SAMPLING PLANS FOR LIGHTNING SURGES TEST PROGRAM

**FINAL REPORT FOR THE PERIOD
MAY 1976 — JANUARY 1977**

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PREFACE

This research was supported by the U.S. Energy Research and Development Administration under contract number E (49-18) 2107. The study was directed jointly by Vinod K. Shrivastava and Ernest J. Mosbaek. Ernest Mosbaek made extensive trips to utilities across the nation to inspect potential sites for inclusion in our sample.

Specific contributions were made by Gordon Brown in the area of model development and estimates of sparkover and predischage voltages, Ernest Goodman in the initial development of the site slelection and site characterization forms, Hubert Lilliefors in the confidence limit calculations and Nirmal Kotamraju in the development of reflection and predischage effects.

The report was edited by Ernest Mosbaek, Vinod Shrivastava and Gordon Brown.

Jeff Serfass acted as the ERDA Project Manager for this study.

Shaaron Perry typed most of the manuscript.

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EXECUTIVE SUMMARY

This report covers the efforts and results of work performed by Jack Faucett Associates, Inc. under one of three contracts by U.S. Energy Research and Development Administration, as part of ERDA's effort to begin a study of lightning induced surges on electrical distribution lines. The other two contracts are held by the General Electric Company and the University of Pittsburgh to independently develop a low cost device to record the waveshape of lightning induced surges.

The study centered on the following basic tasks:

- Prediction of lightning phenomena
- Selection and characterization of instrument placement sites
- Determination of appropriate number of instruments
- Determination of instrument storage and data collection requirements
- Recommendations for future efforts

The work during the course of these tasks involved extensive model development and visits to potential sites for inclusion in the sample. The results of the model development and site visits are presented in detail later in the report.

Conclusions in each of these areas are presented in detail in the main body of this report. The more important conclusions are specifically given below:

1. A BASIC SAMPLE of at least 400 lightning surge recording instruments is recommended. These instruments are to be placed at sites which satisfy the following requirements:
 - maximum lightning exposure of the connected phase or conductor to direct lightning strokes within the area selected
 - no shielding from nearby structures or objects
 - low footing resistance (less than 25 ohms)

Adequate documentation of the instrument sites at the time of installation and any subsequent changes during the data collection period (5 years) is essential.

2. A SUPPLEMENTAL SAMPLE of at least 250 instruments is recommended to cover unusual lightning occurrences throughout the country. The instruments are to be placed in the following manner:

- at sites with unusual lightning activity
- about 1/3 to 1/2 of these instruments on the same pole along with instruments of the BASIC SAMPLE (but on another conductor) to assist in understanding predischARGE phenomena

Adequate documentation of instrument sites is again essential.

3. It is recommended that tight control be exercised over the field installation stage to insure that BASIC and SUPPLEMENTAL sample sites are consistently and properly sought, and that all important variables (e.g. voltage levels) are included.
4. Site characterization methods are presented. The appropriate documentation is developed (site characterization forms, data collection forms) and included in the report.
5. Models for prediction of lightning currents and voltage are developed, presented, and applied to serve as the starting point for establishing sampling and site selection criteria, and to provide a basis for future data analysis.
6. Calculations suggest that insulation crossover of the sparkover of arrester and transformer is a distinct possibility. Sparkover times of the order of 100 nanoseconds or less are expected. Transformer failure due to discharge voltage is believed to be likely to occur only if transformer insulation is degraded.
7. In addition to direct strokes, recording of induced surges can also be of great value in understanding the interaction of distribution lines with lightning, in understanding return streamer formation and propagation, and in corroboration of stroke density studies. It is recommended that the instrument design accommodate the recording of induced surges.
8. Storage capacity of the instruments designed by the General Electric Company and the University of Pittsburgh is adequate for a year's data. Pessimistic maximums might reach roughly 25-30 operations per arrester year in (very) unusual situations of great lightning activity. More realistic expectations for maximums would be 10-15 per arrester year in a region of very high Isokeraunic level.
9. Twenty specific utilities have been recommended to give broad national coverage. Sub-areas of high lightning activity are identified within these companies. The list of utilities recommended in this report is not exclusive and other utilities may be included should they enhance the quality of data.

10. The proposed field study is only a small part of what should be done. Other necessary tasks to reach the ultimate goal of understanding the Lightning Protection Cost-Benefit Problem include:

- Fast front insulation tests of arrester and transformer;
- Tests of arrester discharge voltage as a function of rate of rise of discharge current and systems voltage;
- New laboratory studies of predischage phenomena;
- Pole footing surge impedance testing and line attenuation studies;
- Direct stroke density studies using counters.

Recommendations for future efforts are discussed in detail in Section V of this report.

INTRODUCTION

Lightning on Distribution systems represents a very costly phenomena. It is quite common for even a relatively small utility to lose thousands of dollars of equipment in a single storm and to experience disruption of service to a significant number of customers. This, quite obviously, indicates that, from a cost-benefit standpoint, relatively large sums of money can be afforded in understanding the problem of protection of equipment. Large investments have been made in the past, but major problems still exist. All too often protective equipment fails or fails to protect. The relation between lightning and its interaction with the line is inadequately understood. There has been growing concern for better solutions to the protection cost-benefit problem, and this has reached the point where the U.S. Energy Research and Development Administration has taken the lead in sponsoring a field study in an attempt to determine more accurately just how lightning interacts with the distribution line. The initial thrust of this proposed research has been to develop low cost instrumentation to measure and record distribution system lightning currents that flow through arresters. The ultimate aim, of course, is to understand the lightning-line interaction better, which will lead to a more appropriate solution to the protection cost-benefit problem.

The first step in the ERDA program was the development of an instrument to measure and record the lightning phenomena. This development took the form of two parallel contracts, one with the University of Pittsburgh, and the other with the General Electric Company. At the time of this writing, both instrument prototype designs have been completed, and their laboratory testing is nearly complete.

It was also apparent that a second phase was necessary to parallel the development of instrumentation. This second study became ERDA contract E (49-18) - 2107, in which Jack Faucett Associates undertook to perform several necessary planning tasks.

THE TASKS OF THE JFA STUDY

It was apparent that sufficient planning had to be done to answer several questions on a data gathering effort:

1. How many instruments would be needed?
2. Could any originally unforeseen instrument requirements be identified, so that instrument design could be improved?
3. Where should the instruments be placed?
4. How and how often should the data be retrieved?

In the initial phases, it was also recognized that in order to perform the above tasks, analytical models would have to be developed. Models to predict the number of incidents each instrument could expect to experience, expected frequency distributions of crest currents and rates of rise, and other parameters. It was reasonable to consolidate and extend these models to serve as a rudimentary beginning for data analysis. This then evolves as a fifth task, which can be stated as follows:

5. To develop models for use in predicting line performance for planning of the field study and for aiding future data analysis.

Finally, no project would be responsibly complete without combining all the results from the efforts it has made. Success in future efforts in data analysis, model development, instrument design, and above all, planning for necessary future studies will depend on sharing of insights through a sixth task:

6. Recommendations for future study and analysis.

RELATIONSHIP TO THE CONTRACT WORK STATEMENT

In the contract work statement, four tasks were identified:

1. Site Selection. Examination of criteria for and methodology of test site selection.
2. Test Procedure. Characterization of the site, frequency of collection of data, number of instruments, etc.
3. Cost-Benefit Analysis. Determination of the optimum relation between cost (of instruments and their installation and use) and the increase in knowledge of lightning phenomena on electrical distribution systems.
4. Voltage Distribution. Estimation of surge voltage distributions that can be expected to occur on distribution lines.

The first two (site selection, test procedures) are clearly covered in this report.

The third task (cost/benefit) rapidly changed character in the early stages of the study. Most of the cost/benefit criteria had to be subjective in nature and had to be established with the help of consultants and the project advisory committee.

The criteria originally thought to be amenable to dollars and cents calculations turned out to be relatively unimportant in determining sample size. It was thought that the costs of instruments (design, manufacture, installation, use) could be estimated and shown alongside confidence limits on expected frequency distributions (the more dollars spent, the better the confidence in results). However, after confidence limits estimations were begun, it became apparent that relatively few instruments would be needed. Above about one hundred instruments, the gain in confidence limits with more

instruments shows rapidly diminishing returns. Thus, the criteria for determining the cost-effective number of instruments shifted to a far more subjective judgement of how many instruments would be needed to acquire adequate geographical and climatic coverage for examining predischARGE and unusual situations.

The fourth task (voltage distribution) represents the recognition that model development and prediction had to go beyond that necessary to simply estimate the number of instruments needed. To discern the required model development, it will be helpful to consider the overall Lightning Protection Cost-Benefit Problem in more detail.

THE PROTECTION COST-BENEFIT PROBLEM

To gain perspective, an idealized statement of this problem is a helpful start.

The Idealized Statement of the Problem

1. Cost of an Outage. First, we should determine the statistical distribution of the costs of all possible types of outages. This is the total cost, including such intangibles as the future real cost of current customer dissatisfaction with present system performance.
2. Outage Occurrence. The second need in such an idealized cost/benefit analysis is to develop the knowledge of how often an outage of each possible kind occurs. This should be done for each realistic alternative method of system protection.

If this could be accomplished, reductions in the cost of outages by protection could be compared with the cost of protection and the best protection alternative could be chosen. Needless to say, the relevant measures are difficult to develop, and many of the judgements (particularly costs of outages) have to be made subjectively; with the guidance of experience.

Implications for Model Development

Consider, however, what this view of the problem suggests in terms of model development. First, and foremost, it suggests that we begin with the development of models to predict the most costly outages. While other outages (e.g. terminator failure) may be more costly for some situations, transformer outages are the most important in terms of total potential costs. Any uncertainty emphasizes the need for defining the cost of outages. This, in turn, suggests that models be developed for determining the frequency distribution of surge voltages on distribution systems. Three major types of surge voltages are presently considered to be capable of causing transformer outages.

1. Sparkover. First, any stroke to a distribution line initially produces exceptionally high rates of rise of voltage. (Even a small rate of rise of current, when multiplied by the hundreds of ohms of surge impedance yields very high rates of rise of voltage) This raises the possibility of an insulation crossover at very short times to sparkover. In such cases an arrester would be protected by the transformer, creating a highly undesirable situation.
2. Discharge Voltage. Secondly, it is readily conceivable that if the surge current through an arrester is sufficiently high, and/or the transformer insulation is for some reason degraded, discharge voltage could build up sufficiently to cause a transformer failure.
3. Transformer Saturation. Thirdly, if a surge is of sufficiently long duration, the transformer could conceivably saturate and essentially short circuit, resulting in failure.

The magnitudes of the first two of these (sparkover and discharge voltages) are amenable to rough estimation at the present time, and these estimates are presented in Appendix D of this report. The third (saturation) is not presented because there are insufficient reliable data to estimate the frequency distribution of the length of time that an arrester operates. Thus, flux buildup predictions can't be reasonably made.

It becomes obvious from the above that attaining the protection cost/benefit objective requires a second-order objective—development of models to predict surge voltages. This, in turn, leads to a third-order objective—predicting the distribution of surge currents, since it is surge currents and their characteristics that produce the surge voltages.

Historically, the study began with prediction of surge current as a primary objective since the failure of arresters is an important problem on some systems, and, to solve this problem, prediction of currents is essential. In any case, we need to learn about lightning currents on distribution systems as soon as possible. Hence, the objective of measuring such currents via a field study is of great importance.

Implications for the Field Study

It is thus seen that the proper primary objective of the field study is to enhance prediction of lightning-caused surges on distribution systems. As noted, the objective has been specified as measuring the lightning currents in arresters. It seems proper to reconsider this and to ask whether it might be better to try to measure currents "closer" to the stroke, i.e., in the line itself. At first glance, it would seem that this would enable more precise determination of the interaction between stroke and line. However, the first discovery upon pursuing this task is the need for some mechanism to discriminate between lightning and system current in a cost-effective manner. Immediately we recognize the arrester as such a discriminator and return to the conclusion that the best place for the instrument is in the down lead of an arrester.

However, we can and do conclude that it may be worth considering putting the instruments in the ground lead of any grounded pole, especially those with shield wires. Such instrumentation is a cost-effective way to ascertain the relationship between stroke and distribution line, which should be the major objective of the study, in our opinion.

It should be noted that if transformer saturation is recognized as a possible problem, the instrument threshold should be set sufficiently low to record surges due to induced strokes. Induced strokes will generally produce longer duration surges.

Implications for Data Analysis

There are implications for data analysis as well. Recognition of transformer saturation as a problem also points out the need to specifically consider ways of representing data on long tail surges. This is discussed in Section V.

Implications for Other Needed Studies

There are a host of implications for other studies. For example, we must know the true characteristics of arrester and transformer performance, including (1) sparkover on very fast front surges, (2) time for transformer to saturate at arrester discharge voltage, and (3) arrester discharge voltage as a function of current rate of rise and system voltages and any other system parameters. It is also important to know the characteristics of other equipment, such as cutouts and line insulation. These and other implications for future studies are considered in Section V.

SAMPLING AND SITE SELECTION

General Philosophy

From virtually any viewpoint, the instrument results represent data with which to calibrate a model. The following perspectives are helpful.

- If, for example, lightning phenomena are expected to fit a simple model, then instruments could virtually be placed at random, and the results used to calibrate the model;
- If, on the other hand, they are expected to fit a difficult (but still tractable) model, instruments should be placed with care, in such a fashion as to make calibration of the model easy;
- If, finally, they are expected to fit no feasible present or near-future model, then vast numbers of instruments need to be placed to cover virtually every situation that can occur.

The Most Appropriate Sampling Approach

It is our best judgement that the sampling approach is in the second category, but there is a cautionary note (below). First, we consider the conclusions from assuming that lightning phenomena are expected to fit some difficult but tractable model.

The ultimate model used may, of course, not be the one presented in this report. However, any realistic appraisal of what the right model might be requires that the instruments be placed with great care to ensure easy interpretation of data. This implies several restrictions and priorities, such as the following:

- sites free from the effects of shielding be chosen;
- sites with low footing resistance be chosen;
- single phase lines or lines with vertical configuration and few complications in configuration be given predominance where possible;
- areas of generally high incidence of lightning be chosen.

Other restrictions that became apparent through field discussions and the advice of the project advisory committee and consultants are discussed in Section III.

A Cautionary Note: Defining "Anomalous " Situations

There is, of course, always the possibility that no model will even come close to enabling prediction of lightning phenomena. Further, there may be unexpected facets of reality that require significant modification of any analytical model chosen. Thus, there is a need to search for situations that will help in suggesting model changes, namely, anomalous situations: situations with undesirable lightning performance that do not fit the "first glance" expectations of typical models. Further, such data will enable utilities to find comparable situations and estimate their own performance while awaiting model development.

It is again emphasized that the main thrust must be aimed at the development of predictive models, but there is obvious value in seeking "anomalous" situations.

Regarding the question of how many such situations should be sought, the answer is obviously not easy. Clearly, it is highly subjective. This is especially evident given the widely varying, sometimes ill-informed, but also often strongly held views of many of those contacted in the field interviews and discussions. Initial discussions with the project advisory committee and consultants resulted in the following figures: 80% sites aimed at model development and 20% to cover "anomalous" situations. This, however, was done without consideration to the numbers necessary for model development. As it became apparent that relatively few instruments would be needed (relative to establishing reasonable confidence limits), there was growing concern over the correspondingly small number of "anomalous" sites. Therefore, in reconsideration, based on our field interviews and discussions with consultants, a figure of roughly 250 "anomalous" situations is recommended (vs. 400 for model development). Basically,

it was found that the (suprisingly) low necessary number of instruments for model development led to an unrealistically low number of "anomalous" situations using the 80/20 percent ratio.

In summary, a BASIC SAMPLE of 400 instruments aimed at model development is recommended, and a SUPPLEMENTARY SAMPLE of 250 instruments for "anomalous" situations and other useful data, such as predischarge, is chosen.

An interesting result of the field interviews worth mentioning here because of its importance is that it may be quite difficult to find the most important "anomalous" situations. Those with decision-making authority are not always aware of the unusual sites on their systems and, sometimes, are not even aware that such situations exist. During installation, utilities will have to be encouraged to find the pole or segment of line with most severe lightning incidences.

Consideration of the protection cost/benefit problem has been productive in establishing criteria for model development, additional suggestions for the field study and the instruments, etc. Of course, the required number of instruments is the keystone of sampling decisionmaking. Although still a part of the same problem, decisions concerning cost-effective instrument placement are far more subjective. For example, we know too little about the existence of geographic variations to predict wisely. Too often we are advised that unusual problems are a direct result of lightning, only to discover that they are more system-related. Such factors were taken into consideration for developing rigid procedures for site selection. These procedures are given in detail in Section IV.

FUTURE WORK

A final point is worth noting regarding recommendations for future work. A significant number of insights have resulted regarding what other work should be done. Rudimentary Critical Path Analyses have been made on what we feel should be the overall approach to conducting recommended future work. It is felt that this recommendation is a highly important, though not an initially foreseen, result of this investigation.

STRUCTURE OF THIS REPORT

In light of the above considerations, the following organization for the report seems appropriate:

SECTION I

MODELS FOR PREDICTION OF LIGHTNING PHENOMENA

A sizable portion of this study depends on predictive models. A description of the models used is, therefore, presented early in the report. Detailed descriptions of these models may be found in References 1-3. (Reference 1 is included in Appendix A¹). The appendices and Section II of this report involve the detailed application of the models to estimate the following:

- The number and precise nature of Direct Stroke Incidents,
- The number and precise nature of Induced Surge Incidents,
- The frequency and character of overvoltages,
- Predischage and the characteristics of line and arrester currents.

The following subsections give a qualitative description of the models as well as the justification for their use.

(A) THE STROKE CURRENT

The model used for the current in a stroke component is shown in Figure 1; namely, a constant ramp to crest followed by crest current of "long" duration.

FIGURE 1: MODEL OF STROKE CURRENT

¹With permission of the author, Gordon Brown, who is also a consultant in the present study.

This model has been used and has the major parameters necessary for estimation of distribution system performance, with a few cautions. Low current long tail surges would require some decay time. This can easily be added when the necessary statistics on duration become available. Also, since arrester discharge voltage may be a function of the very earliest stages of the rate of rise, significant refinements of the early stages of the ramp will probably be necessary eventually. Again, the appropriate statistics will have to be developed from analysis of future field data.

The number of components in a stroke is taken into consideration as needed. Although Berger (Ref. 3) (Switzerland) will have much to share in this regard, he has not published the results in suitable form. The "Westinghouse T & D Book" (Ref. 4, p. 563-4), suggests an average (depending on whose data base is used) of order 2 to 4 components.

(B) STROKES TO THE LINE

The model used for determining the number and character of strokes to the line is variously referred to as the "Electrogeometric Model" or "Brown Whitehead Model".

Qualitative Understanding

As the electrical charge is laid down in the stroke leader, fed by pockets of charge in the cloud, voltage stress between the leader tip and the earth, builds up, as illustrated in Figure 2.

FIGURE 2: ILLUSTRATION OF LEADER TIP VOLTAGE STRESS BUILDUP

Sooner or later, sufficient stress will buildup to cause flashover. The distance from leader tip to earth at which this occurs is called the "strike distance." Qualitatively it is clear that:

This suggests that there is (at least approximately) a one-to-one relationship between stroke current and strike distance. This model was first suggested by C. Wagner and A.R. Hileman (Ref. 5). It was extended to include the possibility of leaders approaching at angles other than the vertical in the "Brown-Whitehead" Model (Ref. 1,2). The "heart" of the resulting model as used in this study is illustrated in Figure 3.

$$r_s = 7.1 (I^{0.75})$$

Stroke Current in kA

Strike Distance in Meters

(a) Strike Distance Equation

θ : Stroke Approach Angle

(b) Frequency Distribution of Approach Angle

FIGURE 3: STRIKE DISTANCE AND APPROACH ANGLE

Justification

One asks why precisely 7.1 ($I^{.75}$) for strike distance? Surely there must be a statistical variation. Surely there must be a difference in strike distance to earth as opposed to strike distance to a conductor or mast. The answer is that there certainly are differences. However, recent investigation suggests that such differences are secondary in importance (Ref. 6,7).

Sargent (Ref. 6) in 1972 assumed the strike distance and cosine squared angular distribution as indicated in Figure 3(b). He then considered three different sets of data: Berger (Ref. 8), Poplansky (Ref. 9), and AIEE (Ref. 10). Each of these three represents different frequency distributions of stroke currents. Berger's data involved a very tall mast; Poplansky's data was on a variety of towers; and the AIEE data pertains to lines. Applying the above equations for strike distance and angular distribution, Sargent derived the frequency distribution of strokes to level ground that would be required to result in each set of data. (Figures 4 and 5). Strikingly, all these three sets of data "yielded" the same distribution to level ground.

FIGURE 4: GEOMETRY OF EXPOSURE TO LIGHTNING

Note: In both cases the distributions show that towers or lines "reach out further" (higher strike distances) for higher currents. But they do so in different ways (dome vs. cylinder)

FIGURE 5: SARGENT'S DERIVED DISTRIBUTION OF
STROKE CURRENT TO LEVEL GROUND

In reference 7, Brown used the same approach, acknowledging Whitehead's thesis (Ref. 11) that there are other effects (statistical variation of strike distances or even better basic relationships). He argued, however, that these errors are likely to be secondary. Further, he noted that any researcher using Sargent's distribution to level ground must use the same equations with which Sargent derived that distribution. No other distribution to level ground has yet been published based on other assumed equations. In any case, applying the equations to CIGRE Field Data (Ref. 11), resulted in remarkable correlation between calculated and actual data.

These two studies represent a powerful argument for accepting the model. It is noted that although the model was originally developed for transmission lines, there is no reason that it will not apply for distribution lines. The AIEE data which Sargent used was for "transmission" lines averaging only about 60 feet in height. Further, the feeling of all investigators is that the lower the line the more appropriate the theory (Ref. 12). Deviations are only expected as tower structures get very high rather than low.

Distribution of Rate of Rise of Stroke Currents

Since the "Electrogeometric" Strike distance is a function only of stroke current, one might expect that the frequency distribution of rate of rise of current would be the same for strokes to ground and strokes to lines. However, Berger (Ref. 3) indicates a mild correlation between stroke current and stroke current rates of rise. Brown (Ref. 13) examined this relation and derived the frequency distribution of rates of rise to lines. This distribution has been used in this study.

(C) PREDISCHARGE

Modeling of PredischARGE admittedly needs great improvement. However, the model developed by Wagner and Hileman (Ref. 14,15) and used in a later industry task force study (Ref. 16,17) is the best available. The model assumes that when the voltage between nearby conductors rises above 186kv per foot of spacing, sufficient current will flow between the conductors to maintain the voltage at that level. This is illustrated in Figure 6, assuming a "model" stroke currents.

FIGURE 6: ILLUSTRATION OF PREDISCHARGE CURRENT MODEL

It is shown in Appendix B that predischARGE current lasts only a short time, due to voltage reflections from grounded poles which "wipe out" the 186kv per foot.

The original theory and laboratory tests (Ref. 13,14) indicate that the conductors will flashover if predischARGE lasts for a sufficiently long time (generally several microseconds). However, reflections from grounded poles will nearly always preclude such flashover for the distances between grounded poles found on distribution systems.

There is no question, however that predischARGE phenomena need further study.

(D) INDUCED SURGES

Induced surges result from the collapse of induced fields near the line. The collapse is due to a nearby stroke as it hits the ground. This collapse releases a bound charge which travels as a surge. Precisely what wave form and magnitude surge results on the line hinges heavily on the way in which the return streamer propagates. In as much as this is not a well researched subject, several simple assumptions were made. Velocity of return streamer propagation is assumed to be,

$$r_1 = 0.11 (I^{.375})$$

in per unit of the speed of light (cf Ref. 1,2). The remainder of the model is fully developed in Appendix C.

It is noted that if the instrument thresholds are sufficiently low to record induced surges a great deal of light should be shed on return streamer propagation. The mode of this propagation has a very marked effect on induced surge wave form.

STROKE DENSITY

An essential feature of any model is stroke density. Throughout this report, it has been assumed that stroke density is linearly related to Isokeraunic level:

$$N_o = 0.16 \text{ IKL}$$

stroke density
in strokes/ km²/ yr

Isokeraunic level
(Average number of
thunderstorm days
per year)

In a sense, the instrument is a lightning counter. Two factors seriously limit its use as such. First, trigger threshold may eliminate the recording of induced surges (though we strongly urge that the device be designed to record them). Second, the "antenna" which is the conductor between two grounded poles (with connections outside those grounded poles) varies from site to site and is, therefore, a poor "sensor".

The field study must not be construed as giving a good measure of the relationship between the IKL and the stroke density, though it can certainly serve as corroboration to other studies aimed at the stroke density. In any case, stroke density should be sought directly, without regard to IKL. It may well be advisable to run a concurrent lightning counter study, saving installation costs.

For the purpose of this study, it was felt that the above relationship between stroke density and IKL was the best choice, since it was also used in the studies forming the basis for justification of the model (Ref. 3,7).

(F) ASPECTS OF LINE MODELING

For modeling traveling wave calculations on distribution lines, several simplifications were made to facilitate calculations:

- (1) Pole Reflections. Since poles are only of order of 10 to 20 meters in height, the effects of reflections up and down the poles will be essentially gone by about 100 nanoseconds. This approximation should be reconsidered if the arrester sparkover voltage is found to be a function of current rate of rise over times significantly less than about 100 nanoseconds.
- (2) Crest Arrester Current. As in reference 1, "average" crest arrester current is assumed where appropriate. This is explained in Figure 7.

FIGURE 7: DEFINING "AVERAGE" CREST CURRENT

In Reference 1, (Appendix A) it is shown that this "average crest" is as illustrated in Figure 7.

FIGURE 8: DETERMINATION OF "AVERAGE" CREST ARRESTER CURRENT

- (3) Predischage. As noted earlier, it is assumed that predischage between lines will not result in line flashover on distribution lines.
- (4) Multiconductor Equations. When appropriate, multiconductor traveling wave methods were used, but corona effects on the surge parameters are ignored. This should be reassessed during data analysis and further model development.

(G) SURGE VOLTAGES

The prediction of surge voltages is essential to the effective protection of distribution systems. The two voltages of concern are the sparkover voltage and the discharge voltage. Both of these voltages depend primarily on the rate of rise of surge current.

Sparkover Voltage

The rate of rise of surge current, using appropriate multiconductor equations for the line, determines that rate of rise of voltage that will stress the arrester and equipment insulation. This rate of rise is then used to estimate sparkover voltage, using a simple model of time to sparkover (of an arrester) versus sparkover voltage:

$$V = V_1 t^{-.5}$$

t — time to sparkover in μ seconds
 V_1 — nominal 1μ s flashover voltage
 V — actual sparkover voltage

This model needs verification and improvement through future laboratory testing, but represents, in our view, the best available at the present time.

Discharge Voltage

Increasingly, it is recognized that the discharge voltage is primarily a function of rate of rise of discharge current (see Appendix D). While the constants for a particular brand of arrester will vary, for typical arrester characteristics, the suggested model is:

$$V_D = A \dot{I}$$

The diagram shows the equation $V_D = A \dot{I}$ with three annotations: an arrow points from V_D to the text "Crest Discharge Voltage"; an arrow points from $\dot{I}$ to the text "Rate of rise of Discharge Current"; and an arrow points from A to the text "A constant for an Arrester".

While it is suspected that system voltage level can also affect sparkover voltage, there is, at present, insufficient data to model this aspect. Again, future laboratory tests are indicated.

SECTION II

APPLICATIONS OF THE PREDICTIVE MODEL

The key applications of the model for developing the report are the following predictions for direct and induced surges:

- determining the number of direct strokes, the distribution of their current magnitudes and rates of rise, and their confidence limits;
- determining the number of induced surges, their current magnitudes and methodology for determining rates of rise (data is insufficient to predict rates of rise adequately).

These two applications form the basis for model-related sampling criteria. Also worthy of prediction, however, are:

- the expected surge voltages on systems.

Each of the three applications is discussed below.

DIRECT STROKE INCIDENTS

The Number of Incidents

An arrester "sees" strokes anywhere on either side of its pole out to the next grounded pole. Field interviews suggest a typical distance of 200 meters between grounded poles. Thus, an instrument on such a system provides an "exposed span" of 400 meters of line. (Figure 9)

FIGURE 9: "EXPOSED SPAN" OF INSTRUMENT

Suppose that, as well as a 400 meter "exposed span", the line is in an area with an IKL of 60, and is 10 meters high, unshielded and either single phase or vertical construction. Figure 10 (reproduced from Reference 1) shows that such a line will have

Stroke density

$$n = \overbrace{0.16 (60) (6)}^{58 \text{ strokes/100 km/yr}}$$

Generally accepted constant $\swarrow$ IKL $\nwarrow$ N_o from Figure 10

FIGURE 10: RATE OF DIRECT STROKES TO AN UNSHIELDED LINE

Since this number is directly proportional to IKL, modifications for other situations are easily made.

Our sample instrument (in Figure 9) receives data from a 400 meter long line.

Since 400 meters is .004 "100 km units" it will experience

$$58 \times .004 = 0.23 \text{ direct stroke incidents/yr.}$$

$\nwarrow$ n as just calculated $\swarrow$ length in 100's of km

Again, since the number of incidents per year is proportional to length of line and IKL at a given height, modification is easy. In 5 years, the instrument is expected to see $5 \times .23$ or 1.15 strokes. (The digits beyond the decimal are hardly significant.)

The calculations illustrated above (number of incidents per arrester-year) have been determined for each of the recommended sites. (See Master Table in Section III). The number of direct stroke incidents for unshielded lines with 200 meter spacing between grounded poles as a function of IKL is shown in Figure 11. The figure assumes vertical or single phase configuration (i.e., all strokes hit the phase in question).

FIGURE 11: DIRECT STROKE INCIDENTS PER ARRESTER YEAR

Note: Modifications can be made for other heights as shown in Appendix A. Since the number of incidents is directly proportional to the distance between grounded poles, modification for such variations is easy. For horizontal configuration, each outer phase will receive half the number shown in Figure 11.

The Frequency Distribution of Current Magnitudes

Reference 1 (included as Appendix A) develops the frequency of occurrence of arrester and line crest current for shielded and unshielded lines. The distribution for unshielded lines (virtually independent of height) is given in Figure 12. Shielded situations are detailed in Appendix A.

FIGURE 12: FREQUENCY DISTRIBUTION OF ARRESTER CURRENT
(log-normal graph)

Rates of Rise of Current

The currents through the arrester in Figure 12 are the "average crest" currents discussed in Section I (Figure 7). A similar phenomenon may or may not exist for rates of rise.

Given the possibility of predischage currents, the question of defining arrester current rate of rise becomes difficult. If only the first few hundred nanoseconds are important (before predischage effects reach the arrester), the rate of rise will be identical to that of the actual stroke current. In such a case, Reference 13 derives the resulting frequency distribution of stroke current rates of rise to lines, which is the same as that through the arrester. Figure 4 of Reference 13 is reproduced in Figure 13, and is relabeled.

FIGURE 13: DISTRIBUTION OF INITIAL (APPROXIMATELY THE FIRST 200 NANOSECONDS) RATE OF RISE OF ARRESTER CURRENT.

If larger time spans are of importance, the estimates are much more complex. Appendix B (Predischage Currents) illustrates the difficulty of normalizing data. Although attempts were made, no simple representation for delay of crest or average rate of rise was found that covers all major parameters. This must be left for future analysis and development.

For the present, therefore, we make the assumption that predischage does not affect the rate of rise. This is not as unusual as it would seem at first glance. If the important rates of rise are within a few hundred nanoseconds, there is indeed no effect. For longer front waves, predischage will eventually disappear. Figure 14 illustrates this clearly.

FIGURE 14: ARRESTER CURRENT WITH AND WITHOUT PREDISCHARGE PHENOMENON

INDUCED SURGES

In contrast to the preceding section (Direct Strokes), determination of the number and character of induced surges is far more complex. The major effort is discussed in Appendix C, and a summary of the results is presented here.

Magnitude and Waveform

As noted in the introduction, the collapse of field at the line, due to the nearby strike and return streamer propagation, causes surge current to flow in the line. The nature and magnitude of the surge depend upon the following variables:

- Stroke current magnitude.
- Distance of stroke from line.
- Nature of return streamer propagation.

The first two of these are rather obvious, and, by and large, the crest of the induced surge depends on these. There are several possible modes of return streamer propagation, and far too little is known about the establishment of the return streamer. The importance of this formation process is illustrated by the two assumptions and resulting waveforms shown in Figure 15.

FIGURE 15: IMPORTANCE OF RETURN STREAMER FORMATION

It is known that bidirectional surges occur (Figure 15b), but the nature of the charge lowered during streamer formation is poorly understood. Should the instruments record induced surges, insight on this process is expected.

Fortunately, if location and leader charge are the same, as well as return streamer velocity, the crest of the induced surge is roughly the same. This allows estimation of the frequency of occurrence of surge voltage magnitudes and the resulting crest arrester discharge current. This estimate is shown in Figure 16, for a 10 meter high line.

FIGURE 16: FREQUENCY OF OCCURRENCE OF ARRESTER DISCHARGE CURRENT DUE TO INDUCED SURGES

These results assume that crest is reached before reflections from other arresters. Quite a number of arresters could sparkover, since the effect of field changes "reach" for long distances. Figure 14, therefore represents a conservative estimate. Also, with the relatively low level of current, it is not at all certain that grounded poles without arresters will flashover. So, for accurate calculation another independent variable emerges:

- Presence of nearby arresters.

Better model development must await field results.

Number of Incidents

The number of arresters that will sparkover for any given surge depends primarily upon:

- Surge crest current,
- Line attenuation.

The approach used in Appendix C is to view the problem as determining the length of line that could cause sparkover by a given stroke, making various assumptions for attenuation. The results are shown in Figure 17.

FIGURE 17: NUMBER OF INDUCED SURGE INCIDENTS
PER ARRESTER-YEAR
(IKL of 60 assumed)

As illustrated, for a 10kv arrester and with attenuation of 3% per km, (CF Ref. 18) about four operations per arrester year are expected.

Note that for systems using 10kv (or higher) arrester ratings, the number of incidents is well within instrument capability. Even with a local IKL of 120 and an average of three components per stroke, only about 24 incidents would occur. Available evidence suggests this to be quite pessimistic. It is still, however, within the capability of the instruments, as currently designed (Ref. 19,20), even if thresholds are lowered sufficiently to record all induced surges.

Yearly Variation of Number of Incidents

Although subjective judgement is probably the best guide, there are some quantitative suggestions that can be made regarding expected variation. Reference 11 shows 25 years of lightning performance for one transmission line, indicating 2 years with 2 outages, 10 years with one outage and 13 years with no outages.

This yields an average of 0.56 outages per year and standard deviation of 0.65 or 16 percent higher than the mean. While gaussian statistics can hardly be perfect, we can expect groupings of data (i.e., 5 year averages) to have smaller standard deviations that can be roughly estimated using gaussian methods.

The territory map (Figure 22) suggests roughly 6 covered regions (ignoring the far northeast due to small numbers). With 5 year data, we might expect a standard deviation roughly given by

$$\sigma = \frac{116\%}{5 \times 6} = 22\% \text{ of the mean}$$

If this is accurate, there is a 90% chance that the number of direct stroke incidents for the BASIC SAMPLE will be in the band

$$320 < \text{number of incidents} < 661$$

While the results can hardly be relied upon, it is consistent with our judgement that the figure 400 instruments, is sufficient for the 5-year field study. This judgement is, of course, influenced by the fact that the study could (and almost certainly will) continue beyond 5 years. Furthermore, any lightning "drought" seen in the first few years could be compensated for either by increasing the number of instruments during the later years or by modifying the length of the study.

CONFIDENCE LEVEL OF THE RESULTS

One of the results that the field study "purchases" (through the cost of manufacture and use of the instruments) is the confidence limits on the resulting data. This applies particularly to the frequency distributions of direct stroke current magnitudes and rate of rise. It does not apply to stroke density, since this is not directly measured. It does not apply well to induced surge phenomena, since the models are not sufficiently clear to provide a basis for a priori estimation of confidence limits.

However, consideration of the confidence limits of arrester current magnitudes due to direct strokes was pursued and proved quite enlightening. The detailed methods are given in Appendix E. The major results follow:

Confidence Limits on Frequency of Crest Currents and Rate of Rise

Confidence Limits for the Frequency Distribution of Arrester Discharge current are shown in Figures 18a and 18b. Roughly .25 direct stroke incidents per arrester-year is typical of the lines recommended for sampling. Thus in 5 years, we would expect 1.25 direct stroke incidents per 100 instruments.

Clearly, even beyond 50 instruments, the "returns" for investment in more instruments rapidly diminishes. Since this conclusion is rather important, it was decided to verify the accuracy of the direct calculations of confidence limits with a Monte Carlo study. The results were the same. Therefore, if, the model is accepted, other considerations would be the primary determinant of the required number of instruments. These considerations are discussed in Section III.

FIGURE 18a: 90% CONFIDENCE LIMITS ON ARRESTER CREST CURRENT

FIGURE 18b: 90% CONFIDENCE LIMITS ON INITIAL RATE OF RISE OF ARRESTER CURRENT

SURGE VOLTAGES

As mentioned in Section I, analytical methods for prediction of discharge and sparkover voltages are uncertain. However, using the models of Section I, the distributions of both types of surge voltages are determined in Appendix D. The calculations are done for a 10 kV arrester, and all the major conclusions can be drawn from this example.

Discharge Voltages

Figure 19 illustrates the resulting frequency distributions of discharge voltage.

FIGURE 19: ESTIMATED FREQUENCY OF OCCURRENCE OF DISCHARGE VOLTAGES FOR 10 kV ARRESTER

While problems are possible, typical insulation strengths of transformers suggest that, without degraded insulation, damage is not likely. It does suggest the need for investigation to discover the possibility of degradation.

Sparkover Voltages

The results of calculations of arrester sparkover voltages and times to sparkover, using the model given in Section I (and Appendix D), are given in Figures 20a and 20b.

FIGURE 20a: ESTIMATED FREQUENCY OF OCCURRENCE OF SPARKOVER VOLTAGES FOR A 10 kV ARRESTER

There is clearly a possibility of insulation crossover with protected equipment. Our lack of knowledge of the required data is made abundantly clear by considering the calculated sparkover times, as is shown in Figure 20b.

FIGURE 20b: FREQUENCY OF OCCURRENCE OF TIMES TO SPARKOVER CORRESPONDING TO FIGURE

Clearly, much testing, as well as development of analytical methods, needs to be accomplished.

SECTION III

SAMPLING AND SITE SELECTION

BASIC AND SUPPLEMENTAL SAMPLES

Fundamental Considerations

If the industry had a predictive model of the lightning performance of distribution systems of which it were 100% certain, the field study would be simple. One would need only about a hundred instruments in carefully selected sites to calibrate the model. Needless to say, we cannot be nearly that confident, and we need to consider only those variables (or possible variables) that may affect our predictive capability. The important parameters that need further research include the following:

- Possible variation in frequency distribution with climatic or regional variation
- shielding effects and effects of predischARGE;
- known or suspected situations that are apparently ununderstandable;
- system voltage.

The first of the above parameters (variation in stroke frequency distribution) calls for samples to be taken from a variety of locations throughout the country.

The second (predischARGE and shielding) calls for significant numbers of instruments to be placed on phases other than the top or most exposed phases.

The third (ununderstandable situations) calls for a significant number of instruments to be placed at the discretion of the individual utility, at poles or segments of line with frequent lightning strokes.

The fourth (system voltage) has two aspects. First, variation of voltage level, and second, variation of voltage connection (Δ vs. Y). The latter (Δ vs. Y) is not of great importance, and individual utility discretion should be allowed, in our opinion, to dictate. The instruments will be placed on a variety of systems voltages (it would be difficult to avoid variety). In practical terms, this is of little concern, then, as far as the field study is concerned.

Regarding "Anomalies"

ERDA or the project committee controlling the field study will ensure the geographic spread. For the purposes of site selection by the individual utilities, the other three (predischARGE and shielding, ununderstandable situations, and Δ vs. Y connections) are referred to as "anomalies".

Fundamentally, these are situations for which predictive capability is weak or where model revision is anticipated. With the exception of predischARGE and shielding, it is our opinion that the choice of sites be left completely to the individual utility.

Decision as to the number of instruments to be placed to cover these anomalous situations is at best, qualitative, based on experience and judgement of the project advisory committee, our consultants, and our own field interviews.

On this basis, it is our recommendation that 250 or more instruments be placed in "anomalous situations" at the discretion of the individual utility, subject to the provision that roughly a third to a half be placed with other instruments, but on phases expected to be subject to predischARGE.

Laying down hard-and-fast rules for placement is very difficult here, largely for the following reason:

As a result of field interviews, it is our opinion that utilities will, in general, have to be encouraged to find "anomalies" and to properly place instruments to test the validity of their existence to find out what really happens. Allowing "escape options" may lead to inadequate searching for unusual situations that would be useful for ultimate understanding.

A major conclusion, therefore, is that those responsible for control of the field study must exercise that control continuously in the area of instrument placement for anomalies. This is necessary to ensure that a reasonable number of instruments are placed on just plain strange situations as well as on phases expected to be subject to predischARGE.

Number of Instruments: BASIC and SUPPLEMENTAL SAMPLES

Based on the confidence limit analysis and based on qualitative judgement weighing the advice of the project advisory committee, consultants, and our own field interviews, it is recommended that 400 (or, of course, more) instruments be placed in carefully selected sites chosen to facilitate development of predictive model capability. This group of 400 is hereafter called the "BASIC SAMPLE".

Also, it is recommended an additional 250 (or more) instruments be placed in "anomalous" situations as defined above). This group of 250 is hereafter known as the "SUPPLEMENTAL SAMPLE". Of these, roughly a third to a half should be placed with instruments in the BASIC SAMPLE in such a way as to record predischARGE phenomena or "shielding failures" on phases other than, but nearest to, the most exposed phase. Placement of the other half to two thirds should be at the discretion of the local utility.

SELECTING THE UTILITIES

It became apparent in conducting field interviews that we would have to pick utilities and indeed even sub-areas within utilities, if site selection was to be effective. Accordingly, a large number of visits were made, and utilities and subareas chosen. Of course, the choices can be modified later. It is recommended that the utilities chosen be contacted first. (Simply because of the investigative groundwork laid with those utilities recommended... not because these are in some way "better" than other utilities with significant lightning problems and which may have been overlooked.)

Geographical Distribution

In satisfying ourselves that the choices were reasonable, the sites were mapped and remapped until satisfactory coverage was achieved. The results are shown in the maps in Figures 21-23.

The Recommended Sites

Table 1 shows data for the recommended sites. Based on best available estimates during the field investigations, calculations of expected direct stroke incidents per instrument-year (and in fact a 5-year study) were made. Contacts for the recommended sites at the time of the field interview are given in Appendix F. Table 2 summarizes the major site selection criteria.

Potential Sites

The "potential sites" shown in the maps were not as thoroughly investigated but are believed to be as suitable as the recommended sites. Further comments are given in Appendix F.

SELECTION OF INDIVIDUAL SITES

Specific instructions for selecting individual poles for the BASIC and SUPPLEMENTAL SAMPLES are given in Table 3. The instructions are given in table form so that they can be extracted from the report and used easily. The purpose of Table 3 is to provide guidelines for each of the approximately 20 participating electric power systems. Since the local area for the BASIC SAMPLE will have been pre-selected, there are only two site selections of interest in this section.

1. Specific arresters (or poles with ground leads from an overhead shield wire) within the pre-designated local area for the BASIC SAMPLE.
2. Specific arrester (or poles with overhead shields) for the SUPPLEMENTAL SAMPLE.

The definitions and steps in Table 4 are consistent with the guidelines in the previous sections and are designed to be easily understood by a participating utility.

FIGURE 21: GEOGRAPHIC COVERAGE OF THE SITES RECOMMENDED

FIGURE 22: TERRITORY OF UTILITY COMPANIES COVERING THE SITES RECOMMENDED

FIGURE 23: ISOKERAUNIC LEVELS AND FIRST-ORDER WEATHER STATIONS NEAREST
SAMPLE SITES RECOMMENDED

FIGURE 24: POPULATION DENSITY AND SAMPLE SITES RECOMMENDED

TABLE 1
MASTER TABLE

Location	No. of Instru. in Basic Sample	Estimated IKL		Strokes Per Instru. Year ^a	Shielding ^b	Cost ^c			Ground Rod Resist- tance ^c	Estimated Total 5 Years Observations	Comments
		Co.	Sub Area			Mount	Annual Check	Grd. Resist.			
Vermont	10	25	40	.16	B	\$ 70	15	50	C	8	Expect footing re- sistance reflections.
					C-D						
Cleveland	20	35	70	.19	B	120	20	30	A	19	Arrester every third pole.
Detroit	15	35	50	.10	B	50	15	30	B	7	Expect shielding problems.
N.M.	20	70	100	.60	A				B	60	Lightning reported as more severe 4" ground lead.
	10	70	100	.20	A				B	20	
Colorado	25	60	100	.60	A				B	75	
Wyoming	25	35	70	.42	A	75			B	52	
	25	35	50	.24	A				B	19	
New Orleans	15	70	70	.08	C				A	5	
California	15	20	20	.20	A	100	25	75	B	12	Use Fresno Valley for ground resistance.
Utah	20	50	75	.22	A-B				B	22	
Ohio	15	40	40	.24	A				A	14	Regional coverage
Tennessee	15	40	50	.10	A				B	6	2nd AEP area.
Florida P. Corp.	25	100	110	.33	A				A	41	
Florida, Tampa	25	100	110	.33	A				A	41	
Florida P & L	25	100	120	.16	A	90			A	20	
Georgia	15	60	80	.13	B	30	15	50	B	8	
Louisiana	25	70	100	.16	A	40	15	120	A	20	
Oklahoma	15	50	50	.10	A				A	6	
Illinois	20	50	60	.18	A				A	18	
S. Dakota	20	40	60	.18	A				B	18	
Total	400									491	

^a Based on actual distance between poles B and C, actual pole height, and subarea IKL.

^b A = No shielding problems at all; B = greater instrument dispersion and searching to find unshielded; C = even the best will have some shielding problems, D = severe shielding problems.

^c A = No expected difficulty in finding low ground resistance; B = higher ground resistance will require more dispersion of instruments and more searching for acceptable test sites; C = very difficult problems in finding low ground resistance for all instruments.

* Costs were estimated based upon interviews with individual utilities.

TABLE 2

SUMMARY OF SITE SELECTION CRITERIA

1. Criterion: A BASIC SAMPLE of sites should provide sample data focused directly on stroke characteristics (parameters of the lightning surge wave).
Reason: It is essential that test instrument readings provide opportunity for unbiased estimates of stroke characteristics, unbiased estimates of a typical wave form, and unbiased estimates of cumulative frequency functions of parameters of the wave form). A completely random sample that would, hopefully, provide reliable data on stroke characteristics, stroke density, and anomalies is not cost-effective.
2. Limited number of participating utilities and no utility size restrictions.
Criterion: The cost of explaining the project and explaining the test program should be minimized subject to limits on attaining the variety of conditions.
Reason: Cost-effective data gathering; since this project is not to determine lightning protection or company practices, there is no preference for REA or private-owned and no preference for one size over another.
3. Unshielded lines for the BASIC SAMPLE of instrument sites.
Criterion: No tree, utility line, or building higher than 10 feet less than line height and within 300 feet of the line between the next grounded poles.
Reason: The information in a greater number of incidents is more important for the BASIC SAMPLE than information for interpreting the effect of shielding; unshielding situations provide the greatest information for a given IKL.
4. SUPPLEMENTAL SAMPLE to include shielded and unshielded situations.
Criterion: Selection to be at the discretion of individual utility.
Reason: No a priori specification is likely to produce the best mix of shielded and unshielded situations.
5. Low ground resistance for every site in the BASIC SAMPLE.
Criterion: Less than 25 ohms throughout the year; i.e., the probability of dry conditions that would provide higher than 25 ohms during a month of high lightning in the 5-year test period should be less than 10%.
Reason: High ground resistance (and varying ground resistance during the sample period) making interpretation of test results difficult.
6. Top phase, outer phase, single phase, or overhead shield wire for the BASIC SAMPLE.
Criterion: The arrester or ground lead to which the instruments is attached must be connected to the wire most likely to be struck, such as an outer phase, top phase, a single phase, or a shield wire.
Reason: An upper or outer wire will generate more observations per dollar cost.

TABLE 2 (Continued)

7. Random selection within a locally high lightning incidence area for the BASIC SAMPLE.
Criterion: One or more sub-areas of a participating utility will be selected by JFA and the utility on the basis of relatively high lightning incidence. A central point such as a town or crossroad will be designated for defining a designated radius in which arresters will be randomly selected. The case-by-case determination will generally be less than a 10-mile radius.
Reason: The locally high lightning incidence will generate more observations per dollar costs; the random selection will prevent "single-pole" anomalies in the BASIC SAMPLE.
8. Nationwide coverage
Criterion: The combined BASIC and SUPPLEMENTAL SAMPLES should have good coverage with respect to (1) different IKL levels, (2) arrester density, (3) different system voltages, and (4) geographic regions. If necessary, the BASIC SAMPLE will exclude some regions to avoid high ground resistance.
Reason: The nationwide coverage is essential for both model development and user comparison.
9. Range of system voltage
Criterion: 13, 25, and 34kV will be included in the combined BASIC and SUPPLEMENTAL SAMPLES other voltages can be included to permit other desirable conditions.
Reason: Users who feel voltage is important can find situations similar to their own.
10. SUPPLEMENTAL SAMPLE to include local interest
Criterion: The participating utility can select these sites outside the designated area for the BASIC SAMPLE; in essence, there is no criteria for the SUPPLEMENTAL SAMPLE, but there will be suggestions.
Reason: Allows a participating utility to gather information on its specific problems and to obtain data that may lead to greater understanding of unusual conditions.
11. Nearby thunderstorm count is desirable but impractical in some areas
Criterion: The closest point in U.S. weather service, U.S. forest service, or state climatologists where counts of thunderstorm days is kept reasonably well should be specified, but it is probably not possible to have all sites close to a counting station.
Reason: To relate actual thunderstorm count to readily available IKL information and to relate test results to actual thunderstorm frequency.

TABLE 2 (Continued)

12. Representation of load density and equipment protection
Criterion: Variety of load density and equipment protection should be chosen.
Reason: The combined BASIC and SUPPLEMENTAL SAMPLES should contain situations of interest to users for purposes of comparison. Also, it determines arrester density.
13. Sites to be selected in lightning season
Criterion: Site selections to be made when concern for and knowledge of lightning incidence is greatest.
Reason: Attain greatest accuracy and capitalize on greatest participant company interest.

TABLE 3.—SITE SELECTION INSTRUCTIONS FOR PARTICIPATING UTILITY

1. Define a "site" as a test instrument pole and the nearby area. A test instrument pole is a specific pole in which the test instrument is mounted. Note: The pole must have an arrester (or ground wire from an overhead shield wire).
2. Select two subsamples independently.
 - (1) The BASIC SAMPLE will be within a pre-designated subarea for your system; in most cases this will be within a 10-mile radius of a specified town or crossroad.
 - (2) The SUPPLEMENTAL SAMPLE (in number, roughly 60% as many as the BASIC SAMPLE) can be anywhere in your system area, including (and especially) specific problem situations caused by lightning. One-third to one-half should be placed with instrument of the BASIC SAMPLE, but on the nearest phase. Install an arrester if necessary.
3. Follow these steps in selecting specific sites for the BASIC SAMPLE.

Step 1. Start from the designated point and drive in the direction most likely to produce the first (or next) site that meets the following criteria:

 - (1) An arrester connected to a top phase, outer phase, or single phase line (or a ground lead connected to an overhead shield wire).
 - (2) No tree or structure taller than 10 feet below the line height and within 300 feet of the designated arrester or ground lead from an overhead shield wire.

Step 2. Check ground resistance at test instrument pole and retain site only if less than 25 ohms.

Step 3. Locate the next grounded pole in each direction from the selected pole and verify that there is no structure, line or tree taller than 5 feet below the line height and within 300 feet of the line between the two adjacent grounded poles.

Step 4. Repeat steps 1-3 until you select all sites for the 80% subsample.

Step 5. Ensure that the arrester at the site is a valve-type arrester, if not, install a valve-type arrester.

TABLE 3 (Continued)

4. Follow these steps in selecting specific sites for the SUPPLEMENTAL SAMPLE.

Step 1. Identify candidate sites of special interest for your system by asking division managers and linemen for suggestions on particularly troublesome lightning situations.

Step 2. Pinpoint the candidate location on your system map and send to the ERDA project director. Indicate any priority among sites if the list of candidates exceeds 60% of your designated sample. The ERDA project director will indicate any restrictions and provide suggestions for the final selection of the SUPPLEMENTAL SAMPLE.

Step 3. Check the choice to ensure that one-third to one-half of the instruments on the SUPPLEMENTAL SAMPLE are on conductors nearest to an instrument of the BASIC SAMPLE.

SECTION IV

SITE CHARACTERIZATION AND DATA COLLECTION

Site characterization is defined as the information required for reliable interpretation of sample data from a specific instrument. It is necessary to document site characterization requirements in order to verify that a given sampling plan will generate adequate data for an acceptable confidence interval.

It is also necessary to document data collection requirements in order to ensure cost-effective procedures and to ensure adequate test instrument performance, including instrument storage capacity. Data collection plans are also necessary for providing preliminary results during the 5-year test period.

IMPORTANCE FOR RELIABLE TEST RESULTS

Site characterization is important both for ensuring that data is properly used in development of predictive models and to ensure that interested users can find comparable situations within their own systems.

The number of site characteristics that must be described has been kept to a minimum, but this minimum number must be characterized accurately because a larger sample size cannot adjust for erroneous or missing site data.

The form discussed in the next section and the sample plan have been designed to make site characterization easy and reliable. Again, the site visits for the BASIC SAMPLE have provided valuable insights. Among other things, they helped in the decision to rule out shielded situations because of difficulty in accurate descriptions.

It is important to realize that the test program will provide information to calibrate predictive models and comparative situations that include site-specific characteristics. Whereas a large sample size could give a reliable national average regardless of site variation, it would not allow the added precision in taking site factors into consideration.

PARTICIPANT INSTRUCTIONS FOR SITE CHARACTERIZATION

Instructions for site characterization are provided in Tables 4 and 5. Again, information has been put in tables for easy extraction and use in subsequent phases of the test program.

In order to keep the information form on each site as simple as possible, different forms have been developed for the BASIC and SUPPLEMENTAL SAMPLES. The form for the BASIC SAMPLE is simpler, because there is no shielding that needs description and considerable information of the sub-area will have been documented already.

FREQUENCY OF DATA COLLECTION

The best schedule for data collection is a balance among (1) cost considerations, (2) verification of instrument performance, and (3) publication of preliminary results during the 5-year test program. The participating utility is given some discretion and flexibility subject to the following guideline (and possible new guidelines as more insights are developed):

1. It is recommended that the instrument should be thoroughly checked at installation, and then twice annually. Although the instruments are designed for yearly collection, it seems wise to us that they be checked just before and just after the lightning season. There should be no reason why an interested utility could not check more frequently, if it so desired. A salient point is the control group for the field study should establish "reminder" procedures for checks prior to the lightning season.
2. Equipment loss on test pole
Although the chances of lightning caused line burndown of equipment damage at a sample site are small, the value of information when this happens is so great that Table 6 should be completed and sent in with the tape shortly after equipment loss. A failure or burndown anywhere within the distance to or at a grounded pole should be treated as a failure at the site. (Distance D4 and D5 of Table 6.)
3. Test instrument recording failure
A severed ground lead, an inoperable arrester, or anything else preventing a reading by the test instrument should be reported when detected. There is no need for planned surveillance beyond that indicated in Steps 1 and 2, but any detection of equipment failure that does occur should be reported in order to improve sample efficiency.

TABLE 4.--SITE CHARACTERIZATION FORM FOR BASIC SAMPLE

1. IKL

- a. The local IKL at this site is judged to be "60", or 1.5 times the IKL of "40" for your company's overall area.¹
- b. If you disagree with the judgement, please indicate your best estimate here: _____ IKL at this site.

2. Test instrument connection

- a. The ground lead to which the instrument is connected is from
 - ☐ an arrester (must be valve type)
 - ☐ an overhead shield wire
 (check appropriate box)
- b. If ground lead is from an arrester, check one of the following
 - ☐ Direct connected
 - ☐ External GAP, with a gap of _____ inches
- c. If ground lead is from an overhead shield
 - ☐ overhead shield stops or drops to level of phase wire before pole B or pole C in Figure 1.
 - ☐ Overhead shield continues at the same height above phase wires beyond poles B and C.

3. Grounding at site

- a. Size _____ and material _____ of ground lead shown in Figure 1.
- b. Depth of ground rod (D_1 in Figure 1) is _____ feet.
- c. The instrument you used to measure ground resistance R_1 in the diagram below was _____.
(J.D. Biddle Ground Megger, two terminal method preferred)

¹Note: Actual values will be used instead of the fictitious 60 and 40 in item 1.1 whenever this is sent to a specific utility.

TABLE 4 (Continued)

d. Actual measurements

R_1 at pole A is _____ ohms.
 R_1 at pole B is _____ ohms.
 R_1 at pole C is _____ ohms.

Each must be less than 25 ohms and to be measured with ground lead disconnected.

FIGURE 1 OF TABLE 4: TEST SITE - A SEGMENT OF 3 OR MORE POLES*

*Note: Poles designated B and C are grounded poles; there may be ungrounded poles between B and A and between C and A.

4. Distances and intervening poles

- Distance D_4 between poles A and B above is _____ feet.
- Distance D_5 between poles A and C above _____ (or distance to customer house or equipment if pole A is an end pole _____).
- Number of ungrounded poles between A and B _____.
- Number of ungrounded poles between A and C _____.
- Height of line at a pole to which the instrument is attached (D_6 above) _____.

TABLE 4 (Continued)

5. Additional arrester information, if ground lead is from an arrester

a. Check the box indicating the equipment being protected

- ☐ Line (that is, there is no transformer or other protected pole equipment)
- ☐ Transformer
- ☐ Capacitor
- ☐ URD dip
- ☐ Recloser or sectionalizer
- ☐ Other (describe)

b. Arrester Manufacturer _____

c. Model Number _____

d. Number of years in service _____

e. Arrester type (Check appropriate box)

- ☐ Distribution arrester
- ☐ Intermediate arrester
- ☐ Other; please specify

6. Surrounding Area

- a. Urban _____, suburban _____, or rural _____.
- b. Flat _____, hilly _____, or mountainous _____.
- c. Distance of Lake Erie from this site is _____ miles¹.
- d. Ground elevation is _____ feet above sea level.

7. Construction at this site (Please complete even though there is a separate shield wire or neutral on top)

¹ Note: Any body of water of interest will be known and the actual name will be used instead of "Lake Erie".

TABLE 4 (Continued)

- a. Poles are wood _____, metal _____, concrete _____
- b. System configuration is E _____, F _____, G _____, H _____, or I _____ in Figure 2. If another design, please modify one of the sketches.
- c. The line is sub-transmission feeder _____, distribution feeder _____, tap _____
- d. It is single _____, two _____, or three _____, phase.
- e. System neutral is below _____, on top _____, on cross-arm _____, no neutral _____

Note: ● designates phase wire and o designated neutral wire. N designates system neutral which can be on top or in position shown.

FIGURE 2 OF TABLE 4: LINE CONFIGURATION

- f. Instrument is attached to phase "a" _____, phase "b" _____, phase "c" _____ in the designation above (as viewed from north or east of pole).
- g. The line is multigrounded _____, grounded at substation only _____, not grounded _____
- h. System line to line voltage is _____
- i. Size _____ and type _____ material of the phase wire (or overhead shield wire).

TABLE 4 (Continued)

8. Distances between phase wires (Complete only one of a-e as appropriate).

- a. If configuration E, the distance between "a" and "N" is _____.
- b. If configuration F, the distance between "a" and "N" is _____
and the distance between "a" and "b" (if three phase) is _____.
- c. If configuration G, the distance between "a" and "b" is _____,
between "b" and "c" is _____, between "a" and "c" is _____,
between "b" and "N" is _____.
- d. If configuration H, the distance between "a" and "b" is _____,
between "b" and "c" is _____, between "a" and "N" is _____.
- e. If configuration I, the distance between "a" and "N" is _____,
between "a" and "b" is _____, between "b" and "c" is _____.

TABLE 5.--SITE CHARACTERIZATION FORM FOR SUPPLEMENTAL SAMPLE

1. IKL

- a. The local IKL at a site can vary from about $\frac{1}{4}$ to 4 times the average IKL for your company or the estimate in a national isokraunic map. We would like to have a judgement to this factor.
- b. Please indicate your best estimate of the local IKL as follows:
- ☐ Appears to be same as for overall company
 - ☐ Have no information on the relationship
 - ☐ Seems to differ considerably and my estimate is _____ times the company's average.
- (Check appropriate box)
- c. Please give a one or two sentence description of any special lightning situation at this site and provide the name and telephone number of the person for followup telephone requests.

2. Test instrument connection

- a. The ground lead to which the instrument is connected is from
- ☐ an arrester (must be valve type)
 - ☐ an overhead shield wire
- b. If ground lead is from an arrester, check one of the following
- ☐ Direct connected
 - ☐ External GAP, with a gap of _____ inches
- c. If ground lead is from an overhead shield
- ☐ overhead shield stops or drops to level of phase wire
 - ☐ before pole B or pole C in Figure 1.
 - ☐ Overhead shield continues at the same height above phase wires beyond poles B and C.

TABLE 5 (Continued)

3. Grounding at site

- a. Size _____ and material _____ of ground lead shown in Figure 1.
- b. Depth of ground rod (D_1 in Figure 1) is _____ feet.
- c. The instrument you used to measure ground resistance R_1 in the diagram below was _____. (J.D. Biddle Ground Megger two-terminal method preferred)
- d. Actual measurements

R_1 at pole A is _____ ohms.	} No restriction on magnitude. To be measured with ground lead disconnected.
R_1 at pole B is _____ ohms.	
R_1 at pole C is _____ ohms.

FIGURE 1 OF TABLE 5: TEST SITE - A SEGMENT OF 3 OR MORE POLES*

*Note: Poles designated B and C are grounded poles; there may be ungrounded poles between B and A and between C and A.

TABLE 5 (Continued)

4. Distance and intervening poles

- a. Distance D_4 between poles A and B above is _____ feet.
- b. Distance D_5 between poles A and C above _____ (or distance to customer house or equipment if pole A is an end pole _____).
- c. Number of ungrounded poles between A and B _____.
- d. Number of ungrounded poles between A and C _____.
- e. Height of line at pole A which the instrument is attached (D_6 above) _____.

5. Additional arrester information, if ground lead is from an arrester

- a. Check the box indicating the equipment being protected
 - ☐ Line (that is, there is no transformer or other protected pole equipment)
 - ☐ Transformer
 - ☐ Capacitor
 - ☐ URD dip
 - ☐ Recloser or sectionalizer
 - ☐ Other (describe) _____
- b. Arrester Manufacturer _____
- c. Model Number _____
- d. Number of years in service _____
- e. Arrester Voltage Rating _____
- f. Arrester type (check appropriate box)
 - ☐ Distribution arrester
 - ☐ Intermediate arrester
 - ☐ Other; please specify _____

TABLE 5 (Continued)

6. Surrounding area

- a. Urban _____, suburban _____, or rural _____.
- b. Flat _____, hilly _____, or mountainous _____.

7. Construction at this site (Please complete even though there is a separate shield wire or neutral on top)

- a. Poles are wood _____, metal _____, concrete _____
- b. System configuration is E _____, F _____, G _____, H _____, or I _____ in Figure 2. If another design, please modify one of the sketches.
- c. The line is sub-transmission feeder _____, distribution feeder _____, tap _____
- d. It is single _____, two _____, or three _____ phase.
- e. System neutral is below _____, on top _____, on cross-arm _____, no neutral _____

Note: ● designates phase wire and o designated neutral wire. N designates system neutral which can be on top or in position shown.

FIGURE 2 OF TABLE 5: LINE CONFIGURATION

TABLE 5 (Continued)

- f. Instrument is attached to phase "a" _____, phase "b" _____, phase "c" _____ in the designation above (as viewed from north or east of pole).
 - g. The line is multigrounded _____, grounded at substation only _____, not grounded _____.
 - h. System line to line voltage is _____.
 - i. Size _____ and type _____ material of the phase wire (or overhead shield wire).
8. Distances between phase wires (Complete only one of a-e as appropriate).
- a. If configuration E, the distance between "a" and "N" is _____.
 - b. If configuration F, the distance between "a" and "N" is _____ and the distance between "a" and "b" (if three phase) is _____.
 - c. If configuration G, the distance between "a" and "b" is _____, between "b" and "c" is _____, between "a" and "c" is _____, between "b" and "N" is _____.
 - d. If configuration H, the distance between "a" and "b" is _____, between "b" and "c" is _____, between "a" and "N" is _____.
 - e. If configuration I, the distance between "a" and "N" is _____, between "a" and "b" is _____, between "b" and "c" is _____.
9. Describe the shielding around the instrument location
- a. Type of shielding
Buildings _____, metal tower _____, high trees _____, mountainous terrain _____, other _____.
 - b. Distance to maximum shielding
Object = () meters away from line.
 - c. The nearest shielding object that is higher than the distribution line is _____ feet from the line.

TABLE 6.--REPORT ON LIGHTNING-CAUSED FAILURE AT TEST SITE

The definition of a test site given in Table 5 is repeated in Figure 1 below.

1. Type of failure causing outage

Indicate one of the following: _____ transformer, _____ capacitor, _____ recloser, _____ sectionalizer, _____ arrester broken, _____ line burndown, _____ pole splitting, _____ cross-arm splitting, _____ other.

Note: A blown fuse or a recloser operation without lockout does not qualify as a failure for this report.

2. Time of failure

Since the tape will have a specific time, such as 12:01 January 1, on each stroke, the following information will help identify a specific failure with a specific recorded lightning stroke.

_____ date failure was repaired.
_____ date that stroke is thought to have occurred.
_____ approximate time of stroke.

3. Location of failure

On Figure 1, on the following page, indicate the position on the pole or the line where the failure occurred.

4. Person for more information

Give the name and telephone number of the person who could provide information on this failure.

TABLE 6 (Continued)

FIGURE 1 OF TABLE 6 : TEST SITE - A SEGMENT OF 3 OR MORE POLES*

*Note: Poles designated B and C are grounded poles; there may be ungrounded poles between B and A and between C and A.

Any failures at or between any of the three grounded poles of Figure 1 above should be treated as a failure at the site and reported.

SECTION V

RECOMMENDATIONS FOR THE FUTURE

THE FIELD STUDY

Data Analysis

One of the objectives of this study was to recommend data analysis procedures to be used once the field study is underway. These recommendations are derived primarily from the calculations and modeling done as a part of the present study. In summary, this means:

- Calibration and modification of the models used herein, based upon direct stroke data as it is collected;
- Study of direct stroke data to improve, replace, or modify the models used;
- Study of induced surge data in an attempt to infer models of return streamer propagation, to develop better models for induced surge development and propagation, and to assess their overall impact on systems;
- Analyzing the data (on direct strokes particularly) to improve understanding of predischage phenomena and its modeling for distribution system design. This is particularly important for the portion of the SUPPLEMENTAL SAMPLE specifically designed to obtain data on predischage.
- Thorough follow-up analysis on "anomalous" situations in an attempt to ascertain root causes and to make necessary modifications to prediction methods. This is likely to be costly, since it will almost certainly require field investigation and intensive "trouble shooting".

The Instrument and its Placement

An important recommendation regarding the instrument concerns its threshold levels. There is much to be learned from induced surge data, and it is recommended that thresholds be low enough to allow their analysis.

Placement of the instrument need not be at an arrester designed to protect line or equipment. What is needed is a "switch" that senses lightning, and a lightning receptor. Specifically, an instrument could be placed between a shield wire and its ground wire. The instrument's threshold serves as a switch, since only lightning strokes will cause the instrument to record. A small gap or arrester could, of course, be added, to ensure that system faults do not trigger the instruments.

Field Study Control

Several recommendations for control of the field study have been made that are of significance:

- Utilities should be actively encouraged to seek out unusual lightning situations that perhaps baffle a priori understanding;
- Each utility's site selections should be reviewed carefully for adherence to criteria;
- Prior to field site selection, criteria should be reviewed with the individual utilities. A focus (i.e., someone) for project control should be established at each utility. Training in site characterization is important;
- As wisely suggested by the project advisory committee and instrument manufacturers, a pilot study using a relatively small number of instruments is essential.

A RESTATEMENT OF THE INDUSTRY PROBLEM

Perhaps the most important result of this entire project has been a restatement of the problem, and the consequent outpouring of ideas for work that needs to be accomplished.

Fundamentally, the ultimate goal is to find the optimum solution to the Protection Cost-Benefit Problem. To do this, as noted in the introduction, the cost of an outage must be ascertained, and the occurrence of outages must be predicted.

In order to estimate the cost of outage it will be necessary to determine quantitatively, acceptable outage rates for lines, transformers, and other equipment. Very likely this will rest more on judgement than theory, but it is an essential activity.

A host of significant concerns arise when considering the prediction of outages. It becomes apparent that the field study, with which this project is concerned, is only a small part of what must be done. In a very real sense, if these other tasks are not confronted, the present study will lose its meaningfulness. The other tasks perceived are:

- Laboratory tests to determine the fast-front sparkover characteristics of arresters, transformers, and other protected equipment;
- Laboratory tests to determine the discharge voltage of arresters as a function of rate of rise, system voltage, etc.;
- Field tests to determine stroke density directly. That is, not using IKL as a focal point, and not attempting to use the present instrument as a (high cost) counter;
- Laboratory tests to study predischage phenomena and bring old studies up-to-date;
- Development of complete analytical protection system design models;
- Development and study of scale model laboratory models for lightning protection design to bring old studies up-to-date. This will balance and aid analytical model development;
- Study of footing resistance with full-scale tests to establish a real understanding of the relation between "production" field tests (Meggar or other) and the actual surge impedance of typical grounding configurations and soils;
- Attenuation of surges on distribution lines, while of secondary importance, will become increasingly important as other factors are better defined. It will also open the door to better understanding of induced surges;
- Thus far, there has been little tie-up between models of lightning for system design (strike distance, etc.) and the physics of what occurs in lightning strokes (temperatures, ionization, etc.). Much has occurred in both fields in the last decade and it is time for a fresh attempt to link the two from the perspective of system protection.

Most of the above studies (and doubtless others not foreseen at present) are of the same order of importance as the presently proposed field study. It is urged that these be confronted individually and promptly. Most, if not all, will need financial support, and this needs first attention.

Critical Path Methods

Assuming that the above tasks are indeed desirable and feasible within a 7-year time frame (fitting the proposed lightning instrument field study) and making rough estimates of times required for such studies, network analysis methods were applied resulting in the network shown in Figure 26 (the symbols used there are illustrated in Figure 25).

FIGURE 25: TERMINOLOGY FOR NETWORK OF FIGURE 26

Attempts to set EET's and LET's (see Figure 25 for definitions) break down because of the requirement (desire) that both pilot field study and main field study begin at the start of the 1977 and 1978 lightning season, respectively.

In order to successfully achieve this:

- Pilot instrument manufacture will have to be tightly controlled;
- Instrument redesign will have to be pushed back into the pilot field study, using the early results;
- Mass instrument manufacture will have to be tightly controlled and shortened as much as possible, as will be main field study preparation.

It is our recommendation that, while pilot study can begin with the 1977 lightning season, no attempts be made to "force fit" the main study to the 1978 season.

Bar Charts

It is relatively easy to translate networks such as Figure 26 into bar charts for scheduling, and this has been done in Figure 27. Some minor modifications from the network of Figure 26 have been made.

FIGURE 26: CRITICAL PATH ANALYSIS OF DEVELOPMENT OF UNDERSTANDING OF LIGHTNING PROTECTION

FIGURE 27: SCHEDULING OF LIGHTNING STUDY ACTIVITIES

Comments on Bar Chart

1. Identification of Acceptable Outage Rates is an activity seen as needing a healthy subjective study initially to set the stage, and a final review and reassessment study as knowledge is gained during the overall project.
2. Arrester/Transformer Test Design probably will require a year to arrange funding, to let contracts, etc. Tests include fast-front sparkover as well as tests of discharge voltage vs. rate of rise of current and system voltage.
3. Other Equipment, such as cutouts and lines of various configurations, will need testing to determine more realistically its performance.
4. Predischarge, Footing Resistance, and Attenuation tests could be done in parallel, but are shown proceeding serially, recognizing that this will likely represent efficient use of "manpower".
5. Both the lightning current instrument and stroke counter studies are assumed to flow together, and any installation that could be done in common, will be. Manufacture of instruments for the pilot study is still very tight.
6. Analytical Work Organization is rather nebulous and will almost certainly be a part of laboratory and field program efforts. The charting of these activities separately is useful in revealing when such skills will be most heavily "taxed". Control and coordination of this kind of activity is well advised where there is heavy simultaneous scheduling. (Late 1979 and onward on the bar chart).

FREQUENCY OF DISTRIBUTION ARRESTER DISCHARGE CURRENTS
DUE TO DIRECT STROKES

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ABSTRACT

The "Electrogeometric" Theory, developed for transmission line lightning performance calculations, is applied to distribution systems as a means of predicting arrester discharge currents. The resulting rates of occurrence and frequency distributions compare favorably with presently available information. The effect of stroke location on arrester current is explained and shown to be significant. PredischARGE and pole reflections are shown to have similar effects, and do not significantly affect crest current. Footing resistance is accounted for. Indirect strokes are treated briefly and shown to produce minimal arrester current.

INTRODUCTION

Over the past decade, there has been increasing interest in and concern over distribution system failures caused by lightning. Interest has centered on arresters and the duty they are likely to see. Also within the past 10 years, major advances have been made in the ability to predict the occurrences of lightning to transmission lines. In particular, the

Figure 1. Frequency of Strokes to Level Ground (log-normal graph)

F 76 160-2. A paper recommended by the IEEE Surge Protective Devices Committee of the IEEE Power Engineering Society for presentation at the IEEE PES Winter Meeting & Tesla Symposium, New York, N.Y., January 25-30, 1976. Manuscript submitted July 31, 1975; made available for printing November 14, 1975.

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Nonmembers \$2.00
At Meeting: \$1.00

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"Electrogeometric Theory," or Brown-Whitehead model, has now been extensively used and abundantly verified for HV and EHV systems. (Refs. 1 through 7.) Especially important, Sargent in Ref. 7 makes an impressive argument both for the theory and his proposed distribution of stroke currents to level ground. Using the Brown-Whitehead model and knowing the geometry of tall structures for which data is available, he inferred what the distribution to level ground had to be. Doing so, he was able to very nearly eliminate discrepancies in field data from various investigators, including those used on the "AIEE curve."⁸ Sargent's synthetic distribution to level ground is shown in Figure 1.

In the following, after (I) briefly dispensing with indirect strokes, we will (II) develop the frequency of direct stroke currents to distribution LINES. This will precede (III) relating stroke currents to arrester currents, following which (IV) the desired frequency distribution of arrester discharge currents will be developed. As the first stage in the development, we show that indirect strokes may be dispensed with.

I. INDIRECT STROKES

The electrogeometric theory indicates that a leader tip which will cause an indirect surge cannot be closer than the strike distance. (Fig. 2)

$$E \approx \frac{q}{2\pi\epsilon \sqrt{r_s^2 + 2r_s h - h^2}}$$

(Reference 13)

q = coul/m of leader
 r_s = strike distance
 $= 7.1 r^{.75}$

Figure 2. Geometry of Closest Approach of Indirect Stroke

Referring to Figure 2, the voltage induced in the conductor is approximately hE . Were the charge on the leader instantly collapsed by striking some other earthed point, this voltage would split in two equal surges travelling down the conductor in opposite directions. The strike distance is a function of leader voltage, which is in turn a function of the charge per unit length of the leader channel. (See References 1 and 2) The equations of the electrogeometric model suggest a capacitance to earth of the leader channel of (very) approximately 7.8 pf/m, and a leader voltage of (crudely) $0.76 r_s^{.83}$ kV. Coupling this with the information of Fig. 2 allows rough determination of the maximum surge voltage and current as shown in Table I. Although this analysis is only a rough approximation, it is clear that surges due to indirect strokes produce minimal line and even smaller arrester currents. It is noted that the currents of Table I

Table I

Maximum Arrestor Current Due to Indirect Strokes
Assuming a Line 10m High with 400Ω Surge Impedance

I Stroke Current kA	Leader Closest Approach m	Maximum Possible Arrestor Current amps
10	40	1120
50	135	1100
100	225	1080

are consistent with field data (e.g. Refs. 11 and 12).

II. FREQUENCY OF DIRECT STROKE CURRENTS TO DISTRIBUTION LINES

Before examining arrester currents, consider the problem of determining the frequency of stroke currents to a line.

(A) "Electrogeometric" Model

The geometry of conductor exposure is a function of strike distance (and thus current). At each strike distance, there is an exposed circular arc as shown in Fig. 3a. Note that there is a maximum strike distance (and thus current) for a given shielding configuration as in Fig. 3b. For larger strike distances, the stroke will always be closer to either shield or earth than to conductor, and cannot, therefore, strike the line.

(a) Exposed Conductor (b) Maximum Strike Distance

Figure 3. Geometry of a Line Exposure to a Stroke with Strike Distance r_s .

As shown in Refs. 1 and 2, the number of strokes hitting the line is

$$n = N_0 \int_0^{\infty} X f(I) dI \quad (1)$$

In this equation, the parameters are as follows:

- n = strokes per unit length and time to the line
- N_0 = stroke density (strokes/unit area/yr)
- X = swath (effective exposed width, as in Ref. 1. Related directly to exposed arc of Fig. 3.)
- $f(I)$ = frequency distribution of stroke current magnitudes to level ground (Fig. 1)

The effective swath, X , is a function of the distribution stroke-approach angles (Ψ in Fig. 3a). Again from Ref. 1:

$$X = \frac{2r_s}{\pi} \int_{\theta_2}^{\theta_1} \int_{\psi_2}^{\psi_1} \sin(\theta - \Psi) \cos \Psi d\psi d\theta \quad (2)$$

θ_1 and θ_2 are as in Fig. 3a; ψ_1 and ψ_2 are the limits on the approach angle (e.g. ψ_2 is often $-\pi/2$). [It is noted that recent works (e.g. Ref. 4) suggest slightly different equations for the strike distance. They also suggest a difference between strike distance to ground and to conductor. However, in order to use these, the distribution of Fig. 1 must be redetermined. The distribution of strokes to level ground based on other equations was not available at this writing. In any case, experience with transmission systems shows that the differences in overall performance are not significant.]

(B) Results for Shielded and Unshielded Lines

The rates of occurrence of strokes to lines, for various configurations, are shown in Fig. 4 (unshielded lines) and Fig. 5 (shielded lines). Though the rate for shielded lines is not easily normalized, use of an abscissa of $x/(h+10)$ makes interpretation easier. Note that rates for forested lines can be inferred from the data. For example, for a 10 meter (vertical configuration) high line with a 10m high forest 20m on either side of the line:

From Fig. 4, 60 str./100km-yr (at 10 strokes per sq.km. and yr.).

From Fig. 5, at $x/(h+10) = 20/20 = 1$ and $y/h = 1$, the rate would be reduced to 67% of 60 = 39, were the "forest" on one side of the line. Being on both sides, it is reduced to $2(39 - 60/2) = 18$ strokes per 100 km and year.

Figure 4. Number of Strokes to an Unshielded Distribution Line per 100 km and Year

Figure 5. Effect of Shielding on Number of Strokes to the Line

This approach is valid for tree heights less than or equal to line height. For higher levels, maximum strike distance will likely be very small and the line will be effectively shielded, except for very low current strokes.

From Eq. 1, we can write the frequency function of stroke currents hitting the line as

$$f_L(I) = \frac{Xf(I)}{\int_0^{\infty} Xf(I)dI} \quad (3)$$

And in turn the distribution function is found:

Figure 6. Frequency Distribution of Strokes to Lines (log-normal graph)

$$\text{Probability that current} > I_0 = F_L(I_0) = \int_{I_0}^{\infty} f_L(I)dI \quad (4)$$

The results are shown in Fig. 6. One set of curves is accurate for all reasonable distribution line configurations. There would be slight differences at transmission tower heights.

The frequency of strokes through arresters can be determined if line current and arrester current magnitudes can be related. This is done in the following section.

III. RELATING LINE AND ARRESTER CURRENTS

(A) Effect of Stroke Location

Consider, as in Fig. 7a, a line with arrester spacing T (measured in surge travel time), and a direct stroke impinging at ρT from the arrester being considered. (Though arresters are assumed at each grounded pole, it is only necessary that there be flashovers at the grounded poles.)

(a) Situation

(b) Reflections

(c) A "Block" of Arrester Current

(d) Convention for Travelling Waves

Figure 7. Effect of Stroke Location

Note that in the reflection diagram (Fig. 7b), the analysis of the effects of the surge may be considered as repeated blocks of surge current, the block being the effect of the first wave and the first reflection from the other end. The block is illustrated in Fig. 7c. The wave form is considered as a ramp to a flat crest, I_0 . (Note the convention used for travelling wave signs in Fig. 7d. It is not the usual approach, but the authors believe it to be a better one. Regardless of the origin of a wave, if current is measured in the direction of travel, $v = +zi!$)

(B) Effective Arrester Current

For the stroke wave form assumed (constant ramp to I_0 at time-to-crest T), the amount of current-time area added by the "block" is

$$\int i dt = \frac{I_0}{T_0} [2(1-\rho)T] T_c$$

Since a new "block" is added every $2T$, the average cur-

rent (i.e., the average crest current) in the arrester is $I_a = (1-\rho)I_0$, as illustrated in Fig. 8.

Figure 8. Illustration of Effect of Stroke Location on Arrester Crest Current Magnitude

Although the actual crest will be higher, it is of far shorter duration than the bulk of the wave, and short duration surges through an arrester probably produce smaller gap etchings than long duration surges. To the order of accuracy presently available, it is therefore assumed that the effective arrester current due to a stroke with current I_0 is given by $(1-\rho)I_0$. To be sure, strokes with fronts faster than the travel time between the arresters will produce short duration spikes, repeated every $2T$, but (1) in most situations will involve strokes with fronts much longer than twice travel time, (2) the effect of such duty in comparison with more "normal" waveforms is unclear, though (3) it is certainly less severe than a full steady wave of I_0 . Finally, (4) since the statistics of tail form of strokes (and particularly its dependence on other stroke parameters) are unclear, $(1-\rho)I_0$ is still appropriate as the effective current.

(1) Predischage. As indicated in Refs. 14-16, predischage currents will flow between the struck conductor and nearby conductors to relieve the stress between them. The lines near the point of impact act much like a high discharge voltage (about 186kV per foot of spacing) arrester. As soon as the first reflection from the other grounded pole, predischage current is eliminated. Thereafter, the current flows as if predischage had not occurred. The initial (predischage) "blocks" of current are sufficient to insure that the voltage will not again exceed the predischage level of the line. In extreme cases, this can represent a significant reduction in rate of rise of arrester current (e.g. where time-to-crest is significantly shorter than travel time between grounded poles). However, this doesn't represent a significant fraction of the statistics, and doesn't affect average crest current at all. Hence, the effect of predischage on arrester current is ignored.

(2) Footing Resistance. High footing resistance will reduce arrester currents. The effect is illustrated in Fig. 9. (Recall the convention of Fig. 7d.) For example, with 200 ohm footing resistance and top phase protection, the arrester current would be 70% of its value with no footing resistance. (cf. Fig. 9c) It will be even closer for three-phase protection as shown in Fig. 9d.

(3) Reflections Down (and Up) the Pole. The above ignores the effect of waves travelling up and down the pole. It is relatively easy (but laborious) to show that such reflections do not affect the magnitude of the effective crest. The effect is illustrated in Fig. 10.

(a) High Footing Resistance

(b) Low Footing Resistance (c) 200Ω Footing Resistance

(d) Overall Effect (Approximate)

Figure 9. Effect of Footing Resistance on Arrester Current

Figure 10. Effect of Pole Reflections on a "Block" of Arrester Current (cf. Fig. 8)

As with predischage, the effect is to siphon off a single, small block of charge early (e.g. small fraction of a microsecond), to delay the crest, and to smooth the wave. This adds to the case for using $(1-\rho)I_0$ as the effective crest.

IV. FREQUENCY OF ARRESTER CURRENTS

(A) Strokes to Poles

As just seen, arrester current is a function of stroke location. The Brown-Whitehead model predicts that for lines with significant sag angles, some strokes will hit towers directly. However, for sags found on distribution lines, the strokes will be evenly distributed without regard to poles. This is illustrated in Fig. 11.

Figure 11. Effect of Sag on Stroke Location

(B) Strokes to the Line

In the Appendix it is shown that the frequency function of arrester currents is

$$f_A(I_A) = \int_{I_A}^{\infty} \frac{f_L(I)}{I} dI$$

where $f_L(I)$ is as in Eq. 3. Finally, the distribution function is

$$F_A(I_A) = \text{Probability that Arrester Current Is Greater than } I_A = \int_{I_A}^{\infty} f_A(I) dI$$

This has been performed numerically. The results are shown in Fig. 12.

(C) Example

Find the number of arrester operations on the distribution line illustrated in Fig. 13, if the stroke density is 10 strokes/sq.km/yr (corresponding to an IML of about 60). Also, find the number of arrester operations greater than 65kA.

From Figs. 4 and 5, with 2m outer phase spacing, with $y/h = 3$ and $x/(h+10) = 2.50$, we read

$$\begin{aligned} n &= \text{\# strokes to unshielded line} \\ &= 6.25 \times 10 = 62.5 \text{ strokes/100km/yr.} \\ n/n_0 &\approx 0.55 \end{aligned}$$

Thus, there are $0.55 \times 62.5 = 35$ strokes/100km/yr. to the line. Each produces 2 arrester operations. From Fig. 12:

$$\begin{aligned} r_{s \max} &= \frac{(53.85)^2(30+10) + 2(53.85)50\sqrt{30(10)}}{2(30-10)^2} \\ &= 262\text{m} \quad \text{and} \end{aligned}$$

Figure 12. Frequency Distribution of Arrester Currents (log-normal graph)

Figure 13. Flat Construction Example

$$I_{\max} = \left(\frac{262}{7.1}\right)^{1.33..} = 123\text{kA}$$

Thus (Fig. 12) approximately 0.25% will be greater than 65kA. This represents $0.0025 \times 35 \times 2 = 0.2$ arrester operations per 100km/yr. This is compared with about 0.75% greater than 65kA for an unshielded line, representing $0.0075(62.5)(2) \approx 1$ arrester operation per 100 km per year. For a 30-year lifetime, this represents about one operation for each 3 miles of span.

This calculation assumed arresters on the struck line at every grounded pole, as would be the case with top phase protection or arresters on all phases. If this is not the case, the approach is more complex. If there are arresters at every other grounded pole, for example, it could be assumed that there will be only one arrester operation per stroke. This will be the case if there is an insulation failure at the grounded pole (possible, since the insulation voltage will be at predischage levels for at least twice the travel time between stroke impact and arrester). In the event the voltage is low enough not to flashover the insulation, we lose little by not considering the resulting arrester operation. This is illustrated in Fig. 14.

(a) Insulation Fails (b) Insulation Holds

Figure 14. Interpretation of the Number of Arrester Operations per Stroke

For this case, the number of arrester operations exceeding 65kA would be halved. Similar arguments could be made for considering each stroke to produce fractional arrester operations for more distant arrester placement (e.g. 2 significant operations for every 3 strokes with arresters every third grounded pole).

(D) Multiple Strokes

The effect of multiple strokes is unclear. McCann and Beck¹² suggest that only 30% of arrester operations show multiple components. However, all field data (e.g. Refs. 12, 18, 19) suggest that subsequent components are more than ample to cause arrester operation. On the other hand, the average of the highest of subsequent components is roughly half that of the first component. Hence, calculations of numbers of actual occurrences of arrester currents greater than some given current well above the mean (e.g. 20kA) will not be seriously in error due to multiple components, while those below the mean will almost certainly be low. In essence, we are determining the statistics of the maximum or first component.

(E) Comparison with Existing Information

There is much information in the literature regarding "suggested" distributions of line and arrester currents. As noted earlier (page 1) AIEE recommendations correlate with near perfection our estimates of frequency distributions of strokes to the line. Typical of suggested frequency distributions of arrester currents is found in Ref. 20, shown in Fig. 15 (largely extrapolated). Since this includes incidents due to direct strokes and indirect strokes, and gives no indication of footing resistance, this curve should be lower than our prediction perhaps by as much as a factor of 4. If shielding was present (even to the extent of a wooded area less than the height of the line), the reduction would be even greater. For crude illustration, the curve is also shown redrawn with a multiplier of 5. While the extrapolation is rather extreme, it suggests that the approach given here is appropriate. At the other extreme, Ref. 21 gives data for a test line with arresters apparently particularly susceptible to high currents. A rough approximation suggests the two data points also shown in Fig. 15.

Clearly, much remains to be done in our understanding of distribution arrester currents. It is believed that the present paper will be an aid to those seeking field records in the near future, and ultimately in the application and design of arresters.

CONCLUSIONS

1. The "Electrogeometric Theory" of lightning performance has been extended to distribution systems, and frequency distributions of line and arrester currents due to direct strokes have been predicted. Rates of strokes to distribution lines of various heights are also predicted.

Figure 15. Comparison with Existing Information

2. Indirect strokes are shown to produce minimal (of order 1 kA max) line and arrester currents.

3. The effect of shielding by nearby structures (e.g. HV lines, buildings) and natural shielding is shown. Such effects reduce the number of strokes to the line and increase the frequency distribution of those strokes that do hit.

4. The effect of stroke location on arrester current magnitude is analyzed. It reduces the frequency distribution of currents markedly compared with strokes to the line. An effective arrester current of $(1-\phi)I_0$ is suggested, where ϕ is the stroke location measured as a fraction of the distance between stroke discharge points.

5. Effects of footing resistance, predischage, pole reflections, and multiple strokes are considered and illustrated. Predischage and pole reflection is not expected to significantly affect arrester crest current magnitude.

6. The results are compared with existing information, and the analysis is shown to be quite reasonable. It is clear, however, that much field work remains to be done for full verification.

APPENDIX

FREQUENCY DISTRIBUTION OF ARRESTER CURRENTS

It was shown that a stroke of current I at location ϕ produces an arrester current $(1-\phi)I_0$ as shown previously.

Since stroke location is random, the frequency function of I is

$$f(I) = \begin{cases} 1, & 0 \leq I \leq I_0 \\ 0 & \text{elsewhere} \end{cases}$$

Now, $f_1(I)$, the frequency of strokes to the line, can be readily found, as shown previously. Finally, I and

ρ are independent. Thus

$$f_A(I_A)dI_A = f_L(I)f_\rho(\rho)d\rho dI$$

where the integration may be performed over either variable, maintaining I_a by

$$I_a = (1-\rho)I$$

The most convenient is to integrate over I :

$$dI_a = -Id\rho \quad \text{or} \quad |d\rho| = +\frac{dI_a}{I}$$

$$f_A(I_a)dI_a = + \left[\frac{f_L(I)}{I} dI \right] dI_a$$

The limits are governed by the fact that I cannot be less than I_a :

$$f_A(I_a) = + \int_{I_a}^{\infty} \frac{f_L(I)}{I} dI$$

Finally, the distribution function is

$$F_A(I_a) = \int_{I_a}^{\infty} f_A(I_a)dI_a$$

The alternative form of the frequency function is

$$f_A(I_a) = \int_0^1 \frac{f_L\left(\frac{I_a}{1-\rho}\right)}{1-\rho} d\rho$$

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APPENDIX B

PREDISCHARGE EFFECTS

Two lines next to one another, with a direct stroke to one of them, act much like an arrester. If the surge voltage reaches a level of roughly 186 kV/ft, sufficient current will flow to the non-struck conductor to reduce the voltage to this level.

Analytical Treatment

Let us consider the following two-wire system with a lightning stroke of stroke current I_s impinging at the point shown in Figure B-1.

FIGURE B-1: THE CONFIGURATION OF THE TWO-WIRE SYSTEM

where

I_s is the current in the lightning stroke

I_1 is the current in line 1 due to I_s

I_2 is the current in line 2 due to I_s

V_1, V_2 are the corresponding voltages

V_{t1} is the voltage at the point of impact of the stroke

V_{t2} is the voltage at the point on line 2 that is closest to the point of impact of the stroke

Poles A and B are the grounded pole on either side of the point of impact

V_p is the voltage difference between the two lines at the point of impact

ΣI_{r1A} , ΣI_{r1B} , ΣI_{r2A} , ΣI_{r2B} are the sums of the various current reflections with their proper time relations as shown in Figure B-2.

ΣV_{r1A} , ΣV_{r1B} , ΣV_{r2A} , ΣV_{r2B} are the corresponding voltages

FIGURE B-2: LATTICE NETWORK FOR ABOVE CONFIGURATION
SHOWING THE ADDITION OF THE CURRENT REFLECTIONS TO GIVE US
THE TOTAL REFLECTED CURRENT AT THE POINT OF IMPACT

In the figure above the notations are as follows:

T is the surge travel time between grounded poles

ρ is the fraction of surge travel time that a wave takes to travel from the point of impact to the nearest grounded pole

Arrester current is determined by I_1 and thus if we can calculate I_1 , arrester current can be calculated easily.

I_1 can be calculated in the following manner:

At the point of impact the voltages are as follows:

$$V_{t1} = V_1 + \Sigma V_{r1A} + \Sigma V_{r1B}$$

$$V_{t2} = V_2 + \Sigma V_{r2A} + \Sigma V_{r2B}$$

$$V_1 = Z_L I_1 + Z_m I_2$$

$$\Sigma V_{r1A} = Z_L \Sigma I_{r1A} + Z_m \Sigma I_{r2A}$$

$$\Sigma V_{r1B} = Z_L \Sigma I_{r1B} + Z_m \Sigma I_{r2B}$$

$$V_2 = Z_m I_2 + Z_L I_1$$

$$\Sigma V_{r2A} = Z_m \Sigma I_{r1A} + Z_L \Sigma I_{r2A}$$

$$\Sigma V_{r2B} = Z_m \Sigma I_{r1B} + Z_L \Sigma I_{r2B}$$

$$V_{t1} - V_{t2} = V_P = (Z_L - Z_m)(I_1 - I_2) + (Z_L - Z_m)(\Sigma I_{r1A} - \Sigma I_{r2A}) + (Z_L - Z_m)(\Sigma I_{r1B} - \Sigma I_{r2B})$$

$$V_{t1} - V_{t2} = (Z_L - Z_m) \left[(I_1 - I_2) + (\Sigma I_{r1A} - \Sigma I_{r2A}) + (\Sigma I_{r1B} - \Sigma I_{r2B}) \right]$$

$$I_1 - I_2 = \frac{V_{t1} - V_{t2}}{Z_L - Z_m} - \left[(\Sigma I_{r1A} - \Sigma I_{r2A}) + (\Sigma I_{r1B} - \Sigma I_{r2B}) \right]$$

However, at the point of impact, we have

$$I_1 + I_2 = \frac{I_s}{2}$$

Thus, we have two simultaneous equations and two unknowns. We can, therefore, calculate I_1 and from this value we can compute arrester current.

An Example

Let us consider the two-wire system shown in Figure B-3.

Let us assume, $I_s = 20 \text{ kA}$ $\dot{I}_s = 20 \text{ kA}/\mu \text{ sec.}$ $T_c = 1 \mu \text{ sec.}$

FIGURE B-3: THE CONFIGURATION FOR THE EXAMPLE

The predischage ratio is 186 kV/ft. Therefore, for a wire spacing of 1m the predischage level is given by

$$V_p = 607 \text{ kV}$$

Travel time between poles is 666.7 ns. Before predischage, we have

$$I_2 = 0$$

$$V_1 = Z_L I_1$$

$$V_2 = Z_m I_1$$

$$V_1 = 400 I_1 = 400 (I_s)/2 = 200 I_s$$

$$V_2 = 176.5 I_1 = 176.5 (I_s)/2 = 88.25 I_s$$

$$\therefore V_1 - V_2 = 111.75 I_s$$

Once the predischage begins, we have

$$V_1 - V_2 = V_p = 607 \text{ kV}$$

$$\therefore 607 = 111.75 I_s$$

$$\therefore I_s = \frac{607}{111.75} = 5.43 \text{ kA}$$

For the given stroke current rate of rise predischarge would occur at

$$\frac{1000}{20} \times 5.43 = 271.5 \text{ nsec.}$$

after predischarge,

$$V_1 = Z_L I_1 + Z_m I_2$$

$$V_2 = Z_m I_1 + Z_L I_2$$

$$(V_1 - V_2) = (Z_L - Z_m) (I_1 - I_2)$$

$$V_p = (V_1 - V_2) = 607 = (400 - 176.5) (I_1 - I_2)$$

$$\text{Simplifying } I_1 - I_2 = 2.72$$

$$\text{However, we know that } I_1 + I_2 = (I_s)/2$$

Therefore,

$$I_1 = (I_s)/4 + 1.36$$

$$I_2 = (I_s)/4 - 1.36$$

The above results are summarized below.

FIGURE B-4: SUMMARY OF RESULTS

The initial current through the struck conductor with and without predischage and the arrester currents with and without predischage are plotted in Figure B-5.

FIGURE B-5: ARRESTER CURRENT WITH AND WITHOUT PREDISCHARGE PHENOMENON

The lattice diagram for the configuration of Figure B-3 is shown below:

FIGURE B-6: LATTICE DIAGRAM FOR CONFIGURATION IN FIGURE B-3

From the previous section we know that

$$I_1 - I_2 = \frac{V_{t1} - V_{t2}}{Z_1 - Z_m} - \left[(\Sigma I_{r1A} - \Sigma I_{r2A}) + (\Sigma I_{r1B} - \Sigma I_{r2B}) \right]$$

and also

$$I_1 + I_2 = (I_s)/2$$

Thus I_1 , I_2 can be calculated. In the following calculations the equations have been inferred from Figure B-5.

The first set of reflections arrive at the point of impact at 666.7 nsec. thus for

$$666.7 \leq t \leq 666.7 + 271.5 = 938.2 \text{ nsec.}$$

$$\Sigma I_{r1A} - \Sigma I_{r2A} = (-\dot{I}_s)/2 (t - 666.7) \quad \Sigma I_{r1B} - \Sigma I_{r2B} = (\dot{I}_s)/2 (t - 666.7)$$

$$\frac{V_{t1} - V_{t2}}{Z_L - Z_m} = \frac{607 \text{ kV}}{(400 - 176.5) \text{ ohms}} = 2.72 \text{ kA}$$

$$I_1 - I_2 = 2.72 + \dot{I}_s (t - 666.7)$$

$$I_1 + I_2 = 6.67 + (\dot{I}_s)/2 (t - 666.7)$$

$$I_1 = 4.69 + 3/4 \dot{I}_s (t - 666.7)$$

$$I_2 = 1.97 - 1/4 \dot{I}_s (t - 666.7)$$

The stroke crests at 1000 nsec.

thus for $938.2 \leq t \leq 1000 \text{ nsec.}$

$$\Sigma I_{r1A} - \Sigma I_{r2A} = -2.72$$

$$\Sigma I_{r1B} - \Sigma I_{r2B} = -2.72$$

$$I_1 - I_2 = 2.72 + 5.44 = 8.16$$

$$I_1 + I_2 = 9.38 + (\dot{I}_s)/2 (t - 938)$$

$$\therefore I_1 = 8.77 + (\dot{I}_s)/4 (t - 938)$$

$$I_2 = .61 + (\dot{I}_s)/4 (t - 938)$$

The second set of reflections arrive at the point of impact at 1333.3 nsec.

thus for $1000 \leq t \leq 1333.3 \text{ nsec.}$

$$\Sigma I_{r1A} - \Sigma I_{r2A} = -2.72$$

$$\Sigma I_{r1B} - \Sigma I_{r2B} = -2.72$$

FIGURE B-7: FIRST ORDER APPROXIMATION TO THE EFFECT OF PREDISCHARGE

The effect of important parameters, with this assumption, can be represented as in Figures B-8a and B-8b.

FIGURE B-8a: APPROXIMATE PREDISCHARGE EFFECTS DUE TO VARIOUS PARAMETERS

$$I_1 - I_2 = 8.16$$

$$I_1 + I_2 = 10$$

(the lightning stroke crest magnitude is 20 kA)

$$I_1 = 9.08$$

$$I_2 = .92$$

thus for $1333.3 \leq t \leq 1333.3 + 271.5 = 1604.8$ nsec.

$$\Sigma I_{r1A} - \Sigma I_{r2A} = -2.72 - (\dot{I}_S)/2 (t - 1333.3) \quad \Sigma I_{r1B} - \Sigma I_{r2B} = -2.72 - (\dot{I}_S)/2 (t - 1333.3)$$

$$I_1 - I_2 = 2.72 + 5.44 + \dot{I}_S (t - 1333.3)$$

$$I_1 - I_2 = 8.16 + \dot{I}_S (t - 1333.3)$$

$$I_1 + I_2 = 10.0$$

$$I_1 = 9.08 + (\dot{I}_S)/2 (t - 1333.3)$$

$$I_2 = .92 - (\dot{I}_S)/2 (t - 1333.3)$$

Predischarge is over when $I_2 = 0$

$$\text{i.e., when } 0 = .92 - (\dot{I}_S)/2 (t - 1333.3)$$

$$\dot{I}_S = 20 \text{ kA}/\mu\text{sec.}$$

$$\therefore t = 1425.3 \text{ nsec.}$$

Therefore, predischarge is finished at 1425.3 nsec.

Results

As we can see, attempting reasonable "normalization" of results is not easy. There are simply too many variables to allow easy representation.

If we assumed that the net effect could be approximated by change in rate of rise such that the new rate of rise is represented by the delayed time to crest and the original "average crest" current, then the effect can be represented as in Figure B-7.

FIGURE B-8b: APPROXIMATE PREDISCHARGE EFFECTS
DUE TO VARIOUS PARAMETERS

As can be seen by comparing with Figure B-7, this can only be considered a rough approximation. In fact, it is better to assume that predischARGE has no effect during the first few hundred nanoseconds. A glance at Figure B-5 shows that a better approximation (for longer times) is simply to regard the effect of predischARGE as a delay.

In any event, it is clear that much more investigation of the predischARGE effect is needed. Before sensible model development can proceed, laboratory studies and at least some of the results of the field study will be needed.

Figures B-9 a,b and c give a representative sampling of the result of calculations made.

FIGURE B-9a: ARRESTER AND LINE CURRENTS FOR
 $I_S = 10 \text{ kA}$ $\dot{I}_S = 10 \text{ kA}/\mu\text{sec.}$
 AND A STROKE TO THE MIDSPAN

FIGURE B-9b: ARRESTER AND LINE CURRENTS FOR
 $I_S + 20 \text{ kA}$ $\dot{I}_S = 20 \text{ kA}/\mu\text{sec.}$
 A STROKE TO 1/3 SPAN

FIGURE B-9c: ARRESTER AND LINE CURRENTS FOR
 $I_S + 40 \text{ kA}$ $\dot{I}_S = 40 \text{ kA}/\mu\text{sec.}$
 A STROKE TO 1/3 SPAN

APPENDIX C

THE IMPACT OF INDUCED SURGES

A major reason for predicting the incidence of induced surges¹ is that they are likely to constitute the bulk of the instrument operations. As will be seen, the major uncertainty (e.g., for specifying frequency of sample data collection) is estimating the number of incidents. This, in turn, is due to the possibility that a stroke "tens" of kilometers (km) away could cause an arrester operation. We can have only minimal confidence in assessing the effects of line (i.e., earth) attenuation of a surge over "tens" of kms distances. This justifies a relatively simple model—a model that slightly, but deliberately, overestimates the number and magnitude of arrester currents from induced surges.

A second major reason for investigating induced strokes is to make preliminary suggestions for data analysis. It should be quite feasible to separate direct and induced strokes by studying key parameters of the wave form. Once this is done, examination of the wave-shape of the early stages of the induced stroke should yield significant information about the return streamer formation.

In all of the following discussions, relativistic considerations are ignored. They are relatively easy (conceptually) to incorporate, and should be included when formal analysis of the data is begun. However, they needlessly complicate the actual calculations for the purposes at hand and do not significantly affect the conclusions.

I. EXPECTED ARRESTER INCIDENTS

(A) The Model

The model for the stroke used in these initial calculations is shown in Figure C-1 (cf. References 1 and 2).

¹*A direct stroke hits the distribution line; an induced surge is from a stroke that hits the ground rather than the distribution line.*

ρ = leader charge density
 [coul/m]
 r_s = strike distance [m]
 v = return stroke velocity [m/sec.]
 H = height of leader channel [m]
 D_o = horizontal distance from
 leader to the closest point
 on the line [m]

FIGURE C-1: LEADER RELATIVE TO DISTRIBUTION LINE

(1) Field Near the Line

The field induced at the earth under the line by the (slowly approaching) leader is

$$E = \frac{2 \rho}{4 \pi \epsilon_0} \left[\frac{1}{\sqrt{D^2 + (r_s + vt)^2}} - \frac{1}{\sqrt{D^2 + H^2}} \right], \quad \epsilon_0 = \frac{10^{-9}}{36 \pi} \text{ [MKS units]}$$

D is measured as in Figure C-2; see Reference 32 for illustration.

D_o = ground distance shown in
 Figure C-1 [m]

$$D^2 = D_o^2 + z^2$$

Z = Line distance between instru-
 ment and the point on the
 line closest to the
 leader [m]

FIGURE C-2: LEADER RELATIVE TO INSTRUMENT

The major points can be illustrated with the following example for a 100 kA stroke. From References 1 and 2, the leader charge for a 100 kA stroke is estimated as follows:

$$\rho \approx \frac{I}{v} = \frac{I^{\text{amp}}}{v_1 v_o} = \frac{I^{\text{kA}} (1000)}{(.11) I^{(.375)} (300)} \quad \begin{matrix} \text{m/\mu s} \\ \nearrow \end{matrix}$$

$$= 30.30 I^{.625} \mu\text{coul/m}$$

From References 1 and 2

$$v_1 = .11 [I]^{.375} \quad \begin{matrix} \text{p.u.} \nearrow \\ \text{kA} \end{matrix}$$

$$r_s = 7.1 [I]^{.75} \quad \begin{matrix} \text{m} \nearrow \end{matrix}$$

At 100 kA

$$\rho = 30.30 (100)^{.625} = 539 \mu\text{coul/m}$$

$$4\pi\epsilon_o = \frac{10^{-9}}{9} \text{ (f/m)} = \frac{10^{-3}}{9} \text{ (\mu f/m)}$$

Therefore,

$$\frac{2\rho}{4\pi\epsilon_o} = 9 \times 10^3 (2) (30.30) I^{.625} \text{ Volts}$$

$$= 545.4 I^{.625} \text{ kV}$$

↑
kA

just before the return stroke ($t=0$); this means, that a 100 kA stroke that is 500 m from the line would produce a field of

$$E = 545.4 (100)^{.625} \left[\frac{1}{\sqrt{500^2 + Z^2 + (225)^2}} - \frac{1}{\sqrt{500^2 + Z^2 + H^2}} \right]$$

To (a rather crude but instructive) first order, assume H is very large. Then the E field at the surface of the earth due to the leader is

$$E \approx \frac{9696}{\sqrt{300625 + Z^2}} \text{ kV/m}$$

(2) Charge Induced on the Line

The electrostatic field just described induces a charge (q) on the line, as illustrated in Figure C-3.

FIGURE C-3: INDUCED CHARGE "q"

The induced charge ("bound charge") is just sufficient to maintain the voltage at zero. Defining a "bound charge voltage," V_h , as that due to the leader charge:

$$V_h \approx hE$$

The bound charge, q , cancels this voltage.

$$q = CV_h = \frac{2\pi\epsilon_0}{\ln \frac{2h}{a}} V_h \quad \text{where } a = \text{conductor radius [m]}$$

Thus,

$$q = \frac{2\pi\epsilon_0 hE}{\ln \frac{2h}{a}} = \frac{\rho h}{\ln \frac{2h}{a}} \left[\frac{1}{\sqrt{D^2 + (r_s + vt)^2}} - \frac{1}{\sqrt{D^2 + H^2}} \right]$$

Again, the major points can be illustrated with an example. For the previous $I=100$ kA example and with $D_0 = 500$ m, $h=10$ m, $a=1$ cm at $t=0$, the induced charge is calculated as follows:

$$q = \frac{539(10)}{\ln \frac{20}{.01}} \frac{1}{\sqrt{300625 + Z^2}} \frac{\mu \text{ coul}}{\text{m}}$$

$$= \frac{544}{\sqrt{300625 + Z^2}} \frac{\mu \text{ coul}}{\text{m}}$$

As shown in Figure C-2, Z is the line distance between the instrument and the point on the line nearest the stroke. This example is illustrated in Figure C-4.

FIGURE C-4: INDUCED CHARGE FOR A 100 kA STROKE 500m AWAY

(3) Pre-sparkover Voltage

Determination of the pre-sparkover voltage as the return stroke begins is a bit more complex. To visualize what happens, let us assume that the bound charge voltage (i.e., V_h) drops in discrete steps (Figure C-5).

FIGURE C-5: VISUALIZING THE LINE SURGE

The released charge, expressed as the voltage ΔV_h , is free to flow as a surge (Figure C-5). For a given stroke, the actual voltage of the line is a function of line distance Z and time. Consider first the point nearest the line ($Z=0$). The increment of Figure C-5 (the first ΔV_h) contributes to the voltage as a function of time as in Figure C-6.

$$\Delta V(0,t) = \frac{\Delta V_h}{2}(v_o t, 0) + \frac{\Delta V_h}{2}(-v_o t, 0)$$

↑
line to
ground
voltage
due to
 ΔV_h

FIGURE C-6: VOLTAGE AS A FUNCTION OF TIME "t"

The increment due to a change in V_h at a time later than 0 (i.e., at τ) will contribute

$$\Delta V(0,t) = \frac{\Delta V_h}{2} (v_o t, t-\tau) + \frac{\Delta V_h}{2} (-v_o t, t-\tau)$$

Summing all the contributions yields

$$V(0,t) = \int_0^t \left[1/2 \frac{dV_h}{dt} (-v_o \tau, t-\tau) + 1/2 \frac{dV_h}{dt} (+v_o \tau, t-\tau) \right] d\tau$$

The above equation for voltage changes at another value of Z:

$$V(Z,t) = \int_0^t \left[1/2 \frac{dV_h}{dt} (Z-v_o \tau, t-\tau) + 1/2 \frac{dV_h}{dt} (Z+v_o \tau, t-\tau) \right] d\tau$$

This enables ready determination of $V(Z,t)$, noting that

$$\begin{aligned} \frac{dV_h}{dt} &= \frac{d(hE)}{dt} = \frac{d}{dt} \left\{ \frac{2\rho h}{4\pi\epsilon_o} \left[\frac{1}{\sqrt{D^2 + (r_s + vt)^2}} - \frac{1}{\sqrt{D^2 + H^2}} \right] \right\} \\ &= \frac{2\rho h}{4\pi\epsilon_o} \frac{v(r_s + vt)}{(D^2 + (r_s + vt)^2)^{3/2}} \end{aligned}$$

Noting that $\rho V = 1000 I$ and $4 \pi \epsilon_0 = \frac{10^{-3}}{9} \mu \text{ f/m}$

$$\frac{dv_h}{dt} = 2(9000)hI \frac{r_s + vt}{(D^2 + (r_s + vt)^2)^{3/2}} \quad \text{kV/} \mu\text{s}$$

These functions are readily integrated (e.g., Reference 33), resulting in the following summary:¹

$$V(Z,t) = U_+(t) + U_-(t) - U_+(0) - U_-(0)$$

$$U_{\pm}(\tau) = K \frac{(r_s + vt) \left(\frac{a}{c} \tau + \frac{b}{2c} \right) + v \left(\frac{b}{2c} \tau + 1 \right)}{c \left(\frac{a}{c} - \left(\frac{b}{2c} \right)^2 \right) \sqrt{c \left(\frac{a}{c} \tau^2 + 2 \left(\frac{b}{2c} \right) \tau + 1 \right)}}$$

$$a = v_o^2 + v^2$$

$$b = -2v(r_s + vt) \pm 2Zv_o$$

$$c = D_o^2 + Z^2 + (r_s + vt)^2$$

$$K = 9000hI$$

$$\begin{aligned} r_s &= 7.1 I^{.75} \text{ m} \\ v &= 33 I^{.375} \text{ m/} \mu\text{s} \\ v_o &= 300 \text{ m/} \mu\text{s} \end{aligned}$$

(The accuracy of the above calculations was verified by numerical integration)

The closest position for an induced stroke is as shown in Figure C-7. (If the leader is closer it would "decide" to strike the line producing a direct stroke.)

$$\begin{aligned} D_{o \min} &= \sqrt{r_s^2 - (r_s - h)^2} \\ &= \sqrt{h(2r_s - h)} \end{aligned}$$

Example: for $h=10$, $I=100 \text{ kA}$

$$\begin{aligned} D_{o \min} &= \sqrt{10 [2(225) - 10]} \\ &= 66 \text{ m} \end{aligned}$$

Figure C-7: CLOSEST APPROACH ILLUSTRATION

¹

$U_{\pm}$ corresponds with $\pm 2Zv_o$ in the expression for "b." (The correctness of the equations for calculating K was verified by numerical integration.)

The above model, which assumes no line attenuation "predicts" a peak voltage of nearly 130 kV at a point 100 km down the line. Since this is clearly absurd, calculations which hinge on such considerations must be handled very carefully. The effect of the above specification, however, is simply a moderate overestimate of the number of induced surge incidents.

The previous examples and theory are enough detail for understanding induced strokes. Summaries are available in Figures C-8a, C-8b, and C-8c. In particular, three interesting phenomena are readily apparent.

FIGURE C-8a: 100kA STROKE, AT CLOSEST APPROACH (66m away)

FIGURE C-8b: 100kA STROKE, AT 500m

FIGURE C-8c: 10kA STROKE, CLOSEST APPROACH (26m)

1. Peak voltages do not necessarily occur at $Z=0$ (closest to the stroke). This is, in essence, due to the dependence of the voltage on dV_h/dt , and implicitly on the rate of changes of charge with position along the line. This latter is zero at $Z=0$, peaking at some finite Z . In any case, however, voltage at $Z=0$ is near-peak.
2. Peak voltages do drop off fairly rapidly with distance from the line (D_0), as illustrated in Figure C-9.

FIGURE C-9: PEAK VOLTAGE AS A FUNCTION OF CLOSEST DISTANCE FROM LINE TO STROKE

3. Closer strokes (e.g., the 10 kA, 26 m away) produce sharper rates of rise.

(4) Multi-conductor Lines

It should be noted that the above and following calculations are for a single-phase line with earth return. For multi-conductor systems, the total induced charge (q) would be as calculated earlier, but would split among the conductors as follows:

Using "n" to specify the neutral or "nth" conductor, we have

$$V_1 = Z_s i_1 + Z_m (n-2) i_1 + Z_m i_n$$

$$V_n = Z_m i_1 + Z_m (n-2) i_1 + Z_s i_n = 0$$

Therefore,

$$V_1 - V_n = (Z_s - Z_m) \left(1 + \frac{Z_m}{Z_s} (n-1) \right) i_1$$

But i_1 is proportional to q_1 , and q_1 is reduced. Before the return streamer begins

$$V_1 = 0 = P_{11} q_1 + P_{12} q_2 + \dots + P_{1n} q_n + v_h$$

$$|v_h| = (P_s + (n-1)P_m) q_1$$

$$q_1 = \frac{v_h}{P_s + (n-1)P_m}$$

Therefore,

$$V_1 - V_n = \left[\frac{(Z_s - Z_m)}{Z_s} \cdot \frac{Z_s + Z_m (n-1)}{P_s + (n-1)P_m} \right] V$$

Where V is determined as specified for a single conductor.

Thus,

$$V_1 - V_n = \frac{Z_s - Z_m}{Z_s} V$$

since P and Z are proportional.

For a set of conductors 10 m high with 0.5 m spacing and conductor radius 1 cm,

$$\frac{t_s - Z_m}{Z_s} = \frac{\ln \frac{20}{.01} - \ln \frac{20}{.5}}{\ln \frac{20}{.01}} \approx 0.51$$

Thus, stresses are typically one-half those for a single conductor.

(B) The Number of Incidents (Arrester Operations)

We saw in Figure C-8 that without considering attenuation, surges could cause arrester sparkover far down the line from the point nearest the stroke. Indeed, arrester sparkover could, ignoring attenuation, cause sparkover of every arrester on the line. Attenuation could be rigorously included in the determination of voltage as follows:

$$V(Z, t) = \int_0^t \frac{A(v_o \tau)}{2} \left[\frac{dv}{dt} h(Z - v_o \tau, t - \tau) + \frac{dv}{dt} h(Z + v_o \tau, t - \tau) \right] d\tau$$

where $A(v_o \tau)$ is the attenuation multiplier

For most purposes, however, particularly since attenuation is not well known for distribution systems, we will simply assume that the voltage is that at $Z=0$, which travels down the line and will cause sparkover until it attenuates below sparkover. Attenuation is assumed to be 3% per km [Ref. 34]. The "reach" of a stroke is thus found illustrated in Figure C-10.

* FIGURE C-10: "REACH" OF A STROKE

Since Z_1 is a function only of D_o and I , the number of incidents at a pole is

$$n_1 = 2N_o \int_0^{\infty} \int_{D_o \min}^{D_o \max} Z_1(D_o, I) f(I) dI dD_o$$

where $f(I)$ is the frequency distribution of stroke currents given by

$$f(I) = \frac{e^{-Y^2/2}}{\sqrt{2\pi\sigma I}} \quad Y = \ln I / 13$$

$$\sigma_{\ln I} = 0.74$$

$D_o \min$ = closest approach

$D_o \max$ = value above which no sparkovers occur

It is noted that calculations show that even if another arrester is present within the "reach" zone, and it sparks over, the voltage at the next pole still reaches sparkover (without considering attenuation). This statement is true for several 10's of kms, indicating that attenuation is the decisive criteria for "reach." Figure C-11 shows the peak surge voltages induced at the point nearest the stroke for a variety of currents. Figure C-12 illustrates "reach" for 100 kA, 30 kA and 10 kA, as determined using 3% per km attenuation. The integration for n_1 is then performed with the results in Figure C-13.

Figure C-11: CREST VOLTAGE AT POINT ON LINE NEAREST STROKE

Clearly, the "conclusion" of tens of kms of reach will result in an over-estimate.

FIGURE C-12: "REACH" OF A STROKE (D_0)

FIGURE C-13: INDUCED SURGE INCIDENTS PER ARRESTER PER YEAR: $[n_1]$

Assuming $N_o \approx 0.16$ IKL, the number of incidents is

$$n_1 = .16 \text{ IKL } (.39) = .062 \text{ IKL/instrument/year}$$

For a local IKL of about 60, we expect

$$n_1 \approx .0624 (60) \approx 4 \text{ incidents/instrument/year}$$

(C) Frequency Distribution of Arrestor Crest Currents Due to Induced Surges

When the arrester discharges, for the periods of time in question (several microseconds), the released charge on the line is dumped through the arrester, as shown in Figure C-14, rather than continuing down the line as a travelling voltage wave.

FIGURE C-14: RELEASED CHARGE "DUMPED" THROUGH ARRESTER

Even with other conductors present, once the arrester sparks over, it is the full charge that flows, i.e.,

$$I_{\max} \approx \frac{2V_{g \max}}{Z}$$

where $V_{g \max}$ is the maximum line-to-ground voltage.

(1) The Frequency Distribution of Pre-sparkover Voltages

Continuing the method used for determining the number of incidents, it is readily shown that the frequency function of the crest voltages at a point along the line (called V_m) is

$$f(V_m) \approx \int_0^{\infty} \frac{f(I) dI}{\partial V_m / \partial D_0}$$

In turn, it is readily shown that

$$f(V) \approx \frac{1}{V} \int_V^{\infty} f(V_m) dV_m$$

(It is noted that this voltage is line-to-neutral and includes a coupling factor of 0.5.)

One final step yields the fraction of incidents greater than a given V:

$$P = Z > V = 100 \int_V^{\infty} f(V) dV$$

This is directly related to the arrester current by

$$I_a = \left[\frac{2V}{1-CF} \right] \cdot \frac{1}{Z_s}, (CF = \frac{Z_m}{Z_s})$$

In the calculation of number of incidents, a CF of 0.5 was used.

Figures C-15 and C-16 show quantities proportional to $f(V_m)$ and $f(V)$ respectively. It is noted that since an "infinite" number of zero voltage surges occur, these functions have no value except where there is a limiting voltage (in this case: sparkover voltage).

Figure C-17 shows the final frequency distribution of arrester discharge currents. In all cases, a surge impedance of 400 ohms is assumed (and a CF of 0.5).

FIGURE C-15: A FUNCTION PROPORTIONAL TO V_m

FIGURE C-16: A FUNCTION PROPORTIONAL TO V_i

Note: Line is assumed to be 10m high.

FIGURE C-17: FREQUENCY OF ARRESTER DISCHARGE (CREST) CURRENTS
DUE TO INDUCED SURGES

II. WAVE SHAPE OF INDUCED SURGES

The main effort for this chapter has been to estimate the number of incidents described in Section I. However, a few comments concerning the expected wave form are in order; they have a significant importance for the analysis of the data as it comes in.

(A) Stroke Model—References

The model used in Section I of this Appendix represents a very simple approximation in terms of wave form. Specifically, the model produces unidirectional currents, whereas real induced surge wave forms are typically as shown in Figure C-18.

FIGURE C-18: TYPICAL INDUCED SURGE

Models for the return stroke process must, of course, be capable of approximating such bi-directional voltage (and thus current) waveforms. A number of authors have investigated such models. A summary and brief bibliography is given in Reference 22. The appropriate references are 23 to 30.

(B) Models Producing Bi-Directional Currents—Theory

The models producing bi-directional currents are simple in concept. Basically, the postulate is that at some point in the downward progression of the leader (presumably at the "strike-distance" away from the object to be struck), streamers proceed from leader and/or object (Figure C-19). The current rapidly builds¹ to return stroke levels, depleting the charge in the leader. Precise modeling of the field-producing chargers during this process is extremely uncertain, and the data from the instruments should be most helpful in improving understanding of what really goes on in these early stages. A relatively simple model, which illustrates the effects, is given in Figure C-20. Such a model results in wave forms as illustrated in Figure C-21.

FIGURE C-19: THE EFFECT OF STREAMER CURRENT

¹The precise time-definition of "rapidly" is uncertain.

FIGURE C-20: MODEL USED TO ILLUSTRATE IMPORTANCE TO ANALYSIS

FIGURE C-21: RESULTS OF MODEL OF FIGURE C-20

APPENDIX D

ARRESTER DISCHARGE AND SPARKOVER VOLTAGES DUE TO DIRECT STROKES

INTRODUCTION

Arrester "Exposure"

In the following discussion it is assumed that the "exposure" of an arrester to significant duty is the distance between the nearest grounded pole on either side, as shown in Figure D-1. Strokes outside that "exposure" may cause an operation of the arrester, but it will be limited since the flashover at the grounded pole will absorb by far the bulk of the current. Thus, it is assumed that the only "significant" operations will be due to strokes within this "exposed" span.

FIGURE D-1: "EXPOSURE" OF AN ARRESTER

As shown in Section II, the number of arrester operations for a given distance between grounded poles (exposed span in Figure D-1) is readily determined. Also, it is relatively easy to specify the distribution of crest arrester currents. What remains for accurate understanding of arrester performance and protection is the determination of the distribution of arrester sparkover and discharge voltages.

Discharge Voltage and Arrester Current Rate of Rise

There has been increasing concern that even though discharge voltage bears only an incidental relation to crest current, arrester design is invariably, and almost exclusively,

based on crest current considerations. Figure D-2 shows a typical situation in which it is seen that discharge voltage peaks much sooner than discharge current.

FIGURE D-2: ILLUSTRATION OF A TYPICAL DISCHARGE CURRENT AND VOLTAGE TEST SHOWING THAT VOLTAGE IS ONLY INCIDENTALLY RELATED TO CREST CURRENT

In aiming at better system design methods, we must make full recognition of the distribution of arrester discharge current rates of rise, which will be the primary determinant of arrester discharge voltage.

System Voltage and Lightning Surge Discharge Voltage

There is some evidence that system voltage has an impact on discharge voltage, but incorporation of that effect must await further testing of arrester characteristics with applied system voltage (by the utility industry). For the present, system voltage is not considered.

The Frequency of Discharge Voltage

Typically, arrester characteristics are given as in Figure D-3. For example, the discharge voltage for 10kV arrester will have a 30kV crest for a 10kA crest current and 40kV for a 100kA crest current. Since the waveform is known, the voltage-current relationship can be "translated" into the more appropriate current-rate-of-rise, as shown in Figure D-4. (Note, the rate of rise near $t=0$ is about $1/3$ of crest current for an $8 \times 20 \mu$ s wave).

FIGURE D-3: Typical
10 kV Arrester Characteristics.

FIGURE D-4: Replotted on Basis
of Rate of Rise

For the hypothetical arrester, this can be expressed analytically as

$$V_D = 25.8(I)^{.125}$$

where

V_D = crest discharge voltage kV

I = initial rate of rise of discharge current kA/μs

The definition of "initial" in the rate of rise specification must remain vague; our present knowledge provides no certainty as to what is the critical time in the lightning surge wave that determines crest voltage. Again, the planned test program will provide data, but some preliminary estimates are necessary at this time for sample design. Some recent investigations suggest that the first few hundreds of nanoseconds are important. Unfortunately, no more can be said at present. But in order to obtain "ball park" estimates, we use the best hypotheses and reasonable assumptions. At the very least, we can develop methodology for analysis in a subsequent phase of the test program.

Initial Arrester Discharge Current Rates of Rise

Although arrester current is affected by such things as predischage and pole reflections in some parts of the lightning surge wave, Appendix B shows that the initial rate of rise of arrester current i.e., during the first few hundred nanoseconds, is the same as the rate of rise of stroke current (Figure D-5). Cases with a significant difference represent a statistically insignificant fraction of arrester operations.

FIGURE D-5: DISTRIBUTION OF INITIAL RATE OF RISE OF STROKE (ARRESTER) CURRENT

¹The cases where predischage will have a significant effect occur when the rate of rise is so high that predischage occurs within a few nanoseconds or tens of nanoseconds. Even at $10,000 \text{ kV}/\mu s = 10 \text{ kV}/\text{ns}$, predischage will take many tens of nanoseconds. In any case, analysis of predischage shows that it has only a relatively minor impact on average rate of rise over, say, one μs .

Using $V_D = 25.8(I)^{.125}$ as developed above, this distribution is readily translated into a distribution of discharge voltage crests in Figure D-6.

FIGURE D-6: ESTIMATED FREQUENCY OF OCCURRENCE OF DISCHARGE VOLTAGES FOR A 10KV ARRESTER

Since system voltage may add to this, relatively high discharge voltage is possible. This must be treated only as a strong suggestion until the relation between discharge voltage and system voltage is fully understood and until tests at 100kA/ μ s and up with system voltage applied are performed on distribution arresters. According to the above analysis, only about 1 percent of discharges will result in voltages as high as 30 percent above the nominal sparkover (i.e., 10kA at 8x20 μ s).

The Distribution of Sparkover Voltages

Even less well known than discharge voltage is the sparkover voltage at the very high rates of rise of applied voltage that occur during a lightning surge. Again, however, estimates based upon simple models can be made. The following assumptions allow some preliminary estimates of sparkover voltages:

- (1) Any arrester operation due to induced charge during the Leader stage passes through a current zero. Thus, a direct stroke will, by virtue of the direct stroke current, cause a true sparkover (and not just a marked increase in current through an already-sparked-over arrester).
- (2) Most models for arrester sparkover assume something near the form

$$V_{sp} = At^{-.5}$$

where "t" is time to sparkover and "A" is a constant determined by arrester design tests. The appropriateness of this function for lightning surge waves is far from certain. This is particularly true at times less than $0.5\mu s$, since the arrester tests, have been between 0.5 and $1\mu s$, as shown in Figure D-7.

FIGURE D-7: TYPICAL ARRESTER CHARACTERISTICS

Using the model suggested earlier, we can develop preliminary estimates that will help in sample design and in the analysis during subsequent phases of the test program.

(A) Pre-sparkover Voltages

Before sparkover, the arrester voltage builds up as illustrated in Figure D-8.

FIGURE D-8: BASIS FOR DETERMINING PRE-SPARKOVER VOLTAGE

If we assume that both line and neutral wire impedance, in Figure D-8b are 400 ohms, and both ground lead and mutual impedance are 200 ohms, then the current and voltage prior to sparkover are given in Figure D-9.

FIGURE D-9: ARRESTER VOLTAGE

$$V \text{ sparkover} = 30t^{-0.5}$$

$[kV]$ ← → $[\mu s]$

Using the median rate of rise for stroke
Current $I = 12kA/\mu s$, we calculate

$$125(12)t = 30t^{-0.5}$$

whence $t = .074\mu s$ and $V = 111kV$

The high value in the above calculation leads to one primary conclusion; namely, the industry, as yet, has no real predictive capability for sparkover voltage. In order to be able to accurately predict sparkover, the industry needs to determine sparkover voltages at very high rates of rise (upwards of $5000kV/\mu s$). Again, this presumes that the arrester is not conducting when the direct strike arrives — another factor which needs industry investigation.

Another critical factor in the above analysis is that initial rate of rise of stroke current is the maximum rate of rise as measured by investigators such as Berger. This is unlikely, though it is the best that can be done with current knowledge.

The arrester voltage in the case of Figure D-9 is calculated in the following sequence:

$$\begin{aligned}\dot{V}_1 &= 350 \frac{\dot{I}}{2} \\ \dot{V}_2 &= 100 \frac{\dot{I}}{2} \\ \dot{V}_{ar} &= \dot{V}_1 - \dot{V}_2 \\ &= 250 \frac{\dot{I}}{2} \text{ kV}/\mu s \\ &= 125 \dot{I} \text{ kV}/\mu s\end{aligned}$$

Where $\dot{I}$ is the rate of rise in the stroke current.

Using the assumed relationship for a 10kV arrester shown in Figure D-7, we can determine the sparkover voltage.

(B) Sparkover Voltage Distributions (A Speculation)

In light of the above, any estimate of sparkover voltage must be viewed with extreme caution as to magnitude. Once we know the "true" pre-sparkover voltages from initial rates of rise more accurately and the sparkover-volt-time characteristics of arresters, we

can estimate the frequency distributions of sparkover voltages and times to sparkover can be estimated. This has been done for the above 10kV arrester. The results are shown in Figures D-10 and D-11.

FIGURE D-10: ESTIMATED FREQUENCY OF OCCURRENCE OF SPARKOVER VOLTAGES FOR A 10KV ARRESTER

FIGURE D-11: ESTIMATED FREQUENCY OF OCCURRENCE OF TIMES TO SPARKOVER FOR A 10KV ARRESTER

(C) Equipment Failures

It is clear that before a full understanding of equipment failures can proceed, both arrester characteristics and system characteristics must be understood. For example, a possibility of insulation crossover exists, particularly when gapped arresters are used. Equipment failure estimation, of course, is also possible with the information provided in Figure D-6, with suitable adjustment for the uncertainty of system voltage effects.

APPENDIX E

CONFIDENCE INTERVALS ON FREQUENCY DISTRIBUTION

It is desired to obtain confidence intervals for the quantiles of the lognormal distribution—the apparent mathematical form of the cumulative distribution of crest magnitude and other parameters of lightning strokes. The θ^{th} quantile of a distribution, denoted by X_θ , is defined as that value of X below which the fraction θ of the values of the distribution fall; i.e.,

$$\Theta = \int_{-\infty}^{X_\theta} f(x) dx$$

A random variable Y has lognormal distribution if $\log Y$ has a normal distribution. E.g., the log of the crest magnitude of lightning strokes is believed to be normally distributed.

Given a mean $\bar{X}$ and a standard deviation S , the confidence intervals of the form

$$(\bar{X} + t_L S, \bar{X} + t_U S)$$

are first obtained for the quantiles of a normal distribution. Then a confidence interval (for the same quantile) of a lognormal distribution

$$(e^{\bar{X} + t_L S}, e^{\bar{X} + t_U S})$$

is obtained.

The values for t_L and t_U are obtained as the two roots of the following quadratic equation:

$$t = \frac{Z_\theta \pm |Z_P| \sqrt{\frac{1}{n} \left(1 - \frac{Z_P^2}{2(n-1)}\right) + \frac{Z_\theta^2}{2(n-1)}}}{1 - \frac{Z_P^2}{2(n-1)}} \quad (\text{E-1})$$

where Z_θ is the θ^{th} quantile for the standard normal and is read from any table of the normal distribution; Z_P is the P^{th} quantile for the standard normal distribution (for the 90% confidence level, for example, $P = .95$, and $Z_P = 1.6449$); n = sample size.

The estimated frequency distribution of stroke current to the line has a median of 18 kA. In other words, the mean of the lognormal distribution is $\ln 18$. The standard deviation is 0.69. Results of an example calculation for 90% confidence intervals are given in Table E-1 below, for a sample size of 100 direct stroke incidents.

90% confidence intervals for a median arrester current of 9 kA and standard deviation of 0.8 are calculated. Sample size is 100.

I	% > I	CONFIDENCE LIMITS	
		Lower	Upper
3.23 kA	90 %	2.658	3.809
5.92	70	5.105	6.775
9	50	7.881	10.273
13.69	30	11.951	15.861
25.09	10	21.257	30.456
33.55	5	27.841	41.922
57.87	1	45.902	76.796
106.63	.1	79.984	152.170
176.34	.01	126.055	267.772

The full calculation results are illustrated in Figure E-1.

Figure E-1 shows 90% confidence limits for arrester currents, and Figure E-2 the same for arrester current rates of rise.

FIGURE E-1: 90% CONFIDENCE LIMITS ON ARRESTER CREST CURRENT

FIGURE E-2: 90% CONFIDENCE LIMITS ON INITIAL
RATE OF RISE OF ARRESTER CURRENT

A glance at these two figures reveals the diminishing returns on confidence limits as the sample size increases. There are undoubtedly far more important concerns which dictate numbers of instruments than these numbers.

Derivation of the equation for the confidence limits:

The derivation follows the development given in Reference 31 for one-sided tolerance limits which also provide one sided confidence limits for quantiles. The development below will be strictly in terms of confidence limits for quantiles.

A one sided upper P-level confidence limit for X_θ would be some function of the observations, say U , and have the property that it would be greater than the true value of the quantile X_θ , P% of the times. Stated otherwise, $\text{Prob}(X_\theta \leq U) = P$.

Following the development in Hald, let $U = \bar{X} + t_U S$. Then t_U is chosen such that:

$$\text{Prob}(X_\theta \leq \bar{X} + t_U S) = P \quad (\text{E-2})$$

For the normal distribution the quantiles are given by

$$X_\theta = \mu + Z_\theta \sigma \quad (\text{E-3})$$

where μ and σ are the population values for the mean and standard deviation, and Z_θ is the θ^{th} quantile for the standard normal distribution

Using equations E-1 and E-3: we can specify

$$\text{Prob}(\mu + Z_\theta \sigma \leq \bar{X} + t_U S) = P \quad (\text{E-4})$$

and we wish to solve this relation for t_U .

If the distribution of a set of observations is normal with mean μ and standard deviation σ , then the following holds:

- (a) $\bar{X}$ is normally distributed with mean μ and standard deviation $\sigma/\sqrt{n}$
- (b) S is approximately (for large values of the sample size n) normally distributed with mean σ and standard deviation $\sigma/\sqrt{2(n-1)}$
- (c) $\bar{X}$ and S are independent

It follows from $Y = \bar{X} + t_U S$, that Y is normally distributed with mean $\mu + t_U \sigma$ and standard deviation

$$\sqrt{\frac{1}{n} + \frac{t_u^2}{2(n-1)}}$$

A general statement can be made if $Y = A_1 X_1 + A_2 X_2$ where A_1 and A_2 are constants and X_1 and X_2 are independent normally distributed random variables with means μ_1 and μ_2 and standard deviations σ_1 and σ_2 respectively; namely, Y will be normally distributed with mean $A_1 \mu_1 + A_2 \mu_2$ and with standard deviation $\sqrt{(A_1^2 \sigma_1^2 + A_2^2 \sigma_2^2)}$.

Equation E-4 can be expressed as

$$P = (Y > \mu + \sigma Z_\theta) \quad (E-5)$$

or

$$1 - P = \text{Prob} (Y \leq \mu + \sigma Z_\theta) \neq \int_{-\infty}^{\mu + \sigma Z_\theta} f(y) dy \quad (E-6)$$

where as noted previously, $f(y)$ is the density function for the normal distribution with mean $\mu + t_U \sigma$ and standard deviation $\sqrt{\frac{1}{n} + \frac{t_u^2}{2(n-1)}}$

In general, the calculation of the integral of a normal density function with, say, means m and standard deviation h , proceeds as follows:

$$\begin{aligned} I &= \int_{-\infty}^A \frac{1}{\sqrt{2\pi}h} e^{-\left[\frac{(x-m)^2}{2h^2}\right]} dx \\ &= \int_{-\infty}^{\frac{A-m}{h}} \frac{1}{\sqrt{2\pi}} e^{-[Z^2/2]} dZ \\ &= \Phi\left(\frac{A-\mu}{\sigma}\right) \end{aligned} \quad (E-7)$$

where $\Phi()$ is the cumulative distribution function for the standard normal distribution.

Thus Equation E-6 can be written as:

$$\begin{aligned}
 1 - P &= \int_{-\infty}^{\mu + \sigma Z_{\theta}} f(y) dy \\
 &= \Phi\left(\frac{\mu + \sigma Z_{\theta} - (\mu + t_U \sigma)}{\sigma \sqrt{\frac{1}{n} + \frac{t_U^2}{2(n-1)}}}\right) = \Phi\left(\frac{Z_{\theta} - t_U}{\sqrt{\frac{1}{n} + \frac{t_U^2}{2(n-1)}}}\right) \quad (E-8)
 \end{aligned}$$

Since $\Phi()$ is the cumulative distribution function for the standard normal distribution it follows that the argument of Φ must be the $(1-P)^{th}$ quantile of the standard normal distribution, and

$$Z_{1-P} = \frac{Z_{\theta} - t_U}{\sqrt{\frac{1}{n} + \frac{t_U^2}{2(n-1)}}} \quad (E-9)$$

or

$$Z_{\theta} - t_U = Z_{1-P} \sqrt{\frac{1}{n} + \frac{t_U^2}{2(n-1)}} \quad (E-10)$$

Squaring both sides of (E-10) and solving the resultant quadratic equation in t_U (noting also that because of the symmetry of the normal distribution that $Z_{1-P} = -Z_P$) we finally obtain:

$$t_U = \frac{Z_\theta + |Z_P| \sqrt{\frac{1}{n} \left(1 - \frac{Z_P^2}{2(n-1)}\right) + \frac{Z_\theta^2}{2(n-1)}}}{1 - \frac{Z_P^2}{2(n-1)}} \quad (E-11)$$

Since $\bar{X} + t_U S$ is an upper confidence limit, t_U must be the larger root (it must be greater than Z_θ). This will also be clear when we find below that t_L is also a solution of the same quadratic equation and clearly t_L must be lower than t_U .

A one sided lower confidence limit for X_θ would be some function of the observations, say, L , which would have the property that prior to taking the sample:

$$\text{Prob}(1 \leq X_\theta) = P \quad (E-12)$$

We let $L = \bar{X} + t_L S$ and as in the development for the upper limit, equation (E-12) can be written as:

$$P = \int_{-\infty}^{\mu + \sigma Z_\theta} f(y) dy = \Phi\left(\frac{Z_\theta - t_L}{\sqrt{\frac{1}{n} + \frac{t_L^2}{2(n-1)}}}\right) \quad (E-13)$$

where, as before, $f(y)$ is the density function for a normally distributed random

variable with mean $\mu + \sigma t_L$ and standard deviation $\sigma \sqrt{\frac{1}{n} + \frac{t_L^2}{2(n-1)}}$ and $\Phi(\cdot)$ is the cumulative distribution function for the standard normal.

It follows that the argument for Φ must be the P^{th} quantile of the standard normal distribution, so:

$$Z_P = \frac{Z_\theta - t_L}{\sqrt{\frac{1}{n} + \frac{t_L^2}{2(n-1)}}} \quad (E-14)$$

or

$$Z_{\theta} - t_L = Z_P \sqrt{\frac{1}{n} + \frac{t_L^2}{2(n-1)}} \quad (E-15)$$

Squaring both sides of (E-15) will give the same quadratic equation as before and it follows that t_L must also be given by equation (E-11). Since $\bar{X} + t_U S$ is a lower confidence limit for X_{θ} and $\bar{X} + t_U S$ is an upper confidence limit for X_{θ} it follows that t_U must be the larger root of the quadratic equation and t_L the smaller root. Thus we finally

$$t_U = \frac{Z_{\theta} + Z_P \sqrt{\frac{1}{n} \left(1 - \frac{Z_P^2}{2(n-1)}\right) + \frac{Z_{\theta}^2}{2(n-1)}}}{1 - \frac{Z_P^2}{2(n-1)}} \quad (E-16)$$

$$t_L = \frac{Z_{\theta} - Z_P \sqrt{\frac{1}{n} \left(1 - \frac{Z_P^2}{2(n-1)}\right) + \frac{Z_{\theta}^2}{2(n-1)}}}{1 - \frac{Z_P^2}{2(n-1)}} \quad (E-17)$$

Since prior to taking the sample, we have

$$\text{Prob} (\bar{X} + t_L S \leq \bar{X}_{\theta} \leq \bar{X} + t_U S) =$$

$$\text{Prob} (X_{\theta} \leq \bar{X} + t_U S) - \text{Prob} (X_{\theta} \leq \bar{X} + t_L S) =$$

$$P - (1-P) = 2P-1 = 1 - 2(1-P)$$

we see that $(\bar{X} + t_L S, \bar{X} + t_U S)$ provides a two sided, P -level confidence interval where P is " $1-2(1-P)$ ".

APPENDIX F

SUBAREAS FOR THE BASIC SAMPLE

The subareas for the basic sample in each of 20 utilities have been selected. These areas are shown on the maps in Section III, and they are described briefly below. The letters in the following paragraphs are the code letters on the maps.

- A. The best area in the Central Vermont Public Service Company is approximately 10-30 miles North of Burlington around Highway 105. If low ground resistance cannot be found to the North, the open area along the lake South of Burlington should be acceptable.

The Central office contact is Carl Carmichael. Carmichael directed the search to several areas in the state, but only the Burlington area seemed suitable. Potential areas number 1 and number 2—around Woodstock, Vermont and West of Bradford, Vermont—have shielding problems that will make site selection very difficult.

- B. The Ashtabula, Ohio, area is part of the Cleveland Electric Illuminating, Company. The company contact—Jerry Mambuca—is very familiar with potential sites for instrument placement.
- C. An area East of Columbus along Highway 40 and near Zanesville is part of the Ohio Power Company. The contact has been Richard Bentzel who is with the holding company—American Electric Power (AEP). Vernon Warnock of AEP has requested that initial contacts be with him or Bentzel, rather than Ohio Power Company. Potential Area "3" is the area around Lima and Woodsock, Ohio. The potential area has no apparent advantage over the Highway 40 area described above.
- D. The best area in the Detroit Edison Company is North and West of the city and centered around Farmington. It will be necessary to search for open areas because of the considerable trees. Areas within and closer to Detroit have prohibitive shielding. The company contact—Gil Gaibrois—is familiar with lightning incidence in this area. Potential area number 4 is in the Consumers Power Company jurisdiction and closer to Lansing, Michigan.
- E. The farmland areas within the Illini Electric Company Cooperative near Urbana, Illinois, have good sites. The contact is Walter Smith.
- F. The open areas in the Northern States Power Company near Fargo, North Dakota, have suitable sites. The contact is Jim Krushinski.

- G. The area within a radius of 10 miles East of Cody, Wyoming is one of two areas selected in Wyoming. The local variation in lightning seems great enough to warrant special effort in selecting sites. The company contact is Robert Miller in the Casper, Wyoming, office. Richard Seamon in the Worland, Wyoming, office is familiar with lightning incidence around Cody. The second area around Casper, Wyoming, is described under "Q" below. Potential area number 6, near Cody, Wyoming, is the Hot Springs REA on the Hot Springs Reservation.
- H. The Cedar Mountains, Utah area is the reported high lightning density area within the Utah Power and Light Company jurisdiction. The contacts are William Clements and Dave Ward in the Salt Lake City, Utah office.
- I. The farmland areas around Fresno, California are the best possibility within the Pacific Gas and Electric jurisdiction. Ground resistance could be a problem, but not as severe as the mountainous areas. The company contact is Ray Capra in the San Francisco office. Potential area number 7 is Northwest of Redding, California. Although this area has more lightning than the Fresno area, the shielding and poor ground resistance make it less desirable.
- J. The irrigated valley between Del Norte and Alamosa, Colorado should have numerous sites. Kenneth Anderson is the contact in the company central office in Denver, Colorado. Worth Hage in the Alamosa Division Office is familiar with the area. R. C. Mally in the Del Norte Branch Office is familiar with local variation in lightning incidence. Potential area number 9 is the valley near Royal Gorge, Colorado and within the jurisdiction of the Southern Colorado Power Division of the Central Telephone and Utilities Corporation. Potential area number 8 is the Public Service Company of Colorado line that runs above the tree line in Mosquito Pass, Colorado.
- K. The Springer Electric Cooperative, Inc. lines to the East and near Springer are a good area. The contacts are F. Cumiford and C. Gutierrez.
- L. The rural areas to the Northeast of and near Tulsa, Oklahoma are good areas within the service area of the Public Service Company of Oklahoma. Other places are reported to have slightly higher lightning density, but this area is of greater interest to the Utility. The contacts have been Charlie George and Charles Harvey in the Tulsa office.
- M. The several open areas a few miles South of Baton Rouge will provide good sites. This is reported as the heaviest lightning density within the area served by the Gulf States Utilities Company. The contacts have been Jack Powdrow in the Beaumont, Texas office and Dewey Lytle in the Baton Rouge office.
- N. Most subareas between Sarasota and Arcadia, Florida would be good and provide high density lightning. The contacts have been Robert Frech in the Miami office and Walter Anderson in the Sarasota office.

- O. The Florida Power Corporation and the Tampa Electric Company have expressed interest in working together to place instruments in the Tampa-Orlando area. The very high lightning density and unshielded areas throughout this part of Florida allows considerable flexibility in subareas for the Basic Sample. The contact has been Paul Pierson and Dee Parish.
- P. The area referred to as the North Ridge outside of Atlanta, Georgia, was selected because of the high lightning density. The contacts are Howard Pratt and Travis Johnson in the Atlanta office.
- Q. The area near the Midwest Oil Fields North of Casper, Wyoming have many arrester locations for instrument placement. The outer edges will provide more observations per instrument than the closer spacing of grounded poles in the denser oil well population in the central part of the field. The contact is Robert Miller in the Casper, Wyoming office.

Potential area number 5 is the Shosone Rural Power Inc. jurisdiction near Edgerton, Wyoming.

- R. The area along Highway 84 to the North of Santa Fe, New Mexico is served by Public Service of Colorado. The contacts have been N. Hannah in the Albuquerque office and George Barsuaskas in the Santa Fe office.

Potential area number 10 could be the Kit Carson Rural Electric in Taos, New Mexico or the Jemez Mountains Electric Cooperative, Inc. in Espanola, New Mexico.

- S. This area is the territory served by New Orleans Public Service, Inc. The best subarea is referred to as New Orleans East. The contacts have been John Lozes and Morris West.

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