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SURVEY OF MAGNETIC FIELDS NEAR BPA 230-kV AND 500-kV TRANSMISSION LINES

FINAL REPORT

**Prepared by
PORTLAND STATE UNIVERSITY
Portland, OR**

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Contract No. DE-BI79-89BP01305

May 20, 1991

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ABSTRACT

The purpose of this study was to characterize typical levels and variability of 60Hz magnetic fields at the centerline and edge of right-of-way of Bonneville Power Administration (BPA) 230-kV and 500-kV transmission lines. This was accomplished by taking magnetic field measurements at over 800 spans in Oregon and Washington. The spans were sampled using a stratified random sampling procedure with region (East vs. West), voltage (230-kV vs 500-kV), and circuit configuration as strata. There were five different circuit configuration groups for each region/voltage category requiring a total of 200 strata. Magnetic field measurements were taken at 13 locations under each span using an EMDEX-C as a survey meter. Additional information recorded for each span included conductor height (at 10 locations), right-of-way width, longitudinal and lateral slope, time of day, vegetation, terrain, weather conditions, temperature, wind speed, span length and presence of other lines in the corridor.

Single-circuit and double-circuit configurations were analyzed separately. For the single-circuit configurations, magnetic field measurements were normalized by the contemporaneous line current as recorded by BPA's SCADA system. The eight normalized summary measures computed for each span were: magnetic field at midspan of the center line, average magnetic field along the centerline, maximum magnetic field, average magnetic field, standard deviation of magnetic field, maximum magnetic field along the edge of the right-of-way, average magnetic field along the edge of the right-of-way and standard deviation of magnetic field along the edge of the right-of-way. All summary measures were initially analyzed for differences due to region, voltage, configuration group, span length, presence of other lines in the corridor, terrain and temperature.

No differences in the summary measures were found for the two regions. The normalized summary measures were higher for 230-kV spans than for 500-kV spans because of lower conductor heights. Significant differences were found among the three 230-kV single-circuit configuration groups which could be explained somewhat by different right-of-way widths and conductor phase spacings. No significant differences were found among the three 500-kV single-circuit configuration groups. Because there was no consistent pattern of differences

among groups, it was concluded that configuration did not play a strong role in determining differences in summary measures for this measurement sample. No consistent pattern of differences in the summary measures were found for the other variables.

Current and midspan height accounted for 70 to 80% of the variance in the non-normalized magnetic field summary measures. The remaining variance is likely to be a function of errors in the magnetic field and height measurements as well as errors in the determination of current on the line.

Annual magnetic field levels for most of the single circuit lines were estimated using the normalized magnetic field values and annual current data obtained from BPA SCADA records for 1989. Estimates of annual average midspan magnetic field were 29 mG and 38 mG for 230-kV and 500-kV spans, respectively. The average values of measured centerline fields were significantly higher than the estimated annual average values for all summary measures. This difference is attributed to the lack of randomization of the observations with respect to time-of-day and season.

Magnetic fields were calculated using minimum design conductor height and compared with measured values. The calculated fields agreed reasonably well with the average of fields measured at the edge of the right-of-way. However, on the right-of-way the calculated fields were higher than the observed values.

For 11 (five 230-kV and six 500-kV) single-circuit lines, a minimum of 18 spans were sampled per line to determine the variability along a line of the eight summary measures. The edge of right-of-way summary measures were relatively constant for each line.

Variation in non-normalized magnetic field measurements was examined for double-circuit configurations using spans from three lines. Approximately 80% of the variance of the non-normalized centerline summary measures of a span was accounted for by currents on the two circuits of the line and conductor height. The relationship between magnetic field measurements and these three variables was not as strong for the edge of right-of-way summary measures.

Forty-eight of the spans were measured a second time at the end of the data collection period and these repeat measurements were compared to the original measurements. The differences in the normalized summary measures were within expected limits given the level of error in measuring the magnetic field and determining current on the line.

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TRANSMISSION LINES

1.0 INTRODUCTION

There is increased utility, regulatory and public interest in the levels of 60-Hz magnetic fields present in the environment. This increased interest has been precipitated by some epidemiologic and laboratory research which indicates that adverse health effects are associated with exposure to these magnetic fields. Magnetic fields are produced by the transmission, distribution and use of electrical energy and thus magnetic fields are present in virtually every inhabited area of the country.

One source of magnetic and electric fields that receives considerable public attention and is highly visible is high voltage transmission lines. Because of their relatively simple geometry and balanced loads, transmission lines represent one of the few field sources that can be treated analytically: i.e., there are calculation methods, usually in the form of computer programs, that can predict magnetic (and electric) fields accurately. The calculations, however, usually rely on ideal models that do not take into account terrain, actual conductor height and actual current levels present. Thus, these calculations are used to provide field values for an idealized, not real, situation. Although this approach can be used to characterize maximum field levels, it does not necessarily provide an accurate description of the fields which are actually present under and adjacent to transmission lines.

This project is part of an effort by the Bonneville Power Administration (BPA) to more accurately describe the actual magnetic field environment near transmission lines. The purpose of this study was to characterize the levels and variability of 60-Hz magnetic fields at the centerline and edges of rights-of-way (ROW) of BPA 230-kV and 500-kV transmission lines. The spatial variability results from this work will complement another BPA magnetic field characterization study that is using historical current loading on specific lines to predict their temporal distribution of fields. [1]

The specific objectives of the measurements project reported here were to:

describe typical magnetic field levels measured under and adjacent to a variety of BPA transmission lines and

determine the variability of magnetic fields along selected transmission lines.

These objectives were accomplished by collecting magnetic field measurements and other data at 824 randomly selected spans in Oregon and Washington of the BPA 230-kV and 500-kV transmission line systems. Measurements were performed between January and August, 1990 by two-person teams of Portland State University (PSU) graduate students who were trained in project measurement protocols. Resultant magnetic fields were measured along the centerline of the line and at the edges of the right-of-way using EMDEX-C magnetic field meters (resultant magnetic field is the square root of the sum of the squares of the three measured orthogonal magnetic field components).

To permit meaningful comparisons of field levels and determine the variability associated with spatial factors, magnetic field measurements were normalized by the line current present on the line at the time of field measurement as recorded by the BPA Supervisory Control and Data Acquisition System (SCADA). The normalized field values (mG/A) for each span were combined into several summary measures which characterized fields for the entire span, fields along the centerline and fields at the edge of the right-of-way.

Measurement data for the spans were then analyzed in terms of the following strata: region (East and West), voltage class (230-kV and 500-kV) and design geometry (called "configuration group").

2.0 METHODOLOGY

Study protocols were designed to: take advantage of the latest instrumentation; minimize the amount of equipment required in the field while adhering to appropriate measurement standards; allow the recording of weather data and produce measurement data that can be compared with similar efforts in other parts of the country.

2.1 Protocols

The measurements were performed by two-person teams, one collected measurements while the other recorded them on the data forms. Magnetic field levels were measured with an EMDEX-C magnetic field meter. Three magnetic field measurements were taken at five-second intervals at each measurement location. The mean of these three values was subsequently used in the analysis. Magnetic field measurements were made following standard procedures [2]. Longitudinal and lateral distances under the span were measured with a non-metallic surveyor's tape. Conductor height measurements were obtained with a hand-held optical range finder.

2.2 Instrumentation

After a review of various survey and microprocessor-based magnetic field meters and based on previous experience with such instruments, the EMDEX-C magnetic field meter manufactured by Electric Field Measurements Co. of West Stockbridge, MA was selected for use. This meter is a commercial version of a device originally developed by the Electric Power Research Institute (EPRI) [3, 4].

The EMDEX-C is a small, microprocessor-based magnetic field data logger that displays and stores instantaneous readings of magnetic field from three orthogonal axes. Although developed primarily as a personal exposure meter, the unit can also function as a survey meter. The EMDEX-C meter computes and displays the resultant field, where the resultant field is defined as the square root of the sum of the squares of the three orthogonal field components. The

resultant field constitutes an upper bound on the magnitude of the magnetic field.

The range of the EMDEX-C is from 0.1 mG to 25G in four automatically selected ranges. Proper calibration of all units was verified by the BPA Division of Laboratories prior to the study and found to be within $\pm 2.5\%$ for fields of 10 mG and greater. Inaccuracies of 10% were noted at fields of 1.0 mG.

Operational checks of the EMDEX units were performed when they were initialized by monitoring the three component readings while rotating the unit near a known field source. Comparisons of field readings were made in a known field on a regular basis to detect any change in calibration of the units. The voltage of the EMDEX-C battery was also checked prior to each measurement trip and was replaced if the voltage was below 6.5 volts.

The EMDEX unit requires a personal computer for initialization and downloading of measurement data. The project had one laptop personal computer which, when necessary, was carried into the field to initialize the EMDEX-C's prior to field measurements.

Each two-person measurement team carried two EMDEX units. Initially they were intended to serve as a measurement and a backup unit. However, the teams quickly incorporated both units into the measurement process in order to expedite data collection at a span.

While performing measurements at a span, each team member wore the EMDEX either in a pouch at the waist or around the neck with both positions locating the meter approximately 1 meter above the ground.

Each measurements team was also equipped with a 300-ft non-conducting measuring tape, an optical range finder (6-150 ft), a 35mm camera and a clinometer to determine the slope of the terrain.

2.3 Magnetic field measurement locations

Measured locations within a span are shown in Figure 2.1. The magnetic field for single lines (i.e., lines without additional lines in the corridor) was measured at 13 locations along the span as follows:

- 1) at both edges of the transmission line right-of-way at the two towers of the span (4 locations: 1, 2, 12 and 13) and
- 2) at both edges of the right-of-way and at the centerline at three equal intervals between the span's two structures (i.e., $\frac{1}{4}$, midspan and $\frac{3}{4}$ distance between towers).

The magnetic field for subject lines which were in multi-line corridors (but adjacent to the edge of the right-of-way) was measured at eight points in the span (see Figure 2.1).

- 1) at the edge of the right-of-way along the unoccupied side of the line at the two towers (2 locations: 1 and 8) and
- 2) at the unoccupied edge of the right-of-way and at the centerline at three equal intervals between the span's two structures (i.e., $\frac{1}{4}$, midspan and $\frac{3}{4}$ distance between towers).

2.4 Data collection forms

The data collection forms used to record information in the field consisted of three sections: a profile form, a general information sheet and the measurement form. Each data form was uniquely numbered to facilitate cross-referencing with the measured span. A sample set of forms is shown in Figure 2.2. The forms were printed on water resistant paper which prevented data entries from being obliterated by rain or handling in the field.

The following information was recorded on the profile form for every span:

- 1) team member names;
- 2) initials of the member who sketched the profile;
- 3) initials of the member(s) who performed the measurements;
- 4) date and time of measurements;
- 5) designated group of the measured span, (region/voltage class and circuit configuration);
- 6) line name;
- 7) span length (in feet);
- 8) right-of-way/ROW width (in feet);
- 9) aerial sketch of the transmission line (including: tower numbers, conductors, other transmission or distribution lines (if any) and an indication of North);
- 10) sketch of the cross-section at mid-span looking from the tower where measurements began (including: conductors, overhead ground wires, other lines which may occupy the same corridor and the lateral slope of the terrain);
- 11) temperature (in °F) and wind (in MPH); and
- 12) comments about anything of significance (including landforms, weather changes, or any problems encountered).

The following information was recorded on the information sheet for every span:

- 1) type and approximate height of vegetation found on the right-of-way under the span;
- 2) landuse in and around the right-of-way under the span;
- 3) terrain of the right-of-way under the span; and
- 4) weather during the measurement period.

The following information was recorded on the measurement form for every span:

- 1) the right-of-way width (in feet) (both total width and distance from the centerline to the edge of right-of-way);
- 2) the span length (in feet) (total length and $\frac{1}{4}$ increments);
- 3) the identification number(s) of the EMDEX-C's which were used for the measurements;
- 4) the structure numbers of the beginning and ending towers (i.e., mile and tower number);

- 5) the number(s) of the photograph(s) taken of the span;
- 6) the longitudinal slope (in degrees) between the towers;
- 7) the lateral slope (in degrees) at midspan measured from the centerline to the edge of the right-of-way;
- 8) the conductor height (in feet) for each outside conductor at the towers, at the $\frac{1}{4}$ span, midspan and $\frac{3}{4}$ span measurement locations;
- 9) three magnetic field level readings (in milligauss) for each measurement location (see Section 2.2 and Figure 2.1);
- 10) the measurement start and stop time and
- 11) comments on anything of significance which occurred during the measurement period.

3.0 SAMPLING STRATEGY

3.1 Characterization study

The selection of spans employed a stratified random sampling strategy. The strata were based on region/voltage class and circuit configuration.

The first dimension of the strata was region which consisted of: East and West. The crest of the Cascade Mountains was the boundary between these two regions. Spans were sampled so that 60 percent of the data were collected in the Western region and 40 percent in the Eastern region because of a higher population density West of the mountains.

Two voltage classes (230-kV and 500-kV) comprised the second dimension of the sampling strata. BPA records were used to determine the distribution of these voltages within each region. Half of the lines sampled in each region were 230-kV and half were 500-kV. In consultation with BPA personnel, it was determined that 120 spans would be sampled for each voltage class in the West and 80 spans for each voltage class in the East.

The third dimension of the strata was based on circuit configuration and consisted of five groups. Similar circuit designs were combined to form groups and the five groups with the most transmission line mileage for each region/voltage combination were selected for sampling. This resulted in both single-circuit and double-circuit configurations being present in all four region/voltage classes. Approximately 80 percent of the total line miles in the system were included in these groups. The dimensions for BPA 230-kV and 500-kV transmission line configurations are shown in Figure 3.1.

This sampling strategy ensured that, for each of the two regions, two different voltages were sampled and that, for each region/voltage combination, five circuit configurations were sampled. Thus, each span sampled fell into one of 20 distinct strata. Sampling of spans within each of these strata was proportionate to the line mileage for that strata to ensure that the population of spans within a region/voltage combination were adequately characterized. This

resulted in the configuration groups of a region/voltage combination with the greatest number of line miles having the largest number of sampled spans.

A report of transmission line system data provided by BPA served as the basis for identifying and selecting specific spans. This report included the line name, tower type, conductor, miles of each configuration and tower numbers for each segment of the line utilizing a specific configuration. The span sampling and selection process in the characterization study involved the following steps:

1. Determine which lines were in the West (Puget Sound and Lower Columbia Areas) and which were in the East (Snake River and Upper Columbia Areas) in either Oregon or Washington. Lines crossing the East/West region boundary were treated as two separate lines divided at the area boundary. For purposes of sampling within a region, the length of such lines was computed up to the area boundary.
2. Determine which lines were 230-kV and which were 500-kV. All other lines were disregarded and not included in the sampling process.
3. Combine "similar" circuit designs into configuration groups. Circuit designs were considered "similar" if the conductor phase spacing for several circuit designs was within 10%, where 10% applied to the smallest phase spacing of the designs. The mileage for each configuration group was totaled.
4. Select the five longest configuration groups in each region/voltage class for span selection. This led to the region/voltage class and circuit configuration groups shown in Table 3.1.
5. Determine the number of spans to be sampled from each of the 20 groups. The number of spans was proportional to the ratio of the number of miles in each group to the total mileage of the five configuration groups within the region/voltage class. The total number of spans to be sampled for each group is shown in Table 3.1.

6. Randomly select the desired number of spans for each group. The line segments within each group were listed along with their mileage and the cumulative mileage for the group up to that segment. Random mileages were selected from the total miles for the group and specific spans were selected based on an assumption of five spans per mile. Approximately twice the number of needed spans were selected to allow for rejections as a result of inspecting BPA maps (see Section 4.0).

This list of randomly selected spans for possible measurement was used for the span selection process described in Section 4.0.

3.2 Variability study

The magnetic field variability along a line was examined by selecting 12 lines which were measured repeatedly at different times and locations. Three long lines within each region/voltage class were selected from the longest single-circuit configuration groups (with the restriction that at least two different configurations be sampled in each region/voltage class). Each of the lines selected was measured at 25 or more spans resulting in an additional 300 measured spans.

A study of magnetic field levels under and around transmission lines in New York state reported that the variability of mean magnetic field at the edge of right-of-way was approximately 10.4mG. [5] This estimate was based on 20 sampled spans per line. An increase to 25 sampled spans should produce a more stable estimate of the magnetic field variability of a line and provide mean magnetic field values with an accuracy of approximately ± 2 mG. Thus, a sample of 25 spans per line was selected to provide a sufficiently accurate estimate of magnetic field variability for a given line.

The sampling procedure for the variability study was as follows:

1. Determine the longest lines in the single-circuit configuration groups of each region/voltage class which were included in the characterization (preferably with a minimum length of 50 miles).
2. In consultation with BPA staff, select three lines for each region/voltage class from those identified by the previous step.
3. Perform a random selection of spans for each transmission line using the procedure employed by the characterization study (see Step 6 of Section 3.1). For each line, spans, in addition to those selected for the characterization study, were identified to produce a total of 25 measured spans per line. Sufficient spans were randomly selected to provide a contingency for those found inaccessible by the field measurement teams.

The randomly selected spans were then used in the span selection process (see Section 4.0). The lines ultimately selected and measured for the variability study are listed in Table 3.2.

3.3 Double-circuit lines

Because double-circuit lines are less prevalent than single-circuit lines, the characterization study sampling strategy did not include sufficient double-circuit lines to allow a separate analysis of the double-circuit spans. Therefore, additional double-circuit spans were selected. In each region/voltage class the number of double-circuit spans which were selected as part of the characterization study was first determined. Then additional double-circuit spans were selected to produce a total of 30 spans in each region/voltage class. The required 58 additional double-circuit spans were selected as follows:

Region/Voltage	# spans	Configuration
West/230-kV	5	J2, J18, J12
East/230-kV	21	J1, J2
West/500-kV	16	M14, M24, M27
East/500-kV	16	M24, M27, M19, M20

A list of possible double-circuit spans was randomly selected (see Step 6 of section 3.2) and used as the basis for selecting measurement spans (see section 4.0).

3.4 Quality control sample

To verify measurement accuracy, measurements at 50 spans were repeated at a different time. The normalized measurements obtained on the two measurement visits at a span could then be compared for quality control verification purposes. All spans were randomly selected from the single-circuit lines of the characterization study with 12 selected from the West 230-kV spans, 13 from the West 500-kV spans, 13 from the East 230-kV spans and 12 from the East 500-kV spans.

4.0 SPAN REVIEW AND SELECTION

The collection of potential measurement spans produced by the process described in Section 3 served as the basis for span selection. A list of the spans was first submitted to BPA to verify the availability of current data from SCADA records. If current data were not available for any particular line or span, it was eliminated from further consideration. In some instances the lack of current data was not known until after a span had been measured. For these spans the measured data could not be normalized and was not used in the analysis.

Data entry forms listing all the spans for which current data were available were created. These data entry sheets were then taken to the Portland BPA office where maps were examined and additional data obtained. Each span was located in the mile-map book for its line. The span was examined for appropriateness based on the following criteria: the tower type must be the same at each end of the span; the span must not be next to a transmission substation; if there was more than one line in the transmission corridor, the selected span must be on the line on the outside of the corridor; the entire length of the span must be easily accessible with no water, terrain or structural obstacles.

If the five towers per mile assumption produced a potential span where none existed on the real line, then the span was rejected.

The results of the review of each span were noted on the data entry sheet to provide an audit trail and document any rejected spans.

If a span met all the above criteria, then copies of the plan and profile maps were obtained. The maps were labeled with the appropriate configuration group name, sample number, line name and span number (i.e., mile and tower numbers). Additional information noted for the selected spans included: ownership of the land (government, private, or unknown); township and range number; and right-of-way width. The plan and profile maps also gave information as to the span's length; location within the township, range and section and the location of any roads providing access to the span.

Copies of a variety of maps were also obtained including strip maps for the line and area maps to aid in locating the span. Finally, the locations of selected spans were noted on county maps using township, range and section numbers.

Spans were selected in this manner until the required number of measurement spans were obtained. Usually several extra spans were identified for each group as a contingency for inaccessible spans discovered in the field. The list of measurement spans and associated drawings and maps were then used to plan efficient data collection trips.

5.0 DATA COLLECTION

5.1 Measurement team training and logistics

Two teams of two members each were thoroughly trained in the use of all measurement equipment, proper measurement procedures and field data collection and entry processes. Measurement team training took place over the course of several meetings with project staff and at a nearby transmission line span. A project coordinator, who also participated on the measurement teams, arranged team travel and schedules and coordinated efforts with BPA staff.

Data collection trips began after the team members were sufficiently well versed in project protocols. Trips scheduled in the early stages of data collection were of short duration (roughly a day) and relatively close to headquarters. This permitted ready resolution of any problems or questions that might arise regarding the measurement procedures or equipment.

Measurements trips were scheduled to provide data collection in both the East and the West regions during the winter, spring and summer seasons. Field measurements near the crest of the Cascade Mountains were limited to late spring and summer because of inaccessibility due to snow or other poor weather conditions.

Trips were arranged so that the spans in a given area could be sampled during one or two trips of from one to seven days each. The entire data collection process lasted seven months, from January to August, 1990. During the early stages of data collection, each team provided their own transportation. However, four-wheel drive vehicles from the Oregon State Motor Pool were used for the majority of the project.

Area Transmission Line Maintenance (TLM) offices were contacted by BPA personnel at the initiation of the project. Area foremen were made aware of the project's purpose and processes and were asked to cooperate with project staff. Area TLM offices were notified several weeks before a measurements team was scheduled to be in the area and contacted again just prior to the team's arrival. If necessary, meetings were arranged between the measurement team and the area

TLM foremen to obtain additional information about the lines selected for measurements.

TLM offices provided information about: the accessibility of selected spans; areas to avoid or in which to exercise caution as a result of hazardous terrain, poor roads or unfriendly landowners and scheduled status of the selected lines (especially whether they would be de-energized when field measurements were scheduled). In areas where landowners were felt to be particularly sensitive to measurement activities, the measurement teams received special briefings from the District Engineer regarding their conduct and communications with landowners.

BFA also provided the informational pamphlets "What We Know About E/MF" [6] for distribution to any interested landowners. The name and phone number of a District Engineer was given to all local residents interested in receiving more information about magnetic fields.

5.2 Measurement procedures

After locating a selected span, the measurement process began by taking a photograph of the span with a 35mm camera. The exposure number of the photo, time of day and date were recorded on the data form. The date and time also appeared on the photograph. The required sketches of the span were drawn on the data forms. The ambient temperature was measured with an outdoor thermometer. The wind speed was estimated with a handheld pith ball windgauge. The ground slope along the longitudinal profile (i.e., from the beginning tower to the ending tower) was measured using a clinometer. Ground slope along the lateral profile was also measured at midspan, from centerline outwards to the edge of the right-of-way, using the clinometer. All values were recorded in the appropriate location on the data form.

The conductor-to-ground clearance (i.e., conductor height) for the outside conductors was measured using an optical range finder at the beginning and ending towers and at the three measurement locations between the towers. All conductor heights were recorded on the data form.

As the measurement team traversed the span from tower to tower, the magnetic field was measured using an EMDEX-C meter as a survey instrument. The location for each centerline measurement was determined by measuring the appropriate longitudinal distance between the towers with a non-conducting tape measure. The edge-of-right-of-way measurement locations were then determined by proceeding perpendicular to the centerline to a distance equal to one half the ROW width as measured by the tape.

At each measurement location, the EMDEX-C was positioned at a height of 1 meter above the ground and three successive resultant magnetic field readings were taken at five second intervals and recorded on the data form.

The start and stop time of the measurement period were also recorded on the form. This enabled BPA to estimate the contemporaneous load currents on the line from their SCADA database.

If, upon arrival at a selected span, the span was found to be inaccessible or if measurement was impractical for some other reason (e.g., landowner refused to allow access to the span), then an alternate span was selected for measurement. In these cases, the alternate span was chosen from one of the two adjacent spans on the same line. This practical method of selecting an alternative was deemed permissible in light of the substantial amount of time and effort invested in traveling to a span, even though this approach was a violation of the random selection process.

5.3 Measurement schedule

Data collection began in January 1990 and was completed in August 1990. In January and February data collection was limited to the Western region due to adverse conditions for off-road driving in the Eastern region. This schedule also afforded extensive staff supervision of the measurement teams during the early stages of the data collection. Data collection took place in both the West and East regions during all succeeding months. Data were collected on a part-time basis until mid-June and thereafter collected on a full-time basis by both teams. Data collection by month was as follows:

<u>Month</u>	<u>Total</u>	<u>Number of measured spans - with valid current data</u>
January	7	6
February	28	27
March	99	99
April	112	111
May	129	129
June	161	160
July	188	185
August	100	45
	-----	-----
Total	824	762

Lack of current data precluded 59 of the 824 measured spans from being used in the analysis.

5.4 Data transfer

At the end of each measurement trip, the forms were reviewed for possible omissions or inconsistencies and compared to the plan and profile maps for other possible errors. After review, copies of the measurement forms were forwarded to T. Dan Bracken, Inc. where the data were entered into a database. Data summaries and preliminary analyses were performed as the data were collected to monitor progress and provide quality assurance oversight. A list of the measured spans was then delivered to BPA with a request for the current loads on the lines at the time the measurements were collected. A folder was maintained for each measured span and contained a copy of: the plan and profile maps, the measurement data forms and the photograph of the span.

Data entry was performed on a personal computer using custom software whose video screens mimicked the structure of printed data forms. The data entry process also generated a list of measured spans by date, time, line name and span. This list was forwarded to BPA to obtain hourly line currents for the times the measurements were collected. The current data received from BPA was subsequently entered into the database and a linear interpolation performed to provide a single current value for each span (described in Section 6.4).

The resulting database was a space-delimited ASCII file compatible with the statistical software program used by PSU for analysis of the data. As data were received and added to the database, the file was sent to PSU for interim analyses. Prior to the interim analysis, the data set was reviewed for possibly erroneous data. Any value that did not fall within limits specified by project staff familiar with the magnetic fields produced by transmission lines was compared to the original data sheets to identify possible data entry or recording errors.

5.5 Quality assurance

Quality assurance measures were implemented regarding instrumentation, data forms and measurement data. The EMDEX-C's used by the project were calibrated by the BPA Division of Laboratories immediately prior to and after the data collection process. During the course of the data collection process, operational checks of the EMDEX-C's were also performed each time an instrument was initialized prior to magnetic field measurements. These tests involved rotating the EMDEX near a known magnetic field source and verifying that each of the three orthogonal magnetic field components was being measured. In addition, the optical range finders were calibrated at the outset of the data collection process according to a procedure prescribed by the manufacturer. The optical range finders were also tested for accuracy as discussed in Section 8.1.5.

The data forms completed in the field were reviewed by the measurement team members prior to delivery to T. Dan Bracken, Inc. These forms were then independently reviewed by staff at T. Dan Bracken, Inc. prior to entry in the database. These reviews were designed to identify inconsistent, erroneous or omitted information.

A data record was created for each measured span. Records in the data file were separated by a blank line. There were 88 space-delimited fields per record with a period (".") used to indicate missing values.

Periodically, as data were entered into the database, a copy was delivered to PSU for preliminary analyses which both monitored progress and identified anomalous data. The final analyses employed in producing this report also

subjected the data to thorough testing and was instrumental in isolating data which required correction or clarification.

5.6 Line current data collection

For each measured span, the hour before data collection began, the hour after data collection ended and any intervening hours were reported to BPA along with the line name and span location. Computerized data records from BPA's Supervisory Control and Data Acquisition System (SCADA) provided the current loads for each hour for each line. Line current, the parameter of interest for normalizing magnetic fields, was computed from the line voltage and power records stored in the SCADA database. This same process is being used by BPA to generate annual estimates of the distribution of magnetic fields near a line. [1] For that application, all the hourly records for an entire year are retrieved and used to predict fields at various statistical levels.

6.0 VARIABLE DEFINITION AND CONSTRUCTION

6.1 Summary measures

The magnetic field values for each single-circuit span were normalized to their associated line current prior to analysis. Normalization was accomplished by dividing the measured magnetic field value by the interpolated current value (see Section 6.4). Eight summary measures were employed to characterize the normalized magnetic field levels under the line. The summary measures, used as dependent variables in the subsequent analyses, were:

MID - measurement at midspan on centerline
CENTER - average of the three measurements on centerline
MAX - maximum of the 13 measurements (8 if parallel line*)
AVERAGE - average of the 13 measurements (8 if parallel line*)
STD - standard deviation of the 13 measurements (8 if parallel line*)
ROW MAX - maximum of the 10 ROW measurements (5 if parallel line*)
ROW AVE - average of the 10 ROW measurements (5 if parallel line*)
ROW STD - standard deviation of the 10 ROW measurements (5 if parallel*)

* Parallel: the line was the outside line on a multiple line corridor.

All summary measures for normalized magnetic fields are expressed in mG/A.

6.2 Random-effect independent variables

The possible impact of random-effect independent variables on the eight summary measures was examined. The random-effect variable data were collected at each span along with the measured magnetic field values. They are characterized as random-effect variables because the sampling protocols made no attempt to control for their values in selecting spans. The random-effect

independent variables used in the analysis of relationship to magnetic field were:

line current
average height of the conductor at midspan of the centerline
span length
temperature
terrain
parallel- or single-line corridor

Descriptive statistics for the random-effect variables are reported in Table 8.7 (current, conductor height, span length, wind speed and temperature) and in Table 8.8 (landuse, terrain, vegetation, weather, time-of-day and type of corridor).

6.3 Fixed-effect independent variables

Region/voltage class and configuration group are fixed-effect independent variables because they formed the foundation for span selection and were controlled for in the study: region was either East or West, voltage was either 230-kV or was 500-kV and there were five circuit configuration groups in each region/voltage class.

6.4 Simultaneous current values

Current data collected at hourly intervals by SCADA was linearly interpolated to produce a continuous current value for the period of measurements. The value of the interpolated current at the midpoint of the data collection period was assigned to each span. The data collection period at a span was defined as the period between the start and stop times recorded on the data form.

Prior to using the hourly current values, an analysis was performed to determine if hourly current data were a sufficiently precise estimate of current. SCADA current data were available at ten minute intervals for a limited set of lines. Using this available SCADA current data, actual ten-minute current values were compared with ten-minute values interpolated from one-hour records for the same line. The comparison was done by computing the absolute value of the difference between the actual and interpolated values. The analysis excluded those observations which fell precisely on the hour since the difference, in this case, is always zero. Separate analyses were performed on data from a collection of both 230-kV and 500-kV lines. The results were as follows:

	<u>230-kV</u>	<u>500-kV</u>
Average actual current	277 amps	410 amps
Average difference between actual and interpolated currents	18 amps	25 amps
Average percent difference	6.5%	6%
Number of observations	347	445

For each voltage class cumulative frequencies of the absolute value of the differences were examined. For the 230-kV lines, approximately 50% of the interpolated values were within 5% of the actual ten-minute value and 80% were within 10% of the actual ten-minute value. For the 500-kV lines approximately 72% of the interpolated values were within 5% of the actual ten-minute value and 88% were within 10%.

Additional analyses examined whether the interpolated current value based on hourly current values, consistently underestimated or overestimated the actual ten-minute value. Overestimates and underestimates were found to occur in equal numbers for the 230-kV group. However, in the 500-kV group overestimates occurred in somewhat higher numbers. Although this effect was found to be significant for 500-kV lines, a plot of the differences indicated that the negative and positive values appear to be fairly normally distributed around zero.

After consultation with BPA staff it was decided that the hourly current values were sufficiently precise estimates of the actual current values and were

appropriate for use in the analyses. Therefore all current values used in the normalization of measured fields were estimated using hourly SCADA current data.

6.5 Annual magnetic field estimates

Annual magnetic field levels were estimated using yearly current statistics. For most of the single-circuit lines in the characterization study, BPA provided the annual mean and 90th percentile current for that line based on an analysis of the 1989 SCADA data. To estimate the annual magnetic field levels at a span on a single-circuit line, the normalized magnetic field value at each measurement location was multiplied by the annual mean and 90th percentile current values for that line. Then the eight summary measures were recomputed to produce actual, not normalized, magnetic field estimates for the span. A characterization of the average annual magnetic fields for the group was produced from the spans in that group. To characterize less frequent but higher magnetic fields for that group, the same procedure was followed using the 90th percentile values from the 1989 SCADA current data.

7.0 DATA ANALYSIS

The project database created in the personal computer environment by T. Dan Bracken, Inc. was transferred to the mainframe computer at Portland State University (see Sections 5.4 and 5.5). Analyses of the data were performed with a standard statistical program. [7]

7.1 Characterization study

Statistical measures of central tendency and variability were computed for the summary measures in all region, voltage class and circuit configuration groups. Analysis of Variance (ANOVA) and multiple linear regression (MLR) statistical procedures were used to determine if any of the random-effect or fixed-effect independent variables were associated with the normalized magnetic field measurements. These analyses were performed on either the non-normalized or normalized field values as appropriate. Specifically, the following tests were used to investigate the association of the independent variables with the summary measures:

On non-normalized magnetic fields:

line current - MLR

On normalized magnetic fields:

average height at midspan - MLR

span length - MLR

temperature - MLR

terrain - ANOVA

region - ANOVA

voltage class - ANOVA

circuit configuration - ANOVA

Magnetic fields were also calculated using the BPA Corona and Field Effects computer program and the calculated, normalized summary measures compared to those measured in the field. [8]

The results of analyses on the two standard deviation summary measures, STD and ROW STD, may be difficult to interpret. These analyses investigate variation in measures of variation as compared to variation in mean or maximum values. The standard deviation, summary measures are most useful in the traditional sense of describing and understanding the range and variation of observed values.

7.2 Variability study

To examine magnetic field variability along a line, the mean and standard deviation of the magnetic field summary measures for the spans of each line were computed.

Descriptive statistics for the random-effect variables for each line are reported in Tables 8.15 and 8.16 (current, conductor height, span length and temperature) and in Tables 8.17 and 8.18 (landuse, terrain, vegetation, weather and time of day). Normalized summary measures calculated with the BPA Corona and Field Effects Program were also compared to actual summary measures for the variability study lines.

7.3 Double-circuit lines

Analysis of the magnetic fields produced by the double-circuit lines in the study posed difficulties. With two circuits contributing significantly to the measured fields, normalization of the fields becomes substantially more complex than normalization for single-circuit lines. A lack of information on relative electrical phasing and direction of power flow further complicates interpretation of the measurements. The same problems arise for multi-line corridors but, in this case, the problems are not as significant because of greater distance between the circuits. Because of the difficulty in interpreting the double-circuit results, the analysis emphasized single-circuit lines.

The relationship between magnetic field measures and currents on the two circuits was examined for a subset of the double-circuit lines. The three double-circuit lines with the greatest number of measured spans were selected for analysis. BPA provided current data for both circuits of the lines. Multiple linear regressions were performed to predict each of the eight non-normalized summary measures from the currents of the two circuits. This provided an estimate of the amount of variance in the non-normalized summary measures that could be accounted for by line currents on the two circuits.

In addition, measures of central tendency and variability were computed for each of the eight non-normalized summary measures of the double-circuit lines in each voltage class. Because of the inability to normalize fields from the double-circuit lines, no statistical tests were performed to compare single- and double-circuit lines nor were different double-circuit groups compared.

7.4 Quality control

In order to assess the stability and repeatability of the magnetic field measurements collected at spans in the study, measurements were repeated at 50 of the characterization study spans near the end of data collection process. The magnetic field data from both the original and repeat measurements were normalized by their respective currents and the eight magnetic field summary measures computed for each of the paired measurement periods. Paired t-tests were used to determine if the summary measures were significantly different for the two measurement periods. Mean differences and the absolute value of the differences were analyzed.

In cases where outliers were clearly present in cumulative percentage distributions, the original data sheets and current entries were checked for errors and corrected or discarded as appropriate. The normalized summary measures can be affected by extremely low current readings as well as data entry errors. Spans with currents less than 10A were not included in the analyses. Common data entry errors that were easily recognized were incorrect decimal, wrong line name, transposition of measurement location and keyboard errors. Only 1 span had to be rejected because of inconsistent, unexplainable entries. For this span, readings were self consistent for two groups of four measurements

each, but differed by a possible decimal error between groups. In this case, the span was rejected because changes to the data would have required unwarranted assumptions about the functioning of the EMDEX or the data recording process.

7.5 Experiment-wise error rate

The number of statistical tests performed on the data set was quite large. For each test, the Type I error rate for reporting in this document was set at .05. Thus, for each test, there is a 5% possibility that a reported significant result was caused by random error and not the variable being investigated. Across the entire study, the number of statistical tests expected to be falsely significant is the number of tests performed in the analyses times .05. With approximately 100 tests performed in the characterization study, the expected number of falsely significant results is five. Therefore, statistically significant results from the analyses which do not make logical sense or are contrary to well accepted scientific axioms should be interpreted with caution.

8.0 RESULTS

Data from the single-circuit lines characterization study, double-circuit lines in the characterization study and the variability study single-circuit lines were analyzed separately. Table 8.1 shows the distribution of samples by region/voltage and configuration group as well as their BPA configuration nomenclature. A total of 360 single-circuit spans and 134 double-circuit spans were measured. Table 8.1 also presents the percentage of spans within a group that were located in a multiple line corridor. For 230-kV and 500-kV spans, 70 and 64%, respectively, were in multiple-line corridors.

Table 8.2 presents the distribution of measured spans for the variability study. The Pilot Butte-Chiloquin line was originally included in the East/230-kV class. However, SCADA current data was later found to be unavailable for this line and it was removed from the analysis. This resulted in only two lines in the East/230-kV class of the variability study. Spans for these lines in Table 8.2 that were measured for the characterization study were also included in the variability study. This resulted in more than 25 spans per line for some lines in the variability study (see Table 8.2).

A list of all measured spans is given in the Appendix.

8.1 Characterization study for single-circuit lines

The analyses of the single-circuit line data were carried out in an hierarchical manner with the influences of the fixed-effect variables examined before those of the random-effect variables. First, statistical tests were performed to determine if the summary measures for spans in the West were significantly different than the summary measures for spans in the East. Next, the effect of voltage was examined and then the effect of circuit configuration group. Finally, relationships between the random-effect variables and the summary measures were tested. The results of the analyses of the effects of the fixed- and random-effect independent variables on the summary measures are shown in Table 8.3 and discussed below. Asterisks represent significant effects at the 0.05 level (i.e. Type I error).

8.1.1 Region

The first fixed-effect variable investigated was region. Analysis of variance tests (ANOVA) were performed to compare the mean of each of the eight summary measures for spans in the East region with their West region counterparts. The comparisons between the summary measures were performed for all measured spans as well as between corresponding circuit configuration groups of each voltage class. The test comparing all spans in the West region to all spans in the East region indicated that there were no statistically significant differences for any of the summary measures.

To examine whether differences between regions existed for some circuit configuration groups but not others, the eight summary measures for similar circuit configuration groups in the West and East were compared. No significant differences between the summary measures for West Group SC1 spans and East Group SC1 spans were found for the 230-kV spans. For the 230-kV Group SC2 spans, one of the summary measures, ROW STD, had significantly higher values in the West than in the East. However, this may be a spurious effect, because none of the other summary measures were statistically different between regions. There were no 230-kV Group SC3 spans in the East to compare with those in the West.

Comparisons between the summary measures for the 500-kV Group SC1 spans in the West and East found no significant differences. Comparisons between the West Group SC2 and East Group SC2 for 500-kV should be interpreted with caution because of the very unequal sample sizes: 37 in the West and 5 in the East. For this case, the MID and CENTER summary measures were both significantly higher for the West while all other summary measures were not significantly different. Finally, comparisons between the comparable 500-kV West Group SC3 and East Group SC3 yielded a single statistically significant difference: the ROW AVE was higher in the East than the West.

Because no consistent pattern of differences existed between the summary measures of spans from the East and West and because the vast majority of the statistical tests were not significant, it was concluded that, overall, the region fixed-effect variable does not produce differences in the summary measures for a span. Consequently spans from comparable configuration groups in the West and East were combined in subsequent analyses.

8.1.2 Voltage class

Examination of the summary measures by voltage class indicated that all summary measures were significantly different between the two voltage classes with the exception of ROW STD (see Table 8.3). The 230-kV normalized summary measures were consistently higher than their 500-kV counterparts. This is clearly shown in Figure 8.1 where the cumulative distributions of MAX and ROW to MAX are plotted for both 230-kV and 500-kV spans. Up to the 99th percentile of these distributions the 230-kV summary measure is larger than the comparable 500-kV summary measure. Higher normalized fields for 230-kV lines are consistent with the fact that 230-kV lines are designed with their conductors closer to the ground than 500-kV lines. The lower conductors result in higher and more variable normalized magnetic fields in the ROW. The actual observed fields under 500-kV lines are generally higher than those under 230-kV lines because the larger currents on the 500-kV lines more than offset the height difference.

The normalized summary measures for the 230-kV and 500-kV span magnetic field measurements are given in Tables 8.4 and 8.5, respectively. The mean, maximum, standard deviation, coefficient of variation and standard error of the mean are given for each of the eight summary measures by voltage and by configuration group. The coefficient of variation (standard deviation divided by the mean) describes the variability of the summary measures as a proportion of the mean and the standard error of the mean describes the possible margin of error in the estimate of the mean.

The variability of summary measures, as indicated by the coefficient of variation, is higher for the 500-kV spans than the 230-kV spans. Possible explanations for the increased variability among 500-kV spans are included in the discussions of other independent variables. The standard error of the mean is comparable for both the 230-kV and 500-kV summary measures.

An examination of Figures 8.2 and 8.3 indicates that the distributions of the MID and MAX summary measures are broader, i.e. steeper, than the distributions of the ROW MAX and ROW AVG summary measures. This is consistent with the larger variance of the MID and MAX summary measures when compared to the two edge of right-of-way summary measures. As expected, the distribution of the MID and MAX summary measures are very similar and higher than the ROW MAX or ROW

AVG summary measures: i.e., the maximum normalized fields within a span tend to be at midspan with lower values along the edge of the right-of-way.

Cumulative probability plots for the MID, MAX, ROW MAX and ROW AVE summary measures are given in Figures 8.2 and 8.3 for 230-kV and 500-kV spans, respectively. The summary measure distributions that have sharply increasing values at the higher percentiles indicate a deviation from a normal distribution. In these cases, the high values of the distributions were closely examined to identify the significance of this deviation. The sharp rise in the MID and MAX distributions above the 98th percentile represented very few spans. For the 230-kV spans, the extreme values corresponded to only three of the 168 spans and for the 500-kV spans, the extreme values corresponded to only two of the 193 spans. Closer examination of the extreme values revealed that the spans were all in a multiple line corridor and had low currents (46 to 200 amps) at the time of the measurements. These few spans with extremely high values represent valid data where the assumptions inherent in the normalization process have been violated. However, the mean and median were approximately equal for the distributions with extreme values. Therefore, the departure from normality can be considered negligible.

8.1.3 Circuit configuration

For each of the two voltage classes, differences between the summary measures of the three single-circuit line configuration groups were examined. The 230-kV lines were all of a flat configuration while the 500-kV lines were either delta (Group SC1 and Group SC2) or flat (Group SC3). Table 8.3 shows the pattern of significant differences between circuit configuration groups for the eight summary measures. Tables 8.4 and 8.5 present the statistical descriptors for the summary measures of each configuration group in the 230-kV and 500-kV voltage class, respectively.

The 230-kV voltage class circuit configuration comparisons indicated statistically significant differences between groups for the summary measures most closely associated with the magnitude of fields within the right-of-way: MID, CENTER, MAX and AVERAGE. There were also differences between particular groups for STD. For the summary measures based on field values at the edge of

right-of-way, only ROW AVE showed instances of statistically significant differences between groups.

Examination of the summary measures for 230-kV spans (Table 8.4) indicates that Group SC3 had the lowest summary measures while Group SC1 generally had the highest. This is consistent with Group SC3 having smaller phase spacing than Group SC1 (24 feet versus 26.5 feet) while both groups have the same right-of-way width (125 feet). Group SC2, which has the smallest phase spacing (20 feet) would have been expected to have the lowest summary measures. However, two factors tended to negate the effect of this smaller phase spacing: 1) Group SC2 had a narrow right-of-way (100 feet), resulting in the outside conductor being closer to the edge of the right-of-way and 2) the Group SC2 spans had a lower mean conductor height.

In the 500-kV class, there were no significant differences between any of the summary measures for the three circuit configuration groups. Examination of Table 8.5 indicates a tendency for the flat configuration Group SC2 to have slightly higher mean summary measures than the delta configurations of Groups SC1 and SC3. However, the effect was not statistically significant for the sample of spans measured in the study given the large variability for the 500-kV distributions.

There are no patterns of significance common to the 230-kV and 500-kV groups and no ready explanations for the statistically significant differences observed between summary measures for the 230-kV groups. Therefore, it was concluded that the configuration group did not play a consistent role in determining the differences between summary measures for the sample of spans considered here.

8.1.4 Confidence in estimates of the summary measures

In order to determine the stability of the estimates of the summary measures, the confidence intervals surrounding the mean of the summary measures were examined. The 95% confidence interval gives the range of values for which there is 95% confidence that the interval contains the true population summary measure mean. The interval is bounded by 1.96 times the standard error of the

mean on either side of the sample mean. The largest interval for the 230-kV summary measures (excluding the measures of variability) was for the MID summary measure and spanned .019 from .146 to .164 mG/A. The largest interval for the 500-kV summary measures was also the MID summary measures which spanned 0.017 mG/A from .093 to .110 mG/A. All other intervals were smaller for both voltage classes. Since these intervals do not exceed $\pm 6\%$ (230-kV) or $\pm 8\%$ (500-kV), the estimates of the means of the summary measures appear to be stable.

8.1.5 Current and conductor height

The principal parameters in determining the magnetic fields produced by transmission lines are line current and distance from the conductors. To examine the proportion of variance in measured magnetic fields that can be accounted for by current and conductor height, multiple linear regression analyses were performed using midspan conductor height and current as independent variables. The midspan conductor height used in the analysis was the average of the two height readings made at that location. Because current is an independent variable in this analysis, it is necessary to use the non-normalized magnetic field measurements as the dependent variables. Table 8.6 shows the percent of variance (R^2) in the non-normalized magnetic field summary measures accounted for by current and conductor height (all regressions were significant at the $p=.0001$ level).

For 230-kV spans ($N=166$), approximately 80 to 85 percent of the variance in the non-normalized MID, CENTER, MAX, AVERAGE, ROW MAX and ROW AVE magnetic field measures can be accounted for by conductor height and current. The amount of variance accounted for in the STD and ROW STD summary measures was lower, 71 and 57 percent, respectively. This is not unexpected since these measures are themselves a measure of variability and are probably more dependent on terrain than the others.

For the 500-kV spans ($N=192$), about 75 percent of the variances in the MID, CENTER, MAX, AVERAGE, ROW MAX and ROW AVE non-normalized summary measures are accounted for by conductor height and current. The variances accounted for in the STD and ROW STD summary measures are again lower (71% and 49%).

In an attempt to eliminate uneven terrain and the presence of parallel lines as confounding sources of variance, the analyses were repeated for flat terrain, single-line corridor spans. The results are shown in the column labeled "ideal" in Table 8.6. Controlling for these confounding variables resulted in a marked increase in the amount of variance accounted for by current and conductor height for almost all summary measures. The increase is especially apparent for the STD summary measures where variance accounted for was initially quite low. This indicates that some of the unexplained variance for all the spans is due to the presence of other lines in the corridor and to rough terrain where conductor height varies substantially within the span. The remaining unexplained variance, 5 to 10% for most 230-kV measures and 15 to 20% for most 500-kV measures, is assumed to be accounted for by errors in the field measurement process, the determination of current and the measurement of height. The better correlation of most 230-kV span measures with current and height (91-96% versus 79-87% for 500-kV) for the "ideal" case may be attributed to a larger n and better height measurements for the lower conductors at the lower voltage spans.

Errors in the measurement process include: instrumentation and recording errors and failure to be at the proper lateral or longitudinal location in a span. This latter problem was more prevalent in spans with rough terrain or heavy vegetation.

The margin of error in the estimation of current values at the time of the measurement is at least 6% using hourly data as compared to 10 minute data.

A small study was run to determine the ability of the optical range finder to reliably measure distances. Three people took measurements using the optical range finder at six different distances: 60, 70, 80, 90, 100 and 110 feet from a target. Each person took 4 measurements at each distance. The distances measured with the optical range finder varied considerably. The table below gives the minimum and maximum distances measured with the optical range finder for each distance.

<u>Actual distance</u>	<u>Min Obs.</u>	<u>Max. Obs.</u>
60	50	60
70	55	80
80	65	80
90	72	95
100	80	120
110	75	120

This small study and additional concerns reported by the data collection teams (e.g., that the range finder was difficult to operate in foggy or rainy weather) suggest that the accuracy of the range finder is highly questionable. The resulting lack of reliability in conductor height measurements may introduce error variance into the data. Although unquantified, this variability in height measurements probably accounts for a large fraction of the remaining unexplained variance in the magnetic field summary measures.

Based on these results, we conclude that the variability in the magnetic field measurements can be explained almost entirely by variability in current and height.

8.1.6 Random-effect variables

Tables 8.7 and 8.8 summarize the distributions of the random-effect variables observed for measured spans. Table 8.7 presents the mean, standard deviation, minimum and maximum values for each voltage class as observed for the continuous variables: current, conductor height at midspan, span length, wind speed and temperature. Table 8.8 presents the number of spans from each voltage class that were present in the categories for the categorical random-effect variables.

Some generalizations about the measured spans became clear from an examination of these tables: current on the 230-kV lines was about half that on

the 500-kV lines; the conductors on the 230-kV spans were, on average, almost 10 feet lower than those on the 500-kV spans; the 500-kV spans were longer than those in the 230-kV class; the predominant landuse categories were vacant (48%) and pasture (23%); most spans were flat (47%); low-lying and bush were the predominant vegetation types; almost all measurements were made in fair weather with no precipitation and the measurements were generally distributed from mid-morning on.

The relationships between selected random-effect variables and the normalized summary measures were examined separately for 230-kV and 500-kV spans. Indications of significant relationships are shown in Table 8.3.

No significant differences in any summary measures were found among the terrain categories for any of the summary measures of either voltage class. Temperature was significantly related to ROW AVE for 230-kV spans only, with the ROW AVE decreasing as temperature increases. However, this finding only accounted for 3% of the variance in the ROW AVE and may be a spurious effect (see Section 7.5). Consequently, terrain and temperature were concluded to be unrelated to the summary measures.

Span length was significantly related to the MID (3%), MAX (6%), AVE (2%) and STD (10%) summary measures for 230-kV spans and was significantly related to the MID value (2%) for 500-kV spans. (The percent of variance accounted for by the independent variable is given in parentheses.) For both voltage classes, as span length increased, the value of the magnetic field summary measures also increased. These results are consistent with longer spans having lower conductor clearances which produce higher magnetic fields.

For both the 230-kV and 500-kV spans, all summary measures for spans in corridors with parallel lines were higher than for those in single-line corridors. However, only the differences in AVERAGE (4% and 2%) summary measure for 230-kV and 500-kV spans and STD summary measure for 230-kV spans were statistically significant with respect to parallel lines. These results are not robust but are consistent with the hypothesis that an adjacent line increases the field within the ROW and does not impact fields at the edge of the ROW remote from the parallel line.

Given the lack of consistent statistical test results between voltage classes, the lack of robust effects of any of the random-effect variables on the summary measures and the likelihood of spurious positive results among the large number of relationships tested, it was concluded that the random-effect variables, with the exception of line height and current, have minimal influence on the summary measures of the BPA transmission lines measured by the study. Furthermore, the unexplained variance in the non-normalized summary measures does not appear to be associated with any of the random-effect variables.

8.2 Annual magnetic field levels

To provide a practical, useful result from the study and to take advantage of BPA's capability to estimate current distributions from SCADA data [1], estimates of the annual magnetic field levels for each configuration group were computed as described in Section 6.5. The estimates of annual magnetic field values are shown in Tables 8.9 and 8.10 for 230-kV and 500-kV spans, respectively. Annual current distributions were not available for all lines in a group. The estimated annual mean value and 90th percentile values are presented for each summary measure. To provide an estimate of the variation in these statistical descriptors, the standard deviation and coefficient of variation for the estimated means and 90th percentiles are also given in Tables 8.9 and 8.10.

As expected, the annual magnetic field estimates for the 500-kV groups are almost invariably higher than those of the 230-kV groups because of the larger currents on these higher voltage lines. The coefficients of variation for the estimated annual measures also tend to be greater for the 500-kV spans than the 230-kV spans (with the exception of 230-kV Group SC3), indicating more variation at the higher voltage.

Examination of Tables 8.9 and 8.10 indicates that the annual estimated mean fields at midspan are 29 mG and 38 mG for 230-kV and 500-kV spans, respectively. The peak fields (90th percentile of MAX fields) on an annual basis are 63 mG and 94 mG for 230-kV and 500-kV lines, respectively. The annual mean edge of right-of-way average fields are 10 mG and 16 mG for 230-kV and 500-kV lines, respectively.

The non-normalized summary measures for measurements on the single-circuit lines are compared with the predicted mean fields in Table 8.11 for the 230-kV and 500-kV voltage classes. For all summary measures the mean measured values are significantly higher than the predicted mean annual values when analyzed with paired t-tests. For example, the average maximum field measured in the 193 single-circuit line 500-kV spans was 63 mG while the predicted annual average maximum is 43 mG. These results indicate that on average, point-in-time measurements made under the conditions of this study will provide field values in excess of annual averages. One contributing factor to this result is that these measurements were necessarily made during daylight periods when currents tend to be higher than at night. In order for measurements to more closely approach annual average field values, the measurements would have to be distributed randomly over the hours of the day and seasonally as well as on randomly selected spans.

8.3 Comparison with calculated field levels

To place the measured fields present under the lines in perspective with predicted fields, the normalized summary measures were compared with their calculated counterparts for each configuration group in a region/voltage class. Magnetic fields for the group or line of interest were calculated using the BPA Corona and Field Effects Computer Program. [8] Measured mean and 90th percentile values and calculated values for the MID, MAX, ROW MAX and ROW AVE summary measures are presented in Table 8.12. The calculated values are based on the BPA estimated minimum conductor clearances at 50°C conductor temperature which is the National Electric Safety Code condition for computing electric field strengths. [9] The minimum conductor clearances under these conditions were assumed to be 29 and 33 feet for 230-kV and 500-kV lines, respectively. Such clearances rarely occur and therefore the calculated field values are expected to be substantially higher than measured values. The average span length and conductor height at the tower observed for each group were assumed to estimate other intermediate conductor heights needed in the calculations. The design right-of-way width for each group was also assumed in the calculations.

As expected, the calculated values for the midspan and maximum measures in Table 8.12 were higher than their mean measured counterparts: the midspan

measured values were 39 to 81% of the calculated values and the maximum measured values were 54 to 90% of the calculated values. Measured mean values having the greatest disparity with their calculated values were from 230-kV Group SC3 which had an average observed midspan clearance of 49.6 feet compared to the design clearance of 29 feet. In contrast, the calculated and mean measured values for the summary measures that characterize fields at the edge of the right-of-way were relatively comparable. With the exception of the 500-kV Group SC3, the measured and calculated ROW MAX and ROW AVE were all within a tolerance of $\pm 15\%$.

Comparison of the 90th percentile of measured values with the calculated values in Table 8.12 indicates that the 90th percentile values for the on-ROW parameters MID and MAX more closely approach the calculated values than do the average measured values. However, with the exception of 230-kV Group SC1, the 90th percentile measured values are still 9 to 23% below the calculated values. Several factors could contribute to the 230-kV Group SC-1 90th percentile measured values being higher than calculated values: minimum clearances for some of these spans were less than 29 feet (Table 8.7); and Group SC-1 contained the extremely high values shown in Figure 8.2. The 90th percentiles of the measured parameters ROW MAX and ROW AVE are all higher than the calculated values, again indicating that fields at the edge of ROW can be influenced by factors other than the conductor height, such as terrain and lateral slope.

These results support the use of calculations for predicting average magnetic fields at the edge of the ROW and emphasize that calculations using minimum clearances yield worst case estimates compared to actual measured magnetic fields.

8.4 Variability study for single-circuit lines

Variability of the magnetic field along a line was examined for 11 lines: three in each region/voltage class except East 230-kV where only two lines were available. For each line, measurements were made and summary measures computed for a minimum of 25 spans except for Santiam-Alvey No. 1, a 230-kV line. In that case, several mislabeled spans were identified during analysis and had to be eliminated from the variability study. The distributions of the summary measures were described by their mean, maximum, standard deviation, coefficient of variation and standard error of the mean. These descriptive statistics of the

summary measures are provided in Tables 8.13 and 8.14 for 230-kV and 500-kV lines, respectively. The 95% confidence intervals for the means of summary measures in the variability study are larger than the corresponding intervals in the characterization study, because of smaller sample sizes in the variability study. Overall, the estimates for both the 230-kV and 500-kV lines in the variability study are stable with most of the 95% confidence intervals less than $\pm 11\%$ of the summary measures means. Only the Santiam-Alvey No. 1 230-kV line with $n=18$ had confidence intervals consistently above this level.

In general, the 500-kV lines exhibited lower normalized summary measures than the 230-kV lines. The variability (i.e. coefficients of variation) was comparable for both voltage classes. For both voltages, lines in the East tended to exhibit less variability than those in the West. As in the characterization study, STD and ROW STD summary measures showed the most variability.

Examination of Tables 8.13 and 8.14 indicated that the coefficient of variation for the summary measures that characterize fields on the ROW were almost all less than 0.40 and that three fourths were less than 0.3. For a normal distribution with a coefficient of variation of 0.3, 64% of the field measures along a line will lie within $\pm 30\%$ (one standard deviation) of the mean field and 95% will lie within $\pm 60\%$ (two standard deviations) of the mean.

The cumulative distributions of the MID, MAX, ROW MAX and ROW AVE summary measures for the five 230-kV and six 500-kV lines shown in Figures 8.4 to 8.14 support the assumption of normality: that is, the distributions are linear when plotted on a normal probability scale. All distributions except the Santiam-Alvey No. 1 line with a reduced sample size appear to follow a normal distribution. For the Santiam-Alvey No. 1 line in Figure 8.5, the distributions for the MID and MAX values show a sharp rise at about the 65th percentile indicating a deviation from normalcy.

As expected the MID and MAX summary measures show more variation than the ROW MAX and ROW AVE measures: i.e., the cumulative distributions have a steeper slope. The edge-of-ROW summary measures are relatively constant with the exception of a few spans for all lines.

Statistics for the continuous random-effect variables (current, conductor height, span length, temperature) were also computed for each line in the variability study and are presented in Tables 8.15 and 8.16 for the 230-kV and 500-kV variability study lines, respectively.

Tables 8.17 and 8.18 detail the categorical random-effect variable distributions for each line in the 230-kV and 500-kV voltage classes, respectively. These tables are consistent with the generalizations made about all 230-kV and 500-kV lines (Section 8.1.5): the currents on 230-kV lines are lower; the height of 230-kV spans is lower; the span length for 230-kV lines is shorter; the predominant landuse categories are vacant and pasture; and most spans are flat.

Tables 8.19 and 8.20 present the calculated and measured values for four summary measures (MID, MAX, ROW MAX, ROW AVE) of the 230-kV and 500-kV variability study lines, respectively. As with the spans in the characterization study, the calculated summary measures were based on minimum clearance at 50°C. The calculated MID and MAX summary measures are therefore higher than their measured counterparts and represent the difference between the actual conductor height and the minimum clearance. As with the similar comparison in the characterization study, the edge of ROW measures are much more in agreement with the calculated values than are the MID and MAX measures.

8.5 Double-circuit lines

Magnetic fields were measured at 134 double-circuit spans. However, no appropriate normalization procedure exists because of the influence of the conductors of the adjacent circuit and uncertain electrical phase relationships. However, possible relationships between magnetic fields and currents on the two circuits of a double-circuit line were investigated. BPA provided SCADA current data for both circuits of 59 spans, 19 230-kV spans and 40 500-kV spans. Multiple regressions were performed on these spans using conductor height at midspan and current on both circuits to examine the proportion of variance accounted for in the non-normalized summary measures by these three independent variables. The results are shown in Table 8.21.

Surprisingly, the amount of variance accounted for by the three independent variables for the on-the-ROW summary measures for double-circuit lines exceeds that accounted for in the case of the single-circuit lines. However, the edge-of-ROW measures are not as well accounted for in the double-circuit case: the MAX and ROW STD seem to be the least related to the independent variables. These results suggest that, on the centerline of double-circuit lines, the current and height account for the majority (>90%) of variance in the magnetic field measurements, but that other independent variables affect the fields at the edge of the right-of-way.

The magnetic field levels for double-circuit and single-circuit lines cannot be directly compared using inferential statistics due to the inability to normalize fields from double-circuit lines. In addition, for double-circuit lines, measurements were made on the center line between the two circuits and therefore may not encompass the maximum field occurring on the right-of-way. However, for the sake of comparison, statistical descriptors for the non-normalized magnetic field summary measures for single-circuit and double-circuit spans are presented in Tables 8.22 and 8.23 for the 230-kV and 500-kV lines, respectively. For 230-kV spans, mean non-normalized measures for single-circuit lines on the right-of-way are generally greater than those for double-circuit lines while those at the edge of the right-of-way are comparable for the two 230-kV circuit types. For 500-kV double-circuit spans, the non-normalized summary measures are generally higher than for those for single-circuit spans.

Cumulative distributions of non-normalized magnetic field measurements for single-circuit and double-circuit lines are shown in Figures 8.15 and 8.16, respectively. Magnetic fields on and at the edge of the ROW are large for 500-kV for both single-circuit and double-circuit lines.

8.6 Quality control results

To examine the stability of the magnetic field measurements and the reliability of the normalization process, measurements at 24 230-kV spans and 23 500-kV spans were performed on two separate dates and times. For both the original and repeat measurements, summary measures were computed and differences between these paired summary measures were examined.

The average absolute value of the differences for each of the paired summary measures and the overall mean values for the summary measures are given in Table 8.24. One-tailed paired t-tests were performed to determine whether these differences between paired summary measures were significantly greater than zero and all differences were found to be statistically, but not practically, significant. For example, the average difference for the 230-kV midspan measure was .024 mG/A compared to an overall mean of .155 mG/A.

Examination of the distributions of the differences for each set of paired summary measures for spans in both voltage classes indicated that the negative and positive differences substantially offset each other. In fact, when two-tailed paired t-tests were performed without taking absolute value of the differences of the paired summary measures, none of the paired summary measure differences were found to be significantly different from zero.

The absolute value average differences are what we expect given the 95% confidence intervals of the summary measures and given the variability in the magnetic fields that can be accounted for by current and height (from the regression analyses). Also there is no consistent pattern of negative or positive differences. Therefore, the data collection process led to repeatable results.

9.0 CONCLUSIONS

- Normalized summary measures are higher for 230-kV spans than for 500-kV spans because of lower conductor heights.
- One hour current records are sufficiently accurate to characterize line currents during measurement periods within a range of six to ten percent.
- Regional differences are not significant for the normalized summary measures used and spans from comparable circuit configuration groups in the West and East are sufficiently similar to be combined for purposes of analysis.
- Comparison of spans from circuit configuration groups for 230-kV showed statistically significant differences while 500-kV configuration group comparisons indicated no significant differences in summary measures. Trends in the data could be explained by physical attributes of the groups, such as right-of-way width, phase spacing and flat or delta conductor configuration. However, there is sufficient variation within groups to preclude strong conclusions about differences between groups.
- Current and midspan line height account for 70 to 80% of the variance of the non-normalized magnetic field summary measures. Errors in magnetic field measurements, conductor line height measurements and determination of current likely account for much of the remainder of the unexplained variance.
- Random-effect variables, besides current and line height, have little effect on the summary measures.
- Annual magnetic field level estimates for 230-kV and 500-kV transmission line spans can be made using the normalized summary measures and the annual current data from SCADA. Estimates of annual midspan fields are 29 mG and 38 mG for 230-kV and 500-kV spans, respectively.

- Point-in-time measurements of magnetic field made according to the protocols of this study are significantly higher (approximately 50% for MID and ROW AVE) than estimated annual mean values. This difference is attributed to the lack of randomization with respect to time-of-day and season.
- Calculated fields using minimum design clearance are higher than fields on the right-of-way but are in general agreement with fields at the edge of the right-of-way.
- Examination of magnetic field variability along lines indicated that edge-of-right-of-way measures are relatively constant over a line.
- Most variation in non-normalized magnetic field measures on the right-of-way of double-circuit lines can be accounted for by currents on the two circuits and the height of the conductors. The association between these independent variables and edge-of-ROW measures is not as strong.

10.0 ACKNOWLEDGEMENTS

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12.0 FIGURES

Figure 2.1 Aerial view of the measurement locations for a span.

Single Line Corridor: 13 Measurement Locations					
Edge of Right-of-Way	1	4	7	10	12
Centerline:	Tower	3	6	9	Tower
Edge of Right-of-Way:	2	5	8	11	13
		1/4 Length of span	Midspan	3/4 Length of span	
Multiple Line Corridor: 8 Measurement Locations					
Centerline:	Tower	2	4	6	Tower
Edge of Right-of Way:	1	3	5	7	8
		1/4 Length of span	Midspan	3/4 Length of span	

Figure 2.2 Data collection forms:

- a) Profile Form
- b) Information Sheet
- c) Measurement Form

(see following pages)

BPA Transmission Line Profile Form # 0960

Team members: _____ Profile by: _____ Measurements by: _____

Date: ____/____/____ Time: ____:____ Group: _____ Voltage: _____ kV

Line name: _____ Span length: _____ ft ROW width: _____ ft

Sketch: Overhead view with first measurement location as noted in box
(Indicate: other lines, right of way, north and mile/tower numbers)

Sketch: Cross-section at mid-span looking from starting tower
(Indicate: conductors, over-head ground wire and slope of terrain)

Temperature: _____ °F Wind: _____ MPH

Comments: _____

Key to Vegetation, Land use, Terrain and Weather fields

Use the one term which best describes each aspect of the area where the span is located.

Actual codes entered may be unambiguous abbreviations for the following terms.

Vegetation on the right of way under the span:

- none (less than or equal to 0.5')
- low lying (greater than 0.5' and less than or equal to 3')
- brush (greater than 3' and less than or equal to 10')
- trees (greater than 10')

Land use in and around the right of way under the span:

- vacant/fallow/unused/desert
- forest
- pasture
- cultivated
- residential
- commercial/industrial

Terrain on the right of way under the span:

- flat
- longitudinally sloping
- laterally sloping
- longitudinally and laterally sloping
- undulating
- rough/rugged

Weather during the measurement period:

- clear
- partly cloudy
- overcast
- foggy
- rainy
- snow/hail

BPA Transmission Line Measurements Form

Edge of ROW	1	4	7	10	12	ROW width: _____ ft / 2 = _____ ft
	+-+				+-+	
Center	T	3	6	9	T	Span length: _____ ft / 4 = _____
ft						
Edge of ROW	+-+				+-+	
	2	5	8	11	13	Form #: _____ EMDEX #: _____
Mile/Tower: ____/____						Measurement start time: ____:____

Enter number, mark the position of the decimal point, verify correctness and wait for the next measurement (5 seconds).

Location # 1		Location # 2		Time: ____:____	
Conduct. Ht.: _____ ft		Conduct. Ht.: _____ ft		Pic # _____	
1) <u>7</u>	1) <u>7</u>				
2) <u>7</u>	2) <u>7</u>				
3) <u>7</u>	3) <u>7</u>				
Longitudinal Slope: _____ °					
Location # 3		Location # 4		Location # 5	
Time: ____:____		Conduct. Ht.: _____ ft		Conduct. Ht.: _____ ft	
1) <u>7</u>	1) <u>7</u>	1) <u>7</u>			
2) <u>7</u>	2) <u>7</u>	2) <u>7</u>			
3) <u>7</u>	3) <u>7</u>	3) <u>7</u>			
Location # 6		Location # 7		Location # 8	
Time: ____:____		Conduct. Ht.: _____ ft		Conduct. Ht.: _____ ft	
1) <u>7</u>	1) <u>7</u>	1) <u>7</u>			
2) <u>7</u>	2) <u>7</u>	2) <u>7</u>			
3) <u>7</u>	3) <u>7</u>	3) <u>7</u>			
Lateral Slope: _____ °		Lateral Slope: _____ °			

Form # _____

Edge of ROW 1 4 7 10 12

ROW width: _____ ft / 2 = _____ ft

Center +-+ 3 6 9 +-+
ft |T| |T|

Span length: _____ ft / 4 = _____

Edge of ROW +-+ 2 5 8 11 +-+
13

Form #: _____

Mile/Tower: ____/____ ____/____

Enter number, mark the position of the decimal point, verify correctness
and wait for the next measurement (5 seconds).

Location # 9

Location # 10

Location # 11

Time: ____:____

Conduct. Ht.: _____ ft

Conduct. Ht.: _____ ft

1) 7 . ____ . ____ . ____

1) 7 . ____ . ____ . ____

1) 7 . ____ . ____ . ____

2) 7 . ____ . ____ . ____

2) 7 . ____ . ____ . ____

2) 7 . ____ . ____ . ____

3) 7 . ____ . ____ . ____

3) 7 . ____ . ____ . ____

3) 7 . ____ . ____ . ____

Location # 12

Location # 13

Time: ____:____

Conduct. Ht.: _____ ft

Conduct. Ht.: _____ ft

1) 7 . ____ . ____ . ____

1) 7 . ____ . ____ . ____

2) 7 . ____ . ____ . ____

2) 7 . ____ . ____ . ____

3) 7 . ____ . ____ . ____

3) 7 . ____ . ____ . ____

Measurement stop time: ____:____

Comments:

Figure 3.1 BPA 230-kV and 500-kV transmission line configurations (from BPA Drawing No. 32792)

Figure 8.1 Cumulative percentage distributions of MAX and ROW MAX summary measures in measured spans of 230-kv and 500-kv single-circuit lines.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.2 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 230-kV single-circuit lines.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.3 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 500-kV single-circuit lines.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.4 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 230-kV Alvey-Fairview No. 1 line.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.5 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 230-kV Santiam Alvey No. 1 line.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.6 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 230-kV Ross Lexington No. 1 line.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.7 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 230-kV North Bonneville-Midway No. 1 line.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.8 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 230-kV Grand Coulee-Bell No. 5 line.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.9 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 500-kV Raver-Paul No. 1 line.

Summary Measures

MID - measurement at midspan of centerline
 CENTEK - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.10 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 500-kV Monroe-Custer No. 2 line.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.11 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 500-kV Chief Joseph-Monroe No. 1 line.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.12 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 500-kV Grizzly-Malin No. 1 line.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.13 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 500-kV Buckley-Summer Lake No. 1 line.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.14 Cumulative percentage distribution of MAX, MID, ROW MAX and ROW AVE summary measures for 500-kV Monumental-McNary No. 1 line.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.15 Cumulative percentage distributions for MAX and ROW MAX magnetic field measurements in measured spans of 230-kV and 500-kV single-circuit lines.

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Figure 8.16 Cumulative percentage distributions for MAX and ROW MAX magnetic field measurements in measured spans of 230-kV and 500-kV double-circuit lines.

Summary Measures

MID - measurement at midspan of centerline
CENTER - average of centerline measurements
MAX - maximum of all measurements
AVERAGE - average of all measurements

STD - standard deviation of all measurements
ROW MAX - maximum of edge of ROW measurements
ROW AVE - average of edge of ROW measurements
ROW STD - standard deviation of edge of ROW measurements

13.0 TABLES

Table 3.1: Characterization study sampling plan by region, voltage and configuration group.

Region/Voltage	Group Label *	Configurations **	Row Width, Ft.	Mileage	Spans to be sampled
West/230-kV	SC1	J3, J9	125	476.09	38
	SC2	J7	100	451.61	37
	SC3	J10, J14	125	250.05	20
	DC	J2, J18	125	179.14	15
	DC	J12	125	124.43	10
	Total spans				120
East/230-kV	SC1	J3, J9, J5	125	1167.15	47
	SC2	J7, J8	100	511.37	21
	DC	J1	125	128.74	5
	DC	J2	125	95.29	4
	DC	J30	100	74.55	3
	Total spans				80
West/500-kV	SC1	M1, M3, M15	125	602.62	76
	SC2	M9, M12, M5	140	202.32	25
	DC	M24, M27	125	52.42	7
	DC	M14	165	52.01	7
	SC3	M23	125	40.70	5
	Total spans				120
East/500-kV	SC1	M3, M1, M15	125	1139.33	52
	SC3	M23	125	195.90	9
	DC	M24, M27	125	163.30	8
	DC	M19, M20	130	129.03	6
	SC2	M9, M12	140	119.06	5
	Total spans				80

* SC denotes single circuit; DC denotes double circuit.

** See Figure 3.1 for configuration descriptions.

Table 3.2: Variability study span sampling plan.

Region/ Voltage	Group Label	Config.	Line Name	ROW Width, ft.	Mileage	Spans
West/230-kV	SC2	J7	Alvey Fairview No. 1	100	82.65	25
	SC1	J9	Santiam-Alvey No. 1	125	53.47	25
	SC1	J3	Ross-Lexington No. 1	125	41.21	25
East/230-kV	SC1	J3	North Bonneville- Midway No. 1	125	132.71	25
	SC2	J7	Pilot Butte- Chiloquin	100	110.62	25
	SC1	J3	Grand Coulee-Bell No. 5	125	45.47	25
West/500-kV	SC1	M3	Raver-Paul No. 1	125	66.36	25
	SC2	M9	Monroe-Custer No. 2	140	62.24	25
	SC1	M15	Chief Joseph- Monroe No. 1	125	50.70	25
East/500-kV	SC1	M3	Grizzly-Malin No. 1	125	178.49	25
	SC3	M23	Buckley-Summer Lake No. 1	125	127.59	25
	SC1	M3	Lower Monumental- McNary No. 1	125	60.65	25

Table 8.1: Measured spans for characterization study.

Circuit Type	Region/Voltage	Group Label	Configuration	Measured Spans	% in multiple-line corridor
Single	West/230-kV	SC1	J3, J9	40	83
		SC2	J7	40	38
		SC3	J10, J14	19	47
	East/230-kV	SC1	J3, J9	52	83
		SC2	J7, J8	17	6
	West/500-kV	SC1	M1, M3, M15	72	74
		SC2	M5, M9, M12	37	76
		SC3	M23	6	100
	East/500-kV	SC1	M1, M3, M15	61	75
		SC2	M9, M12	5	80
		SC3	M23	11	91
Double	West/230-kV	DC	J2, J12, J18	26	45
	East/230-kV	DC	J30	29	100
	West/500-kV	DC	M14, M24, M27	32	97
	East/500-kV	DC	M19, M20, M24, M27	26	100

Table 8.2 Measured spans for variability study.

Region/ Voltage	Group	Config.	Line Name	Measured spans	% in Multiple- Line Corridor
West/230-kV	SC2	J7	Alvey-Fairview No. 1	38	5
	SC1	J9	Santiam-Alvey No. 1	18	94
	SC1	J3	Ross-Lexington No. 1	26	0
East/230-kV	SC1	J3	North Bonneville- Midway No. 1	54	89
	SC1	J3	Grand Coulee-Bell No. 5	25	100
West/500-kV	SC1	M3	Raver-Paul No. 1	49	76
	SC2	M9	Monroe-Custer No. 2	28	93
	SC1	M15	Chief Joseph-Monroe No. 1	25	100
East/500-kV	SC1	M3	Grizzly-Malin No. 1	41	98
	SC3	M23	Buckley-Summer Lake No. 1	34	100
	SC1	M3	Lower Monumental- McNary No. 1	27	7

Table 8.3: Significance of relationships between independent variables and summary measures for single-circuit line spans. Significance level indicated as follows: *, <0.05; †, <0.01 and ‡, <0.001.

		Summary Measures							
Independent Variable		M I D	C E N T E R	M A X	A V E R A G E	S T D	R O W M A X	R O W A V E	R O W S T D
Region									
Voltage		†	†	†	†	†	†	†	
Group 230:	1 vs 2			*	*	*			
	1 vs 3	*	*	*	*	*	*	*	
	2 vs 3	*	*	*	*	*	*	*	
Group 500:	1 vs 2								
	1 vs 3								
	2 vs 3								
Span Length - 230-kV		*		†		†			†
Span Length - 500-kV		*		*		†			*
Parallel - 230-kV					†	†			
Parallel - 500-kV					†	*			
Terrain - 230									
Terrain - 500									
Temperature - 230-kV									
Temperature - 500-kV									

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.4: Summary measures in mG/A for 230-kV single-circuit spans.

		Mean	Maximum	Std. Dev.	Coef. of Variation	Std. Error
Group SC1 (Flat) (N=92)						
	MID	.173	.415	.068	.393	.007
	CENTER	.149	.344	.050	.334	.005
	MAX	.183	.415	.062	.337	.006
	AVERAGE	.089	.195	.027	.302	.003
	STD	.052	.129	.021	.410	.002
	ROW MAX	.073	.129	.020	.214	.002
	ROW AVE	.057	.111	.016	.275	.001
	ROW STD	.012	.026	.005	.419	.0005
Group SC2 (Flat) (N=57)						
	MID	.149	.205	.036	.242	.005
	CENTER	.129	.199	.033	.256	.004
	MAX	.152	.211	.036	.237	.005
	AVERAGE	.076	.107	.015	.197	.002
	STD	.037	.065	.011	.297	.001
	ROW MAX	.074	.161	.021	.284	.003
	ROW AVE	.056	.081	.011	.196	.001
	ROW STD	.012	.039	.006	.333	.001
Group SC3 (Flat) (N=19)						
	MID	.085	.159	.040	.471	.009
	CENTER	.086	.145	.036	.384	.008
	MAX	.110	.195	.048	.613	.011
	AVERAGE	.053	.097	.018	.352	.004
	STD	.027	.051	.013	.667	.003
	ROW MAX	.054	.081	.016	1.03	.004
	ROW AVE	.039	.068	.012	.341	.003
	ROW STD	.009	.014	.003	1.57	.001
Overall (N=168)						
	MID	.155	.415	.062	.402	.005
	CENTER	.135	.343	.047	.349	.004
	MAX	.164	.415	.158	.353	.004
	AVERAGE	.081	.194	.025	.315	.002
	STD	.044	.129	.020	.447	.002
	ROW MAX	.071	.161	.021	.290	.002
	ROW AVE	.055	.111	.015	.272	.001
	ROW STD	.012	.039	.005	.459	.004

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.5: Summary measures in mG/A for 500-kV single-circuit spans.

		Mean	Maximum	Std. Dev.	Coef. of Variation	Std. Error
Group SC1 (Delta) (N=133)						
	MID	.097	.550	.063	.654	.006
	CENTER	.086	.472	.054	.628	.005
	MAX	.103	.550	.060	.581	.005
	AVERAGE	.057	.313	.033	.579	.003
	STD	.026	.155	.018	.678	.002
	ROW MAX	.054	.274	.026	.490	.002
	ROW AVE	.041	.218	.021	.509	.002
	ROW STD	.010	.040	.006	.580	.005
Group SC2 (Flat) (N=42)						
	MID	.115	.207	.047	.408	.007
	CENTER	.101	.167	.039	.382	.006
	MAX	.119	.207	.048	.400	.007
	AVERAGE	.066	.105	.024	.366	.004
	STD	.030	.057	.013	.455	.002
	ROW MAX	.059	.099	.022	.366	.003
	ROW AVE	.048	.078	.018	.372	.003
	ROW STD	.009	.018	.005	.507	.001
Group SC3 (Delta) (N=17)						
	MID	.104	.199	.035	.337	.009
	CENTER	.088	.152	.030	.339	.007
	MAX	.104	.199	.035	.331	.008
	AVERAGE	.064	.121	.021	.327	.005
	STD	.024	.039	.010	.422	.002
	ROW MAX	.061	.125	.020	.334	.005
	ROW AVE	.051	.103	.018	.347	.004
	ROW STD	.008	.019	.004	.483	.001
Overall (N=192)						
	MID	.101	.550	.058	.575	.004
	CENTER	.089	.472	.049	.553	.004
	MAX	.107	.550	.056	.523	.004
	AVERAGE	.059	.313	.030	.512	.002
	STD	.027	.155	.016	.613	.001
	ROW MAX	.055	.274	.025	.449	.002
	ROW AVE	.044	.218	.020	.466	.001
	ROW STD	.009	.040	.005	.559	.004

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.6: Results of multiple linear regression analyses of non-normalized magnetic field using midspan conductor height and current as independent variables. The proportion of the variance of magnetic field which was accounted for by these variables is given by R^2 . The "ideal" sample included only spans from single line corridors with flat terrain. All results significant at the $P=0.0001$ level.

Voltage		Summary Measure	R^2	"ideal" R^2
230-kV			(N=166)	(N=27)
	MID		.81	.95
	CENTER		.82	.96
	MAX		.79	.96
	AVERAGE		.83	.94
	STD		.71	.95
	ROW MAX		.84	.80
	ROW AVE		.87	.91
	ROW STD		.57	.49
500-kV			(N=192)	(N=20)
	MID		.72	.83
	CENTER		.74	.79
	MAX		.77	.87
	AVERAGE		.78	.83
	STD		.71	.88
	ROW MAX		.73	.81
	ROW AVE		.77	.81
	ROW STD		.49	.65

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.7: Distributions of observed values for continuous random effect variables.

	N	Mean	Std. Dev.	Minimum	Maximum
Current (A)					
230-kV	168	295	163	24	913
500-kV	192	597	331	47	1382
Conductor Height at Midspan (ft)					
230 kV	166	40.0	9.8	28	77
Group SC1	91	39.1	8.8	28	75
Group SC2	56	38.2	8.7	29	75
Group SC3	19	49.6	11.2	34	77
500 kV	192	49.4	13.1	31	117
Group SC1	133	50.1	13.8	31	117
Group SC2	42	50.4	12.1	35	85
Group SC3	17	43.5	8.6	31	65
Span Length (ft)					
230-kV	167	882	261	230	1500
500-kV	192	1027	216	354	1525
Wind Speed (mph)					
230-kV	168	3.9	4.3	0	20
500-kV	192	4.2	5.6	0	35
Temperature (°F)					
230-kV	168	69.9	11.8	39	97
500-kV	192	68.0	11.0	44	92

Table 8.8: Percentage of observations for categorical random effect variables.

	230-kV N=168	500-kV N=192
Landuse		
Vacant	49	47
Forest	12	11
Pasture	22	24
Cultivated	13	17
Residential	2	1
Commercial	1	0
Terrain		
Flat	40	46
Long. sloping	19	22
Lat. sloping	3	4
Long. & Lat. sloping	22	16
Undulating	12	9
Rough/Rugged	3	2
Vegetation on ROW		
None	19	17
Low lying	41	34
Brush	27	33
Trees	13	17
Weather		
Clear	45	49
Partly Cloudy	27	18
Overcast	15	21
Foggy	3	2
Rainy	10	10
Snow/Hail	0	0
Time of Day		
6-7:59 am	1	0
8-9:59	7	3
10-11:59	18	19
12-1:59 pm	28	27
2-3:59	24	26
4-5:59	13	19
6-7:59	6	5
8-9:59	3	1
Corridor		
Single line	40	23
Parallel line	60	77

Table 8.9: Annual magnetic field estimates in mG for 230-kV groups.

	Annual Mean			Annual 90th Percentile		
	Mean	Std. Dev.	Coef. of Variation	Mean	Std. Dev.	Coef. of Variation
Group SC1 (N=76)						
MID	33	16	.48	75	31	.41
CENTER	28	13	.44	63	24	.38
MAX	35	15	.44	78	30	.38
AVERAGE	17	8	.44	38	14	.35
STD	10	5	.50	22	9	.43
ROW MAX	14	6	.45	32	12	.38
ROW AVE	11	5	.47	25	9	.38
ROW STD	2	1	.53	5	2	.47
Group SC2 (N=47)						
MID	27	11	.40	59	21	.36
CENTER	23	9	.39	51	18	.35
MAX	28	11	.40	60	21	.35
AVERAGE	14	5	.37	31	12	.38
STD	7	3	.50	15	7	.45
ROW MAX	14	5	.34	31	11	.36
ROW AVE	11	3	.33	23	8	.37
ROW STD	2	1	.60	5	3	.58
Group SC3 (N=19)						
MID	18	18	1.03	30	28	.94
CENTER	18	17	.95	30	26	.87
MAX	22	22	.97	38	34	.89
AVERAGE	10	8	.84	17	13	.78
STD	5	5	.96	9	8	.89
ROW MAX	10	9	.83	18	13	.76
ROW AVE	7	6	.83	13	10	.77
ROW STD	2	1	.81	3	2	.74
Overall (N=142)						
MID	29	16	.53	63	31	.49
CENTER	25	13	.50	55	25	.46
MAX	31	16	.51	67	31	.46
AVERAGE	15	7	.48	33	15	.44
STD	8	5	.58	18	10	.54
ROW MAX	14	6	.47	29	13	.43
ROW AVE	10	5	.48	23	10	.44
ROW STD	2	1	.59	5	3	.55

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.10: Annual magnetic field estimates for 500-kV groups (mG).

	Annual Mean			Annual 90th Percentile		
	Mean	Std. Dev.	Coef. of Variation	Mean	Std. Dev.	Coef. of Variation
Group SC1 (N=127)						
MID	39	27	.70	97	80	.82
CENTER	35	23	.67	86	69	.80
MAX	42	26	.63	103	78	.76
AVERAGE	23	14	.62	56	43	.76
STD	11	8	.72	26	22	.85
ROW MAX	22	12	.54	52	34	.65
ROW AVE	17	9	.55	41	28	.68
ROW STD	4	3	.67	9	6	.69
Group SC2 (N=42)						
MID	38	16	.41	90	40	.44
CENTER	33	13	.39	79	34	.42
MAX	39	16	.40	94	41	.44
AVERAGE	22	8	.38	52	22	.42
STD	10	4	.44	23	11	.48
ROW MAX	20	8	.39	47	9	.42
ROW AVE	16	6	.40	38	16	.42
ROW STD	3	2	.52	7	4	.52
Group SC3 (N=17)						
MID	32	14	.43	77	39	.51
CENTER	27	11	.42	64	32	.50
MAX	33	14	.42	77	39	.51
AVERAGE	20	7	.36	46	21	.45
STD	7	4	.51	18	11	.61
ROW MAX	19	7	.37	44	20	.46
ROW AVE	15	6	.36	6	16	.44
ROW STD	3	1	.52	6	4	.59
Overall (N=186)						
MID	38	24	.63	94	70	.75
CENTER	34	21	.61	82	60	.73
MAX	40	23	.58	98	68	.70
AVERAGE	22	13	.57	54	37	.69
STD	10	7	.67	25	20	.79
ROW MAX	21	11	.50	50	30	.60
ROW AVE	16	8	.51	40	25	.62
ROW STD	4	2	.66	8	6	.68

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.11: Comparison of average measured fields with estimated average annual fields for 230-kV and 500-kV lines in mG.

	Measured N=168		Predicted Annual N=142	
230-kV spans	Mean	Std. Dev.	Mean	Std. Dev.
MID	46	30	29	16
CENTER	40	25	25	13
MAX	49	31	31	16
AVERAGE	24	14	15	7
STD	13	9	8	6
ROW MAX	21	12	14	8
ROW AVE	16	9	10	5
ROW STD	3	2	2	1
500-kV spans	N=192		N=186	
MID	58	39	38	24
CENTER	51	32	34	21
MAX	61	39	40	23
AVERAGE	33	20	22	13
STD	15	11	10	7
ROW MAX	32	20	21	11
ROW AVE	25	14	16	8
ROW STD	6	5	4	2

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.12: Comparison of calculated and measured normalized magnetic field summary measures in mG/A. Calculated values assumed: minimum design clearance at a conductor temperature of 50°C, which is 29 ft. for 230-kV lines and 33 ft. for 500-kV lines; average measured conductor height at tower and average span length for each group.

Voltage	Group Label	Summary Measure	Calculated for design height	Mean of measured values	90th percentile of measured values
230-kV	SC1 n=92	MID	.221	.173	.244
		MAX	.221	.183	.244
		ROW MAX	.076	.073	.095
		ROW AVE	.060	.057	.072
	SC2 n=57	MID	.214	.149	.190
		MAX	.214	.152	.194
		ROW MAX	.078	.074	.095
		ROW AVE	.061	.056	.071
	SC3 n=19	MID	.220	.085	.155
		MAX	.220	.110	.188
		ROW MAX	.066	.054	.078
		ROW AVE	.056	.039	.056
500-kV	SC1 n=132	MID	.180	.097	.138
		MAX	.180	.103	.138
		ROW MAX	.055	.054	.072
		ROW AVE	.041	.041	.050
	SC2 n=42	MID	.189	.115	.172
		MAX	.189	.119	.172
		ROW MAX	.081	.059	.084
		ROW AVE	.062	.048	.072
	SC3 n=17	MID	.156	.104	.141
		MAX	.156	.104	.141
		ROW MAX	.042	.061	.081
		ROW AVE	.033	.051	.072

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.13: Summary measures in mg/A for variability study 230-kV lines.

	Mean	Maximum	Std. Dev.	Coef. of Variation	Std. Error
ALVEY-FAIRVIEW NO. 1 (N=38)					
MID	.137	.213	.048	.350	.008
CENTER	.125	.190	.039	.307	.006
MAX	.148	.213	.041	.274	.007
AVERAGE	.073	.113	.015	.205	.002
STD	.035	.057	.012	.338	.002
ROW MAX	.078	.136	.018	.230	.003
ROW AVE	.057	.092	.009	.161	.001
ROW STD	.013	.031	.006	.469	.001
SANTIAM-ALVEY NO. 1 (N=18)					
MID	.154	.240	.065	.422	.015
CENTER	.132	.206	.047	.357	.011
MAX	.166	.240	.057	.340	.013
AVERAGE	.081	.125	.022	.267	.005
STD	.047	.079	.021	.458	.005
ROW MAX	.068	.162	.027	.400	.006
ROW AVE	.052	.090	.014	.274	.003
ROW STD	.012	.036	.007	.611	.002
ROSS-LEXINGTON NO. 1 (N=26)					
MID	.158	.261	.052	.331	.010
CENTER	.138	.201	.040	.291	.008
MAX	.169	.261	.048	.281	.009
AVERAGE	.076	.103	.014	.189	.003
STD	.041	.062	.014	.353	.003
ROW MAX	.081	.132	.019	.234	.004
ROW AVE	.057	.074	.008	.143	.002
ROW STD	.013	.027	.005	.410	.001
NORTH BONNEVILLE-MIDWAY NO. 1 (N=54)					
MID	.172	.261	.055	.319	.008
CENTER	.155	.234	.037	.240	.005
MAX	.187	.261	.040	.212	.005
AVERAGE	.093	.127	.016	.173	.002
STD	.055	.090	.016	.294	.002
ROW MAX	.073	.122	.013	.178	.002
ROW AVE	.058	.074	.008	.134	.002
ROW STD	.011	.028	.005	.462	.007
GRAND COULEE-BELL NO. 5 (N=25)					
MID	.157	.246	.045	.287	.009
CENTER	.144	.219	.034	.237	.007
MAX	.190	.287	.049	.257	.010
AVERAGE	.088	.119	.016	.182	.003
STD	.056	.085	.016	.292	.003
ROW MAX	.076	.287	.045	.586	.009
ROW AVE	.055	.086	.010	.190	.002
ROW STD	.015	.112	.020	1.319	.004

Table 8.14 Summary measures in mg/A for variability study 500-kV lines.

	Mean	Maximum	Std. Dev.	Coef. of Variation	Std. Error
RAVER-PAUL NO. 1 (N=49)					
MID	.092	.157	.030	.325	.004
CENTER	.079	.126	.020	.248	.003
MAX	.096	.157	.026	.269	.004
AVERAGE	.050	.072	.009	.180	.001
STD	.025	.024	.009	.357	.001
ROW MAX	.046	.103	.012	.254	.002
ROW AVE	.036	.058	.005	.148	.0008
ROW STD	.008	.024	.004	.451	.0005
MONROE-CUSTER NO. 2 (N=28)					
MID	.139	.215	.049	.351	.009
CENTER	.119	.183	.038	.321	.007
MAX	.142	.215	.048	.335	.009
AVERAGE	.079	.110	.023	.294	.004
STD	.037	.064	.014	.389	.003
ROW MAX	.068	.099	.020	.295	.004
ROW AVE	.055	.078	.016	.289	.003
ROW STD	.011	.020	.005	.423	.009
CHIEF JOSEPH-MONROE NO. 1 (N=25)					
MID	.092	.150	.030	.330	.006
CENTER	.083	.117	.021	.256	.004
MAX	.101	.150	.027	.270	.005
AVERAGE	.061	.082	.011	.176	.002
STD	.023	.041	.012	.499	.002
ROW MAX	.061	.106	.017	.288	.003
ROW AVE	.048	.082	.013	.270	.003
ROW STD	.009	.029	.005	.502	.001
GRIZZLY-MALIN NO. 1 (N=41)					
MID	.110	.145	.026	.236	.004
CENTER	.092	.119	.017	.184	.003
MAX	.112	.145	.023	.208	.004
AVERAGE	.060	.093	.010	.160	.001
STD	.030	.043	.008	.275	.001
ROW MAX	.051	.090	.010	.192	.002
ROW AVE	.040	.078	.008	.191	.001
ROW STD	.009	.020	.003	.348	.0005
BUCKLEY-SUMMER LAKE NO. 1 (N=34)					
MID	.120	.199	.030	.250	.005
CENTER	.103	.152	.028	.273	.005
MAX	.120	.199	.030	.251	.005
AVERAGE	.072	.121	.014	.194	.002
STD	.029	.056	.013	.445	.002
ROW MAX	.064	.125	.015	.242	.003
ROW AVE	.054	.103	.012	.219	.002
ROW STD	.008	.019	.004	.507	.0007
... Table continued on next page					

Table 8.14 continued...

	Mean	Maximum	Std. Dev.	Coef. of Variation	Std. Error
LOWER MONUMENTAL-MCNARY NO. 1 (N=27)					
MID	.108	.155	.029	.273	.006
CENTER	.091	.121	.021	.231	.004
MAX	.110	.155	.027	.243	.005
AVERAGE	.052	.073	.008	.154	.002
STD	.026	.045	.008	.322	.002
ROW MAX	.052	.078	.007	.138	.001
ROW AVE	.039	.047	.004	.103	.0008
ROW STD	.008	.014	.002	.284	.0005

Table 8.15: Observed distributions of random-effect continuous variables in the variability study of 230-kV lines.

	Variable	Mean	Std. Dev.	Minimum	Maximum
Current (A)					
	Alvey-Fairview No.1	246	78	130	358
	Santiam-Alvey No. 1	133	33	100	236
	Ross-Lexington No. 1	386	197	64	615
	N Bonneville-Midway No. 1	413	117	262	617
	Grand Coulee-Bell No. 5	209	34	145	285
Height at mid span (ft)					
	Alvey-Fairview No. 1	41	12	29	91
	Santiam-Alvey No. 1	45	11	32	66
	Ross-Lexington No. 1	37	8	32	63
	N Bonneville-Midway No. 1	35	10	28	75
	Grand Coulee-Bell No. 5	37	7	26	55
Span length (ft)					
	Alvey-Fairview No. 1	573	165	475	875
	Santiam-Alvey No. 1	947	197	585	1300
	Ross-Lexington No. 1	984	280	510	1515
	N Bonneville-Midway No. 1	908	228	350	1450
	Grand Coulee-Bell No. 5	1021	163	800	1450
Temperature (°F)					
	Alvey-Fairview No. 1	61	6	48	71
	Santiam-Alvey No. 1	60	7	48	71
	Ross-Lexington No. 1	51	20	27	94
	N Bonneville-Midway No. 1	73	12	48	92
	Grand Coulee-Bell No. 5	89	8	78	102

Table 8.16: Observed distributions of random-effect continuous variables in the variability study of 500-kV lines.

	Variable	Mean	Std. Dev.	Minimum	Maximum
Current (A)					
	Raver-Paul No. 1	664	195	336	1024
	Monroe-Custer No. 2	488	234	146	762
	Chief Joseph-Monroe No. 1	655	80	499	757
	Grizzly-Malin No. 1	1125	263	689	1484
	Buckley-Summer Lake No. 1	600	259	132	948
	L Monumental-McNary No. 1	663	282	286	1119
Height at mid span (ft)					
	Raver-Paul No. 1	49	10	39	87
	Monroe-Custer No. 2	45	7	36	61
	Chief Joseph-Monroe No. 1	41	7	32	65
	Grizzly-Malin No. 1	41	6	31	57
	Buckley-Summer Lake No. 1	40	3	31	47
	L Monumental-McNary No. 1	49	11	37	85
Span length (ft)					
	Raver-Paul No. 1	1069	171	692	1550
	Monroe-Custer No. 2	1036	188	438	1275
	Chief Joseph-Monroe No. 1	830	282	303	1525
	Grizzly-Malin No. 1	1110	135	562	1250
	Buckley-Summer Lake No. 1	1094	143	475	1275
	L Monumental-McNary No. 1	1024	196	535	1350
Temperature (°F)					
	Raver-Paul No. 1	63	9	44	78
	Monroe-Custer No. 2	67	11	50	82
	Chief Joseph-Monroe No. 1	85	6	75	94
	Grizzly-Malin No. 1	70	12	53	92
	Buckley-Summer Lake No. 1	65	10	50	92
	L Monumental-McNary No. 1	72	5	63	82

Table 8.17: Percentage of observations for random-effect variables for 230-kV variability study lines.

	Alvey-Fairview No. 1 N=38	Santiam-Alvey No. 1 N=18	Poss-Lexington No. 1 N=26	North Bonneville-Midway No. 1 N=54	Grand Coulee-Bell No. 5 N=25
Landuse					
Vacant	32	6	27	76	56
Forest	5	39	8	6	0
Pasture	63	39	58	4	0
Cultivated	0	11	4	15	44
Residential	0	0	0	0	0
Commercial	0	6	4	0	0
Terrain					
Flat	47	28	46	20	8
Long. Sloping	5	17	15	26	32
Lat. Sloping	3	11	0	0	0
Long. & Lat. Sloping	39	17	19	30	12
Undulating	5	22	19	13	40
Rough/Rugged	0	6	0	11	8
Vegetation on ROW					
None	55	22	46	9	36
Low lying	16	17	35	19	60
Brush	21	56	12	57	4
Trees	8	6	8	15	0
Weather					
Clear	16	50	38	56	100
Partly Cloudy	26	28	4	30	0
Overcast	50	6	35	4	0
Foggy	0	6	0	0	0
Rainy	8	11	23	11	0
Snow/Hail	0	0	0	0	0
Time of Day					
8-9:59 am	26	17	15	4	24
10-11:59	24	17	23	22	20
12-1:59 pm	13	33	42	22	20
2-3:59	18	22	19	22	24
4-5:59	13	11	0	20	8
6-7:59	5	0	0	9	4

Table 8.18: Percentage of observations for random effect variables for 500-kv variability study lines.

	Raver-Paul No. 1 N=49	Monroe-Custer No. 2 N=28	Chief Joseph-Monroe No. 1 N=25	Grizzly-Malin No. 1 N=41	Buckley-Summer Lake No. 1 N=34	Lower Monumental-McNary No. 1 N=27
Landuse						
Vacant	43	32	52	73	62	70
Forest	8	11	32	27	29	0
Pasture	41	54	12	0	3	15
Cultivated	0	4	0	0	6	15
Residential	8	0	4	0	0	0
Commercial	0	0	0	0	0	0
Terrain						
Flat	45	75	32	46	53	37
Long. Sloping	20	0	4	37	41	30
Lat. Sloping	4	0	24	0	3	4
Long. & Lat. Sloping	8	21	32	15	3	22
Undulating	16	4	4	2	0	7
Rough/Rugged	6	0	4	0	0	0
Vegetation on ROW						
None	16	11	4	5	6	37
Low lying	20	32	0	54	47	48
Brush	55	25	48	27	35	0
Trees	8	32	48	15	12	15
Weather						
Clear	31	43	100	51	32	37
Partly Cloudy	4	14	0	41	59	63
Overcast	39	29	0	7	3	0
Foggy	4	0	0	0	0	0
Rainy	22	14	0	0	6	0
Snow/Hail	0	0	0	0	0	0
Time of Day						
8-9:59 am	2	0	12	5	6	19
10-11:59	27	25	28	17	32	26
12-1:59 pm	33	18	24	24	21	22
2-3:59	22	32	20	32	21	15
4-5:59	14	14	16	12	21	11
6-7:59	2	11	0	10	0	7

Table 8.19: Comparison of calculated and measured normalized summary measures in mG/A for 230-kV variability study lines. Calculated values assume: minimum design clearance at 50°C, which are 29 ft and 33 ft for 230-kV and 500-kV lines, respectively; average measured conductor height at tower, and average span length for each line.

Line name	Summary measure	Calculated at design height, mG/A	Mean measured value, mG/A
Alvey-Fairview No. 1	MID	.214	.137
	MAX	.214	.148
	ROW MAX	.078	.078
	ROW AVE	.066	.057
Santiam-Alvey No. 1	MID	.221	.154
	MAX	.221	.166
	ROW MAX	.074	.068
	ROW AVE	.058	.052
Ross-Lexington No. 1	MID	.221	.158
	MAX	.221	.169
	ROW MAX	.077	.081
	ROW AVE	.061	.057
North Bonneville-Midway No. 1	MID	.221	.172
	MAX	.221	.187
	ROW MAX	.077	.073
	ROW AVE	.063	.057
Grand Coulee-Bell No. 5	MID	.221	.157
	MAX	.221	.190
	ROW MAX	.077	.076
	ROW AVE	.065	.055

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.20: Comparison of calculated and measured normalized summary measures in mG/A for 500-kV variability study lines. Calculated values assume: minimum design clearance at 50°C, which are 29 ft and 33 ft for 230-kV and 500-kV lines, respectively; average measured conductor height at tower, and average span length for each line.

Line name	Summary measure	Calculated at design height, mG/A	Mean measured value, mG/A
Raver-Paul No. 1	MID	.177	.092
	MAX	.177	.096
	ROW MAX	.053	.046
	ROW AVE	.039	.036
Monroe-Custer No. 2	MID	.190	.139
	MAX	.190	.142
	ROW MAX	.077	.068
	ROW AVE	.061	.055
Chief Joseph-Monroe No. 1	MID	.179	.092
	MAX	.179	.101
	ROW MAX	.054	.061
	ROW AVE	.049	.048
Grizzly-Malin No. 1	MID	.177	.110
	MAX	.177	.112
	ROW MAX	.053	.051
	ROW AVE	.041	.040
Buckley-Summer Lake No. 1	MID	.156	.120
	MAX	.156	.120
	ROW MAX	.042	.064
	ROW AVE	.033	.054
Lower Monumental-McNary No. 1	MID	.177	.108
	MAX	.177	.110
	ROW MAX	.053	.052
	ROW AVE	.038	.039

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.21:

Results of multiple linear regression analyses of non-normalized magnetic field summary measures for double-circuit lines. Currents on the two circuits and the midspan conductor height were used as independent variables. The fraction of variance accounted for by these three variables is given by R^2 .

	R^2	Prob.
230kV (N=19)		
MID	.87	.0001
CENTER	.85	.0001
MAX	.83	.0001
AVERAGE	.87	.0001
STD	.74	.0001
ROW MAX	.54	.0069
ROW AVE	.67	.0007
ROW STD	.43	.0346
500kV (N=40)		
MID	.92	.0001
CENTER	.89	.0001
MAX	.90	.0001
AVERAGE	.74	.0001
STD	.92	.0001
ROW MAX	.43	.0001
ROW AVE	.41	.0003
ROW STD	.50	.0001

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.22: Non-normalized summary measures in mG for 230-kV single-circuit and double-circuit spans.

	Mean	Std. Dev.	Minimum	Maximum
Single-circuit - (N=168)				
MID	46	30	2	159
CENTER	40	25	2	126
MAX	49	31	3	159
AVERAGE	24	14	1	80
STD	13	9	1	47
ROW MAX	20	12	2	73
ROW AVE	16	9	1	53
ROW STD	3	2	0	15
Double-circuit - (N=55)				
MID	30	24	4	102
CENTER	28	21	4	93
MAX	33	26	4	117
AVERAGE	21	17	3	68
STD	8	6	1	27
ROW MAX	22	22	3	93
ROW AVE	17	16	2	58
ROW STD	4	5	0	21

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.23: Non-normalized summary measures in mG for 500-kV single-circuit and double-circuit spans.

	Mean	Std. Dev.	Minimum	Maximum
Single-circuit - (N=192)				
MID	58	39	4	182
CENTER	51	32	6	164
MAX	61	39	8	182
AVERAGE	33	20	4	99
STD	15	11	1	47
ROW MAX	32	20	4	126
ROW AVE	25	14	3	80
ROW STD	6	5	0	37
Double-circuit - (N=58)				
MID	66	39	11	146
CENTER	60	34	19	123
MAX	71	37	19	146
AVERAGE	44	22	15	96
STD	17	11	2	36
ROW MAX	43	21	16	95
ROW AVE	34	17	13	82
ROW STD	7	4	2	18

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

Table 8.24: Average of the absolute value of the differences between paired quality control spans compared to overall mean summary measures for the voltage class.

Summary Measure	Mean absolute difference, mG/A	Overall mean for voltage class, mG/A
230kV	N=24	N=168
MID	.024	.155
CENTER	.020	.135
MAX	.018	.164
AVERAGE	.008	.081
ROW MAX	.014	.071
ROW AVE	.007	.055
500kV	N=23	N=192
MID	.025	.101
CENTER	.018	.089
MAX	.035	.106
AVERAGE	.013	.059
ROW MAX	.025	.055
ROW AVE	.012	.044

Summary Measures

MID - measurement at midspan of centerline
 CENTER - average of centerline measurements
 MAX - maximum of all measurements
 AVERAGE - average of all measurements

STD - standard deviation of all measurements
 ROW MAX - maximum of edge of ROW measurements
 ROW AVE - average of edge of ROW measurements
 ROW STD - standard deviation of edge of ROW measurements

14.0 APPENDIX

Appendix: SAMPLED SPANS

Spans are designated by line name and mile/tower

1. Characterization Study Single-Circuit Spans

WEST 230 GROUP SC1

Big Eddy-Chemawa No. 1: BIE-CH1

88/4

Big Eddy-Troutdale No. 1: BIE-TR1

67/2 68/1 71/2 73/2 75/6

North Bonneville-Ross No. 1: NOB-RO1

24/2 24/3 25/2 26/4 26/5 27/3 27/4 27/5 28/3

North Bonneville-Troutdale No. 1: NOB-TR1

9/3 23/3 23/4

North Bonneville-Troutdale No. 2: NOB-TR2

9/3

Olympia-South Tacoma No. 1: OLY-SO1

31/2

Olympia-White River No. 1: OLY-WR1

4/3 8/4 13/2 16/1 17/3 18/3

Ross-Lexington No. 1: ROS-LE1

6/5 15/3 15/5

Santiam-Alvey No. 1: SAN-AL1

3/5 4/1 23/5 52/4

Santiam-Alvey No. 2: SAN-AL2

2/1 12/4 19/2

Santiam-Albany: SAN-ALB

15/4 21/5 22/2 16/1

WEST 230 GROUP SC2

Alvey-Fairview No. 1: ALV-FA1

2/3 2/4 2/5 7/3 7/4 11/5 11/7 38/3 48/4 59/2

Chehalis-Mayfield No. 1: CHE-MA1

2/5 10/2 12/2 15/1 5/7

Chehalis-Olympia No. 1: CHE-OL1

10/7 15/2 16/3 17/4 18/1 18/4

Murray-Bellingham No. 1: MUR-BE1

5/1 6/2

North Bonneville-Ross No. 1: NOB-RO1

18/5

Olympia-Kitsap No. 3: OLY-KI3

17/4 24/1 24/5 26/1 29/5 31/1 39/3

Ross-Lexington No. 1: ROS-LE1

33/3

Santiam-Toledo No. 1: SAN-TO1

9/5 10/1 16/5 22/2 24/1 27/5

Snohomish-Murray No. 1: SNO-MU1

4/4 6/1

WEST 230 GROUP SC3

Fairview-Rogue No. 1: FAI-RO1

42/1 42/2 42/3 48/2 59/1 60/1 65/4

Longview-Chehalis No. 1: LON-CH1

23/2 34/4

Santiam-Chemawa No. 1: SAN-CH1

3/4 6/2 6/4 7/2 14/3

Santiam-Toledo No. 1: SAN-TO1

52/3 52/4 58/1

Toledo-Wendson No. 1: TOL-WE1

24/3 24/5

EAST 230 GROUP SC1

Bell-Boundary No. 3: BEL-BO3
35/5
Big Eddy-Midway No. 1: BIE-MI1
101/3
Grand Coulee-Bell No. 5: GRC-BE5
44/4 47/2 51/1 56/1 56/3 65/5 69/4 78/5
Grand Coulee-Columbia No. 3: GRC-CO3
44/4 73/5
Horse Heaven-Harvalum No. 1: HOH-HA1
3/2 4/2 11/4 30/3 38/4
McNary-Santiam No. 2: MarmCN-SA2
7/5
Midway-Columbia No. 3: MID-CO3
44/3
Midway-Grand Coulee No. 3: MID-GC3
6/4 22/2 26/2 73/4 85/4 89/3 89/4
North Bonneville-Midway No. 1: NOB-MI1
1/3 2/6 22/6 28/6 34/2 34/3 36/3 39/2 39/4 39/5 48/5 53/3 58/5
72/3 78/5 89/3 102/4 122/2 123/1 130/2
Vantage-Columbia No. 1: VAN-CO1
7/1 7/3 7/4 17/2 28/4 30/2

EAST 230 GROUP SC2

Bell-Boundary No. 1: BEL-BO1
5/1
McNary-Franklin No. 2: MCN-FR2
4/4 4/5
Pilot Butte-Chiloquin No. 1: PIB-CH1
38/5 40/1 42/2 43/4 45/1 45/5 50/3 50/4 51/3 51/4
Ponderosa-Pilot Butte No. 1: PON-PI1
18/4
Roundup-La Grande No. 1: ROU-LG1
5/1 20/1 20/4

WEST 500 GROUP SC1

John Day-Marion No. 1: JOD-MA1
14/3 81/2 83/2 86/3
Keeler-Alston No. 1: KEE-AL1
26/3 30/2 32/5 39/5
Marion-Alvey No. 1: MAR-AL1
4/1 4/2 7/1 17/3 21/5 22/4 28/4 29/2 34/2
Marion-Lane No. 1: MAR-LA1
4/2 15/1 23/5 25/5 36/3 48/4
Monroe-Custer No. 1: MON-CU1
11/5 14/3 17/4 18/1 32/1 32/4 47/5 56/3 79/1 79/3 82/2 87/2
Monroe-Custer No. 2: MON-CU2
10/3 11/1 60/1 81/3 81/5
Ostrander-Troutdale No. 1: OST-TR1
14/2 19/5 20/5 22/4 22/5
Paul-Alston No. 2: PAU-AL2
15/4
Paul-Olympia No. 1: PAU-OL1
16/3 19/5
Raver-Covington No. 2: RAV-CO2
9/2
Raver-Monroe NO. 1: RAV-MO1
7/5
Raver-Paul No. 1: RAV-PA1
3/3 5/2 8/2 10/5 14/2 17/3 33/3 36/1 37/1 37/2 38/3 40/3 41/2 43/4 48/3
48/4 52/3 55/1 55/2 64/2 64/5 66/2

WEST 500 GROUP SC2

Big Eddy-Ostrander No. 1: BIE-OS1
55/2 55/3

Marion-Alvey No. 1: MAR-AL1
41/2

Marion-Lane No. 1: MAR-LAL
57/5 58/1 61/2 66. 69/1

Monroe-Custer No. 2: MON-CU2
26/1 26/2 26/3 26/4 26/5 27/2 27/3 27/4 27/5 28/2 28/247/3 47/4 47/5 47/6
50/4 51/4 53/2 76/3 85/2 85/4

Ostrander-Pearl No. 1: OST-PE1
11/4 11/5 13/3

Pearl-Keeler No. 1: PEA-KE1
2/2 2/3 2/4 3/1 6/1

WEST 500 GROUP SC3

Paul-Satsop No. 1: PAU-SAL
7/4 8/2 10/5 16/4 19/1

Raver-Paul No. 1: RAV-PA1
34/5

EAST 500 GROUP SC1

Chief Joseph-Monroe No. 1: CHJ-MO1
29/3 63/2

Chief Joseph-Sickler No. 1: CHJ-SI1
7/5 11/1 12/5 18/4 21/1 28/2

Grand Coulee-Chief Joseph No. 3: GRC-CJ3
7/5 15/4 26/5

Grizzly-Malin No. 1: GRI-MA1
2/1 4/3 6/3 7/2 14/4 14/5 19/1 19/2 19/3 19/4 23/4 23/5 25/1 25/2
26/1 26/2 29/5 35/1 35/2 35/4 35/5 45/2

Hanford-John Day No. 1: HAN-JD1
40/3

John Day-Grizzly No. 1: JOD-GR1
12/2 51/3 54/2 63/2 87/3

John Day-Grizzly No. 2: JOD-GR2
5/5

John Day-Malin No. 1: JOD-MA1
19/3 33/2 40/4 45/3

Lower Monumental-Harvalum No. 1: LOM-HA1
7/3 12/2 16/2 43/2

Lower Monumental-McNary No. 1: LOM-MC1
5/3 13/4 18/2 59/1

McNary-John Day No. 1: MCN-JD1
9/1 18/1 18/2 54/1

Sickler-Raver No. 1: SIC-RA1
27/3 52/4 63/1 68/3

EAST 500 GROUP SC2

John Day-Ostrander No. 1: JOD-OS1
19/3 19/4 26/5 26/6

Vantage-Raver No. 1: VAN-RA1
22/5

EAST 500 GROUP SC3

Buckley-Summer Lake No. 1: BUC-SL1
1/3 3/2 70/1 70/2 80/2 84/4 86/3 86/4 92/4 93/1

Lower Monumental-Ashe No. 1: LOM-AS1
34/4

2. Variability Study Spans

WEST 230 Alvey-Fairview No. 1: ALV-FAL

1/1 2/2 2/3 2/4 2/5 5/1 5/2 5/4 5/5 7/2 7/3 7/4 7/5 11/6 11/7
14/1 14/2 15/2 16/4 16/5 19/1 19/2 19/3 19/4 38/3 43/4 43/5
48/4 52/3 55/5 56/4 56/5 59/2 60/2 61/1 61/2 61/5 65/2

WEST 230 Santiam-Alvey No. 1: SAN-AL1

3/5 4/1 13/1 13/2 16/2 18/3 19/2 20/2 23/5
25/2 33/4 37/1 38/1 45/2 45/3 46/4 51/4 52/2 52/3 52/4

WEST 230 Ross-Lexington No. 1: ROS-LE1

1/4 2/2 2/4 5/4 6/2 6/3 6/4 6/5 8/1 8/3 10/1 10/2 10/4 11/2 13/3
15/3 15/5 17/4 19/1 23/1 26/2 26/4 30/2 30/3 33/2 37/2

EAST 230 North Bonneville-Midway No. 1: NOB-MI1

1/3 2/5 2/6 5/5 20/3 22/6 28/6 31/4 33/1 33/2 33/4 33/5 34/2 34/3
36/2 36/3 36/4 39/2 39/3 39/5 40/3 40/4 44/4 48/5 53/3 55/3 55/4
58/4 58/5 62/1 62/2 62/3 62/4 62/5 63/1 67/2 67/3 72/3 73/4 74/3
78/5 89/3 90/4 95/1 95/2 98/4 99/3 102/4 118/5 122/2 122/3 123/1
123/3 130/2

EAST 230 Grand Coulee-Bell No. 5: GRC-BE5

9/3 9/5 10/3 13/4 20/1 21/3 22/2 23/2 26/3 28/2 28/3 29/1 30/2
33/1 34/4 34/5 41/3 41/4 46/5 50/2 50/5 55/5 58/1 66/5 81/1

WEST 500 Raver-Paul No. 1: RAV-PA1

3/3 5/1 5/2 7/2 8/2 10/5 14/2 17/3 18/3 21/2 22/1 31/4 33/1 33/3
33/4 34/4 35/2 36/1 36/5 37/1 37/2 37/3 38/3 39/1 39/3 39/5 40/3
41/2 43/4 45/4 48/3 48/4 49/1 49/2 51/2 51/3 51/4 51/5 52/3 55/1
55/2 56/2 56/3 56/4 56/5 64/2 64/4 64/5 66/2

WEST 500 Monroe-Custer No. 2: MON-CU2

26/1 26/2 26/3 26/4 26/5 27/2 27/3 27/4 27/5 28/1 28/2 47/3 47/4
47/5 47/6 50/4 51/4 53/2 76/3 78/5 80/3 80/4 80/5 83/4 84/3 84/4
85/2 85/4

WEST 500 Chief Joseph-Monroe No. 1: CHJ-MO1

65/4 67/2 67/3 74/3 75/2 75/3 75/4 86/6 89/2 89/4 96/5 97/1 97/4 108/6
109/1 109/5 110/2 110/4 111/2 116/5 117/4 119/3 119/4 120/1 120/5

EAST 500 Grizzly-Malin No. 1: GRI-MAL

2/1 4/3 6/3 7/2 14/4 14/5 19/1 19/2 19/3 19/4 23/4 23/5 25/1 25/2
26/1 26/2 29/3 29/5 35/1 35/2 35/3 35/5 41/3 45/2 46/4 48/3 59/1
62/4 63/2 66/5 75/2 79/1 91/4 92/2 94/2 98/3 98/4 100/4 107/1
119/3 121/4

EAST 500 Buckley-Summer Lake No. 1: BUC-SL1

1/3 3/2 5/3 6/3 20/5 58/3 70/1 70/2 80/2 84/4 86/3 86/4 92/4 93/1
95/1 96/2 99/4 111/2 111/3 113/4 114/2 119/4 120/2 120/3 130/4
134/3 136/2 140/5 143/2 144/3 146/4 148/4 149/1 153/3

EAST 500 Lower Monumental-McNary No. 1: LOM-MCL

5/3 12/4 13/4 15/4 18/2 19/3 20/3 21/4 22/5 23/5 26/4 26/5 27/4 29/2 30/1
32/4 35/3 44/2 45/5 51/4 51/5 56/2 59/1 59/2 59/5 60/1 60/3

3. DOUBLE CIRCUIT SPANS

WEST 230 GROUP DC

Big Eddy-Troutdale No. 1: BIE-TR1
26/2 26/5
McNary-Santiam No. 2: MCN-SA2
8/1 191/4 191/5 199/4 199/5
NOB-RO1
4/2 10/2 19/1

WEST 230 GROUP DC

Allston-Clatsop: ALL-CL1
4/1 13/2
Carlton-Tillamook No. 1: CAR-TI1
37/1 37/4 39/4 40/1 40/5 41/2
Olympia-Port Angeles No. 1: OLY-PA1
14/4 17/1

WEST 230 ADDITIONAL DOUBLE CIRCUITS

Allston-Clatsop No. 1: ALL-CL1
12/4 12/5 13/3
Big Eddy-Troutdale No. 1: BIE-TR1
26/1
Monroe-Snohomish No. 1: MON-SN1
12/1
North Bonneville-Ross: NOB-RO1
8/3

EAST 230 GROUP DC

Bell-Boundary No. 3: BEL-BO3
66/2 69/5 75/7 76/5 79/4 81/4

EAST 230 GROUP DC

Bell-Boundary No. 3: BEL-BO3
55/3 56/1 56/3 57/4 58/4 65/4

EAST 230 ADDITIONAL DOUBLE CIRCUITS

Bell-Boundary No. 3: BEL-BO3
37/8 55/2 56/3 59/5 60/5 66/3 68/2
Big Eddy-Troutdale No. 1: BIE-TR1
25/2 25/3 26/2 26/3 32/4 32/5 33/4 36/3 37/4 37/5

WEST 500 GROUP DC

Ashe-Marion No. 2: ASH-MA2
103/4 106/2 106/3 106/4 110/3 110/4 121/3

WEST 500 GROUP DC

Raver-Monroe No. 1: RAV-MO1
38/2
Tacoma-Raver No. 1: TAC-RA1
3/4 4/4 7/4 12/5 13/4 14/5

WEST 500 ADDITIONAL DOUBLE CIRCUITS

Ashe-Marion No. 2: ASH-MA2
101/1 101/2 101/4 102/3 102/4 103/1 108/3 111/3 115/2
Tacoma-Raver No. 1: TAC-RA1
6/3 6/4 8/5 10/3 12/4 14/3 14/4 18/2 24/2

EAST 500 GROUP DC

Ashe-Marion No. 2: ASH-MA2
44/2 49/1 54/2 56/1 58/4 60/4 67/1 69/1 71/3

EAST 500 GROUP DC

Grand Coulee-Raver No. 2: GRC-RA2
92/3 94/4 97/3

EAST 500 ADDITIONAL DOUBLE CIRCUITS

Ashe-Marion NO. 2: ASH-MA2
3/3 4/4 7/1 10/1 11/2 16/3 24/4 26/3 30/2 31/1 40/5 43/1
Grand Coulee-Raver No. 2: GRC-RA2
97/2 103/1

4. QUALITY CONTROL SPANS

230-kV

Alvey-Fairview No. 1: ALV-FA1

2/3 2/5 5/1 5/4 7/3 7/4 11/7 14/1 16/5 19/1 19/4 38/3 43/4

North Bonneville-Midway No. 1: NOB-MI1

33/1 33/4 34/2 36/3 39/2 40/3 55/3 58/5 62/3 62/4 62/5 67/2

500-kV

Raver-Paul No. 1: RAV-PA1

33/3 37/1 48/4 49/1 51/3 51/4 55/1 56/2 56/5

Monroe-Custer No. 2: MON-CU2

26/4 27/3 28/2

Grizzly-Malin No. 1: GRI-MA1

14/5 19/1 19/2 23/5 25/1 26/1 29/5 35/1 35/5

Buckley-Summer Lake No. 1: BUC-SL1

70/1 80/2 84/4 86/3

END

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