EFFECT OF HIGH ALTITUDE ON HIGH VOLTAGE AC TRANSMISSION LINE CORONA PHENOMENA

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Abstract - This paper summarizes the results of a research effort conducted by Bonneville Power Administration (BPA) to determine the effect of altitude on corona phenomena from high voltage transmission lines. A computer-controlled, reliable, unattended test station was installed at an altitude of 1935 m on a double-circuit 500-kV line near Basin, Montana, to continuously monitor audible noise (AN), radio noise (RI), and television interference (TVI). To obtain comparative data at a lower elevation, another test station was installed on a 500-kV line of similar design near Stayton, Oregon, at an altitude of 277 m. Comparison of the high altitude data with the lower elevation data and with predictions demonstrated that the correction factor of 1 dB/300 m developed in the 1950's and 1960's for radio noise is still valid and is also applicable for AN, TVI and, possibly, corona losses.

INTRODUCTION

It is well known that the air density has an effect on the onset voltage for corona. Large variations in air density due to altitude changes can, therefore, influence conductor selection for high voltage ac transmission lines [1,2].

The influence of altitude on corona phenomena has been studied in the past, primarily in the laboratory to determine corona onset [3] or at high-altitude test stations to determine its effect on corona loss and radio noise (RI) in the AM broadcast band [4,5]. There has been no extensive study to determine the effect of altitude on audible noise (AN) and television interference (TVI).

In many cases, conductor selection for BPA's high voltage lines is based on AN performance [2]. Since the lines being built in Montana are at high altitudes, BPA decided in 1982 to determine if altitude correction factors used in formulas for predicting RI were also valid for AN and TVI. This was accomplished by collecting corona phenomena data from October 1983 to June 1985 on a continuous basis from a double circuit 500-kV line at 1935 m above sea level in Montana and for 5 months on a similar 500-kV line at 277 m in Oregon. A secondary objective of this effort was to collect a minimum of 1 year's worth of long term, continuous data so that annual day-night sound levels (L_{dn}) could be calculated. The State of Montana has recently adopted an annual L_{dn} limit of 50 dB(A) at the edge of right-of-way for high voltage transmission lines [6] in residential or subdivided areas.

In the following sections of this paper, the results of these measurements are presented and analyzed to determine if previously developed altitude correction terms for RI are still valid and if they

can also be used for AN and TVI. This objective is accomplished by presenting the results of all the data collected in 1984. The data from this effort was also used to support the North Boulder River Elk Study, which was an elk winter range study funded by BPA and conducted by Montana State University.

BACKGROUND

The earliest work and the most frequently cited on the effect of relative air density (RAD) on corona was conducted by F. W. Peek [3]. Peek's work consisted of making corona loss measurements to develop a corona loss formula. As a part of this work, he made tests to determine the effect of variations in RAD on what he called "critical disruptive voltage," e_0 . He found e_0 varied directly with RAD. Since the conductor surface gradient of a conductor is directly proportional to the applied voltage, then Peek's results showed that the critical onset gradient of a conductor varied directly with RAD. However, it must be kept in mind that Peek's data were taken over a relatively small range in RAD from 1.078 to 1.158. For comparison, the RAD at 2100 m is 0.828.

In a discussion of [7], Peterson presented an empirical equation for corona loss, but he found e_0 varied as $2/3$ power of RAD. This result, like Peek's, was based on experimental work on smooth conductors in an evacuated chamber.

Because the application of this effect could dramatically affect conductor selection at high altitudes, the Public Service Company of Colorado and Westinghouse Electric Corporation conducted tests on a full-scale test line at 3200 meters near Leadville, Colorado, in the 1950's [1]. Both corona loss [4] and RI [5] were measured on single and multiple conductors in bundles that were similar to conductors tested near sea level (195 m) at the Tidd Project [8,9]. The Leadville tests showed that e_0 varied as $RAD^{1/2}$.

Westinghouse engineers used the Leadville and Tidd data to develop an altitude correction term for their RI prediction formula. This term $40(1-\delta/\delta_0)$ can be found in [10] where δ is the relative air density. In that same reference is an Italian RI formula which also has an additional term for the effect of altitude. That term, $q/300$ m where q is altitude in meters, was developed from the Leadville data and RI data collected in Switzerland [11].

Fig. 1 Comparison of Italian and Westinghouse terms for effect of altitude on radio noise.

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Both the Westinghouse and Italian terms for the effect of altitude on RI have been plotted in Figure 1 as a function of altitude. The relative air density (referenced to sea level) from standard atmospheric tables was used in the Westinghouse formula. Figure 1 shows that the two terms give essentially the same result for effect of altitude on RI. Because of these results, BPA engineers, several years ago, added the term $q/300$ m to all their corona phenomena prediction formulas (including corona loss) so that calculations at higher elevations could be made [12]. The Italian rather than the Westinghouse term was used because the altitude of a line is usually known whereas the RAD has to be either measured or calculated from meteorological tables.

TEST LOCATIONS

The main purpose of this investigation was to obtain AN, RI, and TVI data from a double-circuit 500-kV line by installing a continuous long-term, unattended data collection system at a high altitude test site in Montana. The altitude effect could then be determined by comparing levels predicted at sea level for this line with the actual data. It was decided later in the program to obtain additional data on a line of identical design near sea level. Therefore, another test station was built and installed on a similar double-circuit line at an altitude of 277 m.

The primary test location was installed on the Broadview-Garrison double-circuit 500-kV line located on the Continental Divide near Basin, Montana. This test site was at an altitude of 1935 m. The line uses a vertical-phase configuration, and the geometry of its self-supporting tower is shown in Fig. 2.

The other test station was installed on a similar double-circuit line at 277 m above sea level near Stayton, Oregon. The 500-kV line in Oregon is identical to the one in Montana except the Montana line has two overhead ground wires, whereas the Oregon line has only one.

The Montana test site was located in an area near the Continental Divide where human activity was almost nonexistent. Therefore, the ambient AN was very low. The Oregon test site was located in a fairly quiet rural area; however, during daytime hours, there was a fair amount of human activity. This test site was also only three spans out of a substation in which noisier 500-kV lines than the one being monitored were terminated. Valid RI data could not be collected at this site because the RI propagating from the noisier

Fig. 2 500-kV double-circuit tower type at Montana Test Site.

TABLE I

AVERAGE MAXIMUM CONDUCTOR SURFACE GRADIENTS
(3-40.7 mm Conductors)

Phase	Montana 500-kV Line @ 530 kV (kVrms/cm)	Oregon 500-kV Line @ 542 kV (kVrms/cm)
A1	14.7 (lower)	14.7 (center)
B1	14.1 (center)	15.2 (upper)
C1	15.0 (upper)	15.5 (lower)
A2	14.9 (upper)	14.7 (center)
B2	14.1 (center)	15.5 (lower)
C2	14.8 (lower)	15.2 (upper)

lines predominated at the test site. However, valid AN and TVI data could be obtained. It was not possible to find another test site on this 500-kV line because about 2 miles from the substation, it parallels an existing noisier single-circuit 500-kV line. The average maximum conductor surface gradients based on the average line voltages for the two lines over the test periods are given in Table I. The calculated AN/RI/TVI are the same for these two lines for the same voltage and altitude.

EXPERIMENTAL DESCRIPTION

BPA has had considerable experience in conducting long-term AN and electromagnetic interference (EMI) measurements. Most of the BPA test sites, however, have been within 150 km of the BPA laboratories located in Vancouver, Washington. The most extensive measurement site was the Lyons 1200-kV facility [13], and it was staffed during most of the project duration.

For the Montana high altitude system, the following considerations were important to the design approach.

1. Remoteness of test site (more than 1300 km from BPA's laboratories in Vancouver).
2. No access to the test site due to winter closure of roads (December 1 to May 15), except with a variance permit from the Forest Service.
3. Extremely severe winter conditions (temperatures as low as -50°C) and hostile environment for equipment and instrumentation.

It was decided the system would be designed to require no regularly scheduled maintenance and services. Service to the test site would be on an as needed basis. The goal was to have the system survive the winter with no breakdowns and malfunctions. The entire system was designed, fabricated, assembled, and tested at BPA's Division of Laboratories in Vancouver, Washington, to minimize onsite installation and start-up problems.

Measurement System Design

In order to evaluate the long-term AN and EMI performance of the double-circuit 500-kV line at the Montana site, the AN, RI, and TVI levels together with the weather conditions, needed to be measured and recorded. The following parameters were considered necessary:

- Eight weather parameters (wind direction, wind speed, precipitation rate, solar radiation, barometric pressure, outdoor temperature, indoor temperature, and dew point).

- Audible Noise (A-weighted and Octave bands from 62.5 Hz to 16 kHz).
- Radio Interference (at 500 kHz and 834 kHz).
- Television Interference (at 74.5 MHz).

For AN measurements, a B&K 4921 outdoor microphone with a B&K 4165 microphone cartridge was used in conjunction with a GenRad 1925 Octave band filter and a B&K 4426 noise level analyzer. The microphone was located at a lateral distance of 15 m from the outside phase (22.9 m from centerline) at a 1.5 m height, aimed at the outside phase conductor.

For RI measurements, a 1.1-m diameter loop antenna was installed at a 2-m height at the same lateral distance. Two Singer NM-21FFT RI meters were used. The RI monitoring frequencies were 834 kHz and 500 kHz. Using two instruments also provided redundancy for RI instrumentation.

For TVI, a dipole antenna adjusted to 74.5 MHz was used at a height of 3 m. Two Stoddart NM-30A field intensity meters tuned to 74.5 MHz were used to provide redundancy. These meters were over 20 years old and had the highest likelihood of malfunction. Therefore, redundancy was most important for these TVI measurements, especially at such a remote site.

To ensure the integrity of these instruments and to provide a ready reference for examining the test data, a Stoddart 91263-1 impulse generator was used to generate a reference signal for the daily automatic calibration of the RI and TVI meters. The microphone had a built-in electrostatic actuator for this purpose.

These instruments were set at the anticipated range and scaled to 0-5 volts output for the data system.

The various weather instruments were selected based on the anticipated environmental condition. They were of Climatronics manufacture, except the anemometer which was a Belfort 5-120 HD. Two heated rain gages of different sensitivities were used. These heated rain gages were not too effective in this climate, since the foul weather in the winter months was primarily dry snow, and it tended to be blown around a lot, even by the slightest breeze, plus its moisture content was very low.

All weather instruments were scaled to produce 0-5 volts output via a Climatronics 100081 mainframe with the appropriate translators.

Data System Design

Since this was an unattended site with no regularly scheduled service visits, it was necessary to have the test data available for examination to determine test system status. With that in mind, the Hewlett-Packard 9845 in the BPA Laboratories was chosen as the host computer. It was further decided that some on-site storage capacity would be desirable. An HP 9915 computer with cassette tape capable of 4 days of data storage at the selected sampling rate (23 channels, 2-minute sampling rate), was chosen.

The HP 9915 was programmed to turn on the calibration signals for AN, RI, and TVI at midnight each day. This data was also recorded; therefore the status of each instrument could be determined once all the data was transferred to Vancouver, Washington, which was done every 2 or 3 days. Through a series of relays controlled by the HP 9915, the Stoddart impulse generator provided 5 different levels in 10 dB steps to the RI and TVI meters. Therefore, the tracking over the dynamic range of these meters could also be checked.

There were several options available for the communication link, among them were the BPA microwave system, the National Oceanic and Atmospheric satellite, and the commercial phone line.

While each approach had its pros and cons and offered different technical challenges, the phone line option was chosen due to cost and schedule considerations. It required installing a cable from the test site to the nearest phone line, which was approximately 2 km away. This cable was "piggybacked" onto the station service cable, hence the incremental cost was quite low. The complete system block diagram is shown in Figure 3.

Fig. 3 Block diagram for AN/EMI Measurement System

This test site has been very reliable. There were some start-up problems, but once they were resolved the site was operational for several months before maintenance was required. The RI and AN systems maintained their calibration within 1 dB. The TVI meters, as expected, were not as reliable; however, one instrument did maintain its calibration within 3-4 dB.

The only significant problem was station and telephone service. The test site was served by a 2-km long underground electric and telephone service connected to 40 km of radial feed overhead line from Butte which went over rugged mountain and forest land. During the winter of 1984-1985, electric service was interrupted six times (three were scheduled). In all but one instance, the system restarted after service was restored, went through a self diagnostic routine, and continued. Data that was already in tape storage was not lost. Telephone service was lost the first winter for about 2 weeks and the second winter for about 1 week during periods when temperatures were as low as 50°C; however, data was not lost since the microphone electronics could not operate at these temperatures.

Lower Elevation Test Site

Similar AN/RI/TVI instrumentation was installed at the test site that was located 277 m above sea level, except for the octave band AN channels. All the antennas and microphones were installed at the same heights and at the same location from the outside phase as in Montana. Radio noise was measured at 500 kHz with a Stoddart NM25T radio noise meter, but as was previously discussed, this data was determined to be invalid because of the nearness of noisier lines. Only one Stoddart NM30A meter was used to measure TVI, as redundancy was not needed at this site because of its closeness to Vancouver, Washington. The data was continuously plotted using paper chart recorders from January 1, 1985, to May 1, 1985.

WEATHER CONDITIONS

The high altitude test site, as stated previously, was completely unattended. Therefore, there was no

one at the site to make weather observations. An individual who lived in the nearby town of Basin was hired to make daily weather observations. This data was quite valuable as it gave an indication of the type of weather that was occurring in the area.

The BPA prediction techniques for foul-weather are based upon the levels that would occur during measurable stable rain conditions when the conductors are thoroughly wet, which is very common weather on the west side of the Cascade Mountains in Oregon and Washington. This condition gives a fairly reproducible AN, RI, or TVI level. Such a condition is rare in Montana, as most rains, especially in the summer months, are intermittent and scattered. Foul weather in the spring and fall usually consist of both rain and wet snow whereas in the winter months it is always snow.

Montana is considered a dry state, whereas the area west of the Cascades in Oregon is considered wet. The test site was located near Helena, Montana, which has an annual precipitation of about 280 mm, whereas Portland, Oregon, has an annual precipitation of about 1000 mm. Montana, however, can experience very heavy, localized rains where 20 mm or more can fall in less than 1 hour, unlike the long duration drizzle that is common in Oregon. The rains in Oregon can blanket an entire area and last for several hours, whereas rains in Montana are usually scattered and can be highly localized. Such rainstorms in many instances do not last long enough for the conductors to become thoroughly wet.

Such differences in weather between Oregon and Montana made it imperative to collect at least one year's worth of data to better define altitude effects.

Table II shows the monthly weather data collected at the Montana test site.

TABLE II

MONTANA TEST SITE WEATHER MEANS, 1984

Month	Temp. °C	Relative Humidity %	Relative Air Density	Precipitation Accumulation mm
Jan	- 7.0	64.1	.88	4.3
Feb	- 4.3	66.6	.86	3.3
Mar	- 3.0	76.8	.85	7.8
Apr	0.0	63.6	.85	7.4
May	4.1	61.9	.83	22.6
June	8.2	67.5	.82	70.4
July	15.6	54.7	.81	9.1
Aug	15.3	53.4	.81	30.2
Sept	5.9	60.9	.83	6.4
Oct	- 0.9	67.7	.85	2.5
Nov	- 1.9	68.7	.85	1.3
Dec	- 7.9	69.4	.87	13.9

RESULTS AND ANALYSIS

As previously mentioned, the primary objective of this test program was to collect data on a high altitude line in Montana which then could be used to determine the effect of altitude on AN, RI, and TVI. Because of the new Montana AN noise code which is based upon annual L_{dn} levels, another objective was to collect a minimum of one year's worth of data in the Montana environment so that calculations of annual L_{dn} could be made.

Audible Noise

AN data was collected for 19 months at the high altitude test site in Montana. Mostly double-circuit data was collected; however, at times only one of the two circuits was energized. There were periods when neither line was energized, allowing excellent ambient

AN data over a few weeks to be obtained. Such ambient data is valuable since it can be compared to and/or subtracted from the total AN collected during line energization periods. Ambient AN data is rarely obtained from operating lines because such lines are rarely out of operation. Also, ambient AN data can be extremely variable over any time period such as a day, a week, or a year because of human activity. This was not the case at this test site since human activity was for the most part nonexistent.

Double-Circuit Data: The results of 1 year's data collection from January 1, 1984, to December 31, 1984, at the high altitude test site with both circuits energized are shown in Figure 4. These data are the all-weather distributions both daytime and nighttime for the 16 kHz octave band and the A-weighted channel. The only AN data that were excluded in this analysis were data collected when the wind speed exceeded 5 m/s [14] which was less than 2 percent of the data. In the past at other BPA test sites, because of high daytime ambient noise, only nighttime data were valid. This was not the case at this Montana test site since both daytime and nighttime ambients were very low.

Fig. 4 All weather AN distributions for 1984, A-weighted and 16 kHz, Montana Test Site; Sample size: 166,992.

At BPA the important information to be gained from these all-weather distributions is the L_{50} levels during measurable stable foul weather conditions. At past BPA test sites, measurable stable foul weather was, for the most part, rain which could be measured by sensitive rain indicators. At this altitude, winter foul weather was primarily snow whose intensity is not easily measured, although attempts are made with heated rain gauges. These all-weather distributions for the corona noise shown in Figure 4 can be broken up into three distinct normal distributions, which are based on three fairly distinct weather conditions; the lower one is fair weather (or ambient conditions); the upper one is measurable stable foul weather (both rain and snow); and the one in between is the transition distribution between the other two (mist, fog, very light snow, after cessation of rain or snow, etc). The A-weighted L_{50} level for the upper distribution is 55.5 dB(A), whereas the L_{50} level for the lower distribution is 25 dB(A). However, comparing the lower distribution to the ambient distribution showed that this fair weather distribution was primarily ambient noise. In the past, BPA has estimated fair-weather AN for lines by subtracting 25 dB(A) from the calculated L_{50} foul-weather level [12]. This Montana data, however, indicates that this difference may be greater than 30 dB(A).

Effect of Temperature: Previous investigators [15,16] have indicated that AN levels during snow were less than during rain. It was important to determine if

there was a significant difference between rain and snow AN levels before attempts at determining altitude effects were undertaken, since all the AN formulas including BPA's are based on rain, and the AN data from the lower altitude site was primarily collected during rain or wet snow.

Foul weather in Montana consists mainly of snow. Summer months can be, and normally are, very dry; therefore, good, long-duration stable rain storms similar to those west of the Cascade Mountains in Oregon and Washington are very rare. In fact, most rain storms are more of the scattered, intermittent type. However, AN is primarily a local phenomena. In other words, the microphone primarily responds to the noise from the span that it is located next to, and adjacent spans up or down the line have essentially no effect on the measured level. Therefore, it is the local weather conditions that are important from an AN standpoint which, for the most part, is also true for TVI but not true for RI, as will be discussed later.

To determine if there was any difference between rain and snow AN levels, the data was analyzed in 5° ranges from -10°C to $+10^\circ\text{C}$ and greater than $+10^\circ\text{C}$ and less than -10°C . The results of this analysis showed there was less than 1 dB difference between the L_{50} AN levels for the upper distribution of these all-weather curves either above or below freezing. Even the L_{50} level below -10°C was within 2 dB of the L_{50} levels above 10°C , with the lower temperature data being higher. Such cold temperatures in Montana produce very dry powder snow (the kind skiers love). A comparison of all the A-weighted and 16 kHz AN data for 1984 above and below freezing is shown in Figure 5. The L_{50} level below 0°C occurs at the exceedance percentage of 7 percent, whereas above 0°C , it occurs at the exceedance percentage of 1.5 percent, and these levels are 56 and 55.5 dB(A), respectively.

In an effort to determine why there was no difference between snow and rain AN levels, an analysis was made to determine if heat produced by conductor current could melt the snow which would then cause water to drip off the conductor, similar to what occurs during rain or wet snow. However, this was determined not to be the case since the average subconductor current was less than 100 amperes, which could not raise the conductor temperature above ambient, especially at temperatures below 0°C .

Fig. 5 All Weather AN distributions for 1984 (grouped by temperature), Montana Test Site; Sample size: above zero 92,000; below zero 79,400.

Determination of Altitude Effect: For AN, the altitude effect could be determined by comparing the measured L_{50} level in Montana with the L_{50} level calculated at sea level using the BPA AN formula [17] which has been demonstrated to be quite accurate [18]. The BPA AN formula calculates the L_{50} AN

level during measurable stable rain conditions which in essence is the upper distribution of the all-weather distribution of the cumulative probability plots.

To determine the L_{50} A-weighted level during measurable stable foul weather requires the determination of what part of the all-weather distribution is the measurable stable foul-weather distribution. This is where the higher frequency octave band data, such as 16 kHz shown in Figure 4, is valuable since it is solely an indication of corona noise and is not affected by ambient. This data has two normal distributions (noise floor is 16 dB); the upper being the measurable stable foul-weather distribution and the lower being the transition distribution between fair weather and measurable stable foul-weather. By drawing two straight lines through these two distributions, one can determine at what percentage point the L_{50} level of the upper distribution occurs, which is about 4 percent. The A-weighted L_{50} level at the 4 percent point is 55.5 dB(A). The BPA AN formula predicts 48.9 dB(A) for this line using no altitude correction and 55.3 dB(A) using the 1 dB/300 m correction at the average operating voltage of 530 kV.

To further verify the altitude effects, the data from the 277 m test station were also used. At this station, the ambient noise was much higher; therefore, the A-weighted data were plotted continuously using a strip-chart recorder. Data unaffected by ambient noise were then picked off these charts every two minutes during three good rain storms.

The results of this analysis are shown in Figure 6 where both the Montana and lower elevation A-weighted data have been plotted. To determine the effect of altitude from these two distributions requires determining the difference between the L_{50} levels of the two upper (measurable stable foul weather) distributions. This difference is 5 dB. Adjusted for the voltage difference, $120 \log 542/530$, this difference becomes 6.2 dB. The predicted difference using 1 dB/300 m is $(1935-277)/300 = 5.5$ dB.

Fig. 6. Comparison of A-weighted AN distributions from Montana (1984 all-weather) and Oregon (January 1985 to May 1985, all foul-weather) test sites. Sample size: Montana 166,992; Oregon 720.

Single-Circuit Data: Several times over the 16 months' testing period, only one of the circuits was energized. These data have also been analyzed, but it is beyond the scope of this paper to present the results in detail. However, the measured L_{50} levels during measurable stable foul weather were 49.5 and 52.5 dB(A) for circuits 1 and 2 respectively, whereas the calculated levels using the BPA AN formula and the 1 dB/300 m altitude corrections were 49 and 51 dB(A) respectively. This all-weather data is based on over 24,000 data points.

Radio Noise

The all-weather RI cumulative distributions for the double-circuit 500-kV line at 500 and 834 kHz for 1 year are shown in Figure 7. It should be noted that the transition distribution from fair weather to measurable stable foul weather is very broad for RI as compared to AN. Audible Noise is a local phenomena; that is, a microphone located at mid-span of a transmission line primarily measures the noise from that span. A loop antenna, however, will respond to RI produced for several miles up and down the line. Therefore, it can and will respond to high corona currents produced by distant storms even though it may be dry where the antenna is located. This is the reason the transition distribution is spread out more for RI as compared to AN.

Fig. 7 All-weather RI distributions for 1984; Montana Test Site; Sample size: 169,695.

Effect of Temperature: The same temperature analysis conducted on the AN data was also conducted on the RI data. Above 0°C the RI levels rarely reached the highest levels that occurred below 0°C. The reason for this is not fully understood, but it is speculated the main cause is the previously discussed weather pattern. The scattered rain showers that are most prevalent in the Rocky Mountains do not last very long and can be very localized, therefore not allowing enough of the line for several miles from the test site to experience the same rain intensities.

The results of this analysis at 500 kHz are shown in Figure 8. There is very little difference in the fair-weather levels above and below 0°C. However, there is about 6 dB difference between the L₅₀ levels for the upper distributions which represent the average maximum foul-weather conditions.

Fig. 8 All-weather 500 kHz RI distributions for 1984 (grouped by temperature). Montana Test Site; Sample size: above zero 92,000; below zero 79,400.

Determination of Altitude Effect: As previously mentioned, RI could not be measured at the lower altitude test site because of its close proximity to a substation which had noisier 500-kV lines coming into it. Therefore, to determine the altitude effect on radio noise, the measured levels were compared with predictions using three prediction formulas, BPA [12], CIGRE [19], and Electricite de France (EDF) [20, 21]. The results of this analysis are shown in Table III.

TABLE III

COMPARISON OF RADIO NOISE MEASUREMENTS WITH PREDICTIONS

(Based on annual statistics)
(500 kHz) (Old ANSI QP Specification)
(in Decibels)

Weather	Measurements	Predictions (no altitude correction)		
		BPA	CIGRE	EDF
L ₅₀ Fair	50	45.5	48.0	48.5
L ₅₀ Foul	75	69.5	68.0	68.5

The L₅₀ level during measurable stable foul weather conditions for the Montana 500-kV line was 75 dB, whereas the predicted levels with no altitude correction are 69.5, 68, and 68.5 dB using the BPA, CIGRE and EDF formulas, respectively. These differences between measurements and predictions range from 5.5 to 7 dB, whereas the predicted difference based upon the 1 dB/300 m correction is 6.4 dB.

For fair weather, the differences between measurements and calculations are 4.5, 2, and 1.5 dB for the BPA, CIGRE, and EDF formulas. The air at this high altitude in Montana is very clean; therefore, the high summertime RI levels usually associated with lower elevation lines did not occur. Hence, it is not surprising that calculated fair-weather levels using any of the popular RI formulas would be higher than measurements for this line, irrespective of the altitude correction term used.

Television Interference

Figure 9 shows the TVI data that were collected from December 1984 through April 1985. This is a period where one of the two TVI meters was operating very well. Also shown on Figure 9 is the 16 kHz AN data for the same time period.

Fig. 9 All-weather TVI and 16 kHz AN distributions - December 1984 through April 1985; Montana Test Site; Sample size: 16 kHz AN 77,100; TVI 78,468.

The TVI on Figure 9 is an all-weather distribution and like AN and RI, it also has 3 distinct Gaussian distributions. The change from one distribution to another, however, is not as distinct as for AN and RI. The upper one starts at an exceedance percentage of

30%. The middle one is between about 60% and 30% whereas the lower one is below about 60%. The lower distribution is the instrument residual which is typical for these older vacuum tube meters. The middle distribution is primarily fair weather TVI. Personal observations tend to verify this finding. There were times that the fair weather TVI would as high as 15 dB during dry weather. However, the source of the TVI was corona from the glass insulators which are also highly stressed at this high altitude.

For comparison the 16 kHz AN for this same time period was also plotted on Figure 9 since its all-weather distribution is primarily an all foul-weather distribution. The 16 kHz octave band channel does not respond to fair weather corona activity as the fair weather AN from this line is below the instrument noise floor of 16 dB. The 16 kHz AN breaks out of the noise floor at an exceedance percentage of about 30% which is the same exceedance percentage for the start of the upper TVI distribution. Therefore, this upper TVI distribution must be an all foul-weather distribution. Why the TVI all-foul weather distribution doesn't eventually bend over as for AN and RI is not known at this time. The L_{50} level for this upper distribution is 21.5 dB. The BPA TVI prediction formula, which as for AN is based upon measurable stable rain, predicts 19.5 dB for this line with no altitude correction. Therefore, one could say the increase due to altitude is only 2.0 dB. However, to be consistent with the AN and RI analysis, the same percentage point that was used to compare AN and RI measurements with predictions should be used here. For this time period it was about 5 percent. This L_5 level on Figure 9 is 25 dB which is 5.5 dB higher than the TVI predicted at sea level. In fact, the BPA computer program using the 1 dB/300 m altitude correction predicts 26 dB for this line at the average operating voltage of 530 kV. Therefore, for all practical purposes the 1 dB/300 m altitude correction also applies to TVI.

Figure 10 shows the TVI all-foul weather statistics collected at the lower elevation test site during the same 3 rainy periods mentioned in the previous discussion on the AN data. Also shown in Figure 10 is the all-foul weather TVI distribution for the Montana line which was created by eliminating the two lower distributions on Figure 9. The data for the Oregon line is based upon TVI activity above fair weather; that is from the time the TVI increased above the fair weather level during wet weather to the time it decreased back to the fair weather level. Therefore, it includes all foul-weather conditions (measurable stable rain, wet conductor, after rain, fog, light rain etc.). Again, like the TVI data from the Montana line, the all-foul weather distribution increased steadily and didn't reach a saturation point.

Fig. 10 Comparison of TVI all foul-weather distributions from Montana and Oregon Test Sites; Sample size: Montana 26,053, Oregon 723.

As previously mentioned, the L_{50} level for the all foul weather distribution for the Montana line was 21.5 dB. The L_{50} level for the lower elevation line is 16 dB which would be lowered to 15 dB when corrected to the same voltage as the Montana line. This difference of 6.5 dB between the TVI levels for the two lines is 1.0 dB higher than what would be calculated using the 1 dB/300 m term which gave a difference of 5.5 dB. This is very good agreement, considering the complexity of the TVI phenomena and the age and reliability of the TVI instrument.

APPLICATION OF RESULTS

Audible Noise

The State of Montana has adopted an AN limit for high voltage transmission lines based upon average noise levels, as expressed by the annual A-Weighted day-night scale (L_{dn}). This is similar to the EPA Guideline [22]; however, the EPA recommends a limit of 55 dB(A) whereas the Montana limit is 50 dB(A) at the edge of the right-of-way in residential and subdivided areas unless the landowner waives this condition. Montana feels that the limit for transmission lines should be 5 dB(A) lower than the EPA recommendation, since psychoacoustic tests have shown that corona noise is more annoying than other noise sources because of the high frequency crackling that occurs with corona.

Day-night L_{dn} levels can vary quite a bit for transmission lines depending upon whether there is foul weather or not. Figure 11 shows the monthly L_{dn} 's calculated from the test data over the 19 month test period. This data shows the monthly L_{dn} can be very low during the summer months when the foul weather periods are few or nonexistent. At this elevation which is neither a residential nor a subdivided area, the annual L_{dn} is 54.0 dB(A).

Fig. 11 Comparison of monthly L_{dn} 's and monthly L_{50} (measurable stable foul-weather) levels.

Radio Noise and TVI

Montana, like most of the States in the U.S.A., does not have limits for RI and TVI but expects utilities to have mitigation measures to deal with interference to communication systems [6].

BPA, like most utilities, uses the IEEE Radio Noise Design Guide [22] to design lines that are compatible with radio and TV broadcasting. This guide, which is quite old, does not cover the effects of altitude. Figure 4 of that guide shows a range of operating gradients and conductor sizes for single or bundle conductors for comparable noise levels. That curve could be recalculated for higher altitude using the previously gathered information that conductor surface gradient is proportional to $RAD^{1/2}$. How-

ever, that curve also states that the generated radio noise represents a fair-weather level of 40 dBuV/m at 30 m. lateral distance from the outside conductor at 1 MHz. The Montana fair-weather RI data corrected to 30 m and 1 MHz is 39 dBuV/m.

Corona Loss

Preliminary studies by BPA indicate the 1 dB/300 m altitude correction is also valid for corona loss [2].

Colloquial-type data from long open-circuited lines operating at high altitudes in inclement weather has also added confidence in the use of this term for calculating corona loss. It must be remembered that a 3 dB increase in corona loss is a doubling of the losses.

CONCLUSIONS

1. The previously formulated altitude correction of 1 dB/300 m is still valid. It can be used for AN, RI, TVI and possibly corona loss.
2. There is essentially no difference in AN levels either during stable measurable rain or medium to heavy snow.
3. The increase in RI above fair weather levels was not as great for temperatures above 0°C as below 0°C. The reason for this is not fully understood, but could be due to the nature of the rains that occur in the Rocky Mountains.
4. Annual day-night sound levels (L_{dn}) for this double-circuit 500-kV line at 1935 m above sea level is 54.0 dB(A).

ACKNOWLEDGEMENT

The authors wish to acknowledge the efforts of Grace S. Johnson who performed computer analysis of the data, Monte W. Tuominen and Allen L. Burns who assisted in test site selection and development, Wallace F. Baldwin who performed instrumentation maintenance and calibration, Marvin O. Loftness who built and operated the low elevation test site, and Micki Hayes who typed the manuscript.

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Discussion

N. Kolcio (American Electric Power Service Corp., Columbus, OH): The authors should be complimented for their effort in determining the effect of high altitude correction on corona effects. By reaffirming the previously used RI altitude correction and by providing new altitude correction data for AN and TVI, the authors have done a great service to the industry.

One can follow and appreciate the approach used by the authors in establishing the altitude corrections. This was achieved by comparing the L_{50} of "all weather" points of RI, AN, and TVI measurements between the high altitude and the low altitude lines. What is confusing and unclear is how the authors used the L_{50} all weather data in making a comparison with calculations. This relates directly to the method used in obtaining the L_{50} percent value in the foul weather data. The authors did not use all of the foul weather data but selected a portion of the foul weather which they called as "measurable stable foul weather data." According to the authors, it did not include mist, fog, light snow, etc. This L_{50} level was obtained graphically from the all-weather plot by drawing a straight line through the upper normal distribution. The authors found that the L_{50} "foul weather" level fell on about the L_{50} percent point on the all-weather distribution plot. That is to say that the L_{50} of the "all weather" plot was made equal to the L_{50} of the foul weather.

This is a somewhat questionable approach. One reason is that it is not accurate. The graphical selection of the L_{50} point from the plots given in the paper is subject to at least ± 2 dB error. A second reason is that formulas used in calculating RI, AN, and TVI are based on L_{50} which represents all of the foul weather data rather than just a selected portion of it (stable measurable foul weather) which was used by the authors. Data published previously by BPA in Ref. [13], Table 1 clearly show that for RI, the L_{50} foul weather level does not equal the L_{50} all weather for both measured and calculated values.

	Measured	Calculated
L_{50} (foul)	63.0	61.5
L_{50} (all weather)	71.0	66.0

Also, Ref. [18] discusses methods for calculating AN. Most of the formulas mentioned in this reference are based on rain data where L_{50} value encompasses all rains over a period of time, usually a year.

Could the authors explain why they did not follow the more accepted approach, and the one that BPA has used in the past, of presenting the AN, RI, and TVI results in separate fair and foul weather plots? Also, why did they choose to use the L_{50} "all weather" rather than the L_{50} of "all foul weather" in comparing their measured data in Table III with prediction formulas?

In discussing the fair weather RI results of Table III, the authors felt that the reason that they could not get the desired (1 dB/300 m) high altitude correlation between the measured and calculated levels was because of the summertime high RI level that is associated with lower elevation lines and that the popular RI formulas would reflect these high levels in fair weather. It is unlikely that the fair weather RI predictions calculated by the present formulas are based on and will yield so-called "high summertime RI levels." As a matter of fact, the IEEE Committee Report of Ref. [10] shows that "fair weather" RI calculations are based on "all fair weather" data which includes the four seasons of the year. The industry is well aware of the seasonal fluctuations of the fair weather RI. Data reported from Apple Grove 750 kV Project showed a 6 dB variation in fair weather RI due to the seasonal effect. Thus, the present formulas are more representative of the L_{50} of the all fair weather data.

Perhaps the authors would find a better correlation in fair weather RI between the high altitude measurements and analytical predictions if they could use the fair weather plots rather than estimating the L_{50} from the all weather plots.

Manuscript received January 28, 1986.

J. V. King (American Electric Power Service Corp., North Liberty, IN): The authors are commended for the fine work they have done to acquire corona performance data in such a harsh and remote location as that described in the paper.

The authors have attempted to compare data acquired in two locations which have considerably different weather patterns. The Oregon site experiences gentle, long-duration rains whereas the Montana site has mostly snow, with some heavy localized rains. The authors imply that the length of the test period, one year, will make the results acquired at these two sites more comparable. With such different climates as these

two sites, such an assumption seems fallacious. The only valid way to make comparisons between test locations is to do so for common weather conditions (rain, snow, fog, fair weather, etc.). Also, comparisons must account for differences in precipitation rate distributions in order to be truly reliable. It is unfortunate that the authors did not do this.

Conclusion 2 states that essentially no difference was seen in AN levels during rain and medium to heavy snow. It has been our experience that a heavy, wet snow can produce AN levels comparable to those in rain. However, lower AN levels have been measured for light and medium snow, so it is surprising that no difference was seen in the BPA tests. Short-term testing on a 765-kV line in northern Indiana has exhibited a 3 dB(A) difference between median AN levels in rain and snow. Since the authors base their analysis of altitude effect on the premise that AN is the same for rain and snow, one could question the validity of the conclusion that the altitude correction of 1 dB/300 m holds for AN.

One possible explanation for the difference in RI above and below 0° (Conclusion 3) relates to the comparison of rain and snow RI performance. Experience at AEP's UHV Test Station has been that RI is, on average, higher in snow than in rain. Since the data below 0° would be predominately snow data and the data above 0° predominately rain data, the results are not surprising.

Manuscript received February 18, 1986.

D. N. March (Montana State University, Bozeman, Montana): The need to update high altitude effects on 500-kV lines has been apparent since their use has increased, especially in the Rocky Mountain area. Significant numbers of neighbors to such lines have complained of high corona levels. To those of us working with such lines the question had become "Are the high altitude corrections used by utilities and BPA to predict audio noise, as well as radio and TV noise from 500-kV lines, really valid?"

The BPA work which is well documented in the paper adequately answers the question about the high altitude effects. The data are extensive, the equipment was calibrated, and the analysis was thorough. The comparison between the data and the high altitude predictions was certainly good. The research and paper were well done.

I have only a few comments and questions. In Fig. 9 the three distinct Gaussian distributions on the TVI plot are difficult for me to see from the relatively straight line plot shown. At least two of them were apparent on Fig. 10. I would like to have known the bandwidths used on the RI and TVI monitors as well as the detector weighting function used on the TVI meter. Then, too, Fig. 11, showing the audio L_{50} and L_{dn} levels certainly is a function of the particular weather of the year in question. For example, in some years the month of June is very wet in the area and the audible noise levels from the line would reflect that.

Manuscript received February 25, 1986.

C. H. Gary (Electricité de France, Paris, France): The authors of this paper must be commended for their excellent work: the paper contains a number of fundamental data, as well as interesting observations presented in the discussion of the results.

I would like to emphasize some important points. But to begin, I wish to compliment the authors for their technical achievement, when they succeeded in operating a long-term unattended data collection system in such severe climatic conditions which prevail in mountain areas. We know by our own experience how difficult it is, and the care needed, to operate a reliable automatic measuring station even in mild climates!

Coming to the data obtained, it is clear that the most important result is that the variation law with altitude, 1 dB/300 m, was confirmed for RI, and can be extended in some degree to AN, TVI, and corona loss.

For RI, this confirmation is specially precious, because in Publication 18 of the CISPR "Radio interference characteristics of overhead power lines and high voltage equipment," we introduced the use of this law as a Recommendation.

The fact that this law, when the RI measured in Montana and calculated for sea-level are compared, fits better in rain conditions than in dry weather, is not surprising. It is well known that under rain the surface state of a wet conductor is sufficiently stable and reproducible for enabling a fairly good prediction; on the contrary, the surface state of dry conductors depends strongly on local conditions, like presence of industrial pollution, grease, etc.; as the authors state, it is quite probable that the surface state of the conductors in Montana was better than the average one used for example in the CIGRE prediction formula. This discrepancy can fully explain the apparent "nonfitting" of the 1 dB/300 m law for fair weather.

The only experience of EDF, concerning the effect of altitude, was gained in 1970, when EDF was consultant for a high altitude corona test station installed near Mexico City, at an altitude of 3200 m. From measurements of the RI-excitation function (at 500 kHz) under heavy rain, we could observe that, in the range of surface gradients between about 13 kV/cm and 17.5 kV/cm, the RI level was about 10 dB higher than as calculated for 0 m: this result shows that the 1 dB/300 m law seems to remain valid up to more than 3000 m. However, in the range of gradients above 18 kV/cm, the difference tends to vanish (Fig. 1).

Fig. 1. Influence de l'altitude sur le niveau perturbateur d'un conducteur: variation de la fonction excitatrice en fonction du champ superficiel, à 0 m et à 3200 m.

When the value of the excitation function is plotted versus the relative surface gradient g/g_0 , where g_0 is the Peek critical gradient which takes into account the RAD, then the excitation function, for a given g/g_0 , is 10 dB lower at 3200 m than at 0 m; but the two curves are now strictly parallel (Fig. 2). The fact that, in this representation, the difference is

Fig. 2. Influence de l'altitude sur le niveau perturbateur d'un conducteur: variation de la fonction excitatrice en fonction du champ superficiel, à 0 m et à 3200 m.

Note: These figures are extracts from Ref. [1], p. 472.

now negative (-1 dB/300 m) may find an explanation when considering the expression of the coefficient of the Townsend avalanche $\alpha/p = f(E/P)$, which shows that when the air-pressure p diminishes, α must also diminish, thus producing, for a given relative gradient, a smaller avalanche.

With regard to corona loss p , we could also draw a "cycle" $p = f(g)$ during fair weather only; the obtained data confirmed perfectly our theories interpreting the effect of the RAD. It is possible to introduce an RAD in the expression of the "reducing factor" [1], and here also to plot the "normalized losses" versus the relative gradient. Without going into details, let us show the results of our calculation for a two-conductor bundle, conductor radius 1.64 m, at an operating gradient of $g_{max} = 16$ kV/cm.

		Surface state coefficient m	
		0.8	0.6
loss in W/m	0 m	2	14
	3200 m	19	50
ratio	linear	9.5	3.6
	in dB	10	5.6

This table shows that, for dry conductors (where $m \approx 0.8$) we find in fact a difference in the loss of 10 dB; but this difference tends to diminish under rain ($m \approx 0.6$). Unfortunately, there is a lack of data which could confirm our interpretation, and we hope that the authors, Mr. Chartier et al., will have the opportunity to pursue their important work and to bring new data.

Reference

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Manuscript received February 26, 1986.

R. Cortina (ENEL—Centro Ricerca di Automatica, Milan, Italy): The authors are to be complimented for the systematic investigation conducted and for the important contribution given to the knowledge of the influence of air density on the corona performance of ac bundle conductors.

I am particularly glad to see that the empirical formula $E - E_0 = \frac{q - q_0}{300}$

set up at ENEL some years ago for radiointerference on the basis of the limited experimental data available at that time, has been confirmed by the results presented by the authors not only for radiointerference, but also for TV interference, audible noise, and corona loss.

I have a general comment on the paper. The conclusions drawn by the authors are based on the comparison of data obtained in very different weather conditions. Even if the authors have adopted a quite acceptable criterion to select, from the overall data obtained under snow, a more limited sample of data more comparable with those obtained under rain, the possibility of a general application of the empirical formula needs, perhaps, some further verification; a better knowledge of the physical phenomena associated with the influence of air density on the corona generation could give some help in this respect. What is the authors' opinion on this subject?

Considering all these facts, we have preferred to study the influence of air density not in real lines at different altitudes, but using test conductors in cages in well-controlled conditions.

In fact, in the framework of the 1000-kV project, ENEL in cooperation with ESCOM (South Africa) is conducting an experimental research on EHV and UHV bundle conductors, by using the Suvereto cage (about at sea level) and a similar cage situated near Johannesburg (at about 1600 m above sea level). Different bundle configurations (subconductor diameters in the range 18–32 mm; number of subconductors from 2 to 6; spacings from 380 to 450 mm) were tested, in similar surface conditions, at the two locations, by adopting the same test methods and the same measuring instrumentation. The majority of the tests were performed under artificial rain and during the drying period of the conductors; for some conductors, however, data were also obtained in natural weather conditions, especially during natural rain at different rain intensities.

The research is not completed: in particular some additional data in natural conditions are considered necessary to obtain a more complete picture of the problem; in addition, some verifications are in progress to better understand the physical phenomena involved. It is our intention to prepare, possibly for a future IEEE Meeting, a paper which summarizes all the research.

Fig. 1 intends to present just a few results obtained for radiointerference, audible noise, and corona loss, in artificial heavy rain, on a 6–28.81/400 mm bundle conductor.

The figure shows that, for radiointerference and audible noise, the values measured at Johannesburg (1600 m above sea level) are, on the average, 5–6 dB higher than those measured at Suvereto (sea level), in good agreement with the above-mentioned empirical formula (for audible noise the effect is less pronounced at lower gradients, probably due to the background noise).

For corona loss, the data reported seem to indicate no detectable ef-

Fig. 1. Effect of air density on corona generation. Results of test performed at Suvereto (sea level) and Johannesburg (1600 m above sea level).

fect of the altitude. Verifications are in progress to try to understand this phenomenon; in particular checks on the rain intensity at the two test plants will be made, considering that corona loss are much affected by rain intensity.

Manuscript received March 3, 1986.

E. Jeffers (Public Service of New Mexico, Alvarado, NM): The authors are to be congratulated for their excellent work in the field of high altitude corona effects. This work fills a gap in the technical literature, and will be much utilized by utilities such as mine, Public Service Company of New Mexico. Most of our load is above 1600 m and we are currently designing a 345-kV line that may be as high as 3200 m. The weather in much of our service territory is very dry (about 20 cm of precipitation per year) and sounds similar to your Montana test site.

There are some anecdotal accounts of our dry weather increasing corona effects. For example, some people at my company claim that the dust storms associated with our spring winds increase the RIV radiated from transmission lines. Also, during long dry periods (perhaps 2 or 3 months), one would expect an accumulation of dust and some vegetable matter on the conductors and thereby raise the fair weather audible and radio noise. When the rains do come, they are frequently short, but very intense, and do a thorough job of cleaning the month's accumulation of dust from the conductors, thereby reducing the fair weather noise. Do the data permit the authors to comment on the above phenomena?

Manuscript received March 10, 1986.

V. L. Chartier, L. Y. Lee, L. D. Dickson, and K. E. Martin: We appreciate the broad interest in this paper and thank all the discussers for their comments and questions. Their observations permit us to amplify some of the points which obviously need further emphasis.

Mr. Kolcio is incorrect in assuming that we established the altitude correction by comparing the L_s from the all-weather cumulative probability plots of the AN, RI, and TVI measurements between the high altitude and low altitude lines. We compared the L_{50} of the upper normal distributions of the all-weather plots.

It is obvious from Mr. Kolcio's discussions that there is some confusion as to how this L_{50} level is determined from the all-weather distribution and also its importance. First of all, this approach is not new. Lacroix and Charbonneau pointed out in 1965 that the all-weather RI distribu-

tion can be broken up into three normal distributions [1]. They called these distributions: fair weather, foul weather, and heavy rain. C. H. Gary later determined that this so-called heavy rain distribution was reproducible [2]; therefore, he was in favor of characterizing the radio noise performance of transmission lines based upon the median (L_{50}) point of this upper distribution. Gary also called this upper distribution heavy rain. Based upon the work of Lacroix, Charbonneau, and Gary, it became clear that the RI performance during foul weather could be characterized from this so-called "heavy rain" distribution because it represented a stable conductor surface state. The middle distribution between "heavy rain" and fair weather cannot be used to characterize corona performance of a line because it represents an ill-defined conductor surface state created by ill-defined foul weather conditions such as fog, very light rain/snow, after rain, etc. Such foul weather is also strongly affected by the heat produced by load current which is present on operating lines but is not present on test lines.

We are afraid a lot of researchers do not have a good appreciation for the effect that load current has on corona performance of a line. Fig. 1 shows a comparison between the annual AN cumulative distribu-

Fig. 1. A-Weighted annual all-weather distributions comparing the unloaded Lyons 3-phase 7×41 mm configuration with a nearby loaded 500-kV line with a 2×41 mm configuration.

tions for the unloaded 1200-kV test line that BPA operated near Lyons, Oregon and a nearby 500-kV operating line. Both of these lines were exposed to essentially the same weather. The transition from the fair weather distribution to the steady measurable rain distribution on the operating line is very steep, whereas it is very gradual on the test line. This steep transition on the operating line is due to the effect that load current has on discouraging the formation or retention of moisture on the conductors. If an all-foul weather analysis is done on these data, the 500-kV line would have an L_{50} all-foul weather level of about 56.5 dB(A) whereas it would only be 49 dB(A) on the 1200-kV test line. This is a difference of 7.5 dB whereas it can be easily seen that the difference between the upper distributions (steady measurable rain) is only 1 dB. Fig. 1 is a classic example as to why all-foul weather analysis is not a good technique for comparing corona performance of lines nor should such data be used as the basis for the development of prediction methods.

All of the above research has shown that this L_{50} level during steady measurable rain is repeatable; therefore, it is not necessary to measure rain intensity if enough data are collected to adequately define this upper distribution.

CIGRE Working Group 36.01 in [4] has adopted the work of Lacroix, Charbonneau, and Gary. The only disagreement that we have with any of this work is the definition of the upper distribution. In our opinion it is not a heavy rain distribution, but a steady measurable rain distribution. Experiments have shown that the L_{50} AN or RI levels occur at an L_{50} rain intensity somewhere between 1 and 2 mm/h which in our opinion is not a heavy rain. Also, this L_{50} level can be easily reached during a steady drizzle which has lasted for several hours.

The L_{50} level for these upper distributions are determined by finding the middle point of their respective histograms. This is not necessarily straight-forward. Trinh, Maruvada, Flam, and Valotaire have shown how this can be done mathematically [4]. We have chosen to use a graphical technique. This is done by drawing two straight lines through the upper and middle normal distributions. Where these lines intersect is the percent of time that the RI or AN occurs during steady measurable foul weather.

For AN we prefer to draw these lines on the 16-kHz distribution if it is available since its data are totally unaffected by ambient. In Fig. 4 of the paper this intersection point takes place at an exceedance of 7 percent; therefore, the L_{50} AN level occurred at an exceedance of 3.5 percent of the all-weather curve for an L_{50} AN level during steady measurable foul weather of 55.5 dB(A). We have found that this graphical approach gives the same medium value that would be obtained from the midpoint of the histogram of the upper distribution.

Fig. 6 of the paper compares the all-weather data for 1984 for the line in Montana with the all-foul weather data for the line in Oregon. The intersection point between the upper distribution and the transitional distribution for the Oregon data is 26 percent; therefore its L_{50} AN level during steady measurable rain occurred at an exceedance of 13 percent for an L_{50} AN level of 50 dB(A).

The BPA AN prediction formula is based upon the calculation of this L_{50} level during steady measurable rain. Corona performance of lines cannot be compared based upon "all foul weather" data because of the previously mentioned problems with some foul weather conditions and the differences between test lines and operating lines.

Mr. Kolcio is incorrect in assuming that this is a questionable approach, and it definitely is not subject to the error he has stated. As can be seen from Fig. 11 of the paper, the maximum difference between the monthly L_{50} levels and the yearly L_{50} level of 55.5 dB(A) is approximately 1 dB except for the month of August which was an extremely dry month.

Mr. Kolcio is also incorrect in assuming that formulas used in calculating RI, AN, and TVI are based on L_{50} which represents all the foul weather data. Neither the EPRI [6] nor the BPA [7] AN formulas are based on all-foul weather. The EPRI formula was developed from cage experiments using heavy rain whereas the BPA formula is, as previously stated, based upon steady measurable rain. The EDF [8] and EPRI [9] RI formulas are based upon heavy rain. The BPA RI formula is based upon fair weather, and we add 17 dB to obtain an L_{50} all-foul weather level and 24 dB to obtain an L_{50} steady measurable foul weather level. These formulas are the most widely used in the electric utility industry.

Mr. Kolcio is correct when he says that the methods discussed in Ref. [18] for calculating AN are based upon rain data. However, rain is just a portion of all the foul weather a line experiences.

Contrary to what Mr. Kolcio says and based upon the above discussion, there is no one "accepted" approach to presenting such corona phenomena data. However, it is obvious from the above discussion that the approach that we have chosen to use is closer to what the industry is using than the "all-foul weather" approach that Mr. Kolcio thinks

is the "accepted" approach. All-foul weather is a very nebulous concept because it requires being able to determine at all times the surface state of the conductors (wet or dry) which is impossible to do at an unmanned test station and is not even done at the manned test stations.

We feel that all-weather statistics are becoming more and more important for defining the impact of transmission lines. To calculate the annual L_{dn} which is now the requirement in Montana requires all-weather data for at least one year. To define the impact of a line on either people or communication systems requires knowledge as to what percent of the time certain levels exist, which again can only be accurately obtained from all-weather statistics.

Mr. Kolcio completely misunderstands our statement relating to the fair weather RI being lower at this high altitude test site. What we are saying is that the air at this altitude is clean and pure during all four seasons of the year. The lower elevation test sites such as HVTRF, Apple Grove, Lyons, etc., have much higher aerosol counts during the summer months because of bugs, dust, industrial pollution, etc. Therefore, it is not surprising that the L_{50} annual fair weather level at this Montana test site is somewhat lower, comparatively, than at the traditional test sites because the summertime RI levels are so much lower. For example, at this test site the average difference between the RI levels for the months of June, July, and August was only 1.5 dB higher than the average levels during the months of December, January, and February. Similar differences at other test sites have been as high as 6–12 dB.

We appreciate the comments of Mr. Gary who has made many contributions to the understanding of high voltage corona phenomena. We, obviously, agree with his observation that the fair weather surface state of the conductors in Montana are better defined than the ones used to develop prediction formulas because of the lack of industrial pollution. The average monthly fair weather radio noise level at this test site at 500 kHz during the summer months was 51.5 dB whereas during the winter months it was 50 dB.

We appreciate Mr. Gary's sharing his experience at the high altitude test station in Mexico. We have suspected that there had to be a limit to the range of gradients at which the 1 dB/300 m rule applied. It is also interesting that when excitation functions are plotted versus g/g_0 , the curves for both 0 and 3200 m are parallel. The only problem we have with this approach is that Peek's formulas for calculating critical gradient use RAD to the first power which, as we stated in the paper, was based on extremely limited data.

As far as corona loss is concerned, we have very little data to support a 1 dB/300 m relation; and again we appreciate Mr. Gary's contribution. We know of one situation in the Rocky Mountains where an operating 345-kV line at an average elevation of about 1850 m was open-circuited at one end during a combination of steady rain and wet snow that blanketed the entire area. It was 225 miles long, and the wattmeters at the energized end were reading a total of 20 MW flowing into the line. Using any of the popular corona loss prediction formulas would give a level closer to 5 MW. Therefore, based upon the results at Leadville and specific cases as this one, we become confident that the 1 dB/300 m rule is also valid for foul weather corona losses. Operating lines such as the one in Montana cannot provide data to further verify this altitude correction term. Test stations at high elevations are needed, but very few, if any, such stations exist.

We appreciate the comments of Dr. Cortina and his generosity in sharing the preliminary findings of the research that is being conducted in Italy and South Africa. Such data add to the overall value of our paper. We, obviously, are pleased that Dr. Cortina has found the 1 dB/300 m relationship is essentially valid for RI and AN. Of course, we are also puzzled as to why no altitude correction could be seen for corona loss, and we trust Dr. Cortina and his colleagues have discovered the problem by the time this paper is published as corona loss should also increase with altitude, as has been found by other researchers.

Dr. Cortina is concerned that our conclusions are based upon comparing data obtained in different weather conditions. His concern is justified for RI but not for AN and TVI. As we point out in the paper, the RI during rain did not increase as much above the average fair levels as we have seen at lower elevations in Oregon. However, the AN and TVI did. We also determined that the increase in AN and TVI was essentially the same for both rain and snow.

If we had used only the rain RI data to determine altitude effect, there would have been none. As we state in the paper, we have no clear explanation of this except for the fact that AN and TVI are primarily local phenomena whereas the RI is affected by corona for several km up and down the line. At this time we feel the overwhelming majority of the rain periods must have been highly localized.

We are puzzled by Mr. King's comments. He essentially is saying that since the climates are so different between Oregon and Montana it is

impossible to compare the data between the two test sites. But then, he takes us to task for not comparing the data between the two test sites in common weather conditions such as rain, snow, fog, fair weather, etc., and account for differences in precipitation rates. First of all, the test site in Oregon experienced only one snowstorm and that was a very wet snow which was rare at the Montana test site. Secondly, comparing corona phenomena data during fog conditions on operating lines is foolish because of the strong effect that load current has on water drop formation. Thirdly, comparison of fair weather AN and TVI is also foolish when the data are either the result of local noise sources or the residual noise of the instruments. Fourthly, as we stated in the paper, RI data could not be compared for any weather condition because the Oregon test site was too close to a substation.

Mr. King is wrong in stating that differences in precipitation rate distribution must be accounted for in order for comparisons to be truly reliable. As stated previously, Charbonneau, Lacroix, and Gary have determined that the so-called "heavy rain" distribution is reproducible; therefore, its L_{50} level can be determined without knowing the corresponding rain intensity. Comparison of the L_{50} point of this distribution is more reliable than comparing data based upon a rain rate as measured with all the different rain gauges that exist. It should be remembered that none of these rain gauges is truly an instantaneous measurement of rain, and none of them can measure snow rate.

Mr. King's comments about the differences in AN during rain and snow are puzzling. We would expect lower AN levels during light and medium snow compared to heavy, wet snow. Montana rarely experiences the heavy, wet snow that is seen at lower elevations, but it does experience heavy snows of all kinds and our data show that the AN during heavy snow reaches the same and maybe somewhat higher levels than during heavy rain.

How Mr. King comes up with the statement that since we base our analysis on the premise that AN is the same for rain and snow, then the altitude correction of 1 dB/300 m is questionable, is extremely puzzling to us. We used all the data to come up with the altitude correction. We showed that the L_{50} levels during steady measurable rain and snow were essentially the same. We compared the predicted AN level with the measured level. We compared the measured AN level during rain at a lower elevation with all the data in Montana. All this analysis showed that the 1 dB/300 m altitude correction is essentially valid. Had we conducted this analysis on only the rain data, we would have obtained the same result. Combining the rain and snow data does not change the conclusion.

Mr. King's final comment about the difference between the RI data in rain and snow is also puzzling since the answer can be found in the paper. If we had used only the rain RI data and compared it with predictions, there would have been no altitude correction. From the results of other experiments, we knew that this was false. We also knew from experiments on a lot of operating lines and test lines that the L_{50} RI level during "heavy rain" is consistently about 24 dB higher than during average fair weather conditions. This increase was not seen in Montana for rain, but it was seen for snow. Therefore, the explanation has to be instrumentation problems (of which there were none), or unique weather conditions. At this time we think it is due to unique rain conditions because rains in Montana tend to be highly localized.

We also appreciate Dr. March's discussion, and we agree that the three distinct Gaussian distributions on the TVI plots are difficult to see. The original plots were of course on 8½- × 11-in paper and the distributions were much easier to see. IEEE/PES requires the reduction of such plots for publication. The study of the larger plots showed three distinct Gaussian distributions; however we were surprised that they did not produce an S-shape as was the case for the AN and TVI distributions. As

stated in the paper, the TVI meters were old vacuum tube meters which are not as stable as the modern solid state meters, and they do not hold calibration as well. However, as explained in the paper we fed a calibration signal into the meter once each day and corrected for any drift of the meter off of the original calibration. The meters that were used meet the ANSI C63.2-1980 standard. The bandwidth of the RI meters was 5 kHz and the TVI meter was about 150 kHz. The charge/discharge time constants for the QP detector in these two meters is 1 ms/600 ms.

We also agree with Dr. March's comment that the monthly L_{dn} levels are a function of the particular weather in question, but we doubt very much that the annual L_{dn} would be changed by more than 1-2 dB unless it was calculated from data obtained during an extremely wet or dry year. The L_{50} level during measurable steady foul weather is essentially repeatable as we have discussed earlier, but again it depends upon the line experiencing such foul weather during the month. Such measurable steady foul weather will be experienced several times during a one-year period. On a monthly basis, if one examines Fig. 11 very closely, it can be seen that the monthly L_{50} level is within 1 dB of the yearly L_{50} level of 55.5 dB(A) except for the month of August which was a very dry month.

We appreciate Mr. Jeffers's discussion as his company is operating high voltage lines at high altitudes. The observations of the people at Public Service Company of New Mexico are quite accurate. Corona effects will increase during dry periods in areas where there are increased aerosols, whether caused by nature or man. This has been seen by many observers on lines all over the world at high and low altitudes. Our experience is that the RI levels during these long dry dusty periods are on the average 6 dB higher than normal. After a good rainstorm, the RI will drop by about 6 dB which is due to the rain washing off the conductors. We did not experience such phenomena at our test site in Montana because it was located in an area which consisted of grass and forests. Aerosol increase due to dust, bugs, and organic particles was very small even during the dry periods. Whereas the fair weather RI levels on the line described by Mr. Jeffers can be at least 6 dB greater on the average during the dry summer months than during the winter months, the summertime RI levels at our Montana site as previously mentioned were only 1.5 dB on the average greater than the average level during the winter months.

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