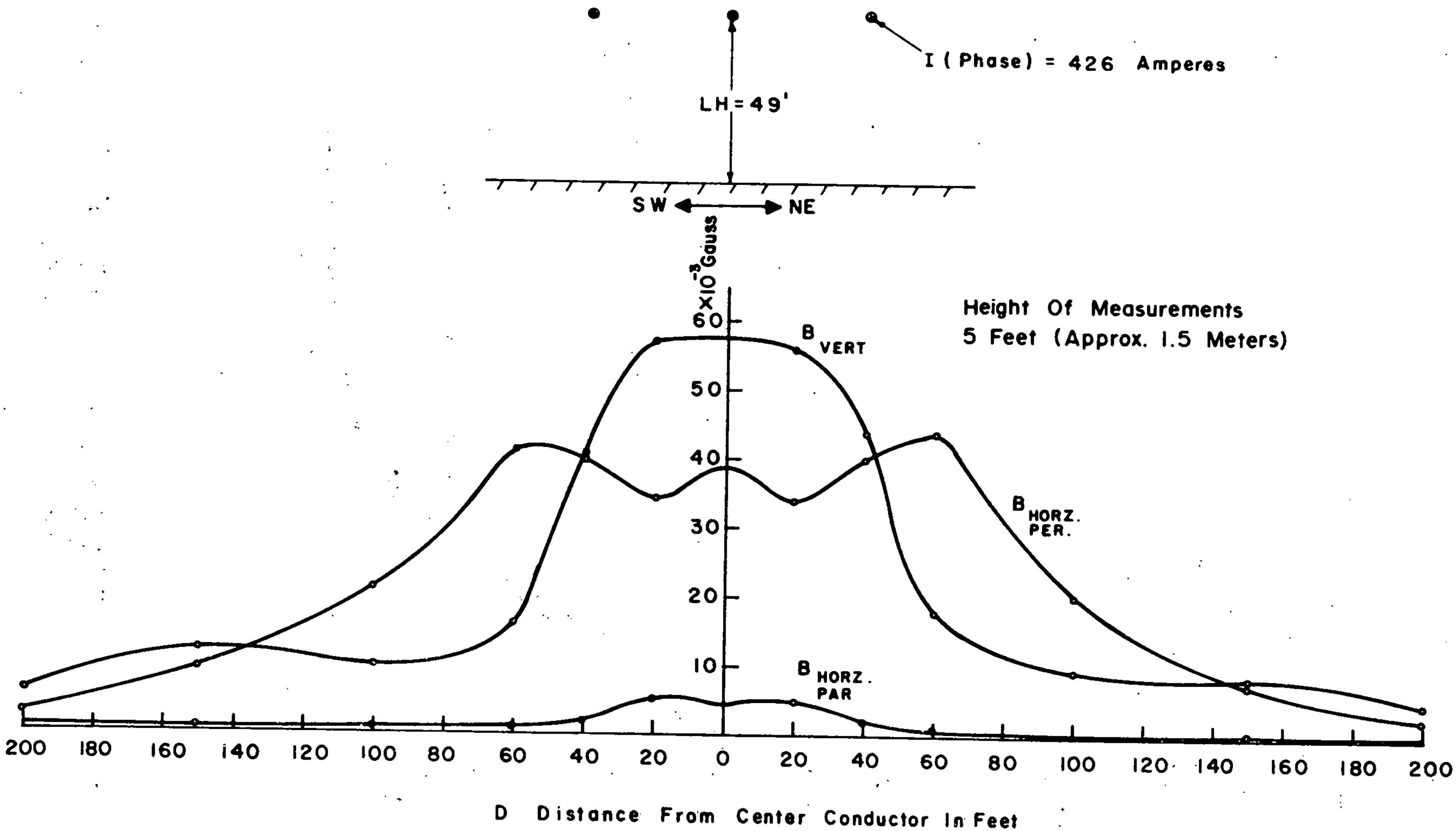

Fig. 4 PROFILE OF THREE MAGNETIC FIELD COMPONENTS UNDER A 765 KV LINE FOR A LINE HEIGHT OF LH = 49 FEET (APPROX. 15 METERS)

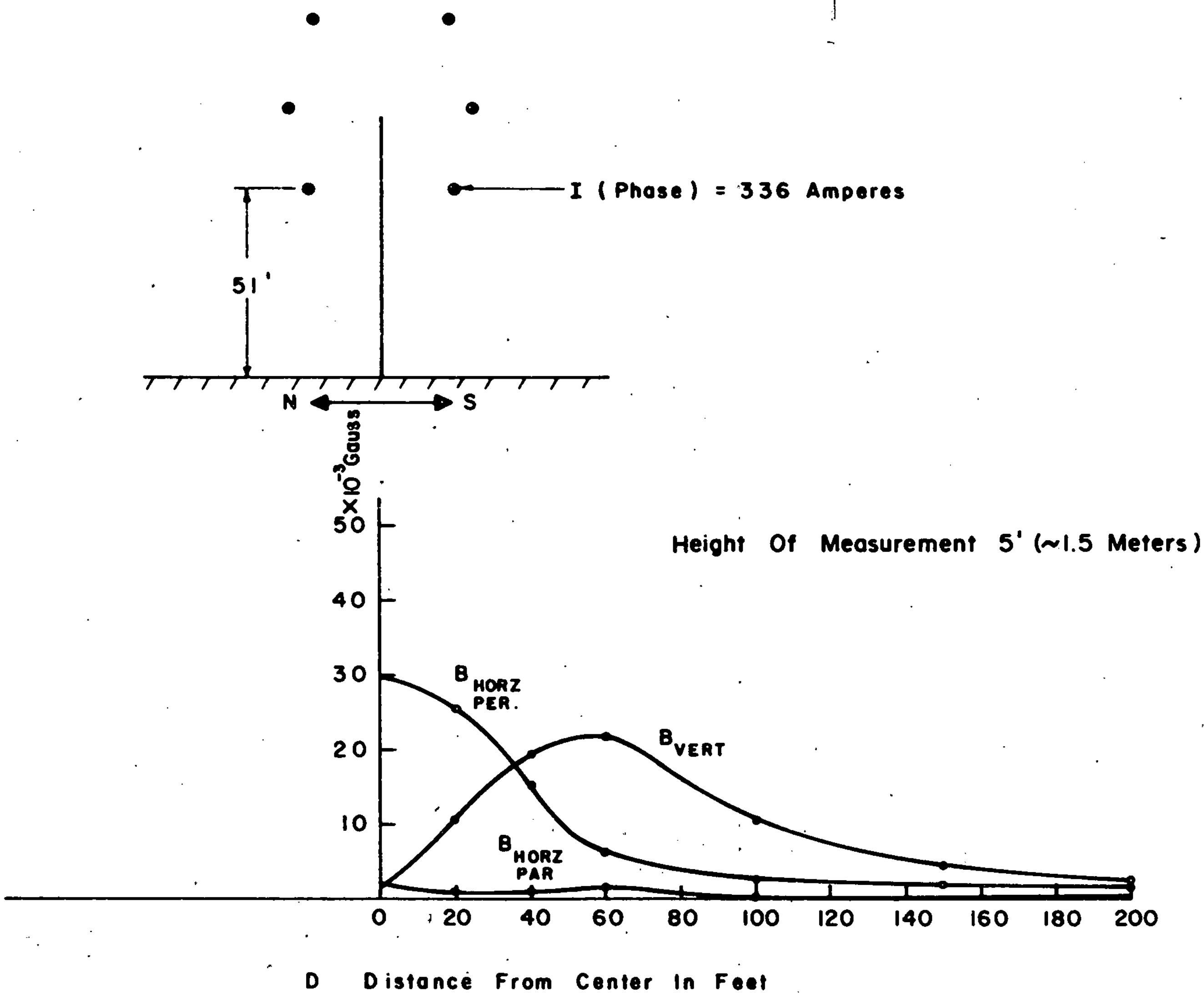

Fig. 5 PROFILE OF THREE MAGNETIC FIELD COMPONENTS UNDER DOUBLE CIRCUIT BRANCH LINE FOR A LINE HEIGHT OF 51 FEET (APPROX. 15.5 METERS)

The line current shown in Figure 4 does not represent a full load current. This current would normally be in the 1000 to 2000 ampere range and could be higher. For these currents, and with the line height decreased to 13.7 meters, the approximate magnetic field strength under the center phase of the 765 kV line is shown in Table 3.

TABLE 3

APPROXIMATE MAGNETIC FIELD UNDER CENTER PHASE OF 765 kV LINE

Line Height = 45 Feet (13.7 meters)

Height of Measurement Above Ground = 1.5 Meters (5 Feet)

Current in One Phase of 765 kV Line	Magnetic Field Strength
1000 Amperes	0.155 Gauss
2000 Amperes	0.310 Gauss

The line height of 13.7 meters is the height at the point where the line sags closest to the ground. Sixty Hertz magnetic fields of approximately one-third gauss can be produced at ground level.

Rigorous field theory can be applied to compute the magnetic field vector near HVAC lines. Simplified generalized curves for the magnetic field, such as are available for electric field calculations,[8] have yet to be developed in handbook format.

HVAC Horizontal Electric Field at Surfaces of Ground

Electric fields exist in the earth beneath power transmission lines. Some measurements of the horizontal components of these 60 Hz electric fields have been made, and Tables 4, 5 from ref. 10 and 6 from ref. 7 summarize this data. The horizontal electric fields in the ground are developed from currents flowing in that ground. These currents arise from three sources: 1) unbalanced, harmonic and fault currents through power system earth counterpoises; 2) displacement currents collected by the ground from the time-varying electric field; and 3) eddy currents induced in the soil by the time-varying magnetic field.

The methods to predict these ground potentials for idealized distributions of ground conductivity and permittivity were developed in the late 1920's and over the 1930's. These developments are summarized by Sunde[11]. The practical thrust of this effort was to investigate grounding related and inductive interference as might be experienced by a telephone line from fields generated by power lines. Also of interest is the computation of induced currents on pipelines to estimate corrosion problems. Simplified methods for realistic situations to calculate field intensities and currents in earth as related to overhead transmission lines remain to be developed for handbook application. Interference into other utilities and related situations, such as common use of rights-of-way, are not considered in this plan.

TABLE 4

HORIZONTAL ELECTRIC FIELDS AS MEASURED AT THE SURFACE OF THE GROUND UNDER THE CENTER PHASE OF A 765 kV LINE

(For Line of Fig. 6 Carrying About 430 Amperes/phase)

Line Height at Location of Measurement	Electric Field Parallel to Line	Electric Field Perpendicular to Line
feet	millivolts/meter	millivolts/meter
49	23	4.0
61	23.5	5.5
79	21	3.25

TABLE 5

HORIZONTAL ELECTRIC FIELDS AS MEASURED AT THE SURFACE OF THE GROUND UNDER THE CENTER OF A 345 kV DOUBLE CIRCUIT LINE

Distance from Ground to Lowest Conductor of Transmission Line	Electric Field Parallel to Line	Electric Field Perpendicular to Line
feet	millivolts/meter	millivolts/meter
51	33.5	2.75

TABLE 6

HORIZONTAL ELECTRIC FIELDS AS MEASURED AT THE SURFACE OF THE GROUND

Location	Electric Field Intensity
	volt/meter
138 kV Line, 66 Amperes (Chicago, Illinois)	0.01
345 kV Line, Two 155 kV Lines (New London, Conn.)	0.01-0.12 0.25-0.59
530 kV Line, 510 Amperes (Portland, Oregon)	0.014
500 kV Line, 300 Amperes (Portland, Oregon)	0.015
Electric Rail Lines, 25 Hz (New England)	0.002-0.11

5.1.3.2 HVDC Transmission Line Environments

The basic understanding of the electric fields from HVDC lines is not as well developed as for HVAC lines, and additional refinement is desirable. The major complicating factor in this understanding is the presence of air ions generated by corona, which modifies the conductivity of the air in the vicinity of the HVDC line. The presence of the unidirectional fields causes movement of the air ions toward oppositely polarized conductors. In the case of ac, it is believed that the periodic reversal of polarity tends to prevent the air ions from leaving the vicinity of the conductor or corona source. For the dc case, a distribution of charges in space is formed near the line which controls the electric field. The spatial distribution of the electric field can be affected by meteorological conditions, such as by the wind imparting an additional velocity bias to the air ions.

Figure 6 presents some preliminary data on the measured electric field[12] from a HVDC line for two different meteorological and line voltage conditions. Note the spatial shift in the observed measurements--which is probably introduced by low velocity movement of air from the positive to negative conductors. The data is considered preliminary because details of the measurement instruments have not been published or discussed in the available literature.

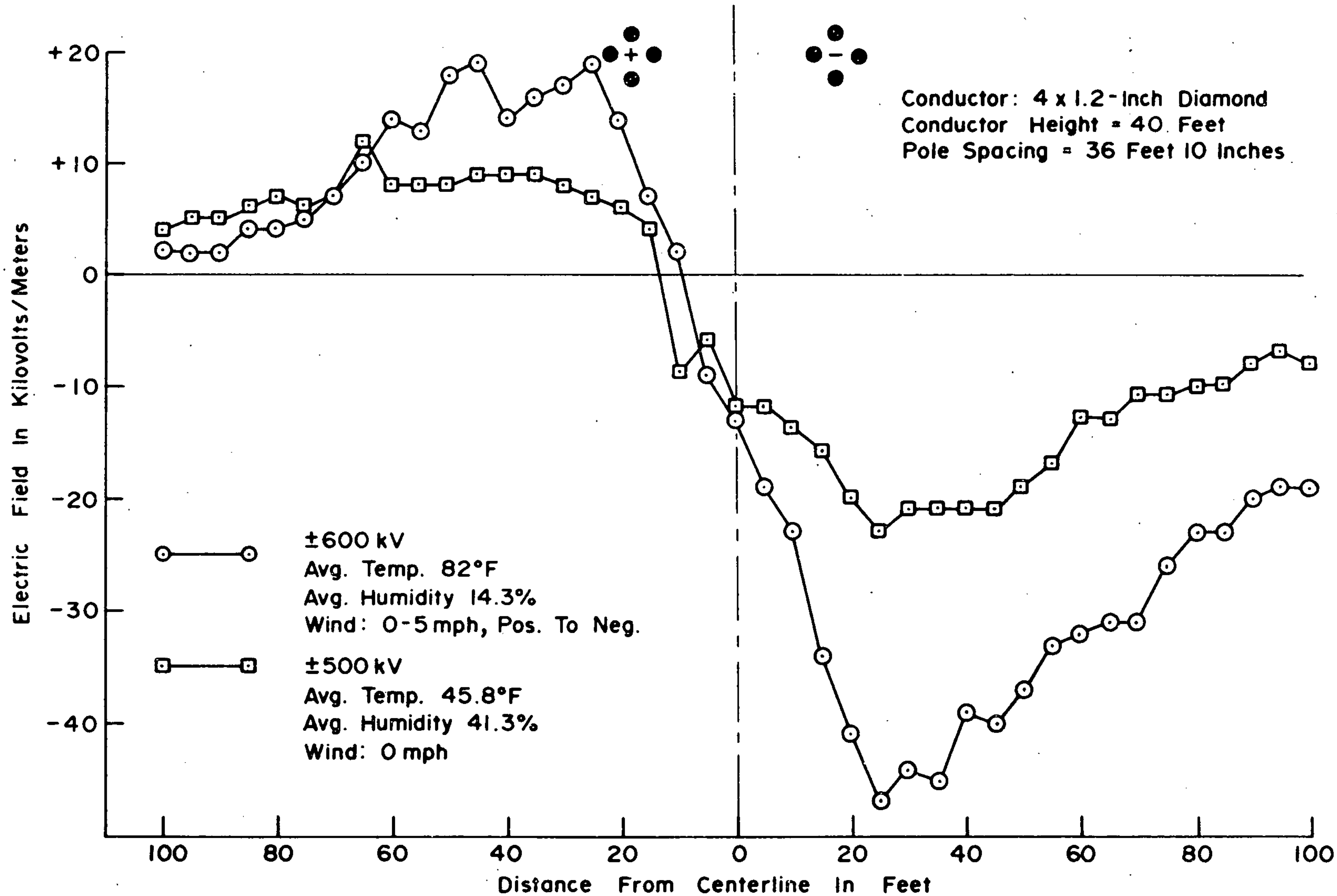

Fig.6 ELECTRIC FIELD PROFILES AT ±500 kV AND ±600 kV IN TEST LINE SECTION 2

A simplified approximate theory[13,14,15,16,17] is available which can be used to predict the long-term average electric field strengths. Figure 7 shows a comparison of the results developed by the approximate analysis[12] and average measurement results for static wind conditions.

5.1.3.3 Future Transmission Systems

There is a clear trend toward high operating voltages; operating voltages in excess of 1,000 kV are being considered for future systems. The general environment produced by these lines will be comparable to those shown earlier. However, the specific magnitudes may vary depending on conductor geometry, line spacing and height, and operating voltages or currents. The use of "shield wires" below the phase wires is currently being considered on one of the tasks at Project UHV, and has been considered previously by experimenters at Apple Grove, and elsewhere. The objective is to reduce electric field strength to some predetermined level while maintaining a better balance between other operating parameters and construction cost trade-offs. Closer spacing of conductors and special geometrical arrangements for multiple circuit lines are also being considered to reduce the field intensities at ground level.

Large magnetic field environments in the immediate vicinity of future underground cables are possible. These cables are likely to carry large magnitude ac or dc currents. These cables will probably be cooled or even operated at temperatures where the cables are superconducting. The

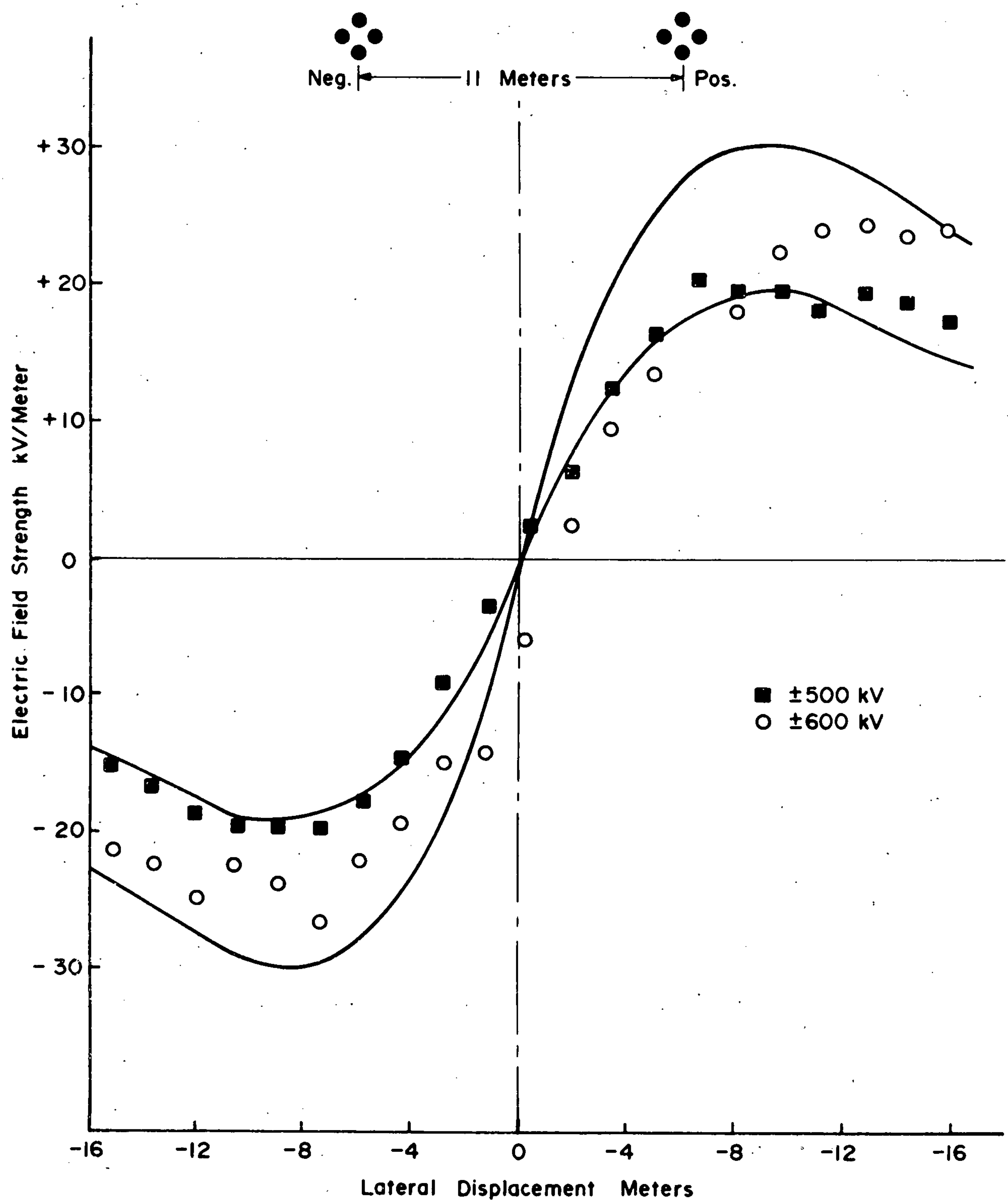

Fig.7 COMPARISON OF CALCULATED AND MEASURED FIELD STRENGTHS UNDER FOUR 1.2 INCH BUNDLE CONDUCTORS WITH LINE-TO-GROUND CLEARANCE OF 40 FEET.

magnetic fields from these cables can be of very large and significant levels if the cables do not employ magnetic field shielding. In terms of present planning, the cryogenically-cooled resistance-reduced lines may or may not employ shielding. The superconducting ac lines that are to be shielded will employ a superconducting outer coaxial shield. Shielding plans for dc superconducting lines are somewhat indefinite at this point, but shielding may be required for efficiency.

Representative environments pertinent to these future systems are not known; and, therefore, program plans for this new technique are not considered. It should be noted, however, that if the on-the-ground or buried cables are not shielded, strong magnetic field levels in excess of one gauss are possible in the immediate vicinity of the cable. These strong magnetic field levels might then create unique environmental situations as yet unassessed.

5.2 Coupling and Effects

5.2.1 Introduction

Electric and magnetic field coupling effects generally arise from a transfer of energy or power from an energized transmission line to some other partially or fully conducting object, animal or system, such as a fence, pipeline, automobile, or adjacent parallel low-voltage transmission line. In most cases, this energy transfer is of little concern unless it triggers or enhances some other often overlooked phenomenon, such as explosions, corrosion or physical shocks.

These effects can be grouped into three major categories in terms of their dominant coupling modes as follows:

1. Capacitive coupling via displacement currents and related ac electric fields;
2. inductive coupling via the ac magnetic fields;
3. conductive coupling via ac or dc ground currents and, in the case of HVDC lines, conduction currents via air ions.

In many cases, coupling can usually arise from two or more of the above modes, especially for larger distributed conducting metallic systems, such as a lower voltage transmission line paralleling an energized high voltage line.

There are a number of situations in which an electrified conducting object is of interest. One situation involves mobile collectors, such as humans, animals, automobiles, farm machinery, irrigation piping or construction equipment, and the other situation involves fixed conducting installations, such as fences, metallic features in nearby buildings, antenna towers, or adjacent transmission lines. Special situations also arise during the construction of new transmission lines, pipelines, or metalwork near energized lines.

Summary of Possible Effects

Electric field effects fall into two broad areas: 1) direct effects on humans, animals and plants; and 2) indirect effects via modification of the field into currents and voltages by conducting objects. The direct effects of electric fields have been considered in detail during a companion EPRI sponsored project[18] and will not be discussed further. In this report, the indirect effects of the fields, expressed in terms of voltages and currents, are of prime interest; and these will be discussed in terms of both biological and non-biological effects. The human considerations include both perceptual (such as annoyance or pain) and hazardous aspects (such as muscle paralysis by electric currents). Other important considerations deal with possible, yet highly unlikely, fire or explosion hazards.

The direct biological effects of voltages and currents have been considered in the context of electrical apparatus rather than with specific environmental situations found at ground level near high-voltage transmission lines. The effects are discussed in terms of body currents which may be either steady-state (such as a continuous 60 Hertz current flowing through the body) or transient (such as the rapid discharge of a capacitor through the body). The effects have been classified as either primary or secondary, but agreement about how these classifications are defined seems to be lacking. A simpler categorization might be: 1) psychological--simple perception, annoyance, and pain; 2) reversible physiological--involuntary reflexes such as inability to release a clasped current-carrying conductor; and 3) potentially irreversible physiological--burns or ventricular fibrillation. Numerous publications on the ranges of values related to these effects have been made. Table 7 is a summary of recently published data summarized by the IEEE

TABLE 7

BIOLOGICAL EFFECTS THRESHOLDS FOR BODY CURRENTS AND SHOCKS

Current Criteria[19]

	Current in Milliamperes			
	Direct Current		60 Hertz RMS	
Effect	Men	Women	Men	Women
1. No sensation on hand	1	0.6	0.4	0.3
2. Slight tingling. Perception threshold	5.2	3.5	1.1	0.7
3. Shock--not painful and muscular control not lost	9	6	1.8	1.2
4. Painful shock--painful but muscular control not lost	62	41	9	6
5. Painful shock--let-go threshold	76	51	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	1000	1000
b) Shock duration 3.0 sec	500	500	100	100
c) Certain Ventricular fibrillation (if shock duration is over one heart beat interval)	1375	1375	275	275

Energy Criteria

Skin burn	0.8 Joules/cm^2	(ref. 20)
Involuntary Reaction	0.25 Joules	(ref. 20)
Ventricular Fibrillation	25-50 Joules	(ref. 19)

Working Group on ES and EM Effects[19], and the involuntary reaction and burn data from an AEC publication.[20]

Some limited data has also been developed[8] on the psychological effects, some as a result of the IEEE sponsored field days.[21]

Possible non-biological effects include improbable fires or explosions. Direct 60 Hertz or harmonic interference into other utilities--pipelines, communications circuits or railway signaling--are long recognized problems which are understood. Obscure changes in non-power-line technology may introduce potential problems in critical installations, near power lines.

Ongoing Efforts

The efforts at Project UHV are directed toward advancing transmission operating voltages into the 1500 kV range. Results to date were recently published in the "Transmission Line Reference Book, 345 kV and Above"[8] for HVAC lines. Currently, Bonneville Power Administration (BPA) is completing a final report on research for HVDC lines. IREQ (Institut de Recherche de l'Hydro-Quebec) is undertaking a related program concerning very high voltage dc lines. IIT Research Institute is undertaking the development of material on the coupling effects of HVAC lines into gas pipelines. All of the above programs are sponsored by at least in part EPRI. The National Bureau of Standards, under ERDA sponsorship, is developing a facility to evaluate and calibrate power frequency field intensity measurement equipment. To insure consistent measurement of the electric field, EPRI recently conducted a workshop which resulted in a recommended E field measurement reporting format.

Other programs are underway to measure field intensities or coupling effects unique to specific lines either existing or proposed. Examples of these are the measurement and evaluation program by the EPA of the U.S. Government, by IITRI for Commonwealth Edison, and by Westinghouse in support of the hearings being held before the New York State Public Service Commission, concerning a proposed EHV line.

The IEEE Working Group on ES and EM Effects of the Power Engineering Society is a professional group with a continuing interest in this area. This group has published position papers[19,22] on electric and magnetic field coupling problems and has sponsored "field days" at high voltage test line facilities to demonstrate various coupling effects and to collect preliminary data.[21] This group has also supplied guidance on the consideration of electric field effects in power line clearance requirements.[19]

5.2.2 HVAC Coupling and Effects

5.2.2.1 Basic Coupling Mechanisms

Basic Electrification Mechanisms for HVAC Lines

When ac voltages are applied to phase wires, a time-varying charge distribution on the phase wires is created. This charge distribution generates electric fields in the vicinity of the overhead transmission line. These time-varying fields cause related charge distribution changes or current flows on nearby conducting objects. These changes cause currents and voltages to appear on the conducting objects.

This phenomena is well understood and has been treated on both rigorous and practical basis.[9,19,21,22,23,24] Simply speaking, any conducting or partially conducting object, either an animal or vehicle, intercepts a certain amount of the "displacement current" or capacitively coupled current flowing between the phase wires and ground. If the object is insulated from ground, it will also tend to develop some potential with respect to ground, depending on the impedance of the insulator to ground.

From these considerations, a Thevenin or Norton equivalent circuit can be developed as shown in Figure 8. These models will then be discussed within the context of additional research requirements. In Figure 8, only the parameters which can be calculated are shown. V_{oc}, I_{sc}, and C_a are complex functions of the geometry of the conducting objects with respect to the transmission line.

V_{oc} is the open circuit voltage of the Thevenin equivalent circuit, and I_{sc} is the related Thevenin equivalent short circuit current. C_a and R_a represent the source impedance of the Thevenin equivalent as parallel connected lumped parameter elements.

If the size of the object is small compared with the height of the transmission line, and is near the ground, the value of V_{oc} is roughly proportional to the average height.

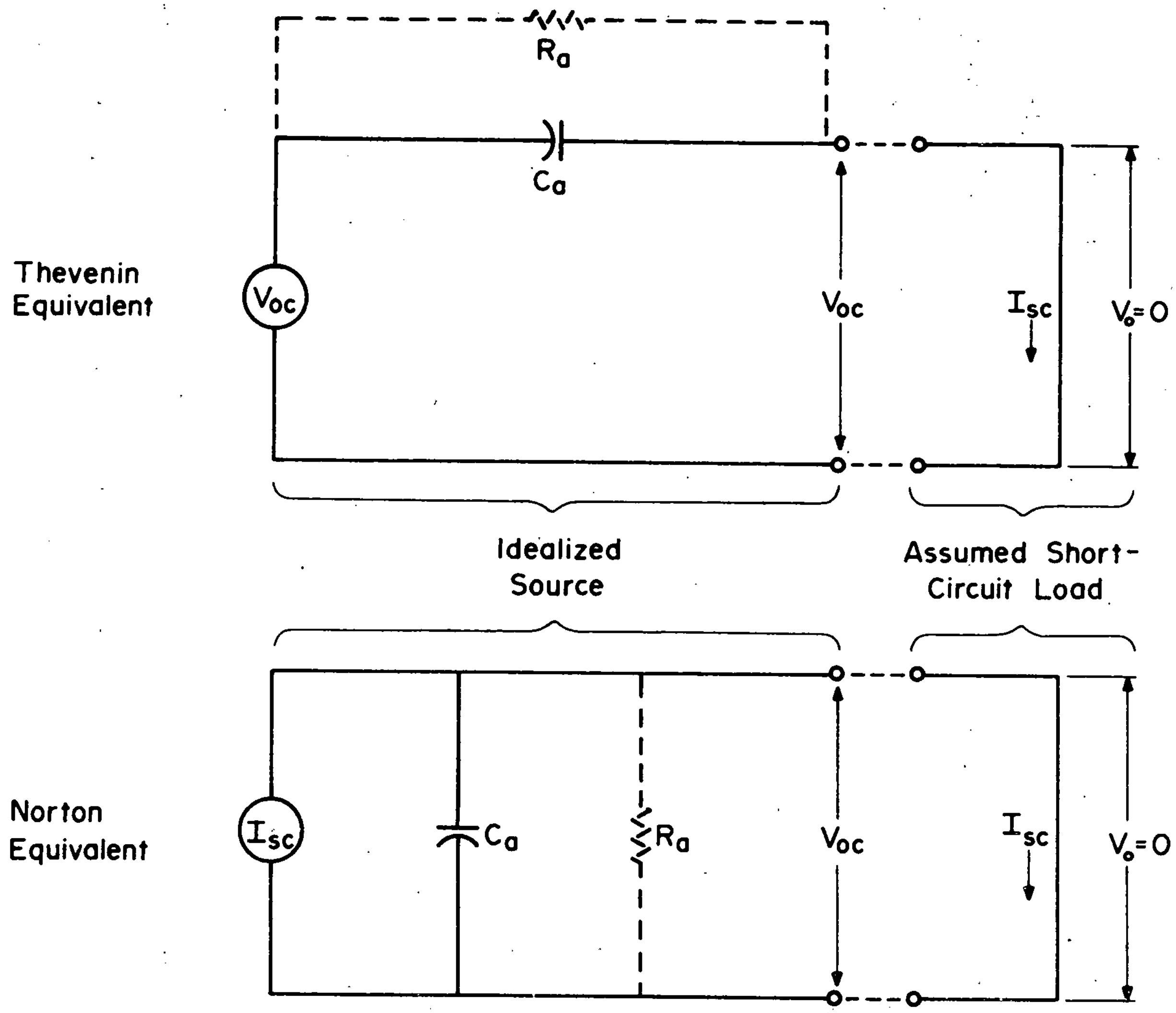

Fig. 8 IDEALIZED NON-REALISTIC THEVENIN OR NORTON EQUIVALENT CIRCUITS FOR ELECTRICALLY SMALL METALLIC COLLECTOR NEAR GROUND

It has been shown[8] that a monopole (a rod-like antenna just above and perpendicular to the ground) which is electrically short (small compared to a wavelength) can be characterized by a Thevenin equivalent circuit employing lumped parameter elements, such as shown in Figure 8. The results show that V_{oc} is related to the vertical electric field intensity as follows:

$$V_{oc} = E_v h_e,$$

where "h_e" is the effective height of the rod, and "E_v" is the vertical electric field intensity.

For electrically short antennas, $h_e = h/2$, where h is the physical height.

C_a may be calculated as follows:[8]

$$C_a = \frac{kh}{\left[\ell(2h/GMR)\right]}$$

where "GMR" is the electrostatic geometric mean radius, and "k" is a constant.

For example, consider a long thin conducting rod, almost touching, but perpendicular to the ground, and ideally insulated. If a very high impedance voltmeter is used to measure the potential of the rod to ground, the recorded potential will double if the length of the rod is doubled, since V_{oc} us directly proportional to h. The short circuit current, I_{sc}, is more roughly proportional to the general size or "apparent area" of the object. For example, in the case of the idealized rod, if both the height and diameter are doubled, I_{sc} is increased by a factor of four.

This may be demonstrated by noting that as all dimensions are doubled, V_{oc} is doubled, and the source impedance $\frac{1}{2 \pi f C_a}$ is halved. (f is the frequency of the applied electric field.) This is also true of a flat, ideally insulated plate near the ground, where, if all the dimensions are doubled, the I_{sc} is approximately quadrupled.

The source impedance, formed by C_a and R_a, in parallel, is an even more complex function of the geometry, but generally decreases (with an increase in C_a) with overall size. In the case of HVAC lines, R_a arises from a finite air conductivity but is so large it need not be considered further; however, it is important for HVDC lines.

On the other hand, as noted earlier, rigorous analytical techniques and good realistic approximations, supported by numerous experimental test results, are available to calculate V_{oc}, the idealized open circuit voltage, and I_{sc}, the idealized or short circuit current, and C_a, the source impedance of an ideally insulated conducting object, such as a vehicle. The principal areas of uncertainties are indicated in Figure 9, in terms of the Thevenin Equivalent Circuit. These are introduced by: 1) the actual impedance of the insulator, such as the tires of the vehicle; 2) by the impedance of the receptor (such as a human touching the truck); and 3) the response of the receptor, such as annoyance, for a human.

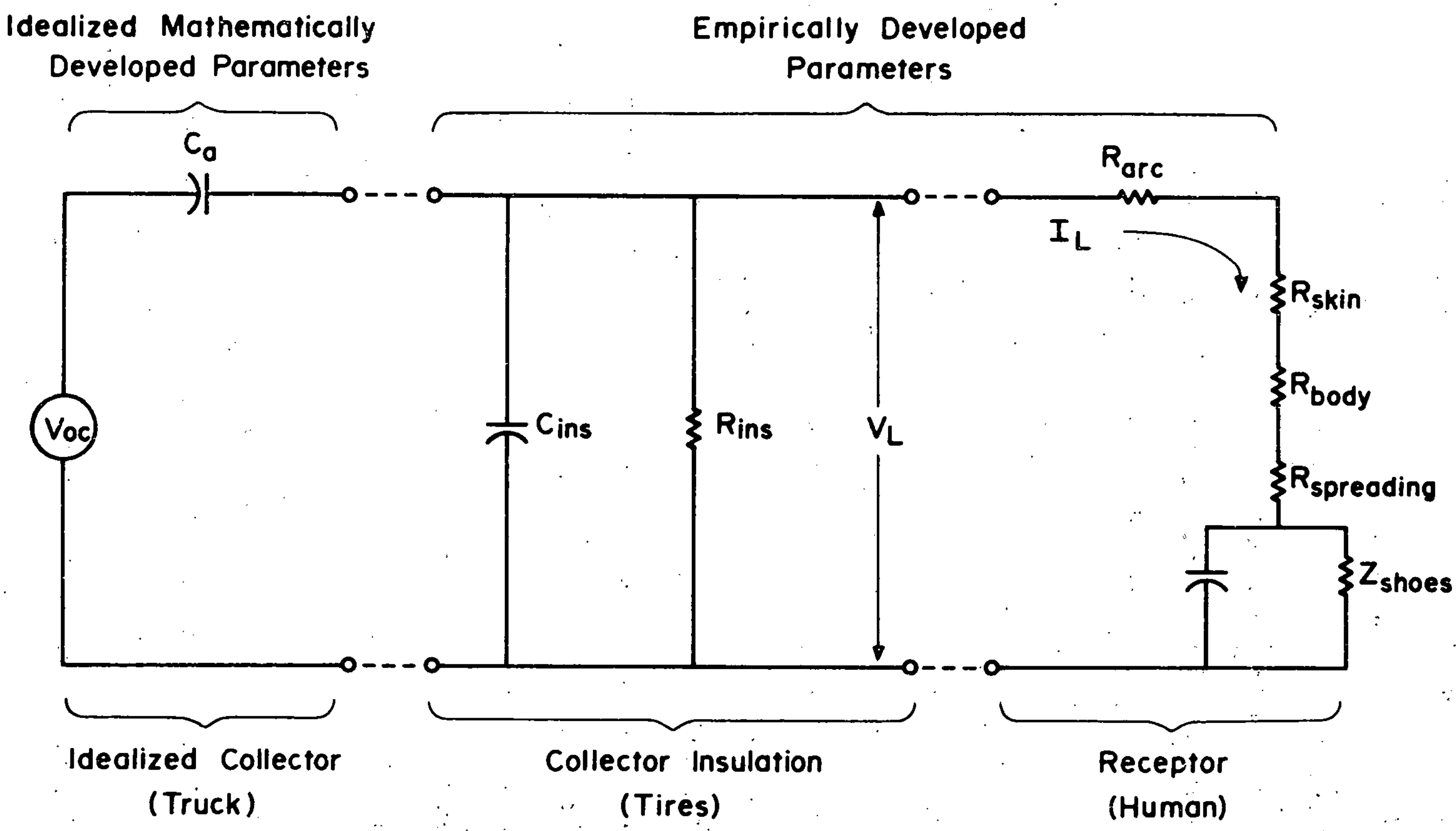

Fig. 9 REALISTIC THEVENIN EQUIVALENT CIRCUIT

5.2.2.2 Voltage Dominant Effects--Psycho-Electric Physical Factors

One power-line effect which is quite significant is similar to that of a normally encountered minor shock experienced on a dry day by a person walking on a rug and then touching a grounded metal object such as a door knob, electric light switch or an elevator call button. Just before touching the grounded object, a small arc jumps from the finger tip to the metal object. In most cases this is just a disagreeable event that can often be painful. A similar arc-over self-discharge can occur beneath power lines between the finger of a person wearing shoes with insulated soles, and a grounded metal object, or between insulated conductor nearby the power line, and a grounded human. However, the mechanism for charging or electrifying the conductive objects, like the human body beneath the HVAC power line is different, as previously discussed. Also, the number of arc-overs are more numerous for the HVAC line case between the time the first arc is initially established and the time the finger makes firm contact or is withdrawn. This effect is important and must be placed in perspective by reviewing the normally encountered carpet arc discharges.

At this point, it is worthwhile to review some of the physical factors which control the nature of a capactive spark discharge. These may be better understood by referring to Figure 9. V_L, the load voltage, R_{arc}, the time and voltage dependent arc resistance, and the impedance of the soles of the shoes are controlling factors. If, in the case of a vehicle, the tires are conducting as they normally are, V_{oc} will be reduced to the smaller value of V_L, the voltage across the load. The body current during discharge, I_L, as well as the joule energy transfer, is partially limited by the impedance of the soles of the shoes to ground. This impedance is much higher where thick crepe rubber soles are worn rather than very thin highly conducting soles.

Dominant Thresholds

The arc-discharge related effects on humans from electrified objects nearby an HVAC line are more related to the psychological responses than to any established hazard. Specifically, when a grounded person touches an electrified object, such as a truck under an HVAC line, a series of small arcs occurs prior to firm contact. The energy for these arcs is supplied by the stored energy in the shunt capacity of the electrified object charged to the value of V_L. This energy is replenished each 60 Hertz half-cycle through C_a and this tends to prolong the series of arcs. After firm contact is made with the vehicle, a continuous ac current will flow through the body.

It can be shown for most situations that the let-go threshold is exceeded prior to other thresholds as the field intensity beneath a HVAC line is increased. For example, the maximum suggested 60 Hertz body current "let-go" criterion allowable via the hands is 5 milliamperes for children.[25,26] The threshold value for single very short pulse discharges has been determined to be approximately 25 to 50 joules using the ventricular fibrillation criterion, and 0.25 joules for involuntary reflexes. In the case of 150 meter long, ideally insulated fence, in an 11 kV/m field, V_{oc} for this fence would be approximately 11 kilovolts with a I_{sc} of 5 milliamperes, at a capacity of approximately 1,000 pF as taken from the example of reference 8. Stored energy at the peak of the discharge can be computed to be approximately 60 millijoules. Since the calculated 60 millijoule energy is some 400 to 800 times below the safe threshold of 25 to 50 joules for the pulse ventricular fibrillation criterion, and several times below the 0.25 joule criterion for involuntary movement, the 5 milliampere "let-go" current which will be discussed later becomes the most likely limiting physiological criterion.

In the case of voltage dominant effects--the subjective responses to short duration discharges are of most interest since these may be experienced at or below both the "let-go" thresholds and perception levels for steady-state body currents. The human psychological responses to spark-like very short pulse discharges, range from simple perception, annoyance, and pain, and possibly include certain involuntary reactions under unanticipated conditions.

The perception-annoyance-pain levels have been investigated by a number of researchers using a limited number of subjects.[8,21,27,28,29] Frequently, the actual field conditions were simulated in the laboratory using questionable techniques and procedures. In some cases, only dc charged capacitors were employed. In others, methods to directly relate observed responses were not reported. Evaluation of the subjective aspects of transient pulses where perception, annoyance, pain, and surprise involuntary reactions is also a strong function of the psychological conditioning of the subject. For example, in the case of "let-go" current tests, higher "let-go" thresholds could be observed where the subject was challenged by means of a small wager. Also, the tests published to date have not related in detail the responses relative to the small arc discharges which are naturally encountered, such as carpet shocks.

Quantitative measures of reliability and productivity in a working environment which includes arc-discharges are possible. Such measures would include psychomotor skills, decision making, and cognitive functions. Such an approach has been used to evaluate the effects of annoying acoustical working environments.

One non-subjective response for impulse discharges which could be considered as a more definitive criterion is dermal tissue damage which arises in the vicinity of the arc discharges. One investigator[29] has briefly considered this skin damage, but only for a very limited range of capacitances and charging voltages, using animal test subjects. A level of 0.8 J/cm^2 is noted in another publication.[20]

Unknown Factors Yet to be Assessed

From Figure 9 it can be seen that a number of variables which can affect the thresholds are not easily idealized in terms of the electric field near the ground and the response of the receptor to small arc discharges. These variables are the impedance of the insulator (such as the tires of the truck), the resistance of the arc and duration, R_{arc}, the skin resistance, R_{skin}, body resistance, R_{body}, spreading resistance (increase in resistance due to a limited contact area), $R_{spreading}$, and the impedance of the footwear, R_{shoes}, to ground. All of these physical factors are strongly influenced by a wide variety of non-idealizable conditions, in particular, weather (such as wind, precipitation and humidity), soil conditions (such as soil dampness, sponginess, conductivity) or the kinds of cloth worn (such as leather versus rubber soles on the shoes). Another factor may be how rapidly firm contact is established. Many of these factors, fortunately, are subject to measurement. These measurements have yet to be made in detail and tabulated on a statistically significant basis as a function of the terrain, weather, clothing, vehicle size, and vehicle insulation. The sociological and physchological unknowns must also be assessed in terms of subject--sex, age, and background.

5.2.2.3 Current Dominant Effects--"Let-Go"

Physical Factors

As noted earlier, the physiological response which is dominant for HVAC lines arises from the passage of steady-state current through the human body. This occurs when an electrified object, such as a vehicle beneath a power line is firmly grasped, and the subject makes good contact with the ground. As the electric field intensity is increased, this current increases until current is perceived and involuntary reflexes are noted. The first important one is the "let-go" current.

Reference to Figure 9 illustrates some of the dominant parameters. Factors which reduce the level of this current include a lower value of insulation impedance, such as the usually conducting tires, and higher values for skin resistance, spreading resistance, and impedances to ground via the shoes.

"Let-Go" Criterion Not Directly Applicable

It should be noted 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 bare-footed electrical worker standing in salt water firmly grasping an uninsulated salt-water wetted metallic set of pliers connected to a current or voltage source. As noted in Table 7, the first serious biological effect encountered is the inability to "let go" or release the grasp of the pliers. This threshold is 9 milliamperes for men, 6 milliamperes for women, and has been recommended to be about 5 milliamperes for children.[26] Other steady-state current thresholds as noted in Table 7 exist. Since these are much higher than the "let-go" threshold, they will not be considered further.

Factors Needing Development

The foregoing considerations, despite the unknowns, have been used on a theoretical basis to develop a guide for the maximum field intensities. Since the I_{sc} can be analytically expressed in terms of field intensity and vehicle or collector geometry, the maximum field is calculated on the basis of producing body currents just below the "let-go" current threshold. In some calculations,[8,26] any specific value for body resistance is ignored, since this value is difficult to determine. Also, any finite value for insulation resistance (the resistance to ground) is chosen to be infinite (i.e., ignored) since data on this parameter is not available.

Safe yet realistic values for the total body impedance, V_L/I_L of Figure 9, have been suggested[25] to be in the order of 1500 ohms. The value is comparable to that noted by Dalziel[30] for the resistance between a hand wetted with salt water holding a conductor and the feet when immersed in a metal pan 3/4" full of salt water. Values for skin resistance have been noted[31] to range from 1000 to 10,000 ohms in context of a body resistance of 500 ohms.

This 1500 ohm lower bound on a total body resistance and 5 milliampere "let-go" thresholds imply an applied voltage of only 7-1/2 volts. This voltage value seems low to many who have worked with electrical equipment, and have repeatedly touched terminals at somewhat higher voltages. This can be explained by noting that the "let-go" thresholds were developed in a special way[32] which may not be directly relatable to the transmission line environmental conditions. During these tests, human subjects grasped a conductor and the current increased through the conductor to a point where an attempt was made to release the conductor. If released, the test was repeated by attempting a similar release as the current was increased but at a higher current level. Thus, it may be conjectured that, as the voltages and currents were progressively increased, the resistance of the skin during any given test had an opportunity to decrease so long as contact was maintained. The skin or total body resistance seems to be an inverse function of the applied voltage and duration of the applied voltage. The basis for this has been noted by several experimenters, especially Dalziel:

> Human tissue has a negative resistance characteristic, i.e., the body resistance decreases with both increasing current and with increasing time of contact, with the result that doubling the voltage more than doubles the current. (Ref. 33)

Others have considered the nonlinear behavior of skin or body resistance[31], and it would appear that this factor is subject to wide variations.

The "spreading resistance" of a human to ground arising from the finite contact area of the foot or shoe to a partially conducting earth is also important. Some additional current limitation is also possible if spreading resistance factors are entailed.

These foregoing test conditions are contrasted to the power line electric field situation where a person might touch a truck beneath the power line. In this case, a charged capacitor is first discharged into the body, possibly causing a retraction of the hand. Even if a grasp contact were made, the skin resistance may not break down sufficiently to prevent rapid release of the grip, assuming that the observation regarding the time-dependent nature of the skin resistance is correct.

5.2.2.4 Combined HVAC Electric Field, Magnetic Field, Earth Current and Earth Potential Effects

The previous discussion concerned effects largely unique to the electric field. However, many effects occur which are not necessarily specific to the electric field, and may also be induced by magnetic fields and earth potentials as follows:

1. coupling largely via induction into partially grounded parallel circuits of potentially hazardous voltages and currents;
2. development of high electric fields in the ground via conduction currents, especially near grounding rods;
3. coupling into other utilities and services, such as buried pipes, railroad catenaries, communication circuits via distributed coupling of the electric and magnetic fields.

Partially Grounded Parallel Conducting Circuits

Many of the coupling problems, analytical approaches and methods of resolution have been discussed in detail in a summary paper prepared by the Working Group on EM and ES Effects of the IEEE.[34] Major difficulties arise in the case of very long conductors close to the ground, such as an insulated, above-ground fence wire which parallels a transmission line and which is only grounded at one end. Both by induction and earth potential gradients, the potentials develop at the end of the fence opposite the ground, which could prove troublesome in terms of the biological hazards previously discussed. Most of the problems generally occurred during construction, such as a lower voltage line adjacent an energized line or during the erection of permanent fixtures such as fences. In the case of fixed installations, the normal practice is to use multiple grounds which would alleviate the problem.

Effects in the Vicinity of Ground Rods

The IEEE summary paper[34] also considers earth potential gradients, particularly in the context of earth currents near ground rods during fault conditions, where earth potentials are developed under unique conditions such as very dry high resistance soils. Such special cases are not considered in the development of this research plan.

Coupling into Other Services

Coupling via capacitive, inductive or conductive mechanisms into other services, such as pipelines, railway catenaries, communication circuits, has, as mentioned earlier, been the subject of investigations[11] which began in the late 1920's. These coupling problems into other utilities or services are not considered further in this plan. The relationship of past work and current problems may be sufficiently complex to justify a separate development of a research plan.

Modern electronic equipment which could be installed in buildings or enclosures off the transmission line right-of-way may be sensitive to 60 Hertz interference. Documentation is needed for the degree of this susceptibility and the amount of shielding provided by the buildings.

Fire and Explosions

A possible effect is the undesired ignition of fuel vapors and other flammable mixtures by small amounts of electrical energy, usually in the form of arcs. The arc may be energized from metallic collectors, such as vehicles or fences drawing energy from either the electric or magnetic fields. The principal area of concern arises from electric field coupling effects; although the other mechanisms are conceivable, these are highly unlikely.

It has been postulated that when a truck is refueled beneath a power line, an arc can be developed between the gasoline can spout and the filler pipe on the vehicle. This arc could conceivably supply sufficient energy to ignite fuel vapors which could lead to an explosion. Similar situations can be conjectured for other flammable mixtures or for explosives.

Some of the uncertainties previously discussed regarding insulator impedance (such as the tire impedance of a vehicle) apply here. Further, only a limited range of mixtures of fuel vapors and air are easily ignited. The amount of energy required, even for the more easily ignitable mixtures, is still significant and is increased for realistic shapes and distances between the electrodes--which establishes the arc. The larger the electrodes, the more easily the electrodes tend to dissipate the heat of the arc, and more energy will be required to ignite the mixtures. Thus, the minimum air energy for actual ignition under fueling conditions will be significantly increased over the published minimum energies.[35]

Another uncertainty is the establishment of easily ignited mixtures in the vicinity of the arc, and more importantly, some chance spatial distribution of the mixtures which would permit propagation of the flame into reservoirs of combustible material. Preliminary studies to date[8] have shown that simultaneous occurrence of all factors necessary to cause an explosion are highly improbable. In addition, human perception of spark discharges are also likely before refueling and these should provide a healthy warning not to refuel. No incident where refueling vehicles beneath power lines has caused a fire has been reported in the literature.

5.2.2.5 High Voltage AC Instrumentation

Principal factors of interest in the environment include the electric field, the magnetic field, and earth potential gradients in the vicinity of the power lines. The earth parameters such as conductivity and permittivity at 60 Hertz and related harmonics are also of interest.

Techniques to measure these fields or parameters are available and well understood, at least within limited circles. To provide proper information dissemination of these techniques, the IEEE Working Group on ES and EM Effects has sponsored field days at test line facilities.[21] During these field days, measurement of electric and magnetic fields and other related measurements are demonstrated. Methods to calibrate the instruments were also discussed. At least two manufacturers offer electric field measurement equipment, and equipment to measure ground resistance parameters is among standard manufactured items.

Special setups are sometimes required to measure the open circuit voltages or short circuit currents but these can be easily accomplished with existing state-of-the-art equipment. Some improvement in all equipment, however, is required to make this equipment less dependent on periodic calibration, more weather resistant and less subject to human error.

5.2.3 HVDC Coupling and Effects

5.2.3.1 Basic Coupling Mechanisms

Electric field induced air-ion current effects predominate for HVDC lines. Magnetic field levels produced by these lines are comparable with the earth's magnetic field. Also, the time rate of change of these fields is quite small, such that any inductive coupling effects are generally negligible.

Another coupling mode associated with HVDC lines can arise due to earth potentials when the line is connected in the monopolar configuration. This mode of operation, however, is not anticipated for any substantial time duration in the United States and therefore will not be considered further in the development of the research plan.

Application of the dc potential to a bipolar overhead HVDC line causes charges of opposite polarity to appear on the wires. These charges produce very intense field gradients in the vicinity of the conductor and other nearby metallic objects. These field intensities produce ions,[36] possibly at local minute corona points. The presence of the unidirectional field causes movement of air ions toward oppositely polarized conductors. The presence of the air ions causes the air to conduct, thereby permitting current flow between the conductors as well as between the ground and conductors.

This current flow is similar to the displacement current flow under HVAC lines in that it serves as the source of coupling between the line and an object. The exact mechanisms and phenomena are not well quantified. However, as the height of an insulated conducting object is increased, the value of V_{oc} will be increased.[36] See Figure 8. In addition, the amount of ion current intercepted may be roughly proportional to the area under the line, as was the case for the HVAC systems. An equivalent circuit, for coupling effects similar to that shown in Figure 8, also appears plausible; however, present theory has not justified such a circuit on a rigorous basis.

Another factor which is not at all present in the case of HVAC lines is the drift of an ion well away from the line. The air ions are believed to have a fairly long life, perhaps on the order of several minutes. The air ions are not always swept from one conductor to the other, but can be blown away from the power line over considerable distances causing the so-called "ion drift." The presence of these air ions has been detected in excess of several hundred feet away from the rights-of-way of HVDC lines. These air ions upon encountering a conducting object either charge the object if insulated, or cause a current to flow if the object is grounded.

5.2.3.2 Voltage Dominant Effects

As was the case for HVAC lines, an important effect is the sudden discharge of current from a charged capacitor into the human body. While much remains to be learned, it is probable that all the mechanisms and uncertainties associated with the HVAC discharges also apply in the case for HVDC lines. However, several tests under HVDC lines indicate some significant differences such as:

a) slow charging rate

b) effect of finite value of normal insulation

c) discharge occurs infrequently (not every 1/120 of a second as is the case for HVAC)

One notable difference is the potential to which an insulated object, such as a human on highly non-conducting footwear (i.e., crepe rubber soled shoes), can be achieved. Values in excess of several tens of kilovolts have been noted[37] for individuals walking in crepe rubber soles beneath HVDC test lines. Even voltages in excess of 100 kV during abnormal corona conditions have been noted on very well-insulated metal objects near HVDC test apparatus.[38] Such high voltages are expected to be rare under actual operating line conditions because of the slow charging rate.

This suggests that the major problems regarding biological effects of HVDC lines will include the capacitor discharge phenomenon.

Although impulse current discharges of fairly substantial joule values are unlikely for metal objects with normal insulation of reasonable size in the vicinity of HVDC lines, nevertheless, thought should be given to reevaluating the hazard thresholds associated with impulse currents.

In the area of potentially hazardous effects for capacitive discharges, the literature searched to date provided only limited data on involuntary reflexes, such as jerking an arm away from the source of the shock. The one reference noted[19] a 0.25 joule threshold for involuntary movement.

Such reflexes if unexpected, could cause falls from ladders. This aspect is well recognized by power companies, and it is a standard procedure to ground all metallic conductors on fixed installations in the vicinity of a power line. Relatively lower energy shocks are encountered only in the case of mobile collectors which are at ground level. Typical mobile collectors, such as discussed in the example presented elsewhere,[8] produce joule energies in the order of 5 millijoules for HVAC lines--which is some 50 times less than the 0.25 joule level, previously noted. However, for HVDC, high values could occur only in special, low probability situations.

Aside from the involuntary movement criterion of 0.25 joules, the next threshold of importance for HVDC lines is the single-pulse capacitive discharge of 20 to 50 joules to cause ventricular fibrillation. However, it should be noted that the joule energy threshold for capacitive discharges 50 joules, has been extrapolated from data developed during tests on animals, and other closely related data such as threshold responses to short sequences of 60 Hertz currents to cause fibrillation or the current and energy required to defibrillate the heart.[31] Based on one published comment,[40] the number of tests which were conducted appeared to be sufficient to address indirectly any potential problem associated with the vulnerable period of the heart. Capacitive discharges synchronized with the R-wave to occur in the vulnerable period of the heart have not been made.[41]

While power-line transient problems are excluded from consideration here, it should be noted that power line transients arising from distant lightning strokes striking a line can induce substantial capacitively couples energy onto vehicles near power lines.[39] Here, very short duration but high level discharges could occur into humans touching the vehicles. This possibility, though remote, places great importance on the extrapolations discussed in the previous paragraph.

5.2.3.3 Current Dominant Effects

In the case of HVDC lines, not much is known about the steady-state current which can be intercepted by a conducting object and possibly flow into the human body, although some limited tests have been made.[37,42] Typical maximum currents appear to be below any thresholds of significance such as "let-go" for a human in contact with a fairly large conducting metal object insulated from ground. However, the detailed conditions under which these current values were observed were not reported, and obviously additional effort, and publication is required before firm conclusions can be drawn regarding the direct current shock hazards.

5.2.3.4 Combined HVDC Electric Field and Current Coupling Effects

As was the case for the HVAC lines, the possibility that an arc discharge created by HVDC field and air ions igniting flammable mixtures also exists. In this case, factors which influence the ignition of the flammable mixtures and propagation of a flame would be comparable to those previously discussed for the HVAC situation. One notable difference is that the arc can be struck only infrequently, since it may take several seconds to several minutes for the air ions to recharge the capacitance formed between the insulated object and ground. This is in contrast to the HVAC case wherein the charge in the capacitor can be replenished once every half-cycle of the 60 Hertz rate.

5.2.3.5 HVDC Instrumentation

HVDC instrumentation is embryonic compared with the development of HVAC instrumentation. Electric field intensity meters which are capable of measuring the HVDC electric fields are available from commercial sources. However, the operation of this equipment in the presence of high air ion currents has yet to be investigated in the power line environment. Use of more sophisticated electric field mills which measure both electric field intensity and the so-called "J current" (which is the air ion current expressed as a current density) have yet to be made. Modification of the conventional field mills to measure both the field intensity and the "J current" simultaneously is possible.

The nature of the air ions has yet to be explored. The mass and charges of the air ions could be of biological interest. The life time of the air ions may also be important, particularly in situations where ions are collected at some distance away from the power line.

5.3 Conclusions and Consolidation of the State-of-the-Art

The exchange of information developed at the workshop* confirmed the conclusions resulting from the survey of the literature. For HVAC no additional research was needed to calculate the fields from overhead lines, to improve the instrumentation or to predict the coupling mechanisms on an idealized basis. The principal problems in the HVAC case appeared to be associated with key parameters which cannot be analytically predicted. These include the impedance of insulation (such as the resistance of tires to ground) and the response of typical receptors, such as humans or flammable mixtures.

It was generally agreed that additional HVAC effects work was needed in the three major areas as follows: 1) determining "let-go" and capacitive discharge safety thresholds specifically related to power line environmental situations; 2) developing flammable mixture ignition hazard

*Identified in Section 1 of this report.

probabilities and identifying other effects of changing non-power-line technology; and 3) ascertaining psychoelectrical responses of annoyance, perception and pain.

There was also reasonable agreement between the results of the workshop and the review of the literature regarding HVDC line effects. In short, the HVDC state-of-the-art is quite primitive compared to HVAC. While some of the existing and current studies can be drawn upon, additional effort is obviously required to expand the basic understanding of how the fields and currents near the ground are generated, how these fields and currents couple into systems, and lastly, how to instrument the measurements of the fields, air ion currents, and air conductivity.

5.4 Research Program Plans for Electric and Magnetic Effects

5.4.1 Fire, Explosions and Other Hazards in Perspective

Background

Under contrived conditions, it is possible to demonstrate the ignition of fuels and other flammable mixtures underneath power lines. However, in practice, the possibility is extremely remote, since critical mixtures, or chance situations necessary to cause a hazardous situation are very unlikely to occur. In addition, the parameters necessary to generate the voltage buildup which would cause an arc with sufficient energy to result in an explosion are similarly unlikely. However, a complete hazard analysis which indicates the probabilities of explosion for different kinds of fuel conditions, meteorological conditions, source voltages and energies and hazard scenarios appears to be desirable. Ignition threshold data pertinent to power-line arcs also appear to be inadequate.

Objective

The primary objective of this effort would be to develop statistical data on fuel ignition and related liquids beneath HVAC power lines.

Tasks

Ignition threshold data based on laboratory tests relevant to real-life conditions would be developed. Statistical data would be amassed on the degree to which it is possible to generate the necessary voltages and energies to provide ignition. Scenarios leading to a potentially hazardous condition would be explored, and the probabilities of a hazardous occurrence would be assessed. These will include vehicle refueling combustible particulate situations, and use of electroexplosive pyrotechnical devices. Field experiments would be conducted for several representative situations to validate the conclusions.

5.4.2 Non-Power-Line Technology Trend Analysis

Various technological, economic and social non-power-line changes are bringing about possible annoying or hazardous conditions. For example, tires can now be purchased which employ silicon rather than carbon filler. This increases the resistivity of the tire significantly. Hospitals are being sites near power lines. Reliance on highly susceptible digital circuits for critical functions is growing at a number of sites near power lines.

Objective

The objective of effort would be to assess the critical factors in the non-power-line changing technology and social conditions, and to recommend remedial action.

Tasks

The tasks for this project are by necessity vague but during this effort non-power-line technology would be surveyed to identify potentially hazardous trends. Laboratory measurements to illustrate possible problems would be conducted on a preliminary basis. Actions by professional societies and industries, possibly by the government, would be identified to resolve potential problem areas. Wherever possible, low cost techniques such as labeling and educational approaches would be emphasized.

5.4.3 Psychological Responses to Nonhazardous Currents and Discharges

Background

The prompt or acute responses to currents and discharges range from simple perception through annoyance to catastrophic hazards such as ventricular fibrillation. The prompt catastrophic effects of either currents or discharges have been investigated. The non-prompt, long term, or chronic possible biological effects of currents or voltages are addressed in programs recommended for the EPRI program on possible biological effects. However, the annoyance and perception levels of arc discharges and leakage currents associated with power lines need to be further explored and compared to those of non-power-line sources.

Past efforts in the annoyance/perception levels have included brief studies performed at Project UHV and during various IEEE field days. Comparable studies for arc discharges arising from HVDC lines have not been undertaken. Comprehensive, definitive studies that account for all factors are needed. The major need is to provide quantitative measures rather than relying exclusively on subjective data.

Objective

The objective of this effort would be to obtain data which places the human responses to nonhazardous currents and discharges from objects near HVAC power lines in perspective with shocks from non-power-line sources. This information would then be used in design of transmission lines.

Tasks

It is envisioned that four major areas would be considered: 1) survey of power line and agricultural workers, 2) development of the technology to measure the ambient HVAC power line and non-power-line leakage and discharge type environment in households, factories, farms near and distant to transmission lines, 3) development of relative annoyance rating factors, and 4) the development of quantitative response measures.

The survey would include responses of power line and agricultural workers who may be subject to leakage or small arc discharges. The perceptual responses and possible psychological adjustment of these workers to the leakage currents and environments will be considered.

The ambient spark and leakage current environments would also be measured. These would include spark discharges such as carpet shocks, spark discharges from automobile ignitions, or television sets while under repair and related situations. Sources, either power-line induced or otherwise, in households, farms and factories will be identified and statistically characterized. While Underwriters Laboratory provides some limitation on leakage currents from current equipments, ambient leakage current measurements from present and old equipments would also be considered, and these would include appliances, radios, motors, desk lamps, and similar equipments.

Based on the ambient measurements, relative rating factors of a general annoyance level in the existing environments would be developed using human subjects. Also, in the absence of comparative environments, similar rating levels would be based on design tests which eliminate preferential biases. The statistical characteristics of various voltage sources having different capacities and joule energy storage levels would be developed. Based on the foregoing factors, a psychoelectrical response to nonhazardous currents and discharges would be assessed and summarized in a form suitable for design purposes. A statistical model of power-line induced sources would be developed for these design purposes.

Quantitative measures of psychological factors in an arc discharge environment would also be made. This should include psychomotor skills, decision making and cognitative functions.

Special situations within or near rights-of-way should be considered. This will include housing near the line and various living and work pattern scenarios.

5.4.4 "Let-go" Current and Capacitor Discharge Safety Criteria

Background

Insulated metal objects, such as vehicles or fences, near overhead transmission lines can assume a potential other than that for ground. Mechanisms for this are well understood in the case of HVAC lines. Mitigation techniques can be incorporated where required to reduce the short circuit continuous current flowing through a human touching the electrified object. The maximum safe value of continuous body current is termed "let-go" current. The value assumed for this "let-go" current is crucial in determining the maximum electric field for a given collector. The body current is also a function of other factors, such as the impedance to ground, soil conditions, and weather. These factors may also be critical in determining maximum allowable fields for a given collector.

Capacitor-like discharges may control the biological effect for HVDC lines. These in turn may provide some limitation for the maximum allowable fields and air ion currents for a given collector in the case of HVDC lines.

Some reservations have been voiced about extending the existing body current data, particularly on "let-go" current thresholds to children, since a number of assumptions regarding body weight and geometry are involved. In addition, the current "let-go" test data on adults only considers a low voltage source, whereas a current source better characterizes the transmission line situation. In this more realistic situation, electrical sparking will tend to prevent a person from clasping an electrified object.

Single-pulse capacitor discharge ventricular fibrillation thresholds have been extrapolated from short-duration bursts of 60 Hertz current on quadripeds. Further review may be needed in view of the critical nature of the effect and uncertainties involved. Additional data on involuntary reaction and burns is sparse and further refinement appears desirable.

Objective

The primary objective of this effort would be to relate the existing biological current, voltage or shock criteria more adequately to the overhead power line situation with emphasis on possible effects on children. A secondary objective would be to evolve experimental approaches to extend existing data.

Tasks

The effort would be initiated by a careful study of past and, possibly, related ongoing work. Data on all pertinent serious incidents would be accumulated for guidance.

Statistical data on non-biological parameters which control body currents, either continuous or transient, would be developed. These would include data on various collectors, soil and terrain factors, and meteorological conditions for both HVAC and HVDC lines.

Body current tests using human subjects would be made to determine the validity of the existing "let-go" thresholds for HVAC power line situations. This would include statistical data on skin resistance, body resistance, footwear impedance, and spreading resistance in terms of age, sex, body weight, terrain and weather.

The data on "let-go" current and the extrapolation rationale for children would be reviewed in light of previously developed data. Further tests, involving human subjects at current levels above "let-go" thresholds would be devised if required. Limited tests, using animal subjects to confirm assumptions or data may be conducted as required.

A detailed review of past and present efforts regarding unipolar, capacitive discharge biological effects would be made. Preliminary tests using animal subjects would be conducted to evaluate existing unipolar pulse-current criteria.

For some tests, pulses would be triggered to fall within the vulnerable period of heart. More elaborate tests will be delineated as appropriate.

Special situations within and just beyond the right-of-way would also be considered. This would include possible problems with living or work patterns and home design features.

5.4.5 Basic Analytical Understanding of High Voltage DC Electrostatic Effects

Background

The fields beneath the high voltage dc power line are controlled not only by the geometry of the conductors and the operating potentials, but also by the generation and distribution of the ions in the air. The presence of air ions also controls the amount of charge or voltage assumed by insulated objects in the immediate vicinity or, in some cases, at great distance from the line. Meteorological factors such as wind direction and velocity can also play a major role. Very little information of a definitive nature has been published on the electrostatic environment near a high voltage dc line. While some efforts are currently under way, it appears that these recent and past ongoing studies should be greatly augmented to resolve the nature of the environment near a high voltage dc line.

Objective

The objective would be to develop a basic understanding of HVDC line phenomena to predict the pertinent environmental factors and coupling results.

Tasks

Several complementary but somewhat overlapping parallel studies to permit peer review and discussion are recommended to determine the environmental effects associated with the high voltage dc power line. The following areas would be addressed, among others: generation mechanism for the air ions, methods of predicting the air conductivity, air ion density and resultant field intensities as a function of conductor geometry, operating voltages, meteorological conditions, and corona losses. The ion current production parameters and recombination rates would also be considered. At least one of the recommended programs would consider the use of sophisticated computer programs which are capable of developing the necessary parameters for any arbitrary conductor geometry, tower spacing, positioning, size or shape. Methods for predicting the voltages appearing on insulated objects near and distant the line as a function of the line parameters, meteorological conditions would also be considered.

5.4.6 Experimental Coupling Studies for HVDC

Background

Very little information of a definitive nature has been published concerning measurement of HVDC electrostatic coupling effects. While some efforts are currently under way, these should be greatly augmented to resolve a number of problem areas. A series of carefully planned and executed experimental studies is required which considers the coupling characteristics of fields and air ions near HVDC lines. Statistical data regarding all of the variable factors are also needed.

Objective

It would be the objective of this effort to identify and characterize statistically the pertinent coupling features near a HVDC line using largely experimental techniques, supplemented by simple analyses.

Tasks

The effects of meteorological parameter, terrain, conductor geometry, and operating voltages would be considered. The pickup characteristics of typical collectors as a function of weather conditions would also be considered, preferably on a statistical basis. Utilizing the interim and final results of the analytical studies wherever possible, the coupling effects would be statistically characterized.

5.4.7 Instrumentation for HVDC

Background

While some instrumentation has been employed to measure field gradients below HVDC lines, the present instrumentation appears to be unduly sensitive to variations in meteorological parameters. In addition, there has been some concern expressed that present instrumentation may be inaccurate in regions of high air ion densities. Instruments employed for power-line measurements have not considered the air conductivity or various concentrations of air ions with different masses or polarities. Special problems are indicated in the measurement of air ions in the presence of very high electrostatic fields.

Objective

The objective of this effort would be to develop and validate the measurement instrumentation and techniques necessary to characterize the design parameter for the ES coupling effects of HVDC lines.

Tasks

Several studies which, to some extent, are complementary, are necessary to develop the necessary instrumentation and techniques. This would permit peer review and adequate discussion of various alternative approaches. This effort would include a thorough review of related disciplines to adapt possible existing measurement methods. After thorough study of alternatives, prototypes of models would be built, tested and compared. The instruments would consider the measurement of the electric field in a conducting medium, the measurement of air conductivity, the measurement of air-ion current and the measurement of air ions having different masses and polarities, all in the presence of strong electrostatic fields. Microwave or optical methods to measure the air ions or air conductivity may also be considered.

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[36]Y. Murakushi, U. Amano and Y. Sakamoto, "A Study in the Voltage Induction Phenomenon Due to Ion Flow on the Objects Under the HVDC Transmission Lines," a paper presented at the IEEE PES Summer Meeting in San Francisco, California (July 20-25, 1975).

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Barthold, L. O., *et al*. "Electrostatic Effects of Overhead Transmission Lines, Part I--Hazards and Effects." Paper no. 71 TP 644-PWR presented at the IEEE Summer Meeting and International Symposium on High Power Testing in Portland, Oregon (July 18-23, 1971).

ABSTRACT: This paper summarizes effects of various AC shock currents on humans and animals and cites a number of practical situations, associated with high voltage transmission which may lead to shock hazard. The material presented is limited to electrostatically induced voltages and currents. A companion paper describes methods of solving problems in electrostatic coupling.

Barthold, L. O., *et al*. "Electrostatic Effects of Overhead Transmission Lines, Part II--Methods of Calculation." Paper no. 71 TP 645-PWR presented at the IEEE Summer Meeting and International Symposium on High Power Testing in Portland, Oregon (July 18-23, 1971).

ABSTRACT: This paper interprets electrostatically coupled objects in circuit form, reduces the problem to Thevenin equivalents and develops practical methods for computing such equivalents. Means for representing irregularly shaped objects, both by analytical and analog methods are discussed. A companion paper describes the effects of induced currents on humans and animals, and cites examples of hazards sometimes encountered in operation of high voltage lines.

Bracken, T. D. "Field Measurements and Calculations of Electrostatic Effects of Overhead Transmission Lines." Paper no. F 75 573-6 presented at the IEEE PES Summer Meeting in San Francisco, California (July 20-25, 1975).

ABSTRACT: The results of an electrostatic measurements program held in conjunction with the IEEE Working Group on E/S and E/M Effects of Transmission Lines and attended by representatives of several organizations are presented. Measurements were made at ground level under an energized 525-kV line of electric field intensity, of induced currents and voltages on objects, and of perception and annoyance levels of men, women, and children for steady state and transient shocks. Three types of field strength meter were employed. They gave consistent readings in agreement with predicted field strength. Analytical estimates of short circuit currents for various objects are in agreement with measured values.

Brown, J. E., et al. "Developing Safe Working Procedures for EHV DC Hotline Maintenance." IEEE Transactions on Power Apparatus and Systems PAS-87, no. 4 (April 1968), 1044-1050.

ABSTRACT: An important phase of the investigative work preparatory to the operation and maintenance of the Pacific Northwest-Southwest dc intertie is the development of safe working procedures. This paper describes the laboratory and field tests performed to determine the dc characteristics of hotline tools, and to gain more knowledge of certain phenomena peculiar to dc systems which may influence maintenance procedures.

Comsa, R. P. and Yu, L. "Transient Electrostatic Induction by EHV Transmission Lines." IEEE Transactions on Power Apparatus and Systems PAS-88, no. 12 (December 1969), 1783-1787.

ABSTRACT: Transient electrostatic induction by EHV lines on objects such as large vehicles is studied. Attention is drawn to the need of further investigation with regard to hazards to persons touching the object and being submitted to current pulses of very short duration. An analytical expression for the electrostatically induced voltage wave is derived. The calculated numerical values are checked experimentally on the air model and the results show good agreement.

Dalziel, C. F. "Dangerous Electric Currents." Transactions of the AIEE 65 (August/September 1946), 579-585.

ABSTRACT: This paper discusses lethal electric currents and their accompanying physiological effects, and interprets the data of a previous paper in accordance with an original method of analysis found useful by the author in his own investigations of let-go currents. The present analysis concerns itself with threshold currents likely to produce instantaneous electrocution in one-half per cent of a large group of normal men. Although the conclusions are derived from tests made on animals, it is believed that the results may be indicative of what might be expected to occur in man. The majority of the work is based on experiments made at 60 cycles with shock durations of 0.03 to 3.0 seconds. Predictions of lethal currents for both direct current and capacitor discharges, while more speculative because of the limited data available, are included because of their importance due to the greatly increased use of direct current and electronic equipment.

Dalziel, C. F. "The Effects of Electric Shock on Man." U. S. Atomic Energy Commission Office of Health and Safety reprint from IRE Transactions on Medical Electronics PGME-5 (May 1956).

Dalziel, C. F. "Electric Shock Hazard." IEEE Spectrum (February 1972), 41-50.

ABSTRACT: A long-standing expert on electric-shock hazards summarizes the studies that determined the effective body impedance under varying conditions. He describes perception currents, reaction currents, let-go currents, and fibrillating currents. Turning to means for reducing low-voltage (120-240-volt) hazards, double insulation, shock limitation, isolation transformers, and the use of either high frequency or direct current are discussed for various environments. Macroshock is always a hazard in the home, in industry, and in the hospital. But the extreme vulnerability to microshock of patients with cardiac catheters, for example, requires special precautions in intensive-care and coronary-care units. Equipment such as the ground-fault interrupter (GFI) and a special isolation transformer are cited.

Dalziel, C. F. "Reevaluation of Lethal Electric Currents." IEEE Transactions on Industry and General Applications IGA-4, no. 5 (September/October 1968), 467-476.

ABSTRACT: Low-frequency electric currents of a few milliamperes through the body cause muscular contractions. In the arm current may make a subject unable to let go of a live conductors highest currents which 99.5 per cent of men and 99.5 per cent of women are able to let go have been shown to be 9 and 6 respectively. Currents somewhat larger than this, passing across the chest may arrest respiration leading to unconsciousness, and even death.

Dalziel, C. F. "A Study of the Hazards of Impulse Currents." AIEE Transactions (October 1953,) 1032-1043.

ABSTRACT: Correlation of research from scientific laboratories in Europe and America, together with accident records obtained from several nations, permits tentative criteria for the hazard from short shocks and impulse discharges. The hazard from short shocks, those obtainable from both power frequency circuits and apparatus capable of producing impulses, is believed primarily to exist because of the energy contained in the discharge; the crest of the initial current, quantity in the pulse, and shock duration being related quantities of secondary importance. Formulas for reducing the electric shock hazard to the proposed criteria for safety are derived for both surge discharges and impulses of an oscillatory nature. Applications of the formulas are illustrated with examples. It is anticipated that this study may be of value in establishing the hazard from industrial equipment capable of producing impulses, or in reducing the hazard; in evaluating the effectiveness of lightning grounds; and in other similar applications.

Dalziel, C. F., Langen, J. B. and Thurston, J. L. "Electric Shock." AIEE Transactions 60 (1941), 1073-1079.

Dalziel, C. F. and Massoglia, F. P. "Let-Go Currents and Voltages." AIEE Transactions II (May 1956), 49-56.

ABSTRACT: Let-go current curves are presented for commercial 60-cycle-a-c and for direct current. New data are presented which confirm previously published let-go current curves for direct currents having various amounts of a-c ripple content, together with new data for 60-cycle a-c let-go voltages. The voltage analysis is extended to cover direct current, thus rounding out the subject of let-go hazards. Reasonable safe let-go currents and voltages are computed from tests made on substantial numbers of normal, healthy individuals. It is believed that reasonably safe limits may be based on the predicted response for 99½ per cent of a large group. The probability of receiving dangerous electric shocks must be anticipated, and preventive measures must be considered vital ingredients in the design of machines, in the framing of operating instructions, and in work procedures.

Dalziel, C. F., Ogden, E. and Abbott, C. E. "Effect of Frequency on Let-Go Currents." AIEE Transactions 62 (December 1943), 745-750.

ABSTRACT: This paper on electric shock covers the subject of sine-wave let-go currents for both men and women and contains an analysis which permits improved accuracy in predicting the response for large groups based on experiments made on a relatively small number of subjects. It should be of especial interest to persons who have had accidents in which they barely escaped "freezing" to an electrified conductor and also to those interested in electrical safety. The range of frequencies covered is from 5 to 10,000 cycles and also direct current. The paper is the most comprehensive treatment of the subject yet published as the analysis permits predicting currents of a specified degree of safety for both men and women for this wide frequency range.

"Electromagnetic Effects of Overhead Transmission Lines--Practical Problems, Safeguards, and Methods of Calculation." Paper no. T73 441-3 presented at the IEEE PES Summer Meeting & EHV/UHV Conference in Vancouver, British Columbia (July 15-20, 1973).

ABSTRACT: This paper summarizes practical problems associated with electromagnetic currents induced by high voltage transmission lines. It deals with the safeguards necessary to counteract these currents and develops a method of calculation of electromagnetically induced voltages and currents.

Ferris, L. P., et al. "Effect of Electric Shock on the Heart." A paper presented at the AIEE Summer Convention in Pasadena, California (June 22-26, 1936).

Keesey, J. C. and Letcher, F. S. "Human Thresholds of Electric Shock at Power Transmission Frequencies." Arch. Environ. Health 21 (October 1970), 547-552.

ABSTRACT: Reliable quantitative data about electric shock to humans at power transmission frequencies are available for three physiological responses to electrical stimulation: perception, uncontrollable muscular contraction, and death. Some humans can perceive less than 0.5 ma of 50 to 60 Hertz currents, depending upon the type of hand contact made with an electrically energized circuit. Most adult male workers should be able to release 9 ma of 50 to 60 Hertz current. A safety threshold of 5 ma, recommended for the general population including children, is based upon the conclusion that current in excess of release threshold should be regarded as hazardous and potentially lethal. Relevant threshold conditions include body size, current pathway, contact duration, and total resistance. Voltages calculated from reliable experimental data on effective currents and expected resistences are lower than voltages generally recommended to be safe.

Kouwenhoven, W. B., et al. "Effect on Breathing of an Electric Shock Applied to the Extremities." Paper no. T71 087-0 presented at the IEEE PES Winter Meeting in New York (January 30-February 4, 1972).

ABSTRACT: Electric shock frequently causes the arrest of breathing. This paper reports on an experimental investigation of this phenomenon. A convulsion is a likely consequence of a high voltage shock applied to the extremities. It is suggested that this convulsion may be responsible for breathing failure.

Kouwenhoven, W. B. and Milnor, W. R. "Electric Defibrillation." Paper no. 55-95 presented at the AIEE Winter General Meeting in New York (January 31-February 4, 1955).

Lee, W. R. "Death from Electric Shock." Proceedings of the IEEE 113, no. 1 (January 1966), 144-148.

ABSTRACT: Recent studies have advanced our knowledge of the mechanisms of death from electric shock. It is known that biological effects are related to the passage of current rather than to applied voltage. The paper considers only the fatalities resulting from accidents at power frequencies. There are three possible mechanisms of death: ventricular fibrillation (incordinate action of the heart), respiratory arrest (at one time believed to be very common, and hence the usual advice on artificial respiration) and asphyxia resulting from a prolonged 'hold-on' type of shock passing across the chest. Unfortunately the appearances at post mortem do not help to distinguish between these different mechanisms of death, and so reliance must be placed on circumstantial evidence, in which the pathway of the current through the body is important. It is probable that the great majority of electrical fatalities are due to ventricular fibrillation, which brings the circulation to a standstill. The currents and times necessary to produce this effect have been suggested; but in deriving these, certain assumptions have been made. These assumptions are discussed, for it is important to recognise them when assessing the use of devices such as earth-leakage circuit breakers.

Lee, W. R. "Deaths from Electric Shock in 1962 and 1963." British Medical Journal 2 (September 11, 1965), 616-619.

McCauley, T. M. "EHV and UHV Electrostatic Effects: Simplified Design Calculations and Preventive Measures." IEEE Transactions on Power Apparatus and Systems PAS-94, no. 6 (November/December 1975), 2057-2073.

ABSTRACT: Approximate formulae are developed for predicting overhead transmission line electrostatic effects. These formulae, which are based on numerous computer simulations, allow slide rule calculations of sufficient accuracy for preliminary design work. Measures to reduce electrostatic effects, such as increasing conductor height or erecting shield wires are compared. Shield wires are found to be quite effective.

Murakushi, Y., Amano, Y. and Sakamoto, Y. "A Study on the Voltage Induction Phenomenon Due to Ion Flow on the Objects Under the HVDC Transmission Lines." Paper no. A 75 562-9 presented at the IEEE PES Summer Meeting in San Francisco, California (July 20-25, 1975).

ABSTRACT: The static induction in ac UHV and EHV overhead transmission lines is one of the important factors in determining the minimum height of transmission line conductor above ground to eliminate the electric shock hazard to the people under the line.

With the progress of studies on UHV dc transmission, it has been revealed that appreciably high voltages were induced on human bodies under the 600 kV full scale test line at Shiobara Station of this Institute. Because of the scarcity of reports available on dc induction, the mechanism of induction and the levels of induced voltages had been almost unknown.

For the purpose of clarifying this phenomenon, the authors conducted a basic indoor experiments and tests using test lines. It is identified that the mechanism of the phenomenon is quite different from that of ac static induction, that is, particles charged by the corona discharge on the surface of the conductor carry the charge to the objects under the line. They designated this phenomenon "ion flow induction". Actual examples of such induced voltages will be described below.

Rene, J. and Comsa, R. P. "Computer Analysis of Electrostatically Induced Currents on Finite Objects by EHV Transmission Lines." IEEE Transactions on Power Apparatus and Systems PAS-87, no. 4 (April 1968), 997-1002.

ABSTRACT: A method is presented which allows the evaluation of electrostatically induced currents by EHV transmission lines in objects where fringing effects are not negligible and consequently the problem cannot be reduced to the two-dimensional case. A digital program is developed based mainly on experimental results obtained on an air model, the validity of which is shown by comparison with measurements made in the field and in the electrolytic tank. General equations are derived based on these results and a digital program is established for their solutions.

Sarma, M. P. and Janischewskyj, W. "Analysis of Corona Losses on DC Transmission Lines: I--Unipolar Lines." IEEE Transactions on Power Apparatus and Systems PAS-88, no. 5 (May 1969), 718-731.

ABSTRACT: Theoretical calculation of corona losses for practical unipolar dc transmission line configurations presents considerable difficulty because of the nonlinear nature of the equations describing the space-charge fields. The application of numerical methods to obtain solutions of practical interest is discussed. One of the difficulties in the analysis of space-charge fields is the determination of the actual charge distribution around the conductor in the corona. A numerical iterative method of computing this charge distribution is presented. The method is applicable to any general configuration for which the space-charge-free field can be calculated. The line-to-plane configuration is considered. A method of including the effect of conductor surface irregularities in the theoretical calculation of corona losses is outlined, and it is suggested that, by the same method, Popkov's formula may also be modified to make it applicable to lines with practical transmission-line conductors. Calculations by the method of analysis developed as well as by the modified Popkov equation are compared with experimental results.

Sarma, M. P. and Janischewskyj, W. "Analysis of Corona Losses on DC Transmission Lines: Part II--Bipolar Lines." IEEE Transactions on Power Apparatus and Systems PAS-88, no. 10 (October 1969), 1476-1491.

ABSTRACT: As in the case of unipolar corona, theoretical calculation of corona losses for bipolar dc transmission line configurations involves the analysis of the nonlinear ionized field in the interelectrode region. However, the complexity of the analysis is increased considerably because of the presence of ions of both polarities in the region.

The problem of the bipolar dc ionized field is stated in terms of the defining equations, and the difficulties of obtaining analytical solutions are discussed. A numerical method of solving the equations applicable to any general bipolar conductor configuration is proposed. By making appropriate simplifying assumptions, the essentially two-dimensional field is reduced to its equivalent one-dimensional form, and the complex problem of the ionized field is transformed into one of solving a set of two-point nonlinear boundary value problems along a number of flux lines of the space-charge-free field. The boundary value problems necessitate the solution of two simultaneous nonlinear equations, and the numerical iterative methods of solving these equations are described.

The proposed analysis is applied to a simple bipolar dc transmission line configuration, and it is shown that the theoretical calculations are in good agreement with experimental results obtained on a full-scale outdoor test line.

Sarma, M. P. and Janischewskyj, W. "Corona Loss Characteristics of Practical HVDC Transmission Lines, Part I: Unipolar Lines." IEEE Transactions on Power Apparatus and Systems PAS-89, no. 5 (May/June 1970), 860-867.

ABSTRACT: The method of calculating corona losses, developed for unipolar operation mode, is used in the paper to study corona loss characteristics of several practical HVDC transmission lines. Detailed results on the influence of various line parameters upon corona loss characteristics of monopolar lines with single as well as bundle conductors, of homopolar lines, and of monopolar lines with overhead ground wires are given.

Sarma, M. P. and Janischewskyj, W. "Corona Loss Characteristics of Practical HVDC Transmission Lines, Part II: Bipolar Lines." Paper no. 70 TP 638-PWR presented at the IEEE Summer Power Meeting and EHV Conference in Los Angeles, California (June 12-17, 1970).

ABSTRACT: The theoretical analysis of bipolar corona developed by the authors in an earlier paper is applied to study the corona loss characteristics of practical bipolar HVDC transmission lines. Detailed results of the influence of the line parameters on the corona loss characteristics of single-conductor as well as of bundle-conductor bipolar lines are given in the paper.

Spiegel, R. J. "Electromagnetic Fields in the Near Vicinity of Transmission Line Towers." Paper no. F 76 204-8 presented at the IEEE PES Winter Meeting in New York (January 1976).

ABSTRACT: Electromagnetic fields in close proximity to transmission line towers are calculated using moment method procedures. The method of moments is especially suited to problems which involve electromagnetic coupling to metal objects and, in principle, most any type geometry can be solved. Generally, this technique involves the solution of an intergral equation for the current and charge induced on the object by an external field. Metal transmission line towers are modeled as a collection of straight cylindrical sections of varying radii. Because the wavelength of a 60 Hz field is much larger than the cross sectional area of the segments, the problem can be categorized as "scattering by thin wires". The current and charge distributions induced on a 230/138 kV double circuit transmission line tower are calculated. Utilization is made of the induced current and charge for the purpose of determining the fields near the tower. Comparison is also made between calculated and measured near fields.

Tranen, J. D. and Wilson, G. L. "Electrostatically Induced Voltages and Currents on Conducting Objects Under EHV Transmission Lines." IEEE Transactions on Power Apparatus and Systems PAS-90, no. 2 (March/April 1971), 768.

ABSTRACT: A study is made of the steady state short circuit I_{sc}, and open circuit voltage, V_{oc}, to ground for conducting objects under E.H.V. transmission lines. This is carried out in a computer program and on a scaled down laboratory model of a transmission line. In addition, tests are conducted at the American Electric Power Service Corporation and Westinghouse Electric Corporation E.H.V. test site at Apple Grove, West Virginia. The Apple Grove results are used for comparison with the other two approaches. Values of I_{sc} within a few percent of the field data and of V_{oc} within about 30 percent are predicted by the computer program. For the transmission line model, the measured values of I_{sc} are within a few percent of the Apple Grove measurements and the values of V_{oc} are within approximately 15 percent.

6. MULTIPURPOSE PROGRAMS

A number of projects were suggested which involved more than one discipline or objective and which could be more economically conducted as multipurpose programs. These include exemplary measurement van for the RI, TVI, and acoustical noise data collection, special studies to reduce all corona effects, transmission line effects trade-off studies for both corona and coupling phenomena, and a reliability/maintainability evaluation for corona-related effects.

During the workshop,* several projects to evaluate or improve the high-voltage cage measurement techniques were considered. Later, these were reconsidered and dropped from immediate consideration. Most of the difficulties with HVAC cage measurements are sufficiently well understood that more overriding considerations influence any choice between this technique and others for the evaluation of corona effects. In the case of HVDC lines, the basic understanding of voltage gradient and air-ion phenomena is too premature to initiate any cage evaluation studies at this time.

6.1 Exemplary Measurement Van

Background

Baseline data on corona effects, such as acoustical noise and electromagnetic interference, are needed to

*Described in Section 1 of this report.

upgrade the accuracy and utilization of corona test cage and test line results. The IEEE Working Group on Corona and Radio Noise is accumulating such information, but so far their efforts have not achieved the desired goals due to a lack of manpower and, possibly, the nonstandard measurement equipment. Currently, a number of utility companies are considering designing and building measurement vans which could be used to conduct acoustical noise (AN) and electromagnetic interference (EMI) measurements at a number of sites. This will require some engineering effort on the part of each individual utility and may not result in the same type of measurement equipment being employed by different utilities.

To minimize the required design effort on the part of each individual utility, and to assure measurement uniformity, the design for an exemplary van should be made. Based on this design, a minimum of engineering on the part of each utility would be required and would result in the same measurement instrumentation being used.

Objective

It would be the objective of this effort to develop engineering design specifications for an exemplary van to measure acoustical noise, electromagnetic interference and other key parameters.

Tasks

An exemplary measurement van/trailer would be designed and built which will measure AN and EMI along with their relative parameters, such as drop size distribution of rain and field interactions. The specific tasks would include the following: (1) coordinating with interested and contributing groups, such as the IEEE Working Group on Corona and Radio Noise, staff members at various utilities, and key members at government agencies; (2) conducting a survey of the existing practices by various utilities and laboratories; (3) conducting a survey of existing measurement equipment and recording apparatus; (4) developing an integrated overall measurement design plan and recommended measurement procedures; (5) implementing this design in one exemplary trailer or van model; and (6) conducting demonstration measurements.

6.2 Special Techniques to Reduce Corona Effects

Background

A number of techniques have been or are under consideration to reduce the overall corona effects, particularly those occurring during foul weather. Techniques currently being considered include surface aging, wetability and configuration modification, and techniques to reduce the accumulation of surface water along the line.

Objective

It would be the objective of this effort to initiate, on a case-by-case basis, feasibility studies to develop additional or improved corona effect suppression techniques. Another objective would be to evaluate the existing promising approaches in greater detail.

Tasks

The tasks on this effort cannot be defined since these would be dependent on the proposed techniques.

6.3 Transmission Line Effects Trade-Off Study

Background

A variety of design options exist which will meet certain trade-off criteria. For example, if it is desirable to reduce the voltage gradient near ground level, this can be done by placing the conductors closer (within limits imposed by other factors) together or by using a shield or guard wires. However, such a procedure increases the voltage gradient near the conductors which, in turn, increases corona effects. At some additional expense, the conductor size can be increased to reduce the gradient near the conductor. But it is not always clear whether such a procedure is worth the cost, because certain corona effects are not always reduced in proportion to the local conductor gradient due to the increase in conductor surface area.

Objective

It would be the objective to characterize transmission line side effects and design options and to conduct representative trade-off analysis.

Tasks

The following tasks are envisioned. (1) The various mitigation techniques to suppress transmission line effects would be surveyed. These would include conductor geometry, wire size, strand treatment, location of conductors, use of guard wires or other field canceling techniques, and variation of the conductor height. (2) The various transmission line side effects would be surveyed, and pertinent criteria for these side effects established. This would include corona effects, electric and magnetic coupling effects, and related biological influences, if any. (3) These factors would be analytically characterized to develop various design trade-offs in terms of economical (or factors which could lead to relatively quick economic assessment) mitigation approaches and transmission line effects criteria. (4) Trade-off studies for representative situations would be conducted. (5) Computer programs and other analytical tools would be documented and published.

6.4 Reliability and Maintainability

Background

In some instances, it has been found that a significant cost item in the maintenance of power lines is associated with the television interference generated by hardware, and possibly by insulator strings. At this point, little is known about how the hardware or insulator strings deteriorate to create gap type interferences or other reliability problems. A general study appears to be desirable, therefore, to minimize maintenance costs by developing a better understanding of how hardware designs create television interference or degrade in the long-term.

Objective

It would be the objective of this study to develop a better understanding of the role of insulators and other hardware in producing interference and to reduce maintenance costs.

Tasks

The basic reliability and interference features of hardware and insulators which may ultimately contribute to interference problems through bad maintenance, poor installation, or initial design, would be investigated. If appropriate, a recommendation would be made for future work to expand results into handbook form.

APPENDIX A

Participants of the Ad Hoc Workshop

We would like to acknowledge gratefully those individuals who gave presentations during the ERDA-IITRI Ad Hoc Workshop.

These individuals and the titles of their presentations follow in order of their presentation:

Robert W. Flugum-ERDA
"Role of ERDA and Objectives of the Ad Hoc Meeting"

Dr. Harry Kornberg, Frank S. Young-EPRI
"Function and Objectives of EPRI"

Dr. W. Janischewskyj-University of Toronto
"Role and Activities of the IEEE Working Group on Corona, Subcommittee on Radio Interference from Transmission Lines"

E. Lambert-Pacific Gas and Electric
"Role and Activities of the IEEE E/S and E/M Effect of Transmission Lines Working Group"

Samuel E. Probst-OTP
"Role of the Office of Telecommunications Policy"

David Janes-EPA
"Role of Environmental Protection Agency"

Arthur Wall-FCC
"Role of FCC"

Dr. Gilles-G. Cloutier-Hydro Quebec
"Activities of IREQ"

Dan C. H. Shih-AEP
"State-of-the-Art: Ozone From Transmission Lines"

R. M. Morris-National Research Council of Canada
"State-of-the-Art: Acoustic Noise from Transmission Lines"

Vern Chartier-BPA
"State-of-the-Art: Radio and TV Interference from Transmission Lines"

Dr. D. Deno-Project UHV (G.E. Co.)
"State-of-the-Art: Electromagnetic Fields from UHVAC Transmission Lines"

Dan Bracken-BPA
"State-of-the-Art: Electric Fields from UHVDC Transmission Lines"

Donald Batorsky-Bell Laboratories
"Special Problems: Co-Location of Utilities"

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