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FIELD DETERMINATIONS OF HVDC OZONE
PRODUCTION RATES

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FIELD DETERMINATIONS OF HVDC OZONE PRODUCTION RATES

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Abstract -- The environment near a high voltage direct current (HVdc) transmission line experiences corona effects, including the production of oxidants. Field determination of ozone production rates were made at the Bonneville Power Administration (BPA) HVdc Test Facility, the Dalles, Oregon, in fall and winter 1977. A novel micrometeorological profiling technique was used to identify sources of ozone plumes. The results indicate that even during precipitation the atmospheric ozone concentrations from HVdc lines at voltages up to +550 kV are relatively small. Measured atmospheric ozone concentration plumes are consistent with laboratory data predictions of ozone concentrations based on corona, line parameters, and ambient dispersion. This confirmation under worst-case field conditions demonstrates the validity of previous estimates of a very low magnitude of the potential ozone effects.

INTRODUCTION

Transmission of electrical energy by high voltage direct current (HVdc) transmission lines over long distances has proven to be an attractive alternative to high-voltage alternating current (HVac) transmission lines, primarily because of the greater efficiency of HVdc transmissions. The +400 Celilo-Sylmar HVdc Intertie between Oregon and California has demonstrated the feasibility of long-range HVdc systems in the United States; other HVdc transmission lines are in planning and construction stages. However, implementing this relatively new technology raises concerns about potential environmental effects.

The environment near HVdc transmission lines is affected by the operation of the lines, which are designed to operate at high voltages with the conductors near or in corona. Environmental effects include: complex electric fields, space charges, noise, radio and television interference (RI, TVI) and oxidants. This paper discusses one environmental concern--unresolved ozone production rates under actual field conditions from the operation of a HVdc transmission line.

Although laboratory tests of corona discharge [14, 16] have provided the basis for models that predict low concentrations of ozone [13], questions have been raised concerning the validity of extrapolating laboratory tests to actual lines and conditions. For example, the greatest corona losses on operation of either HVdc or HVac lines occur during precipitation, a condition difficult to model in laboratory tests.

In wind-tunnel studies, the ozone production rates per corona current were unit-greater for a negative pole than for a positive pole [14]. In these studies, ozone production rates increased as the square of the magnitude of the surface gradient factor, and ozone production rates on the HVdc conductors were directly related to the corona losses.

In addition, corona loss has been shown to vary with transmission-line configuration and changes in ambient atmospheric conditions [2]. The corona loss on HVdc transmission lines was shown to be a function of wind speed, rain, snow, and fog, with a slight dependence on relative humidity. The Bonneville Power Administration Study showed that the corona loss on an operational HVdc line typically increased between a factor of 2 and 5 during the onset of precipitation conditions, with the greatest change being an order of magnitude increase. With regard to wind speed, the empirical relationship for variation of corona loss was:

$$CL = 1.6 + 0.44 V \quad (1)$$

where CL was corona current per kw per conductor (km) and V was the wind speed between 0 and 10 m/s.

The study discussed herein sought to define the ozone concentrations attributed to corona losses under actual field conditions. To accomplish this objective specially formulated field studies were conducted over a range of natural conditions at a HVdc transmission test line. These studies included detailed profiles of ozone temperature and moisture using a roving probe system. Corona losses were determined using the total current losses on the test conductors. These measurements were used to define the magnitude of the ozone line-source term on the HVdc test lines.

Although the causes of and the influences on ambient surface-layer ozone concentrations may be debated ([15], [3], and [10]), the magnitudes of typical ozone concentrations are defined here for comparative purposes.

Values ranging from a few ppb to 50 to 60 ppb are typical ambient values at remote sites and values over 100 ppb are not uncommon at sites under urban influence.

OZONE PRODUCTION RATE ESTIMATES

Ozone production rates from corona on the conductors can be estimated in two ways: from the line operating variables with a normalized source term, or from measured increases in atmospheric ozone concentrations.

For computation based on line operating variables, the rate of ozone production is assumed to be directly related to the rate of corona loss. Basing their production rates on wind-tunnel tests, Roach et al. [14] give the production rates $P_{\pm}$ for ozone from dc-corona as:

$$P_{-} = 1.26 \times 10^{-9} \text{ g/W/s} \quad (2)$$

$$P_{+} = 0.38 \times 10^{-9} \text{ g/W/s} \quad (3)$$

These production rate values were derived over a relatively wide range of conditions.

These production rates were applied to The Dalles HVdc test line to generate the source strength (S_+) for the dc-test line at the site for each 1 mA of corona current and for each 100 kV of voltage:

$$S_- = 1.9 \times 10^{-2} \text{ ppb/m/s} \quad (4)$$

$$S_+ = 0.6 \times 10^{-2} \text{ ppb/m/s} \quad (5)$$

For computational purposes a combination source strength, S , was defined,

$$S = 1.2 \times 10^{-2} \text{ ppb/m/s} \quad (6)$$

for each 1 mA of corona current and each 100 kV of bipolar voltage.

The ozone produced on the conductors consisted of two elevated parallel line sources of ozone, one on each pole. Using a Gaussian plume model for flow perpendicular to the conductors, the centerline ozone concentrations (χ) from a conductor was given by:

$$\chi = \frac{1.60 Q_L}{\sigma_z \bar{u}} \left\{ 1 + \text{EXP} \left[-\frac{2h^2}{(\sigma_z)^2} \right] \right\} \quad (7)$$

where

- χ is air concentration, mass per volume;
- Q_L is the source term, mass per time per length;
- σ_z is the vertical standard deviation (downwind distance appears implicitly in this value);
- $\bar{u}$ is the average wind speed.

Observations of the visible corona on HVdc test lines to 600 kV support the use of uniform line source assumption, particularly for rain conditions [8]. For computation of the source term on the line from the atmospheric concentration observations, we solve Equation (7) for Q_L :

$$Q_L = \frac{\chi \sigma_z \bar{u}}{1.6} \left\{ 1 + \text{EXP} \left[-\frac{2h^2}{(\sigma_z)^2} \right] \right\}^{-1} \quad (8)$$

The above discussion provides two independent methods of computing ozone production rates on the energized conductors. Equations (4), (5), and (6) are based on test line operating variables alone (line voltage and corona loss). Equation (8) expresses ozone production rates as a function of atmospheric variables (peak value, standard deviation, and wind speed).

MEASUREMENT METHOD

The ozone source terms were studied using sensitive, micrometeorological profile techniques that incorporate a roving input system and provide better vertical resolution than fixed-height monitoring systems. This technique has its origin in studies of the structure of the natural ozone profiles in the atmospheric surface layer from the viewpoint of estimating natural surface dry-removal rates of ozone ([12], [1], [8], [7], [4], and [5]).

Using a single-intake line and monitoring system results in profile accuracies much better than those received using multiple fixed-height systems. The relative calibration errors between monitors are eliminated. The profile accuracy depends on the sensitivity of the ozone monitor (± 0.34 ppb). The detailed vertical profiles allow definition of upwind sources of ozone in terms of the peak values and widths of the

plumes (Figure 1). Upwind ozone concentrations are monitored at line height to define the changes in ambient ozone concentrations.

FIGURE 1. Diagram of Effects on Ozone Profiles Upwind and Downwind of an Energized HVdc Transmission Line.

Figure 1 also illustrates the effect of the earth's surface as a sink. The natural vertical ozone upwind profile reflects the ozone-removal processes at the earth's surface. Changes of 1% to 10% in ozone concentrations between conductor heights and the near-surface values (1m) are the normal order of magnitude for this variation, which depends on the ambient atmospheric conditions.

The profiles in Figure 1 refer to average profiles at an ideal site with a good uniform fetch for development of vertical profiles. Individual, instantaneous natural profiles will show more variability than that illustrated in Figure 1. The complex flow and generally poor fetch at the site indicate that complex influences can be anticipated. The profile technique is still a powerful tool under nonuniform conditions, although a more detailed analysis is required to assure that the origins of ozone concentration changes are identified. Tracer tests assure that the airflow from the conductors passes by the measurement points. Concurrent detailed profiles of ozone, temperature and moisture are made. Corresponding profile structure reflects the local flow patterns. Ozone from the conductors will appear as a measurable change in the ozone profile without corresponding changes in the temperature and moisture profiles or in the upwind ozone monitor.

SITE

The field studies were conducted at BPA's HVdc Test Facility at The Dalles, Oregon. The field data were taken on a sloping site adjacent to studies being conducted by BPA. This sloping field site was located on section 1, which had 40-mm conductors for each pole supported by truncated, double-circuit, steel towers. The poles were spaced 12.2 m apart with 457 mm sub-spacing of conductor. The average conductor height on this section of line was 18.3 m; for the entire site the average height was about 12 m.

Figure 2 is a schematic diagram of the site, and includes the experiment installation and instrumentation. The figure shows the instrumentation in an ideal configuration on a flat site with horizontal distances collapsed. The actual site was on sloping terrain with about a 2.5 m drop from under the conductors to the base of the profile tower.

This site does not correspond to ideal sites (good fetch, uniform surfaces upward, no slope, etc.) for which dispersion data are available ([11, 17].) The complex influences at the site are expected to result

in greater dispersion than the 1- to 3-m range of σ_z values estimated for a corresponding uniform site.

The field installation (see Figure 2) had ozone monitors at both sides of the conductors. Based on the prevailing wind direction at the site, the left side of this site, as shown in Figure 2, was instrumented with the "upwind" monitor for ozone concentrations at the conductor height. The right side was intensively instrumented as the "downwind" monitor. The right side included roving-profile capabilities for ozone, air temperature and humidity. Fast-response wind and temperature sensors were at three fixed heights on the "profile tower." The site was also instrumented for precipitation. A fixed-height wind speed and direction system was used for real-time monitoring. Except for the latter system, the outputs of all systems were recorded on magnetic tape in data blocks at the rate of 1.5 Hz per data block.

FIGURE 2. Schematic Diagram of The Dalles Test Site

The profiles were measured with an Ozone Analyzer Model 10516 manufactured by Monitor Labs. The response time of this instrument is about 60% in 1 s. The fixed-height monitor was a Beckman Model 950 Ozone Analyzer with response time of about 7 or 8 s. Tests were conducted to assure that the monitors gave comparable readings of ozone concentrations.

The ozone monitors were calibrated with an Analytical Instrument Device (AID) ozone generator at ambient atmospheric pressures. A conservative, absolute accuracy of ozone calibrations is 10% of a full scale. The relative calibration between the two ozone monitors calibrated side-by-side will be considerably better and is estimated to be on the order of $\pm 3\%$ of full scale.

RESULTS

The ozone profile results were analyzed in terms of observed and predicted ozone emissions by the energized conductors.

Two tracer tests from the conductors were performed: one during unstable conditions and the other during near neutral conditions. The conductors were not energized during these tests.

Considerable variability in the plume height existed at the profile tower during both tests. Although the "average" plume intersected the profile tower near 12 m, the variation was great enough for the plume positions to vary from ground level to the top of the tower (18.3 m). For unstable conditions, there was a definite tendency for the plume to rise upwards away from the general downslope of the site. A shallow upslope wind, under and about perpendicular to the winds at conductor height, contributed to this upward tendency of the winds at conductor height. The variability of the plume height was greater for the unstable case.

The effects of the energized lines on the tracer trajectories were studied with the source on the wooden pole upwind of the conductors. The conductors were alternately energized up to +600 kV and de-energized to test for effects of energized conductors on tracer movement past the lines. Observations showed no local effects on either the tracer plumes passing immediately by the conductors or on the height of the tracer plumes downwind of the lines.

With the exception of two cases during precipitation, the vertical profiles of ozone concentration demonstrated no discernible evidence of ozone plumes originating from the energized conductors. Ozone plumes, if any, were masked in the natural, background ozone variability, an expected effect, considering the very low ozone concentrations predicted for conditions without precipitation.

Two data sets, both with precipitation and evidence of ozone from the energized conductors, are the only two cases in the field studies in which ozone concentrations were discernible over background ozone concentrations. Comparisons to predicted concentrations can be made from these data sets.

An example of the individual profiles of ozone concentrations, air temperature, mixing ratio and relative humidity are plotted in Figures 3 and 4. Note that the direction of sensor movement is labeled as upsweep and downsweep. The u, v, and w average wind-speed components at conductor height are given in m/s after the time period. The winds are nearly directly across the conductors towards the profiling tower. The fixed-height (12 m), ozone-monitor data are plotted for time-series reference on the same scale to allow point-by-point comparison of the fixed-height ozone data with the profile data.

FIGURE 3. Vertical Profiles for December 2, 1977

This series of profiles illustrate an event that is not attributable to the energized lines. The "large depression" of ozone concentrations that clearly registered on both the upwind and downwind monitors is only about a 6-ppb change in concentration. The profiles demonstrate both that the roving ozone monitor and the fixed-height ozone monitor on opposite sides of the HVdc conductors respond in an identical fashion to ambient ozone concentrations and that profiles with structure features of several ppb can be detected and identified with the data from both monitors.

Profile Case Study 1 - Low Wind Speeds and Precipitation

The first of two data sets with evidence of ozone from energized conductors will be referred to as Profile Case 1. Profiles were obtained from 14:53 to

18:00 on November 28, 1977. During this late afternoon test, the winds were near calm and shifting. Steady precipitation amounting to 2.19 mm occurred during the 3-h measurement period.

The corona loss values for this case, as summarized from the records at the BPA HVdc control room, are given in Table 1. These corona loss values are typical of the larger values associated with precipitation at the test facility. The highest observed values in earlier tests at this facility were on the order of 100 mA for the negative pole [13]. The values in Table 1 are about 70% of the worst-case corona loss values.

FIGURE 4. Vertical Profiles for December 2, 1977

TABLE 1. Corona Loss for Profile Case Study 1

Time	Positive Corona Current, mA	Negative Corona Current, mA	Bipolar Potential, kV
14:30	30	28	500
15:00	57	52	550
15:30	59	60	550
16:00	65	57	550
16:30	36	38	550
17:00	55	36	550
17:15	70	67	550
17:30	38	45	550
18:00	34	39	500

Ambient ozone concentrations in unperturbed profiles were on the order of 2 to 4 ppb. Although near the detection limit of the monitors, the dual ozone tracers were consistent during unperturbed periods.

Two individual plots of ozone, temperature, and moisture are given in Figures 5 and 6. A major peak of 5 ppb occurs at about 20 m in both the upsweep and downsweep as shown in Figures 5 and 6. A second "near noise" peak of 1 to 2 ppb occurs close to the 12-m height. These peaks are suggestive of the positive and negative poles. The next sequential profile (not illustrated) shows a slight upper-level peak and no discernible peak at 12 m. The subsequent several profiles demonstrate no discernible peaks.

A predicted ratio of the peaks for Figures 5 and 6 is 0.38 (5 to 2). This was computed from test-line parameters independent of the profile, accounting for the different distances to the conductors; corona currents (59 mA for the positive pole and 60 mA for the negative pole); the unequal production rates for each pole; and the 500 kV voltage on the conductors. This ratio is close to the ratio of the observed peaks.

The consistency of profile and predicted ozone production rates may be checked by solution for the implied wind speed. The profile peak has a value of about 5 ppb and a vertical standard deviation (σ_z)

of about 4 m. Equation (7) may be solved for the wind-speed component perpendicular to the conductors, $\bar{U}$. For the voltage (550 kV) and the negative conductor corona loss (60 mA), an estimate of the implied wind speed component is 0.5 m/s.

FIGURE 5. Vertical Profiles for November 28, 1977

FIGURE 6. Vertical Profiles for November 28, 1977

FIGURE 7. Vertical Profiles for November 28, 1977

The minor peak at 12 m is not as well defined as the peaks at 20 m. Assuming a positive conductor source and $\sigma_z = 3$ m (negative pole σ_z adjusted for a shorter distance), the peak of 1 to 2 mb produces estimates of $\bar{U} = 0.3$ to 0.5 m/s.

The maximum corona loss occurred at 17:15 (see Table 1). This maximum loss was associated with several ozone profiles with larger changes in ozone concentrations. The peaks in profiles, such as shown in Figure 7, range up to 10 ppb with large vertical standard deviations. Solving Equation (7) for $\bar{u}$, using 137 mA as total corona loss, produces a predicted value of $\bar{u}$ of 0.25 m/s.

FIGURE 8. Vertical Profiles for December 2, 1977

In all cases, the computed winds are in the observed range of 0 to 1 m/s. These computations demonstrate consistency between the observed profiles and computed ozone production rates.

The change in the z values is an important difference in the above two examples. The first example has a z value of about 4 m (the approximate magnitude expected for neutral conditions and a 26-m fetch.) The second example has a much larger z value, estimated to be 10 m. The larger z values are indicative of a longer distance to the source. Because winds at an angle to the conductor will have a longer travel distance, the difference may be the result of different wind directions.

Profile Case Study 2 - Moderate to High Wind Speeds and Precipitation

Data for 52 vertical profiles (the second data set) were obtained from 7:13:32 to 10:27:55 on December 2, 1977. Figure 8 shows an example of the ozone, temperature, and moisture profiles and fixed-height ozone plots for this case study.

The corona loss and voltage levels for this period are shown in Table 2. These values are from the BPA HVdc control room records. The corona loss values are about 50% of the worst-case historical values for the test facility. There was 0.95 mm of precipitation during the 3.25-h study period.

TABLE 2. Voltages and Corona Loss Data for Profile Case Study 2

Time	Positive Pole		Negative Pole	
	Voltage, kV	Corona Loss, mA	Voltage, kV	Corona Loss, mA
07:00	501	24	496	34
07:30	506	37	495	57
08:00	506	65	495	38
08:30	503	46	497	39
09:00	503	49	495	51
09:30	503	63	497	47
10:00	506	59	496	41
10:30	503	48	496	52

The wind direction was relatively steady with a downwind component across the conductors towards the profile tower. The speeds were between 6 and 10 m/s. The average speed was 7.5 m/s compared to the average speed component of 7.3 m/s perpendicular to the conductors. In contrast to the first case study, the winds during the second case study allow a clear, consistent definition of trajectories. The average, vertical-velocity wind component is consistently downward in each profile set. The magnitude matches approximately the value for flow parallel to the sloping site. The average, intersection point on the profile tower is near the 12-m conductor height.

Although almost masked by the background variability, discernible peak ozone features that are attributed to ozone from the energized conductors occur in several of the downwind profiles. Based on observations, no corresponding peak structure exists in the upwind monitor record. These downwind ozone peaks are identifiable because their peak values and vertical extents are larger than those exhibited by the background variability. These downwind peaks are not coupled with variations in temperature or moisture profiles and occur in cases with relatively smaller wind speed variability.

The upsweep profile for 07:34:52 to 07:40:11 is an interesting example that has both natural and apparent conductor-derived ozone variations (see Figure 8). The dual ozone traces show similar variations up to 10 m, indicating natural variations. At 13 and 19 m, ozone peak features occur, both with peaks of about 1.5 mb and a vertical standard deviation of 1.5 m. Lack of similar structure in either the upwind or concurrent micrometeorological profiles indicates that a local source caused these peak ozone variations.

There are two alternative interpretations for this dual peak: the ozone plumes from the conductors may have been intersected twice by the roving sensor, or the two peaks may be separate plumes from the two energized conductor lines.

Table 3 contains a comparison of observed and predicted ozone source terms for this dual peak example and several other profiles with similar ozone peaks. Table 4 presents the values used in the derivation of Table 3. Predicted values are computed both for an average source term (Equation 6) and single poles (Equations 4 and 5). The observed source term values are computed from Equation (8) using values of X and σ_z from the ozone profiles and u (the wind component perpendicular to the conductors) as measured by the 12-m Gill anemometer. A bias in Table 3 for slightly larger observed estimates than predicted estimates results from using observations for maximum conditions (ozone peaks) and predictions based on half-average values (corona currents).

TABLE 3. Comparisons of Observed and Predicted Ozone Source Terms for Case Study 2

Profile Figure in Reference [6]	Profile Source Terms, ppb/m/s	Predicted Source Terms, ppb/m/s	
		Both Poles	Single Poles (a)
G-1	18.0	4.8	4.4
G-2	6.4	5.8	5.5
G-3	8.0	6.2	4.5
			1.5 (P)
G-3	8.0	6.2	4.5
G-5	15.1	5.7	4.3
G-7	9.5	6.9	4.5
G-10	8.0	6.9	4.5
Averages	10.4 $\pm$ 4.4	6.1 $\pm$ 0.7	4.5 $\pm$ 0.4

(a) Computed based on emission from the negative conductor; positive values indicated by (P).

The results in Table 3 show that conductor source-term interpretations of the peaks in this series are consistent with the predicted ozone production rates. The agreement in Table 3 is quite good, considering the variability in the profiles and uncertainty in the corona-loss estimates. The observed values are slightly higher than the predicted values but are still within one standard deviation of the range of the observed values.

TABLE 4. Summary of Profile and Conductor Variables for Case Study 2

Profile Figure in Reference 6	Observed Variables				Conductor Variables		
	Observed Profile Peak, ppb	Vertical Standard Deviation, m	Height of Peak, m	Wind Speed, m/sec	Bipolar Potential, kV	Corona Loss, mA Both Poles	Corona Loss, mA Single Pole
G-1	1.5	2.0	15	9.6	500	47	46
G-2	1.0	1.6	10	6.4	500	94	57
G-3	1.5	1.2	11.5	7.1	500	99	43
G-3	1.5	1.2	19	7.1	500	99	51(a)
G-5	1.2	2.4	17	6.9	500	93	45
G-7	0.9	2.0	13	8.4	500	110	147
G-10	1.0	1.6	12	8.0	500	97	48
Averages	1.2	1.7	13.9	7.6	500	97	48

(a) Computed based on emission from the negative conductor

CONCLUSIONS

The test results indicate that environmental ozone from HVdc transmission lines at voltages up to +550 kV, even for worst-case conditions, are reasonably predicted by extrapolating ozone production rates from wind-tunnel tests. This confirmation of the production rates is based on consistency between independently observed and predicted ozone production rates during precipitation conditions.

The magnitudes of changes in ozone concentrations attributable to the energized conductors are small for all conditions. For fair weather conditions, the effects, if any, are not detectable in the natural variability of ambient ozone. The worst-case for an elevated plume is a 10-ppb increase for low-wind precipitation conditions 26 m from the conductor centerline at +500 kV and 137 mA total corona current. The surface-level increase in ozone is less but of the same order of magnitude. This value and extended vertical distribution is attributed to the long fetch created by winds nearly parallel to the conductors.

The roving-profile technique has proven to be an effective method for defining the low concentrations of ozone emission from HVdc transmission lines. The origins of ozone plumes are identified in a reliable and consistent fashion. This success is the result of the sensitivity of the approach for determining small changes in ozone concentrations.

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