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An Assessment of DOE-Sponsored Lightning Research at the University of Florida

August 1980

MASTER

Prepared for:

U.S. Department of Energy

Assistant Secretary for Resource Applications

Office of Electric Energy Systems

Under Contract No. AC01-79ET29242

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Assistant Secretary for Resource Applications

Office of Electric Energy Systems

Washington, D.C. 20461

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AN ASSESSMENT OF DOE-SPONSORED
LIGHTNING RESEARCH AT THE UNIVERSITY OF FLORIDA

I. SUMMARY

A. PURPOSE

Studies of lightning protection seem anachronistic at first glance, considering that the concept has existed since the time of Franklin. However, such studies are important in that losses of distribution equipment by U.S. utilities during lightning storms exceed \$3 to \$5 million per year.⁽¹⁾ These losses are high for two reasons: first, the absence of shield wire protection techniques used on higher voltage transmission lines increases the exposure of distribution lines to the effects of direct lightning strokes. Second, the relative lack of useful research data prevents the economic and technical evaluation of suggested protective techniques.

In response to this problem, the Department of Energy (DOE), the Electric Power Research Institute (EPRI), and the electric utilities have been involved in a program to reduce the amount of lightning-caused damage to distribution lines. The program has focused on the development and evaluation of new instruments and techniques for lightning observation. Information from these instruments will provide for improved predictive models of lightning behavior, which, in turn, will be useful for answering the engineering questions associated with the protection of distribution equipment.

The initial development effort revolved around the development of the "transient surge recorder," a device for assessing the ability of lightning arresters to protect distribution equipment. The General Electric Company developed a prototype of the surge recorder, which was subsequently modified by the Jet Propulsion Laboratory (JPL). Twenty-eight of these devices were available for field trials at the beginning of 1978.

At that time, emphasis in the program shifted because of a unique opportunity to transfer technology developed by researchers in atmospheric physics to the problems of utilities. The key contributors to this project were Dr. M. Uman and Dr. M. Darveniza. Dr Uman's contribution from his studies of lightning physics is the Lightning Location System (LLS) which can determine lightning locations and other characteristics from a distance. Dr. Darveniza's contribution from his utility-related work in Australia is to interpret the results of the LLS in terms of utility outages, which are now logged automatically by digital data acquisition systems. The association between utility damage and individual strokes represents a key advance in lightning studies because such a direct connection between cause and effect has been very difficult to establish in the past.

The current status of the program is that during the summers of 1978 and 1979, these two researchers at the University of Florida have been coordinating a comprehensive observational program in the Tampa area. In addition to using the key pieces of observational equipment mentioned above, the program also included measurements from a wide variety of supporting equipment which will be discussed later.

Now that the data collection phase is over, there is a need to assess the accuracy of the data, the applicability of the data to predictive lightning models, and finally, the applicability of the data to solving the damage problems of distribution systems. One key problem in assessing the state of the project is the one of the principal investigators, Dr. Darveniza, has returned to his former position at the University of Queensland in Australia. While Dr. Darveniza is still actively involved in processing the data, communications problems have made interfacing among the University of Florida, the utilities, and DOE difficult.

B. SCOPE

DOE asked Arthur D. Little, Inc. to examine (1) the extent and type of data collected in Florida, (2) the quality of these data, (3) the present state of data analysis, (4) the suitability of these data for extended analysis, and (5) the desirability and justification of this extended analysis. The findings of this report result from interviews with the principal investigators and with the representatives of participating utilities and from an examination of the data both at the University of Florida and at the General Electric Company in Pittsfield, Massachusetts.

C. FINDINGS

The experimental work in Florida was conducted in a professional manner with a serious effort to ensure the integrity of the data. While the experiments did not go completely as planned and the data are not as comprehensive as one would have liked, the effort deserves much commendation as research in a difficult field that has many unknowns even after decades of research. In spite of obvious communications problems after the departure of Dr. Darveniza, both principal investigators are dedicated to extracting as much worthwhile information as possible from the data base.

D. RECOMMENDATIONS

In view of the above findings, we recommend continued funding of the data analysis including (1) evaluation and improvement of the new observational techniques, (2) improvement in the theoretical models of lightning, (3) improvement in the operational procedures of utilities during storms, and (4) identification of equipment loss mechanisms. Since the key justification is in the identification of equipment loss mechanisms and since this issue is only partially addressed by the current program, consideration should also be given to research focused on those questions of damage analysis for which the data are not relevant.

II. INTRODUCTION TO LIGHTNING AND LIGHTNING RESEARCH

Since the research program for the Florida lightning study was designed to address several lightning issues simultaneously, one must have an overview of lightning research in order to understand the use and purpose of each of the twelve different types of observations made in Florida. An outline of the important topics of lightning research appears in Table 1 to give the reader a perspective of the theoretical questions involved in studying lightning. The top line in the table lists the physical objects involved in the progression from a charged cloud to a voltage surge at a distribution transformer. The middle line in the table lists the various physical models which utility-oriented lightning research has produced. Finally, the bottom line lists the Florida measuring equipment under the primary topic to which this equipment can make a contribution. Readers who will want more detailed information on lightning theory than the following paragraphs provide should consult References 2, 3 and 4.

As shown in the top line of Table 1, research in lightning begins with an understanding of how thunderstorms form, how charged areas develop within thunderclouds, and how breakdown channels or "leaders" bring the charges from the cloud towards the ground. From the utility standpoint, the important issue in thunderstorm development is a prediction of the lightning hazard as a function of geographic area. This hazard is normally expressed in terms of a lightning density that has historically been tied to the "isokeraunic level" or the number of days per year that the weather bureaus report thunder. Isokeraunic level, while based on many years of weather bureau statistics, is a very inaccurate way of estimating the lightning hazard in terms of incidence per square kilometer per year.

The leaders bringing the cloud charge to ground presumably are evenly distributed within any given geographic area. However, once the leader is within about 100 meters of the ground, the mechanism of the

TABLE 1

ORGANIZATION OF LIGHTNING RESEARCH TOPICS

General Research Subject	Cloud Physics & Stroke Channel Development	Final Breakdown Between Channel & Ground Object	Return Stroke	Transmission Line	Transformers
Research of Interest to Utilities	Distribution of Flash Density to Ground	Electrogeometric Theory (Attractive Distance)	Stroke Current Magnitudes & Waveshape Distri- bution	Traveling Wave Theory Footing Resistance Theory Corona Effects Fredischarge Theory Induced Stroke Theory	Insulation Strength vs. Waveform Protective Theory: Arrestor & Fuse Characteristics
Florida Instrumentation	Lightning Location System Flash Counters Thunder Ranging Visual Observations Television System		Electric & Mag- netic Field Measurements Still & Streak Photography	Magnetic Strip Recorders Transient Surge Recorders Direct Voltage Measurements	Automated Data Acquisition Systems Trouble Reports

leader propagation changes; and discharges from the nearest grounded object attract the leader to that object. Researchers need to know what this "attractive" distance is in order to model how well a tall object attracts lightning to itself while shielding adjacent lower objects. The best available attractive distance theory is the semi-empirical "electrogeometric theory" which relates the distance to the subsequent lightning current.

When the final contact with ground occurs, currents on the order of 1000 to 100,000 amperes flow with durations on the order of 40 microseconds. Since these "return strokes" cause most lightning damage to insulation, one needs to know the probability distribution of these currents and their current waveshapes. In addition to the direct injection of currents into a transmission or distribution system, indirect electromagnetic coupling is also possible: in effect, the motion of charges within the leader channel (normally connected with the "return stroke velocity") produces electromagnetic waves which, in turn, generate voltages on the power line conductors. To date, no satisfactory theory of these "induced surges" has evolved.

Generally, not one but several return strokes flow along the same channel as several different pockets of cloud charge are neutralized in an event which is collectively known as a "flash." While the "first stroke" in each flash generally has a higher crest current magnitude, the "subsequent strokes" also present an insulation hazard through the relative rapidity of the "front time" or the time necessary for the current to reach crest magnitude.

The median "front time" for a subsequent stroke is about one microsecond, which is a time so short that light travels only 1000 feet in this interval. Since this dimension is not large in comparison to the size of transmission and distribution systems, estimating the voltages produced by the lightning current waveforms becomes a complicated exercise in "travelling wave theory" which must account for the

propagation time of current waves along conductors between supports and up and down the supporting towers and poles. While travelling wave theory is well defined, the extremely high current and voltage levels involved produce non-linear effects, notably "corona" as charge leaves the conductor surfaces and footing resistance changes from discharges between soil components. At exceedingly high voltages, the corona losses become "predischage currents" which follow conducting paths in the air and redistribute charges on the transmission line to suppress an imminent breakdown across the air gap.

Overvoltages on distribution lines can cause damage by producing flashovers of insulation. In itself, a flashover may be harmless providing that it carries relatively little current and extinguishes as soon as the normal 60-Hz line voltage reaches a zero crossing. However, each flashover has a probability of developing into a power arc which can burn indefinitely. For this reason, fuses and circuit breakers are available to interrupt the power follow current. Such operations, however, are not 100% desirable because of the interruption of service to the customer, the expense of fuse replacement, the wear on the circuit breaker, and the wear on transformers from the high magnetic forces of the short circuit currents. Furthermore, a power arc internal to a transformer is destructive even for short duration power arcs. For this reason, each transformer is equipped with a lightning arrester which is designed to conduct during overvoltages and maintain a safe voltage at the transformer terminals. Unfortunately, some question exists concerning the ability of the arrester to operate quickly enough, and once operating, to absorb all of the energy of the surge.

III. THE FLORIDA EXPERIMENTAL PLAN⁽⁵⁾

A. INTRODUCTION

The ultimate test of the above lightning theories is their assembly into a comprehensive computer model which can make predictions concerning the lightning performance of a transmission line. The input parameters

for such a model are the line geometry, the local thunderstorm activity, and the soil conditions. The resulting prediction is the number of circuit breaker operations expected per unit distance per year. Although such models have been available for twenty years, their predictive accuracy is not better than a factor of two even after the model assumptions are empirically adjusted to provide results that conform to the actual performance of selected transmission lines.

At this stage of model development, lightning researchers still disagree on some points. Some, notably Dr. Darveniza, feel that continued research in lightning will ultimately reduce the large uncertainties of the predictive models. Others, like Weck,⁽⁶⁾ feel that the uncertainties in input parameters, by their intrinsic nature, defy quantification. A complete characterization of footing resistance, for example, would require detailed knowledge of soil conditions and buried metallic objects under every pole or tower and a knowledge of how the effective resistance of these footing materials varies as a function of current magnitude and waveshape. The collection of such detailed knowledge may never accurately predict lightning performance for the distribution line in question.

Even though absolute accuracy in modelling may be an unrealistic goal, models are still useful for relative comparisons between different transmission line designs and for identification of failure mechanisms, that have not previously been recognized. This latter application is not unlike detective work, in which the evidence is available before the hypotheses are fully formulated.

Collection of experimental data on lightning is not easy because the normal lightning incidence at any given site is too low to justify expensive instrumentation. While lightning incidence on tall buildings or on tall towers is much greater, there is good evidence that lightning parameters measured at these sites are significantly different from those which might be measured on lower distribution structures.

Because of this difficulty with on-site measurements, the real promise of Dr. Uman's work is the ability to measure lightning locations and stroke currents from a distance by the radio rangefinder technique embodied in the LLS. This apparatus, which is the key to the entire Florida experimental plan, consists of two sets of rangefinder antennas. Each set provides the direction of each stroke so that the stroke position is obtainable through triangulation across a 45-miles baseline. The LLS results consist of the flash location, the flash time, the number of strokes in the flash, and an estimate of the stroke current magnitude. Procedures have been established to transfer these results to IBM-compatible magnetic tape so that analysis of the data is relatively easy.

The advantage of the LLS is that for the first time, researchers have available a record of lightning flashes over a large geographic area. In order to interpret this information in terms of utility damage, the utilities now have available automatic data acquisition systems which can generate IBM-compatible records containing all circuit breaker operations together with the location of the breaker and the time of the operation. This time-tagging makes possible the first correlation between the lightning flash responsible for the breaker operations and the actual operation of the breaker. In the past, not even the breaker operations were considered important events, and researchers had only damage reports, which were not generally compiled with sufficient detail to determine the exact cause of the damage be it from lightning or from some other coincidental event.

On this foundation of the LLS and the circuit breaker reports, the project evolved to include three additional types of equipment: the flash counters, the Mobile Lightning Laboratory, and the transient surge recorders. The flash counters will be the basis for a potential nationwide project to determine the ground flash density (flashes/km²-yr) on the basis of radio impulse noise rather than on the basis of the isokeraunic level. Each flash counter responds to the noise generated by nearby lightning strokes but with an unknown radius of response

depending on the installation site. The LLS provides an excellent way to calibrate the flash counters by correlating each count with the distance of the lightning stroke.

The Mobile Lightning Laboratory consists of a variety of measurements, including electric and magnetic fields, television images, thunder records, high-speed photography, and visual observations. Collectively, the Mobile Lightning Laboratory instrumentation enhances the LLS capabilities by providing information that is not available in the LLS printout. For example, stroke current waveshape information is obtainable through the electric and magnetic field measurements of the Mobile Lightning Laboratory but not through the printout of the LLS.

Finally, the experiment in Tampa provided the ideal site for the trial of the transient surge recorders which had been developed to study lightning arrester characteristics. Because these recorders were placed in an environment which allows confirmation of experimental results through many other simultaneous measurements, each surge recorder record is verifiable in terms of independent observations. One such independent measurement was provided by the magnetic strip recorders which are extremely simple and reliable devices for measuring peak lightning currents by means of controlled erasure of ordinary magnetic tape. These strip recorders, a new form of magnetic link, were installed at each transient surge recorder site.

B. EXPECTED BENEFITS

Because of the wide variety of measurements taken, the benefits of this research will be equally extensive in the following categories:

- (1) evaluation and improvement of the new observational techniques,
- (2) improvement in the theoretical models of lightning, (3) improvement of the operational procedures of utilities during storms, and (4) identification of equipment loss mechanisms. These categories are listed in terms of increasing benefit to the utilities whose greatest expense is

the repair and replacement of transformers and other equipment damaged by lightning. Other considerations, such as the loss of revenue from customers, are not easily justified in economic terms.⁽¹⁾

The evaluation and improvement of new observational techniques depend upon four of the devices described earlier: the LLS, the transient surge recorders, the magnetic strip recorders, and the RSA-10 flash counters. Since all these devices are relatively new, there is a need to evaluate their applicability to lightning studies in terms of their accuracy and the ease with which data may be obtained from them. This information will be important in the design of future experiments involving lightning. The LLS/flash counter calibrations will also provide information on whether or not postulated local differences in flash density exist.

The improvement of theoretical models of lightning is part of an ongoing effort to provide mathematical descriptions of the phenomena in order to identify the important damage mechanisms and to provide economic comparisons between proposed transmission line geometries. Researchers are interested in improving: (1) the ability to measure lightning currents at a distance, (2) the theory of induced surges, and (3) the theory of direct strokes. The first effort is necessary because the stroke current estimates of the LLS depend upon an idealized theoretical model of what the current distribution in the lightning channel should look like. This model requires verification of the ability to match direct measurements of currents injected into tall towers and careful photographic observations of return stroke velocity, which is a very important parameter in the model. (This verification effort is not DOE funded.)

The theory of induced surges⁽²⁾ was first proposed by C. Wagner in 1956 and has been the subject of much discussion ever since. Basically, the theory suggests that lightning does not have to strike a distribution line to produce a voltage surge but can influence the line with a stroke to nearby ground. This action at a distance is accomplished through

electrostatic coupling between charge in the lightning channel and the distribution line. The problem, however, is that the charge distribution within the lightning channel is uncertain and that there have never been careful confirming observations. Because of this need, observations of approximately 2000 induced surges were collected on an unenergized distribution line segment at the Mobile Lightning Laboratory. Dr. Uman's expertise in interpreting these records should provide an important contribution to this theory, which in turn, could identify an important lightning hazard mechanism for distribution lines.

The theory of direct strokes is perhaps the oldest of the computerized models of lightning on transmission lines. Dr. Darveniza is now the most experienced researcher worldwide in the development of these models. His specific modelling goals for this project are to: (a) improve the electro-geometric description of the attractive distance, (b) incorporate multiple-stroke rather than single-stroke descriptions of lightning flashes, and (c) revise the Australian distribution line techniques to reflect American practice.

Improvements in the operational procedures of the utilities are possible because of the potential for the display of "real time" information to system operators and repair crews. The LLS can provide immediate information concerning the presence of storms in an area, their direction, and their possible severity. Such information will be useful in the scheduling of repair crews in order to minimize outage durations. A second utility benefit from a non-DOE-sponsored portion of lightning research is a study of the ability to predict an imminent lightning stroke with enough advance warning to improve the safety of line crews.

Finally, identifying equipment loss mechanisms depends on the ability of lightning arresters to provide the necessary protection against frequent circuit breaker and fuse operations and against catastrophic transformer failure. Many issues in this area stand unresolved because of heretofore ineffective field observation. First,

there is a need to confirm whether lightning is indeed causing every short circuit or whether some other factor such as high winds or inadequate tree-trimming programs might be involved. Second, there is a need to verify that the Florida practice of placing an arrester every six poles on a distribution line really does reduce the number of power arcs. Third, there is a need to assess the quality of arrester protection: (a) whether corroded or defective arresters produce excessive fuse operations, (b) whether power dissipated during a lightning flash is too great for the arresters to withstand safely, and (c) whether the arresters operate quickly enough to keep transformer overvoltages to a safe level.

C. ISSUES NOT ADDRESSED

Unfortunately, some additional equipment loss mechanisms are not properly addressed by the Florida program. Possible additional mechanisms of transformer damage can come from insulation deterioration from aging, short circuit current force damage, and overheating.⁽⁷⁾ In each of these cases, the insulation quality deteriorates below the protective level of the lightning arrester so that a study of the arrester currents is not very useful unless time-tagging can note their absence at the time of a transformer failure. Identification of relative importance of the above three mechanisms of transformer failure requires widespread measurements on the transformers themselves.

D. DATA COLLECTION

1. QUALITY

In general, the experimental work was carried out in a professional manner with careful attention to the integrity and quality of the data. However, the novelty of the approach and the intrinsic difficulty in studying lightning naturally led to a series of experimental difficulties which affected the basic experimental plan. Three problems, however, stand out in making the answers to some questions in the "Expected Benefits" section above difficult. These are (1) the positional accuracy

of the lightning location system, (2) the bandwidth limits of the electric and magnetic field measurements, and (3) the performance of the General Electric transient surge recorders. The best accuracy of the lightning location system is not sufficient to decide whether any given flash actually hit the distribution line or simply came close. As a result, the evaluation of the damaging effect of flashes will have to depend on a more desired direct correlation. The electric and magnetic field measurements are difficult to digitize and have bandwidth limitations which may reduce the applicability of the results to the "crossover" problem -- the ability of the lightning arresters to respond to extremely short secondary stroke front times. The data, however, should still be adequate for a preliminary contribution to this problem. Finally, key data from the General Electric surge recorders are scarce and may not provide adequate verification of the computer models devised for the intensive study of the Leonard-Lee road area of the Tampa Electric Company system. These computer models may have to be rewritten to make use of Jet Propulsion Laboratory surge recorder results in the less intensively studied Florida Power Corporation district.

While the problems above limit the scope of the data analysis, no one problem area is sufficiently critical to influence the data quality enough to prohibit further analysis.

2. DATA TYPE, STATE, AND USEFULNESS

This section considers each information source in turn with respect to the amount and usefulness of data collected. All comments on quantity apply to the 1979 lightning season because the 1978 season was dedicated primarily to a shakedown test of the equipment, and experimental problems during this earlier season make the data much more difficult to interpret. During 1979, the surge recorders were installed in April, but the rest of the equipment was not completely operational until about June 24. The planned duration of the measurement phase

was originally two months but was extended into September because of an unusually low frequency of thunderstorms for most of August. Finally, Hurricane David on September 4 and Hurricane Frederick on September 14 provided the opportunities for recording additional lightning flashes.

a. Lightning Locater System

As mentioned above, the LLS is basically a radio direction finder system that uses triangulation on a 45-mile baseline to determine stroke locations. Also available from the system are the number of strokes power flash and an estimate of the crest current.

The accuracy of the locater is 1° rms with peak errors of up to 5° . Dr. Darveniza found that, with careful calibration, the accuracy could be improved to 0.5° . This accuracy presents a major problem because the best positional error range with the above baseline is ± 1000 feet, an order of magnitude above the typical attractive distances which define the effective area of a distribution system. As a result, there is no way of knowing whether a given stroke has hit the distribution line unless there is a concurrent circuit breaker operation reported by the utility data acquisition system. Even then, there is no way of knowing whether the circuit breaker operation was caused by a direct surge or by an induced surge. Such information will have to be deduced indirectly from the theory of induced surges which will be developed as part of the data analysis.

While the count of the number of flashes in a stroke is unquestioned, the estimate of maximum stroke current depends upon a theory which is not completely proven with respect to direct measurements of lightning currents at ground level. These estimates also require measurement of the return stroke velocity which is not available for most strokes. As a result, the accuracy of the current measurement is at best $\pm 20\%$. However, additional theoretical work and experimental work may improve this accuracy.

The LLS data are now (February 8, 1980) on IBM-compatible tape up to September 6, 1979. Copies of this information are in Australia and at the Florida Power Corporation as well as in Gainesville. The Gainesville information is also being transferred to a PDP minicomputer to reduce computer expenses.

b. Television Camera System

This system can measure stroke directions to about 1° accuracy and can also determine the number of strokes, the stroke intervals, and the presence or absence of continuing current. Because of the small baselines involved in the heavily instrumented Leonard-Lee road area, this positional accuracy should be sufficient for distinguishing between direct strokes to the distribution system and nearby strokes. All of the results are on 83 magnetic tapes for the 1978-1979 seasons, and about 90% of these tapes are cataloged in data books with respect to the times of stroke occurrence, the number of strokes/ashes, and the intervals between strokes. About 50% of the flash position data has been examined for events observed on two or more cameras which allow for position triangulation. A new placement scheme for the five cameras was adopted in 1979, but this scheme resulted in only a small percentage of all recorded events being seen by two or more cameras. At present, the sifting of the catalogs for these multiple records is not digitized.

c. Flash Counters

Approximately 240,000 flash counts from three counters on the Tampa Electric Company system and two on the Florida Power & Light Company system have been time-tagged and placed on an IBM-compatible file. The analysis of these data is complete and will be discussed in Section E.

d. Thunder Ranging

Thunder ranging is the common practice of determining lightning distance through the difference in the speed of light and the speed of

sound. This method is accurate to ± 1000 feet and is useful only in confirming locations generated by the LLS and the television camera system. These records are presently on strip charts with no catalog of individual events.

e. Visual Observations

These records in data books and on audio magnetic tape will be used to confirm evidence of events recorded by other means and to confirm calibration settings. No transcript of the tape-recorded observations is available, and two copies of the data books are available -- one for each of the principal investigators.

f. Still and Streak Photographs

These photographs provide the return stroke velocity measurement which is an important parameter in Dr. Uman's theory for relating electric and magnetic field measurements at a distance to the stroke current waveshape at ground level. For lack of better values, the theory now has the assumption that the return stroke velocity is constant at one-third of the speed of light. However, evidence is available⁽⁸⁾ to suggest a factor of two variability in return stroke velocities, an error which translates directly into a factor of two uncertainty in the current estimates.

g. Electric and Magnetic Field Measurements

The electric field is measured with a flat plate sensor, and the magnetic field is measured with a pair of loop antennas. These same loop antennas constitute the sensing elements of the LLS. However, the LLS uses only a fraction of the information available from the antenna, and the additional electric and magnetic field recordings can supply valuable backup information -- especially in terms of front times for the fields. All of the electric field measurements are on approximately 100 rolls of

film with data and time information and a recording bandwidth of about 2 MHz or a response time of about 0.1 microsecond. The electric and magnetic field information is also on 96 rolls of magnetic tape with data and time information and a recording bandwidth of about 0.5 MHz with a response time of about 0.3 microsecond on the FM channels.

Since about 5% of the front times for negative subsequent stroke currents are shorter than 0.3 microseconds⁽⁹⁾, the above recording capability is marginal for determining the distribution of front times in the important range where the response time of lightning arrester protection is difficult to define. Actually, the recording bandwidth limitations are not evidence of poor experimental design, but a reflection of the more fundamental problem of dispersion of the wavefront as the electromagnetic waves propagate over the surface of the earth. This dispersion is low only over ocean propagation paths for which 30-MHz measuring equipment is considered more appropriate. Consequently, the waveforms reconstructed from the electric and magnetic field observations will be optimistic in terms of the arrester response problem. At best, the results can show whether there is a tendency for shorter front times in subsequent strokes to produce events which require circuit breaker operation.

One problem with the information recorded on the magnetic tape is that digitization of these records is an extremely slow process requiring three days of work per flash or an extremely expensive process requiring \$5000 per flash with the facilities at Eglin Air Force Base. With available equipment, the tape has to be replayed approximately 100 times for full digitization with Biomation oscilloscopes, a process that tends to damage the tape. A higher quality tape recorder has been purchased which should resolve this tape deterioration problem. However, only a small number of selected stroke waveforms will be digitized.

h. Induced Voltage Measurements

As mentioned above, a five-span unenergized transmission line was erected with non-DOE funding, and the tape recorder system normally used for electric and magnetic field measurements was used to measure the voltages on this distribution line. The tape recorder was switched to the unenergized line whenever a storm approached the vicinity of the Mobile Lightning Laboratory, and during these periods several thousand voltage records were obtained. Mr. Manick Master* has the task of interpreting about 200 voltage records in an effort to improve Wagner's theory of induced surges and to make a realistic estimate of the true hazard of this lightning damage mechanism.

i. Magnetic Strip Recorders

These devices are effectively an improved form of the magnetic link to record crest stroke current polarity and magnitude on a transmission line conductor. Laboratory accuracy is about 3% for the current magnitude, and the equipment necessary to determine polarity is not yet available. For the 1979 season, a total of 181 records exist, 174 of which have been analyzed. These records are useful primarily in the confirmation of the transient surge recorder results. Accuracy in field installations is probably somewhat lower because of problems in defining the geometry of arrester down leads.

j. Transient Surge Recorders

The transient surge recorder⁽¹⁰⁾ is a sophisticated device for accurately determining the waveshape and magnitudes of currents flowing in arrester down leads. Once triggered, the recorder collects measurements at intervals as frequent as 0.2 microsecond from a Rogowski coil current transformer. In the original General Electric version of the recorder, sample storage is on an ordinary audio tape cassette. In the modified Jet Propulsion Laboratory (JPL) version, sample storage

* Graduate student working with Dr. Uman at the University of Florida.

is in digital memory. Both versions have date and time information available for each recorded surge.

During 1979, the JPL recorders were installed in the Florida Power Corporation territory. These recorders registered 27 strokes in 12 flashes, all time-tagged and catalogued. Six of these records showed discrepancies with the currents measured by the magnetic strip detectors, and additional investigation is necessary to determine the cause of this mismatch.

The GE recorders were installed in the more intensely studied Tampa Electric Company area. These recorders registered seven strokes in five flashes, but the time tagging and cataloguing information is incomplete. Of the flashes reported, four occurred during the project setup period when magnetic field measurements and television observations were not yet available. The fifth result does not agree with the magnetic strip record and is probably an equipment failure.

Because of the importance of the GE transient surge recorder data for the confirmation of computer models of the Leonard-Lee distribution line, all of the data available in Pittsfield, Massachusetts were examined. The results of this study appear in the Appendix, and there are two major findings: (1) three additional records appear to be the result of lightning flashes and not calibration tests, and (2) about 25% of the tape cassette records had never been examined because of a funding cutoff. Unfortunately, these records, which contain the information from the two September hurricanes, may be permanently lost. This problem means that verification of the computer models may require that the computer programs be rewritten for the JPL installations.

k. Circuit Breaker Operations

All data from the Florida Power Corporation are still in St. Petersburg where analysis will proceed in-house for correlations between circuit breaker operations and LLS events. Since Florida Power Corporation has digital descriptions of their system maps, the correlation procedure will be completely computerized.

The Tampa Electric Company data acquisition system information is being put on IBM tape and is supplemented by more accurate records from a 10-channel Dranetz data acquisition system. The Dranetz system monitored nine circuit breakers and the LLS because the data collection algorithm and the timing accuracy of the Tampa Electric Company system were not completely suitable for the purposes of the lightning study. About one half of the Tampa Electric Company data base of approximately 3000 circuit breaker operations is now in IBM-compatible format. Since reclosing breakers are not monitored by the Tampa Electric Company system, six voltage recorders were placed in the Leonard-Lee area for a complete record of all breaker and recloser operations. Since the Tampa Electric Company system maps are not digitized, correlations of breaker operations with LLS events must be done by hand.

1. Damage Reports

Tampa Electric Company reports of approximately 1000 fuse operations and 600 transformer failures are now being digitized. The inspection of 70 failed arresters has revealed that perhaps 80% had corrosion problems from water ingress. This arrester failure mechanism, however, is fail-safe in the sense that the arrester spark-over voltage is lower than usual.

E. ANALYSIS COMPLETED AND PRELIMINARY RESULTS

Since the end of the data-collection phase of the project, most of the work effort has been directed to the proper cataloging and preservation of the data. However, preliminary analyses have been performed, and the results of this work do provide an indication of the usefulness of the data base. The reader is reminded that the results reported here are subject to further verification before the principal investigators can be confident of presenting them in a formal report.

1. CORRELATION OF LLS AND CIRCUIT BREAKER MONITORING

The purpose of this effort is to determine which fraction of circuit breaker operations result from lightning flashes and which from other weather-related causes. The results of a two-day study suggest that over 90% of the circuit breaker operations are associated with lightning strokes. As a result, the expense of special tree-trimming operations in order to reduce wind-related accidents is probably not justified.

One interesting result of this correlation is that the distribution of crest currents and strokes per flash is the same whether or not a circuit breaker operation is involved. This result is interesting in that it runs counter to usual outage predictions which suggest that only high stroke currents are responsible for damage. Careful study of these distributions is necessary because of possible suggested changes in lightning protection philosophy.

2. FLASH COUNTER CALIBRATION

The purpose of this effort is to judge whether the RSA-10 flash counter developed in South Africa provides similar performance in Florida. If so, then these flash counters might be used throughout America in order to provide a more accurate determination of ground flash density than is obtained with the current use of thunderstorm day information.

Critical questions are whether geographic variations in ratios of cloud-cloud vs. cloud-ground flashes and positive vs. negative polarity flashes will significantly affect the flash counter calibration.

In order to provide an accurate calibration of the flash counter, Mr. Francisco de la Rosa* compared approximately 240,000 flash counts from three counters on the Tampa Electric Company system and two on the Florida Power Corporation system with the locations determined by the LLS. His results show that the effective range of the Florida installations is within 10% of the effective range of the South African installations. The remaining discrepancy may be a function of calibration method differences which are now under further evaluation. To be completely convincing, this work probably needs repeating at a more northerly latitude because of the proven difference in the distribution of stroke polarities with latitude.

3. CRITICAL ANALYSIS OF SURGE RECORDER EVENTS

This analysis involves the collection of evidence with respect to the ability of lightning arresters to reduce circuit breaker operations and to reduce damage to transformers without themselves failing. Several conclusions concerning this effort are listed below.

The distribution of arrester rise times from the transient surge recorder results suggest that the 8 x 20 microsecond test wave is not really appropriate. The measured rise times are in agreement with existing theoretical models which predict shorter rise times. Whether or not these short rise times produce an additional insulation hazard to the transformers is debatable; the slowness of the arrester response may be matched by the delay in transformer oil breakdown under rapid transient voltages.

* Graduate student working with Dr. Uman at the University of Florida.

The existence of multiple component strokes (one flash consisted of seventeen strokes) may call for better power dissipation ability in arrester design because of the severe power follow currents that must be interrupted in rapid sequence. This failure mechanism, however, may not be significant in comparison with the observed corrosion problems in about 80% of the arresters that failed in the field.

A possible problem with present arrester protection philosophy is that one flashover occurred only one span length from an arrester which was supposed to prevent such a flashover. This observation might lead to better construction techniques or to reduced usage of arresters at evenly spaced intervals on the distribution lines. One benefit of this flashover problem is that the distribution of crest currents diverted by the arresters is smaller than the distribution predicted by the Faucett study.⁽¹¹⁾

4. IMPROVEMENT OF COMPUTER MODELLING

Dr. Darveniza has continued to develop his computer models which predict the flashover probability on distribution and transmission lines. While these programs may never be accurate enough to predict the outage frequency to within a factor of two, they will be useful for the analysis of the Florida results. Three phases of program improvement were carried out in 1979 by graduate students at the University of Florida.

The first effort is the improvement of the electro-geometric attractive distance model⁽²⁾ of Brown and Whitehead. This model is purely empirical and describes how transmission line conductors attract descending lightning leaders and in this process, shield adjacent, lower structures from direct strokes. The current effort is an attempt to produce a more physical description of the attractive distance by accounting for the spatial characteristics of the lightning channel. This exercise, however, will not be validated until more observations

of the leader charge distribution near ground level are available. Hopefully, the analysis of the induced surges on the unenergized distribution line will provide evidence regarding this charge distribution.

The second effort is the modelling of backflashover calculations with multiple strokes rather than a single stroke. A backflashover occurs when a stroke hits a grounded tower or a grounded shield wire and raises the voltage of this stricken object high enough over the phase conductor voltages to cause a flashover. The magnitude of the voltage depends both on the peak current and on the current rate of rise, and although subsequent strokes do not have high crest currents, they do have high rates of rise. Preliminary modelling results suggest that the fast front times of subsequent strokes do become important for transmission at and below 115 kV. Distribution lines generally have no shield wires so that the backflashover mechanism is not important.

The third programming effort consisted of the revision of the unshielded Australian distribution line model to agree with the American practice at the Leonard-Lee line. Preliminary results suggested that the currents measured by the transient surge recorders are very similar in waveshape to the currents injected into the line. Estimation of these injected currents is possible through the electric and magnetic field observations at the Mobile Lightning Laboratory. However, the scarcity of GE surge recorder data for the Leonard-Lee line means that verification of the computer model will be difficult unless the model is revised for analysis of results at a JPL recorder site. In the meantime, the Leonard-Lee line model is useful for checking the match between crest current predictions and the crest current measurements of the magnetic strip recorders.

IV. FUTURE PLANNED WORK

During the next few months, the tasks defined in the current DOE-sponsored project will be completed. This additional work includes completion of the data cataloging effort for all measurements made in 1979 and the preparation of reports called for in the contract agreement. Dr. Uman and Dr. Darveniza then plan to submit a proposal for continued analysis work involving two graduate students each for about 2 1/2 to 3 years. Since the details of this proposal have not yet been specified, the following paragraphs provide only an idea of the nature and level of funding of the proposed work. These plans were obtained from an interview with Dr. Uman and Dr. Darveniza and are in general accordance with the expected benefits and the quality of the data base as outlined above. Required funding for these projects will be approximately \$100,000 per year. Since Dr. Darveniza has copies of the data books and the IBM tapes, he will be able to participate actively in the analysis as a subcontractor.

The first effort will be the improvement of the theoretical models for induced voltages and will involve analysis of voltage surges recorded on a five-span unenergized distribution line. As stated earlier, the literature contains disagreements whether induced voltages substantially affect transmission and distribution line performance, and therefore, any light shed on this subject will be welcome. This work will be performed by doctoral students.

The second effort will be a statistical study of storm development and impact on utility systems. The goals of this effort are to study the matches between lightning stroke statistics and distribution failures in order to provide predictions of which developing storms are likely to cause excessive damage and to provide a better indication of which stroke characteristics are responsible for the damage. This effort will be a one-year project.

A third effort will be the improved modelling of direct strokes to distribution lines and the exercising of these models to obtain new design data. The computer programs for this effort are already available but are in need of verification against the data collected in the Florida project. In the absence of an abundance of transient surge recorder results, "verification" may not come easily. However, enough supporting data are available to raise the quality of verification over that normally associated with lightning studies. Once verified as well as possible, these computer models will be exercised in order to obtain new guidance for distribution line and equipment design.

The fourth effort will be a critical analysis of individual lightning flash events in order to more fully understand the mechanisms of distribution line performance under lightning. This work will rely heavily on piecing together all of the evidence in search of new hypotheses which may have been overlooked by previous investigators. While the results are uncertain, this work is highly important because of the apparent failure of existing theories in keeping down the level of damage on distribution lines. Dr. Darveniza himself will conduct this part of the investigation.

The final effort will not be DOE-funded, but will have important implications with regard to the accuracy with which lightning currents can be estimated from distant measurements. This work will involve an experimental confirmation of Dr. Uman's predictions which are based on changes in distant electric and magnetic fields. While the predicted current distributions match electric and magnetic fields well, there is still the need to measure the actual currents at ground level. This matching work will probably be accomplished by using the transient surge recorders for measurements on a tall tower and by using the streak cameras to determine the important return stroke velocity parameter. The results will probably improve the current accuracy of estimations from the information in the existing data base.

V. RECOMMENDATIONS

Lightning study is difficult and is governed primarily by advances in observational instrumentation. The university-utility link is, in this writer's opinion, a healthy way of assuring continued progress towards answering the many questions concerning lightning that plague utilities. The Florida research project represents a positive move in this very promising direction.

The analysis work of the Florida lightning project should receive continued support from the Department of Energy. The quality and organization of the data are adequate to provide contributions towards improved understanding the effects of lightning on distribution lines, including the causes of distribution equipment damage.

Dr. Darveniza will have a continuing role in the progress of the research in spite of his unexpected departure. However, additional funds may be necessary for his travel or for a coordinator to ensure that the analysis addresses utility problems in the most efficient way.

Since only a small number of transient surge recorders were in operation during the 1978-79 lightning season, the data from these recorders are still sparse. Consequently, an effort should be made to continue to build an arrester current data base with these functioning units. Most of the JPL recorders should go to those utilities willing to maintain them. One or several recorders should go to Dr. Uman for use in verifying his stroke current models. The GE recorders have been serviced and may perform better upon re-installation. Data reduction problems may be resolved by next year, although additional funding of GE for this reduction will be necessary.

Construction of a large number of additional transient surge recorders is not recommended at this time. GE and JPL plan to meet with EPRI to decide what changes are necessary in the instrument to assure good performance at reduced cost. Furthermore, some of the objectives of the transient surge recorder program might be met with some more limited studies such as (1) a comparative study of zinc oxide vs. valve arrester performance or (2) continued funding of the Uman-Darveniza effort to identify and predict arrester failure mechanisms.

Nationwide installation of flash counters is of benefit only in providing a calibration for lightning prediction techniques and not in addressing issues of relative economic benefits. Interested utilities should be able to participate in such a flash counter program at minimal expense.

The information collected in the Florida study is the best available, but it is by no means complete and comprehensive. The IEEE committee on lightning performance of distribution lines should be urged to address questions which will not be directly answered by the present study. The most pressing need is for answers to questions concerning the degradation of transformer insulation through insulator aging, short circuit damage, or overloading. A simplified arrester counter with time and date tagging might be all that is necessary to identify the relative role of the above three mechanisms as a source of transformer damage.

APPENDIX

ANALYSIS OF GENERAL ELECTRIC TRANSIENT SURGE RECORDER DATA

This appendix is the result of a visit to General Electric in Pittsfield, Massachusetts on February 13-14. The visit was made to examine the transient surge recorder tapes because of a problem in the quantity of results reported from this very important component of the DOE-funded lightning program.

The documentation found with the tapes is in three forms (1) on-site data book entries made by Mr. Virgilio in GE data book #1945 and DOE data book #15; (2) preliminary tape content assessments made by Mr. Stillwell, and (3) surge recorder damage reports provided by GE's Ordnance System Division, which had responsibility for refurbishing the units.

An inspection of the tapes themselves revealed that triggering problems with the Nicolet oscilloscope prevented Mr. Stillwell from reading all of the events from the tapes. Furthermore, problems with the speed sensitivity of the FSK decoder prevented Mr. Stillwell from recovering all of the time and date information from the six recorders that had properly functioning clock units. Because of these problems, every available tape cassette was re-examined for the total number of events recorded and the time of their occurrence. An "event," for the purposes of this appendix, is defined as either a calibration pulse or a lightning surge. The quality of the data track signal was not re-examined.

Future transient surge recorder designs should have some means, separate from time and date codes, of positively identifying calibration pulses. Several tapes have more than the usual number of calibration pulses but no supporting time and date information. No written record exists at Pittsfield of how many calibration pulses were entered at each change of tapes.

Where time and date information are available, there are three calibration-like pulses that have unexpected dates and times but which have not been included in the GE surge data evaluation report. These events are:

Site 5B Tape 19 3:00 PM 7/18

Site 7B Tape 8 ??:?3 8/29 (drive shut-off too soon;
possibly 6/29)

Site 8B Tape 6 5:12 PM 7/16

Before these records are confirmed as lightning events, there is a need to check the above times to be sure that no technician or lineman visited the recorders on the dates in question.

All of the GE documentation and the new findings are summarized in the tables that follow. These tables contain information pertinent only to the operation of the recorders and do not include comments on pole damage, storm activity, the magnetic strip recorders, and changes in arresters or conductors. As of February 14, 1980, seven tapes and their contents were lost and four tapes and their contents were overwritten with data recorded subsequent to the October 1979 completion of the field project. However, only four of these tapes (Nos. 54, 61, 63 and 91) come from transient surge recorders with malfunctioning counters as reported by GE's Ordnance Systems Division and may have registered surges without any visible counter indication.

Because the comments in the tables are extracts from data books, many of them may seem brief or cryptic. All inquiries concerning these entries can be addressed to the indicated source.

Site	Recorder	Date	Time	Tape Out	Tape In	Count Before	Count After	Time & Date	Tape Drive	Main Batteries	Comments
1B	30	4/25	9:05am	-	31	0					
		6/26	2:54pm	31	9	0	0	1 min slow; reset	Bad	Replaced	VIRGILIO - Minor problem with tape drive pin - seems O.K. on departure. STILLWELL - (see Site 5B), Decoded FSK. LOS - Two events: 1) 10:12 am 4/25 2) 10:13 am 4/25.. Additional events recorded at site 5B.
		8/02	2:14pm	9	63	0	0	2 min fast; reset	O.K.	Replaced	STILLWELL - Calibrates only; tape bursts. LOS - Four events: 1st and 2nd are corrupted. 1) no FSK, 2) 2:20 pm 8/02, 3) 2:20 pm 8/02, 4) 2:20 pm 8/02.
		10/02		63		0		O.K.	O.K.	Low main battery	VIRGILIO - No arrester. LOS - Thirteen events; no FSK data; apparently recorded on another unit. ORDNANCE - Event counter probably intermittent or did not work in field.
2B	27	4/25	10:49am	-	30	0					
		6/26	3:10pm	30	10	0	0	Good		Good	LOS - Re-installed in Site 3B. See comments there.
		8/02	2:30pm	10	34	-	-	Good		O.K.	STILLWELL - Calibrate only -- signal channel failure no meaningful data. LOS - Five events -- no usable FSK.
		10/02		34		-		Good	Good		VIRGILIO - No arrester. LOS - Two events recorded at site 3B. Three additional events -- no useable FSK. ORDNANCE - Replaced one-shot ahead of Manchester CRT. -- FSK is probably all 0's. Also had an intermittent type of failure.

Site	Recorder	Date	Time	Tape Out	Tape In	Count Before	Count After	Time & Date	Tape Drive	Main Batteries	Comments
3B	26	4/25	11:41am	34		0					
		6/26	3:30pm	34	11	0	0	Good		O.K.	LOS - Two events: 1) 11:47 am 4/25, 2) 11:48 am 4/25, additional events recorded at Site 2B
		8/02	2:46pm	11	30	-	-	O.K.		O.K.	STILLWELL - Calibrates only. LOS - Three events: 1) 2:46 pm 6/26, 2) 2:47 pm 6/26, 3) 1:41 pm 8/02.
		10/02		30		0		Good	Poor		VIRGILIO - No arrester. Tape drive needs more tension. LOS - Many events that start will, before usual position. One dated 2:21 pm 12/29 and apparently recorded in Pittsfield. ORDNANCE - O.K. Needs alignment.
4B	17	4/25	1:16pm	35		0					
		6/26	4:05pm	35	26	1	0	Good		O.K.	VIRGILIO - Changed magnetic strips. STILLWELL - One small surge at 1028 (PHI-DECK position counter number) LOS - Six events-FSK data was not interpretable.
		8/02	3:35pm	26	64	0	0	6 min fast; reset		O.K.	STILLWELL - Calibrates -- one possible but not likely, small surge. Signal channel hangup (3rd surge). LOS - Six events -- FSK data was not interpretable.
		10/02		64		-		2 min fast	O.K.		VIRGILIO - Arrester changed. LOS - Tape not available ORDNANCE - Transistor in Manchester circuit was bad FSK random or steady 1's and 0's. Transistor in motor drive is bad.

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Site	Recorder	Date	Time	Tape Out	Tape In	Count Before	Count After	Time & Date	Tape Drive	Main Batteries	Comments
5B	28	4/25	2:35pm	39		0					
		6/26	4:05pm	39	19	2	0	7 min fast; reset		O.K.	VIRGILIO - Changed magnetic strips. STILLWELL - Calibrate and triple surge at 1026; low level surge. Decoded FSK. LOS - Six events: 1) 2:57 pm 4/25, 2) 2:40 pm 4/25, 3) 5:12 pm 6/22, 4) 3:11 pm 6/23, 5) 3:33 pm 6/26, 6) 4:34 pm 6/26. STILLWELL - Four calibrates signal. Data channel failure. LOS - Four events: 1) 4:34 pm 6/26, 2) 4:35 pm 6/26, 3) 3:00 pm 7/18, 4) 9:20 am 7/24. The second event has a flaw on the tape apparently produced by a tape drive problem.
				19	83	-	-				
		8/02	4:30pm	83	31	0	0	2 min fast; reset		O.K.	STILLWELL - Calibrates only. LOS - One event: 1) 9:22 am 7/24.
		10/02		31	1	-		12 min fast		O.K.	VIRGILIO - Two calibrates, arrester changed two weeks before. STILLWELL - (6) calibrates. Decoded FSK. LOS - Two events recorded at Site 1B. Four events: 1) 3:13 pm 8/2, 2) 3:13 pm 8/2, 3) 3:55 pm 10/2, 4) 3:55 pm 10/2. ORDNANCE - Bad transistor in the motor drive.

Site	Recorder	Date	Time	Tape Out	Tape In	Count Before	Count After	Time & Date	Tape Drive	Main Batteries	Comments
6B	25	4/25	3:10pm	44		-					
		6/26	4:45pm	44	14	1	0	O.K.			STILLWELL - Calibrates and surge at 1037. LOS - Five events -- FSK all 0's.
				14	82	-	-		No advance		VIRGILIO - Visited on 7/9 at 8:50 and 7/24 at 8:40 by S.H. - problems on 7/24 with triggering. STILLWELL - Four calibrates. LOS - Three events -- a possible 4th event did not have an FSK code.
		8/02	8:25am	82	61	-	-	3 min fast; reset. Adjusted		Low; changed	STILLWELL - Calibrates only. LOS - Two events - FSK all 0's.
		10/02	8:35am	61		0		Good	Good		VIRGILIO - Two arresters removed and tagged. LOS - Many events beginning before usual start position -- apparently recorded in Pittsfield.
											ORDNANCE - Manchester and event counter failed. FSK is all 0's.
7B	14	4/25	4:24pm	54		-					
		6/26	2:10pm	54	8	0	0	9 min fast; reset		Low; replaced	LOS - Tape subsequently used at Site 8B. Tape not available.
				8	12	-	-				VIRGILIO - Visited on 7/3 at 9:00 pm by J.L.S. Bad counter. STILLWELL - One calibrate at 1001, nothing else on tape.
		8/02	9:34am	12	91	-	0	5 min fast; reset		Good	LOS - Three events: 1) 1:46 pm 8/26(?), 2) 2:40 pm 8/26(?). 3) ?? 8/29 (Recorder shut-off too soon). VIRGILIO - Bad wafer switch. STILLWELL - Equipment failure. No useable data.
		10/02	9:19 am	91		0		9 min fast	Not working	Low	LOS - Two events: 1) Bad record-motor did not stop, 2) 9:38 am 8/2. VIRGILIO - Three arresters removed. LOS - Tape is not available.
											ORDNANCE - '1' on date comes out as '7'.

Site	Recorder	Date	Time	Tape Out	Tape In	Count Before	Count After	Time & Date	Tape Drive	Main Batteries	Comments
8B 29		4/26	8:30am		61	-					
		6/26	1:50pm	61	6	0	0	5 min fast		? replaced	LOS - See Site 6B.
		8/02	12:50pm	6	54	0	0	7 min fast; reset	Belt adjustment	O.K.	STILLWELL - Calibrates. One possible surge -- more than likely a calibrate.
		10/02		54		0		Good	Tape too tight		LOS - Five events: 1) 2:16 pm 6/26, 2) 2:16 pm 6/26, 3) 5:12 pm 7/16, 4) 1:08 pm 8/2, 5) 1:08 pm 8/2.
											VIRGILIO - No arrester.
											LOS - Tape not available.
											ORDNANCE - OK -- event counter failed.
9B 24		4/26	9:50am		63	-					
		6/26	10:46am	63	2	0	0	2 min fast; reset		Neg. batteries low	LOS - See Site 1B, see comments there.
					2	?	13	5			VIRGILIO - Visited 7/3 at 9:42 by J.L.S. and 7/10 at 10:05 by S.M.H., observed 5 counts. Trouble with advance and counter. Changed tapes and battery twice (?).
											STILLWELL - One calibrate at 1002, nothing else on tape.
											LOS - Noise -- no useable information. Perhaps Tape #15 installed here.
		8/02	10:35am	13	92	5	0	Bat replaced; reset		Replaced	STILLWELL - Equipment failure -- no useable data.
											LOS - Noise -- no useable information.
		10/02	11:15am	92		0		5 min fast		Low	VIRGILIO - Arrester changed.
											LOS - Tape is not available.
											ORDNANCE - Timing generator didn't work. Counter problems.

Site	Recorder	Date	Time	Tape Out	Tape In	Count Before	Count After	Time & Date	Tape Drive	Main Batteries	Comments
10B 7	4/27				66	-					
	6/26	11:23am		66	3	0	0	10 min fast		Good	LOS - See site 13B. Tape not available.
				3	84	7	0				VIRGILIO - Visited on 7/24 by S.H. who saw 7 counts and docks not working; erratic drive and replaced tape 84 with tape 15.
											STILLWELL - Three calibrates, one small positive surge, no dates.
	8/2	11:09am		84	93	0	0	8-9 min fast, reset. Adjusted		Down?	LOS - Four events; FSK not interpretable.
											STILLWELL - Calibrate and equipment failure - no other usable data.
											LOS - Two events; first is corrupted from tape pop; FSK is available but not interpretable.
	10/2	11:45am		93		0		Time bad, date good.		Low	VIRGILIO - Arrester changed.
											LOS - Tape is not available.
											ORDNANCE - Analog shift register problem - first data point is abnormally large - hung up.
											Note: Tape #15 was completely blank; perhaps 7 counts should really read Tape #7.

Site	Recorder	Date	Time	Tape Out	Tape In	Count Before	Count After	Time & Date	Tape Drive	Main Batteries	Comments
11B 20	4/27			71		-					
	6/26 11:45am	71	4	1	0	10 min fast			Good		STILLWELL - Nothing on tape. LOS - Blank.
		4	16	-	-						VIRGILIO - Visited by W.S. on 7/12 at 13:00. STILLWELL - Nothing on tape. LOS - Blank.
		16	85	-	-						VIRGILIO - Visted by S.H. on 7/24 at 10:12. STILLWELL - Nothing on tape. LOS - Blank.
	8/02 11:35am	85	86	-	-						STILLWELL - Equipment failure. No useable data. LOS - Blank.
	10/02	86		0		Good			Good		VIRGILIO - Arrestor changed. LOS - Tape is not available. ORDNANCE - Drive wouldn't shut-off after a surge.
12B 16	6/26 8:55am	1		0							VIRGILIO - Newly installed.
	8/02 10:09pm	1	90	0	0	31 sec (sic) slow; reset			Replaced		STILLWELL - Calibrates only. LOS - Three events: 1) 10:29 am 6/26, 2) 10:30 am 6/26, 3) 10:13 am 8/2.
	10/02 11:00am	90		-		Good			Low		VIRGILIO - No arresters. LOS - Has many events, beginning before usual position. Two events read 9:15 am 12/31 and 9:58 am 12/31, apparently recorded in Pittsfield. ORDNANCE - O.K. -- aligned.

Site	Recorder	Date	Time	Tape Out	Tape In	Count Before	Count After	Time & Date	Tape Drive	Main Batteries	Comments
13B 18	6/26	1:05pm	5	-							VIRGILIO - Newly installed.
			5	18	-	-					VIRGILIO - Visited by W.L.S. on 7/12/79 at 1:40. Visited by J.L.S. on 7/24/79 at 10:38. clock and tape bad.
											STILLWELL - One calibrate at 1001. Nothing else.
											LOS - Four events -- extremely slow as if tape drive was running in FAST FORWARD.
				18	87	-	0				STILLWELL - Equipment failure - no useable data.
											LOS - Noise.
	8/02	11:49pm	87	66	-	0	1 min fast; reset	Drive replaced	Good		STILLWELL - Equipment failure - no useable data.
											LOS - Tape available - not examined.
	10/02			66		0	Bad	Not working			VIRGILIO - Arrester changed.
											LOS - Tape is not available.
											ORDNANCE - Timing generator and clocks did not work.

REFERENCES

1. Arthur D. Little, Inc. "Evaluation of Transient Recorder Program." Memorandum to Jeffery Serfass, U.S. Department of Energy under DOE Contract No. EC-77-R-01-5036, Task Order No. 001. Cambridge, Massachusetts, January 9, 1978.
2. Darveniza, M., et al. "Modelling for Lightning Performance Calculations." IEEE Transactions on Power Apparatus and Systems: 98 (6), 1900-8 (November/December 1979).
3. Uman, M., et al. "An Unusual Lightning Flash at Kennedy Space Center." Science: 201 (4350), 9-16 (July 7, 1978).
4. Uman, M. A. Lightning. New York: McGraw Hill, 1969.
5. Darveniza, M. and M. Uman. "Lightning Studies of Distribution Lines." Proceedings of the Conference on Overhead and Underground Transmission and Distribution sponsored by the IEEE Power Engineering Society, Atlanta, Georgia, April 1-6, 1979.
6. Weck, K.H. (FGH, Mannheim-Rheinau, Germany). Informal comments made at the Renardieres Group Meeting in Cardiff, Wales, 1977.
7. Kaufman, G. H. Impulse Strength of Distribution Transformers under Load. Final Report, February 1975-September 1976. NTIS Report No. CONS/2157-1.
8. Boyle, J. S. and R. E. Orville. "Return Stroke Velocity Measurements in Multistroke Lightning Flashes." Journal of Geophysical Research: 81 (24), 4461 (August 20, 1976).
9. Kroninger, H. Further Analysis of Professor Berger's San Salvatore Lightning Current Data. Prepared for National Electrical Engineering Research Institute of the Council for Scientific and Industrial Research, Pretoria, South Africa, July 1974. CSIR Special Report ELER 53.
10. Humphreys, D. Solid-State Surge Recorder. Final Report. Prepared for the Energy Research and Development Administration under Contract No. E(49-18)-2070, April 1, 1977.
11. Jack Faucett Associates, Inc. Sampling Plans for Lightning Surges Test Program. Final Report, May 1976-January 1977. Prepared for the Energy Research and Development Administration, March 1977. NTIS Report No. CONS/2107-1.