EVALUATION AND IMPROVEMENT OF ELECTRICAL STORM WARNING SYSTEMS

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16. Abstract (Limit: 200 words) An analysis of mining explosive accident reports indicate a need for clear and ample warning of approaching electrical storms to reduce injuries/fatalities due to lightning induced premature detonation. During the Spring and Summer of 1979, six lightning warning devices were comparatively evaluated at three test sites. The devices tested were: (1) Flash counter, (2) Corona point, (3) Radioactive probe, (4) Field mill, (5) Azimuth/range locator, and (6) Triangulation locator. The test sites were chosen to provide system evaluation under varied thunderstorm conditions. The devices were tested at San Antonio, Texas, Kennedy Space Center, and Langmuir Laboratory, New Mexico.

Comparative performance evaluation is reviewed in terms of alarm reliability, false alarm and failure to alarm probabilities. Improved lightning warning system requirements and methods of relating warning criteria to explosive hazard are discussed.

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FOREWORD

This report was prepared by Southwest Research Institute (SwRI) Electromagnetics Division, 6220 Culebra Road, San Antonio, Texas 78284 under USBM Contract Number J0387207. The contract was initiated under the Coal Mine Health and Safety Program. The contract was administered under the technical direction of the USBM Pittsburgh Research Center with Mr. J. E. Hay acting as Technical Project Officer. Mr. W. R. Mundorf was the contract specialist and Mr. A. G. Bolton the contracting officer for the Bureau of Mines. This final report is a summary of work recently completed as a part of this contract during the period 22 May 1978 to 21 November 1979. This report was submitted by the authors on 21 November 1979.

EVALUATION AND IMPROVEMENT OF ELECTICAL STORM WARNING SYSTEMS

INTRODUCTION

The objective of this study is to evaluate the adequacy of electrical storm warning systems and to recommend improvements if necessary. Mine safety standards specify that "when electric detonators are used, charging (of blastholes) shall be suspended...and men withdrawn to a safe location upon the approach of an electrical storm." These federal health and safety standards apply to metal and nonmetal open pit and underground mines, sand, gravel, and crushed-stone operations, surface coal mines, and surface work areas of underground coal mines.

The intent of the safety regulations is clear. Evacuation reduces injuries associated with lightning-induced premature explosions, providing that there is clear and ample warning of approaching lightning storms. Mine accident records indicate a distinct need for improvements in early detection of approaching electrical storms in order to allow sufficient time for workers to withdraw to a safe location. For example, in 1977 there were three fatalities within a month due to two separate accidents: one at a strip mine in Tioga County, Pennsylvania, and two near Van Lear, Kentucky (see Appendix A).

The Bureau of Mines has sponsored the acquisition and dissemination of information on the characteristics and adequacy of devices and systems designed to give warning of atmospheric electrical activity. It is also within the scope of Bureau of Mines concerns to develop improvements in such devices and systems if necessary. Under the purview of this study, SwRI has evaluated six conceptually distinct lightning warning devices in side-by-side tests at three sites. These tests provide directly comparable results under thunderstorm conditions initiated by the three major sources of thunderstorm activity, viz. movement of frontal air masses, convection due to localized surface heating, and unstable air masses due to mountainous terrain (orographic) effects.

A review of previous work in the comparative evaluation of lightning warning systems reveals that a side-by-side study was conducted by the USAF Air Weather Service at Cape Canaveral AFS during the period April-September 1970. Five devices were evaluated in this effort. A prototype device developed by the Air Force Geophysical Laboratory was determined to best satisfy USAF requirements (1978). No copy of the test plan nor details of the results has been located. Of the devices tested, two are currently being manufactured commercially.

A comprehensive theoretical review was done by Cianos and Pierce (1974), Pierce (1977), using an existing statistical data base of thunderstorm and lightning parameters available in the literature. This effort addressed the general problem of lightning warning. Conclusions and recommendations were made based on the theoretical or projected performance of the systems analyzed.

In other studies, the performance of single sensor types has been evaluated. These include an evaluation of a radioactive probe by Buset and Price (1975), a field mill by the USAF Air Weather Service (1977), an azimuth/range locator by Schneider and Mangold (1979), and a triangulation location system by Vance (1979).

This report summarizes the results of all known types of lightning warning systems which are commercially available. The results of this effort are directed toward providing a cost effective solution for timely warning of atmospheric electrical activity appropriate to the general mining industry requirement.

ACCIDENT AND INCIDENT REPORT REVIEW

The available reports over the past 25 years regarding accidents and incidents caused by atmospheric electricity in mine blasting operations have been reviewed. The following sections summarize the results of this effort.

1. Mine Safety and Health Administration

The Mine Safety and Health Administration in Washington DC proved to be the most productive source of premature explosion accident reports. Individuals in that organization had requested a copy of all premature explosion reports from coal and metal and non-metal district offices. This resulted in a collection of several hundred reports. SwRI personnel identified the report ID number and the originating district office for applicable reports. These reports were then obtained by writing the appropriate district office. As a result of this correspondence effort, a total of 13 MSHA reports were acquired.

Of the 13 reports, 11 listed lightning as the cause of premature explosion during blasting operations. Nine accidents occurred in surface mines and two accidents occurred in underground mines. One of the reports described a premature explosion during blasting operations caused by stray currents from electrical sources. The other report attributed the explosion of stored explosives to a fire caused by lightning.

The Mine Safety and Health Administration central library facility in Denver, Colorado makes available both government generated accident reports and mine company reports. Accident reports for coal mines were computerized beginning in 1972 and for metal and non-metal mines beginning in 1975. A computer listing of these reports was obtained subsequent to the Washington MSHA office visit. The computer listings for coal and metal/non-metal mines contained several reports regarding premature explosions caused by several reasons including lightning (cause code 1301). All of the code 1301 reports on the computer lists were duplicates of previously identified reports.

The Denver MSHA office was visited to review microfilm files of mine company premature explosion reports. No new reports were found as a result of this effort. A further review of available reports at Denver on premature explosions and a second computer listing of the coal and metal and non-metal accident reports through November 1978 failed to produce additional reports.

2. Department of Defense

The chairman of the DoD Explosive Safety Board provided a copy of one applicable military report and information on military data bases of explosive accident reports for the three branches of the armed services. This office also furnished a list of explosive accidents covering a period from 1918 through 1976 where lightning was listed as the cause. Only two of the accidents on this list were relevant to this contract. Of these, one report on a premature explosion in an underground tunnel project is included in this discussion. The second concerning a mine explosion in Pottsville, Pennsylvania in the 1930s could not be traced in detail.

3. Military Services Reports

Computerized data bases of explosive accident reports for the Air Force at Norton AFB, California, the Army at Ft. Rucker, Alabama, and the Navy at the Surface Weapons Laboratory, Dahlgren, Virginia were searched for appropriate reports following a certification of a need-to-know by the Contracting Officer. The results were negative in all three cases.

4. Results Summary

A synopsis of each of the 13 reports applicable to this contract (including the 3 underground incidents) is given in Appendix A. Analysis of these reports is summarized in Tables 1, 2, and 3. Table 1 shows the number of accidents by type of mine.

The type of terrain for each mine was determined by locating the mine (or the general area of the mine) on aircraft VFR sectional charts. Table 2 summarizes the type of terrain by general terrain classifications. It can be seen that 6 of the accidents occurred in very hilly terrain with one or more mountain ranges nearby in 4 cases.

TABLE 1. - Number of Accidents by Type of Mine

Type of Mine	No. Accidents
Surface Coal Mine	4
Surface Limestone Mine	4
Surface Copper Mine	1
Underground Metal Mine	2
Surface Disposal of Explosives	1
Underground Tunnel Construction	1

TABLE 2. - Number of Accidents by Type of Terrain

Type of Terrain	No. Accidents
Very hilly within 10 to 20 nmi of 3000 to 4000 foot mountains	3
Very hilly with no nearby mountains	2
Foothills within 10 nmi of 6000 foot mountain range	1
Moderate hills	1
Low rolling hills	2
Flat with low rolling hills	1
Flat	1
Unknown	2

Table 3 shows the status of the evacuation at the time of premature explosion by number of accidents and injury/fatality occurrence. The importance of evacuation procedures on the approach of a thunderstorm is apparent.

It is interesting to note that evacuation was complete in only 3 of the 13 cases. In 3 additional cases evacuation was in progress and there were no fatalities or injuries. Fatalities and injuries occurred when the full crew did not evacuate, work was prematurely resumed following a storm, work was continued during adverse weather conditions, or lightning struck without warning as a thunderstorm developed overhead. In 2 other cases, workers took shelter close to the blasting area (for reasons not clear) but no one was injured. Overall, those that took cover at most suffered injury but no fatalities. This demonstrates the benefits obtained when lightning warning is effective.

EXPERIMENTAL DESIGN

Blasting area vulnerability to lightning is based on two primary conditions: (1) Thunderstorms move into the blasting area, e.g. due to weather front or convective cell movement, (2) a thunderstorm builds up in place over the site. In the first case electromagnetic emanations from the cloud and the lightning discharge can be used to detect storm approach. In the second case, the first sign of danger may be a lightning strike occurring without warning. On relatively clear days thunderstorm activity can be directly observed. However, under overcast conditions, thunderstorms may occur within the area without being detected until cloud-to-ground lightning events are initiated.

Thus, effective lightning warning requires (1) capability to detect storms at a distance resulting in alarm, for example, 30 minutes prior to dangerous approach and (2) capability to detect static buildup in the immediate vicinity of the site. The comparative evaluation of lightning warning systems requires that both capabilities be evaluated in terms of (1) false alarm and failure to alarm rates, and (2) alarm reliability in terms of dangerous electrical energy dissipation in explosive detonators.

To achieve these test goals, the comparative evaluation test was implemented as follows: (1) a survey of all known methods of lightning warning was performed and representative devices were acquired for test, (2) an optical lightning location system was developed to provide proximity data on cloud-to-ground strikes, (3) a detonator simulation circuit was developed which simulates both bridgewire and bridgewire-to-case arcover detonation, and (4) selection of three test sites representative of the prevalent thunderstorm generating conditions. At each site a perimeter of

TABLE 3. - Summary of Evacuation Status at the Time of Accident

Status	No. of Accidents	No. of Accidents w/Fatalities or Injuries	Total No. of Fatalities	Total No. of Injuries
All Personnel Evacuated	3	0	0	0
Partial Evaculation (one person remained in area)	1	1	0	1
Personnel Evacuated to an Area Close to Blasting Area (sudden storm)	2	0	0	0
Evacuated but Resumed Work Following a Storm	2	2	3	7
Continued to Work During Adverse Weather Conditions	1	1	1	3
Sudden Thunderstorm (No evacuation)	1	1	1	0
Evacuation Started	3	0	0	0
TOTAL	13	5	5	10

ten nautical miles (nmi) about the array of sensors was established within which warning indications as thunderstorms approached was monitored. Assuming a mean storm movement of nominally 20 knots, this provided a 30 minute warning capability.

Data from the study is analyzed based upon alarm indications from the candidate electrical warning systems, meteorological data from weather radar facsimile, the NWS (16 mm film archive at Asheville, North Carolina), eyewitness observations by the site operating personnel, and lightning flash locations from the photographic sensors. Criteria used for comparative analysis of system performance include alarm reliability, failure-to-alarm rate, and false-alarm rate of the warning systems determined from observed electrical activity and the two detonator simulation records.

LIGHTNING WARNING SYSTEMS

1. Flash Counter

A lightning flash counter senses the atmospheric radio emission from a lightning discharge (sferic) and indicates the received sferic (flash) rate. The higher the rate, the more intense and/or nearer the proximity of the storm.

A review of the development of lightning flash counters and their utility as warning devices is given by Chalmers (1967). Comparative performance data of the Pierce-Golde, modified Prentice, and a Czechoslovakian flash counter is given in a study by Laitinen (1975) in Finland. A recent survey is also given by Anderson (1977). The use of a flash counter as a lightning warning device has been advocated frequently, but its primary utility has been in the acquisition of thunderstorm electrical statistics such as ratio of cloud-to-ground versus intracloud discharges, or number of strikes as a function of storm duration, etc.

The principal advantages of a flash counter for electrical storm warning are: (1) low cost, (2) generally long-range capability, (3) simple to operate, and (4) easily transported. The disadvantages are: (1) does not warn of the first strike in a storm, and (2) frequently exhibits a high false-alarm rate or a high failure-to-alarm rate depending upon radio receiver sensitivity settings.

A survey of commercially available flash counters indicated six sources of stock items. The units had similar designs and packaging: however, the capability of sensitivity adjustment was the deciding factor in selecting the candidate unit for test. The flash counter tested was a 455 kHz tuned receiver with switch selectable ranges of 100-, 50-, 25-, and 10-mile warnings. The receiver gain and meter sensitivity could be adjusted from rear panel rotatable knobs.

Figure 1(a) shows the monopole antenna used for the flash counter. The manufacturer recommends a 45-degree mounting to monitor both the vertical and horizontal electric fields. Figure 1(b) illustrates the flash-counter (receiver) electronics.

2. Corona Point

A summary discussion of the corona point principle is given by Latham and Stromberg (1977). The corona point device is perhaps conceptually the simplest of the lightning warning systems. In paraphrase of Cianos and Pierce (1974), if a sharp point is raised to a height h above a ground plane, the corona current i in the presence of an electrostatic field E and wind speed w is given by:

$$i = ah\ (E-E_o)\ (w^2+c^2E^2h^2)^{1/2}. \tag{1}$$

where a and c are constants and

$$E_o = \text{threshold field to initiate corona} \sim 1\text{kv/m}.$$

If the wind velocity is zero, equation 1 becomes

$$i = ah(E-E_o)\ (cEh). \tag{2}$$

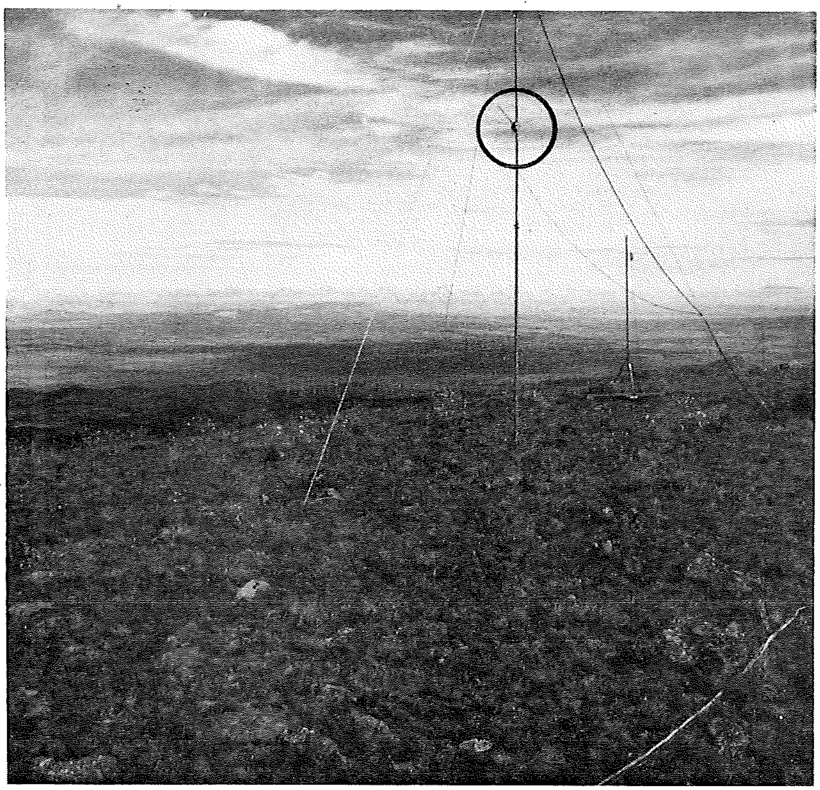
For small field values, $E<E_o$, the corona current is essentially constant. Under the conditions of thunderstorm activity, the wind velocity term is such that $w>cEh$ and equation 1 reduces to

$$i = ah(E-E_o)w \tag{3}$$

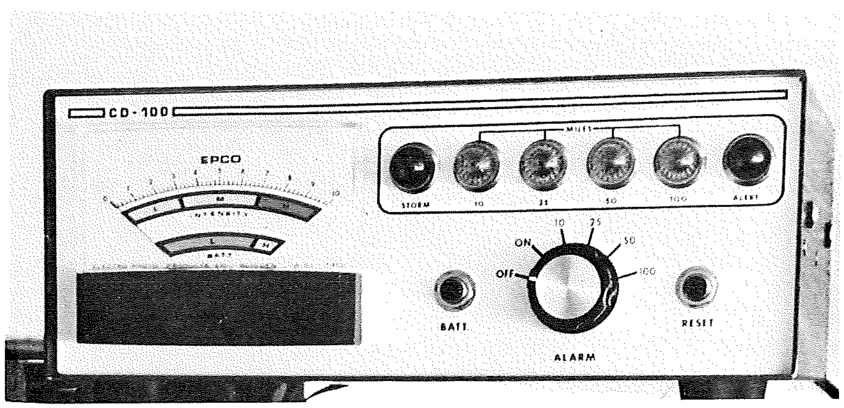
Warning levels of corona current should allow for enhanced current due to high wind speeds.

The principal advantages of corona point devices are: (1) relative simplicity, (2) low cost, (3) simple to operate, and (4) low maintenance requirement. The disadvantages are: (1) relatively short range due to insensitivity below the corona threshold field, and (2) susceptibility to noise interference due to low current levels being measured.

Commercially available corona point devices are made by a single source. The candidate unit used in the test was a sphere of approximately eight inches in diameter with two rows of four-inch spikes welded on the perimeter to enhance corona discharge (Figure 2(a)). This device is mounted atop a 60-ft tower as shown in Figure 2(b). (From equation 1, the amount of corona current is a function of the effective sensor height). Figure 2(c) shows the sensing and alarm electronics. The alarm level used for this evaluation was 15 microamperes.



(a) Flash Counter Antenna



(b) Flash Counter Electronics

Figure 1. Flash-Counter Warning System

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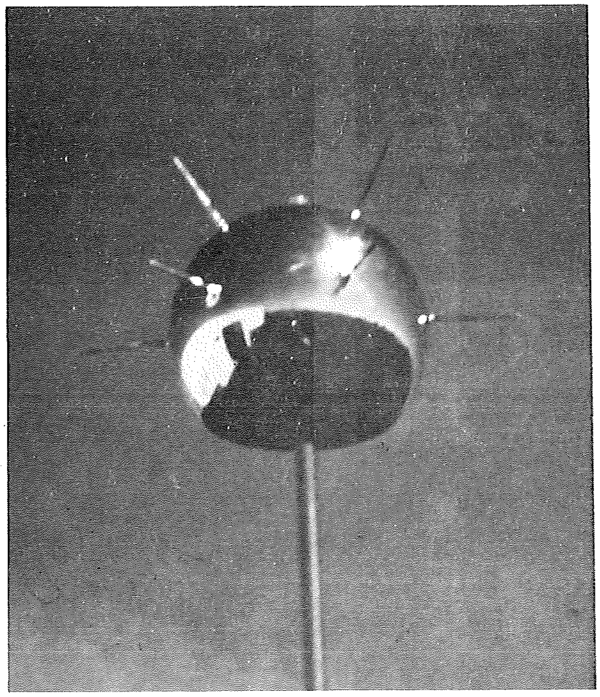
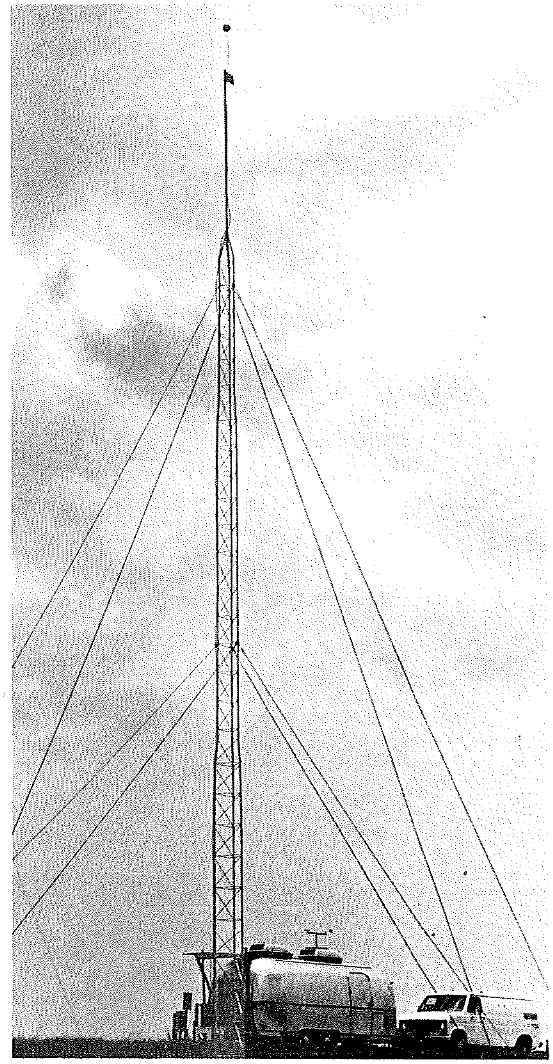
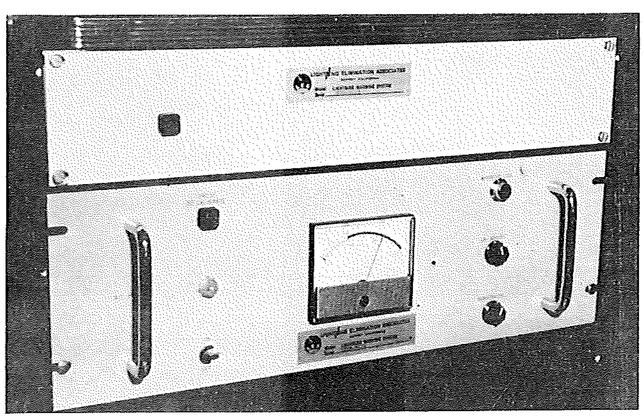


(a) Corona Point Element



(b) 60 Foot Mast



(c) Corona Current Measurement Electronics

Figure 2. Corona Point Warning Device

3. Radioactive Probe

A description of the radioactive probe device is given by McCready (1958). Also summaries can be found in Cianos and Pierce (1974) and Chalmers (1967). In principle, the radioactive probe measures the electrostatic field in the presence of ionizing particle emission. The probe is connected to a conductor. The emitted particles ionize a small volume of air about the probe which brings the potential of the conductor to that of the atmospheric gradient. Potential is estimated by measuring the current through the conductor and using a knowledge of the coupling resistance of the probe to the surrounding air. Commonly used radioactive sources are polonium and tritium.

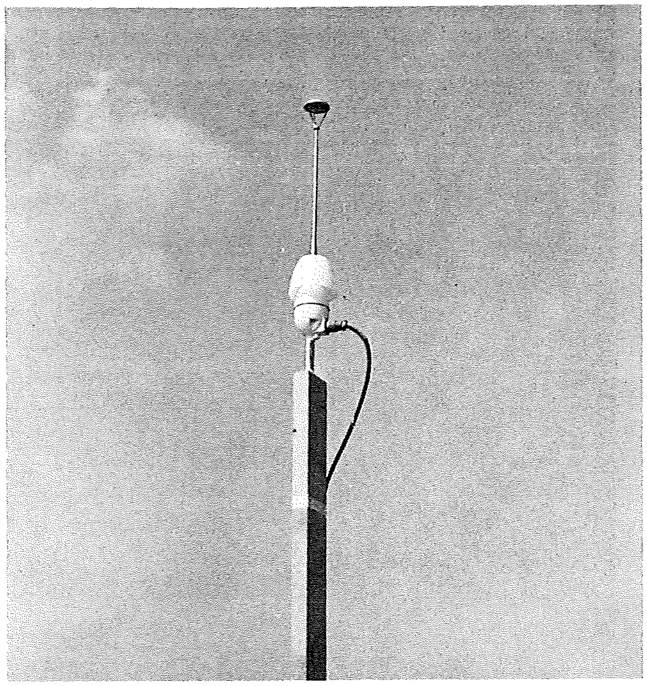
The advantages of a radioactive device are: (1) reasonably good sensitivity in the 100 v/m to 1 kv/m range, and (2) low maintenance requirement. The disadvantages are: (1) relatively slow response time, and (2) difficulty in maintaining a high impedance between the probe and ground during rain or high humidity.

A survey of commercially available radioactive probes revealed two sources. One manufacturer uses a polonium emitter and the other uses tritium. Both devices measure the potential gradient; however, the polonium device also records field changes and magnitude of the change. Since a test of the two parameter measurement device implicitly includes a test of the single parameter device, the polonium probe was selected as the unit for this evaluation.

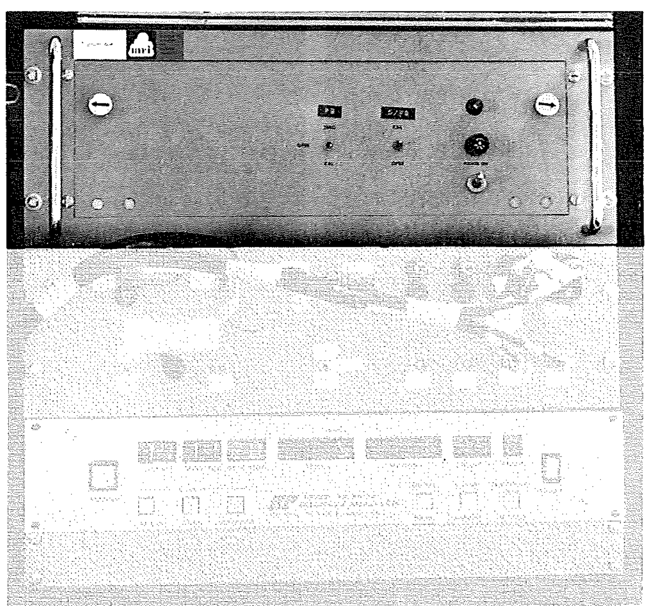
Figure 3(a) illustrates the radioactive element and the probe with rain shield. Figure 3(b) shows the electronics used to measure the field gradient and change in gradient.

4. Field Mill

Field mill devices are described by Uman (1969), Israel (1973), and Chalmers (1967). In paraphrase of Chalmers summary, the field mill device consists of a fixed test plate with a circularly disposed array of conducting surfaces. Rotating above this plate is a circular plate with circularly disposed apertures corresponding in geometry to the conducting surfaces on the fixed plate. By rotating the upper plate, the conducting elements are alternately exposed to and shielded from the electric field lines between the earth and atmosphere. The upper rotating plate is generally grounded to earth and the conducting elements, which become charged during the exposure cycle and are discharged during the shielding cycle through a resistor-capacitor network. The resulting sinusoidal signal is rectified and measured. The amplitude of the sinusoidal signal is proportional to the charge deposited upon the conducting surfaces and thus proportional to the electric field strength.



(a) Radioactive Element



(b) Potential Gradient Electronics

Figure 3. Radioactive Active Probe System

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The primary advantage of the field mill device is that it can measure very rapid changes in the electric field. It is widely used in scientific data acquisition to study fine structure of thunderstorm electrical phenomena. The disadvantage is that the moving and conducting plates require frequent cleaning and maintenance.

There are four manufacturers currently marketing field mill devices. One of the devices uses the field change measurements or first derivative of the sensed field to determine an alarm condition. Two of the devices use a combination of electrostatic field and field changes to detect an impending lightning event. The fourth system is a three parameter system which uses the electrostatic field but includes an LF flash counter to measure lightning events and a VLF measurement of the ambient noise level.

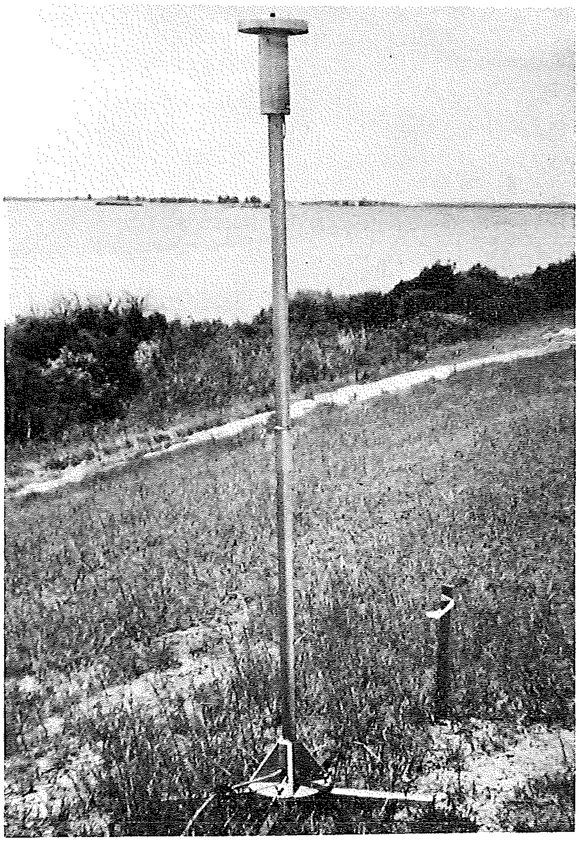
The field mill device has two warning levels--yellow and red. Yellow alert is indicated when: (1) the electrostatic field intensity exceeds 1 kv/m and the atmospheric noise exceeds a preset threshold level, (2) one lightning event is registered and the atmospheric noise exceeds the threshold level, (3) field intensity exceeds 2 kv/m, and (4) two lightning strikes registered within 100 seconds. The red alert is illuminated when: (1) yellow condition 1 exists and one lightning strike is registered, (2) yellow condition 2 exists and a lightning strike was detected within 100 seconds after the first, (3) yellow condition 3 exists and a lightning strike was detected, (4) yellow condition 4 exists and a lightning strike was detected within 100 seconds after the second strike, (5) field intensity exceeds 2 kv/m and the atmospheric noise exceeds the preset threshold level, and (6) field intensity exceeds 3 kv/m.

The field mill system is shown in Figure 4 including field mill sensor (Figure 4(a)) and the warning electronics (Figure 4(b)). The metal support for the field mill (Figure 4(a)) also serves as the RF antenna for both the lightning event and atmospheric noise measurements.

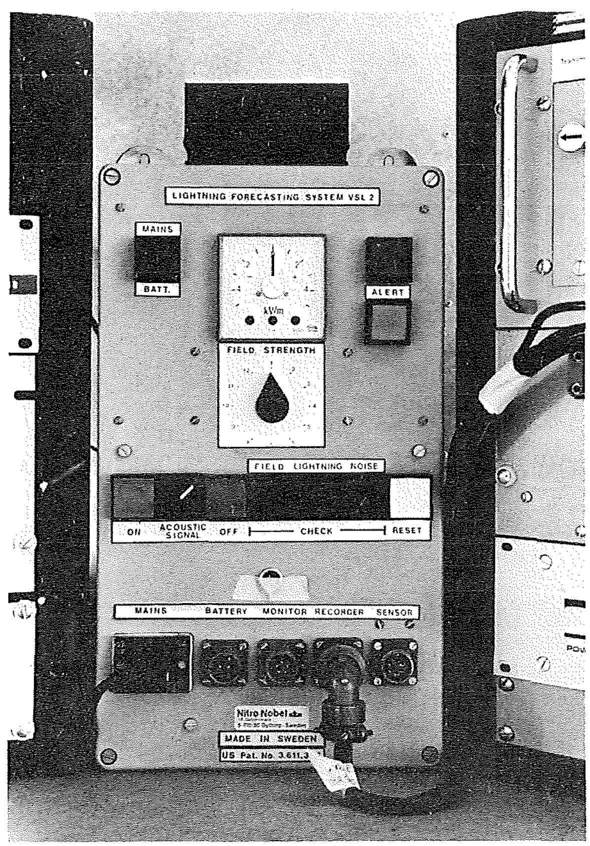
5. Azimuth/Range Locator

Description of an azimuth/range location system are given by Harth and Pelz (1973), Sao and Jindoh (1974) and Ryan and Spitzer (1977). The technique described here is a paraphrase of that proposed by Ryan and Spitzer (1977). The sensor is a conventional crossed loop direction finder with a monopole sense antenna as developed by Watson-Watt and Herd (1926). The receiver is broad band tuned with a center frequency of 50 kHz.

The crossed loops are also quadrature summed to form a composite signal which is compared to a threshold level. Provided the signal exceeds the threshold value, the analog signals from each crossed loop are integrated for a period of 500 μseconds. The integrated signals are then effectively divided by the square of the composite signal, in what is termed a "foldback method," so that the "folded back" signal is smaller in magnitude for a larger received signal and larger in magnitude for a smaller received signal.



(a) Field Mill Sensor



(b) Alarm System for Field Mill Input

Figure 4. Field Mill Warning System

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This signal, then, results in a range estimate which coupled with the directional data, produces a dot on a CRT screen. The points of electrical activity resemble the polar trace of a weather radar CRT.

The device has three range coverages of 40/100/200 nautical miles. The range values are calibrated assuming a peak return stroke current of 19 KA and a far field propagation model.

One of the principal advantages of this device is the easily interpreted display. In general, major storm movements can be determined. As a lightning warning system, it has the disadvantage that range estimates may be in error due to the large variance in peak return stroke currents.

Only one commercial manufacturer of azimuth/range systems was identified. The crossed loop and monopole sensors are shown in Figure 5(a). The display electronics are shown in Figure 5(b).

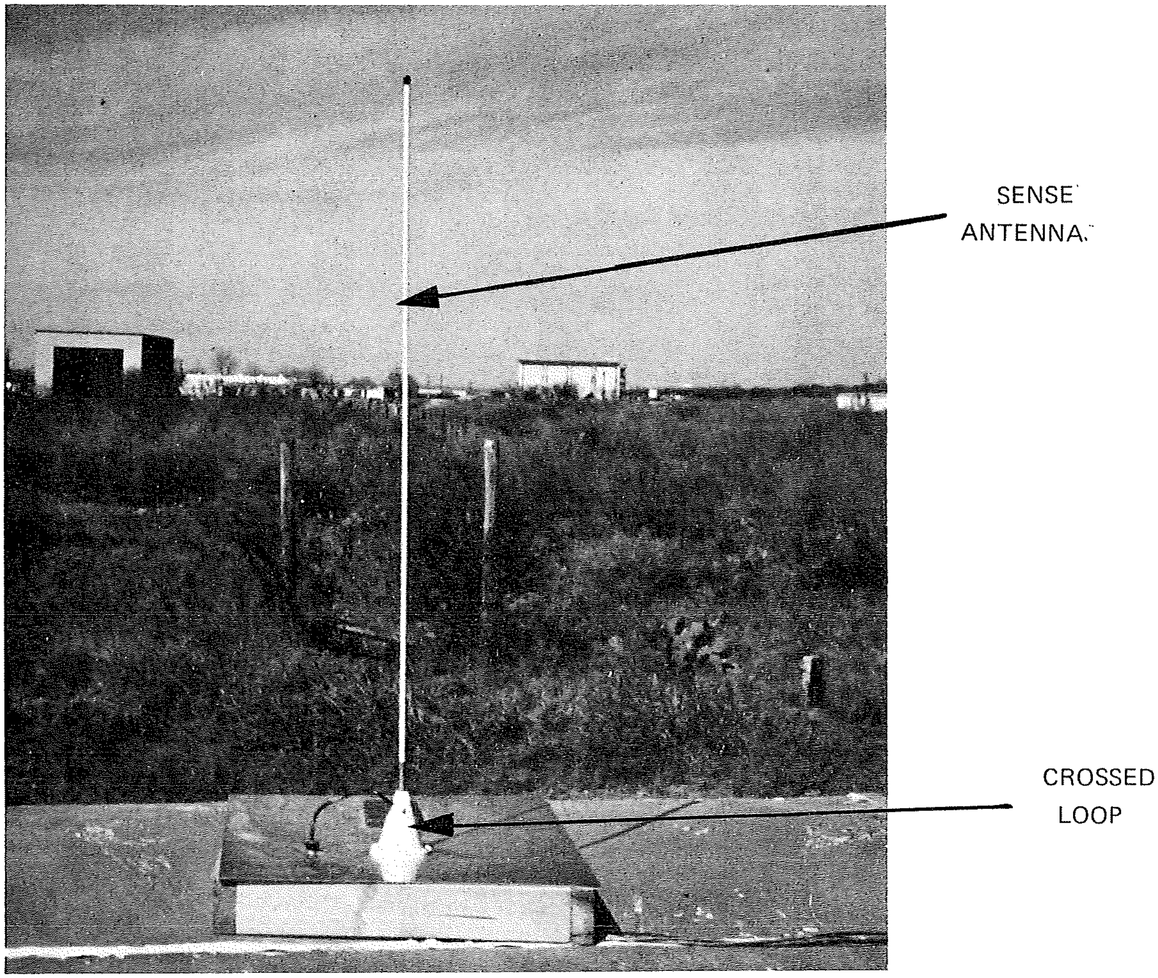
6. Triangulation Locator

A review of lightning triangulation location techniques is given by Horner (1964). Recent techniques are reported by Detzel and Pierce (1969), Cianos, et. al. (1972), Krider and Noggle (1975), Krider, et. al. (1976), and Herman, et. al. (1976). Other techniques reported which have been used are by Lennon (1975), Taylor (1978) and Warwick (1979). The system described herein is a paraphrase of Krider, et. al. (1978).

The direction finding technique described in the previous section, using a crossed loop sensor, exhibits significant directional errors when the magnetic field has an appreciable horizontal component. To overcome this problem, a system has been developed to: (1) discriminate between intracloud and cloud-to-ground discharges, and (2) to gate the direction finder on the initial portion of the cloud-to-ground strike which emits a predominately vertically polarized magnetic field, typically occurring during the first 100 meters of the return stroke channel.

The system consists of two remote DF stations which transmit data to a centralized facility. The function of the central site is to determine a point of intersection of the directional data reported by each remote site. Two sensors are located at each remote site, a crossed loop antenna and a flat plate antenna. The flat plate antenna is used as a sense element to resolve the 180 degree ambiguity of the crossed loop. The system is designed to operate only upon negative cloud-to-ground strikes, that is, those discharges which lower negative charge-to-ground.

The two sensor outputs are processed by an analog signal processor which determines whether or not the waveform resulted from a negative cloud-to-ground discharge. If this criterion is met, an angle of arrival is computed. Essentially the cloud-to-ground test is based on two criteria: (1) time to initial peak, typically less than 5 to 10 μseconds, and (2) decay



(a) Crossed Loop and Sense Antennas

(b) Display Electronics

Figure 5. Azimuth/Range Warning System

Appearance of specific brands, equipment or trade names in this report does not imply endorsement by the Bureau of Mines.

time, approximately 40 μseconds. If these conditions are satisfied, the initial peak value is used to determine the angle of arrival. The 180 degree ambiguity is resolved by the E field flat plate sensor which indicates a positive field change for negative ground discharges and vice versa for positive ground discharges.

Also located at the remote site is a digital processor which computes the angle of arrival of each stroke in the flash, tests the results for agreement, and averages the computations. The digital processor then transmits the result to the central site over a 200-baud land line pair of wires.

At the central facility, the location of the lightning strike is computed from the intersection of the two respective bearings reported by the remote sites. The positional data are output to teletype giving time, northing, easting, number of strokes in the flash and relative signal strength at each of the two sites. Also the position is presented graphically on an X-Y plotter.

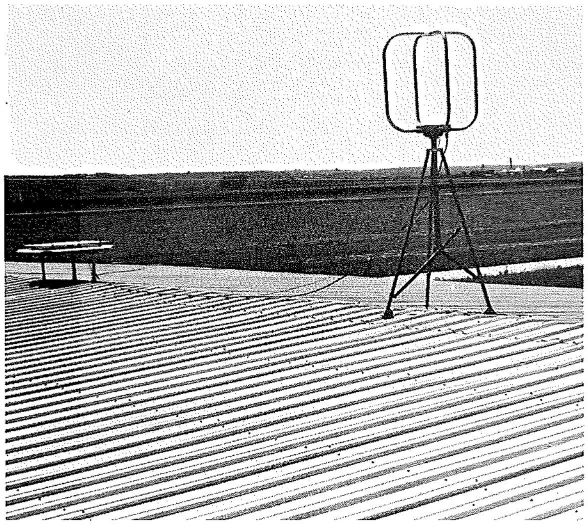
The advantage of this type device is an enhanced accuracy in tracking electrical activity, and which cannot be accomplished by conventional weather radars. The disadvantages are: (1) relatively high cost, (2) no warning for a storm which develops directly overhead, (3) requires laboratory environment for remote sensors and (4) land lines for communication.

There existed only one manufacturer with an operational system at the time of procurement. Subsequently, a second manufacturer has developed a three station DF/locator system. The test system is shown in Figure 6. Figure 6(a) shows the crossed loop and flat plate sensors used at the two remote sites. Figure 6(b) illustrates the analog and digital electronics deployed at the remote sites. Figure 6(c) shows the central position analyzer, plotter and teletype used to determine strike location.

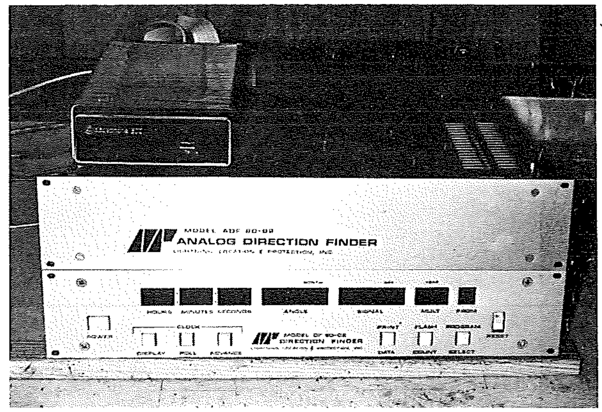
DISCUSSION

Several of the lightning warning systems include a color coded dial indicative of lightning intensity. These dials imply a manufacturer determined warning threshold. However, only one system tested (viz, the field mill device) contains manufacturer determined alarm criteria. Warning level thresholds for the other systems must be chosen by the user.

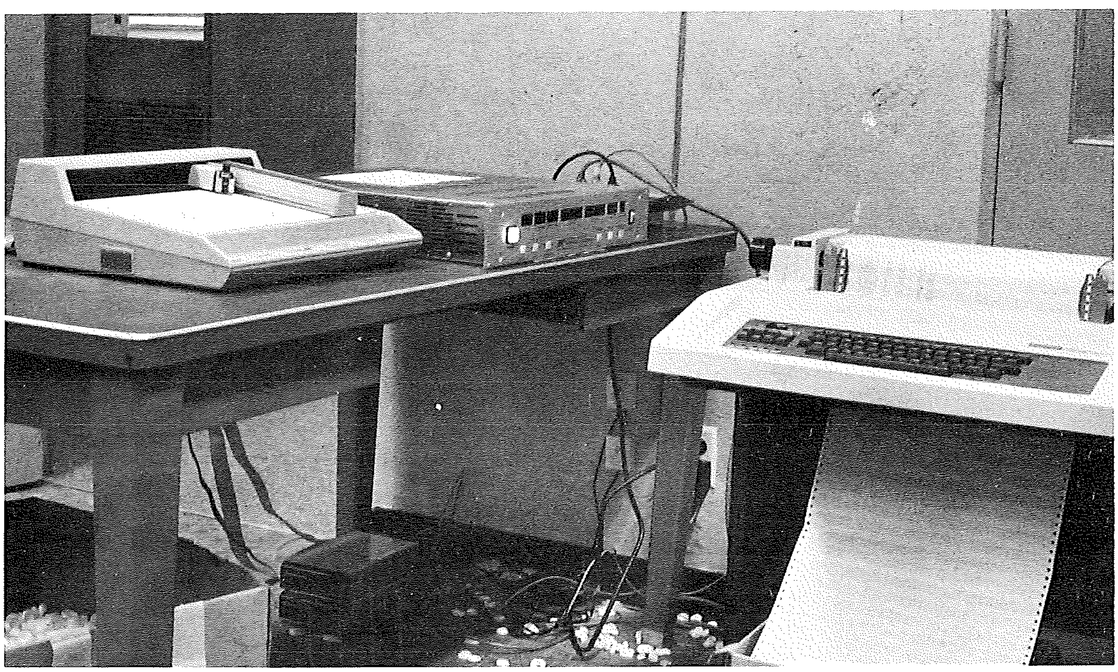
From the user standpoint, this flexibility of warning criteria is both useful and potentially dangerous. It is useful in that the user can establish his own warning thresholds based on the location and operating characteristics of his mine. However, the alarm settings should be made with a reasonable understanding of the principles and operating characteristics of the warning system.



(a) Crossed Loop and Flat Plate Sensors



(b) Analog and Digital Electronics



(c) Central Facility

Figure 6. Triangulation Location System

Appearance of specific brands, equipment or trade names in this report does not imply endorsement by the Bureau of Mines.

Thus, the flexibility of threshold setting is potentially dangerous for an uninformed user. The manufacturer color coded dial tends to imply alarm criteria which do not exist for most units. Unwarranted confidence in the warning system operation can thus result in ineffective and hazardous application.

TEST INSTRUMENTATION

1. Optical Lightning Location System

The review of accident/incident reports of premature detonations induced by lightning indicate that electrical energy is coupled from a cloud-to-ground strike. This indication is plausible since the ground strike represents a significantly higher energy discharge than the intracloud discharge. The optical lightning location system was developed to provide ground truth data on the location of the ground strike. The system consists of a ground flash (sferic) discriminator at a central site. When a ground flash is detected, a VHF transmitter is pulse keyed. The transmitted pulse activates the shutter of three all sky cameras deployed in an equilateral triangle. The direction to the flash from each camera provides sufficient information to locate the strike point through triangulation.

The ground flash detector is a modified form of flash counter developed by Prentice, et. al. (1975). The circuit shown in Figure 7 has a passband of 100 to 2500 Hz. The detection antenna is a six-foot monopole modified to achieve the desired frequency response. In addition a variable input resistor is used by the operator to hold off or significantly alter the sensitivity of the circuit, thus discriminating against weaker (or more distant sferics). The crystal controlled transmitter keyed by the flash counter has nominal output of 235 MHz. The receivers at each of the three sites, as well as the transmitting monopole and 11-element directional receiving antennas, were acquired as stock commercial equipments.

Shown in Figure 8(a) is the camera and associated electronics which are powered by the 12-volt storage battery located beneath the stand. The camera views a parabolic reflector which images the visible sky to the horizon. The camera shutters are activated by the initial lightning stroke with an inherent delay time of 95 milliseconds.

The closeup view in Figure 8(b) illustrates the access to the camera and receiver electronics located in the upper portion of the stand. When the hinged door is closed, the camera looks down upon the convex parabolic reflector and a clock as shown in Figure 8(c). A lightning strike is shown in Figure 8(c) illustrating the triangulation algorithm. Each camera was surveyed so that 0 degree on the template is aligned with true north. In the case shown, lightning struck ground at an azimuth of 345.5 degrees from the site.

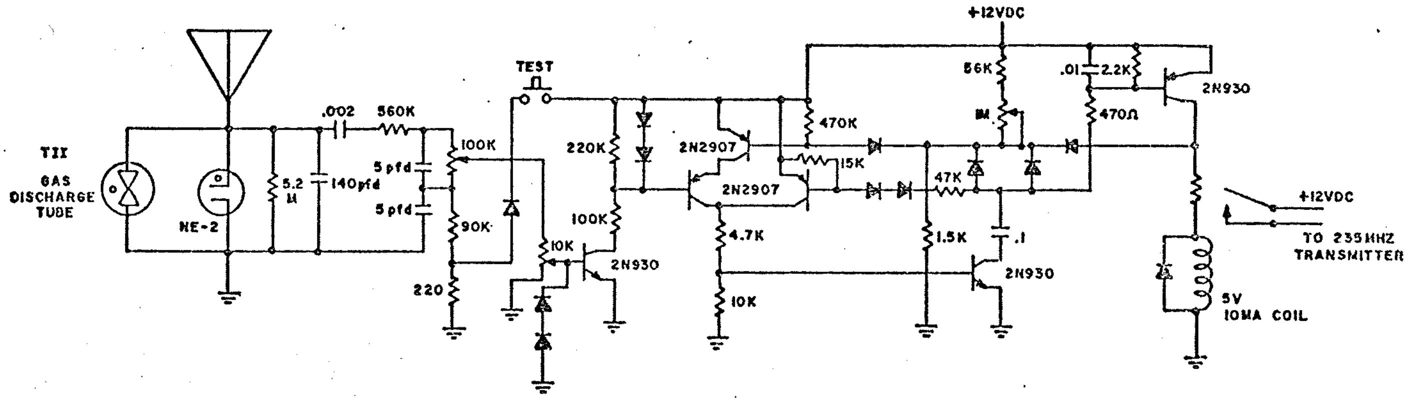


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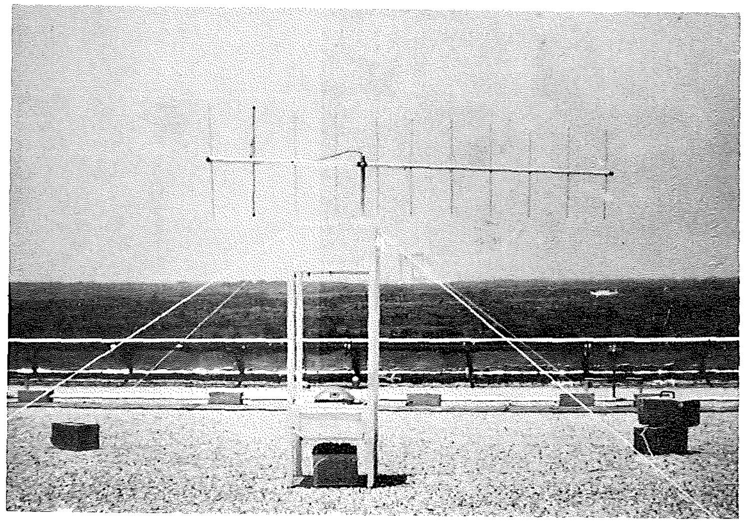
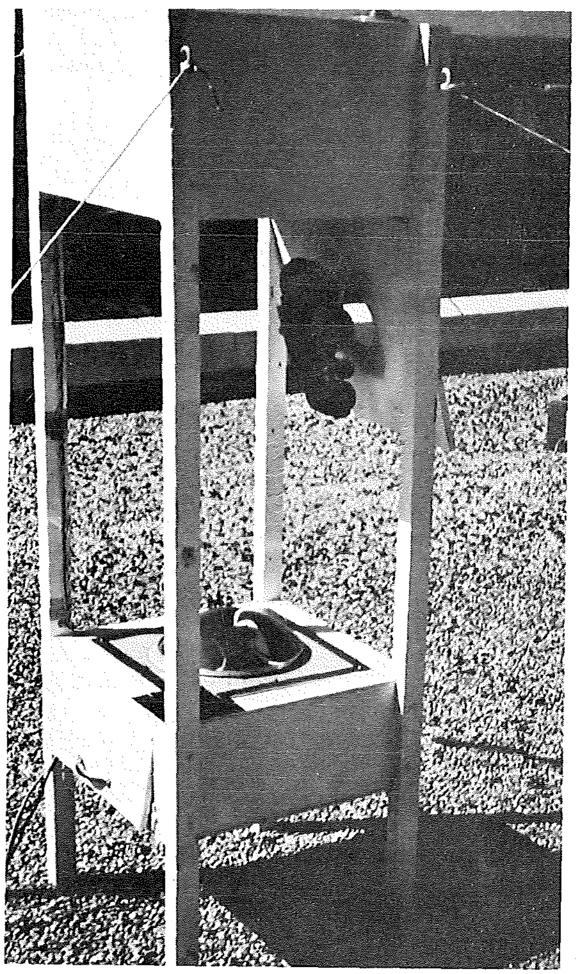
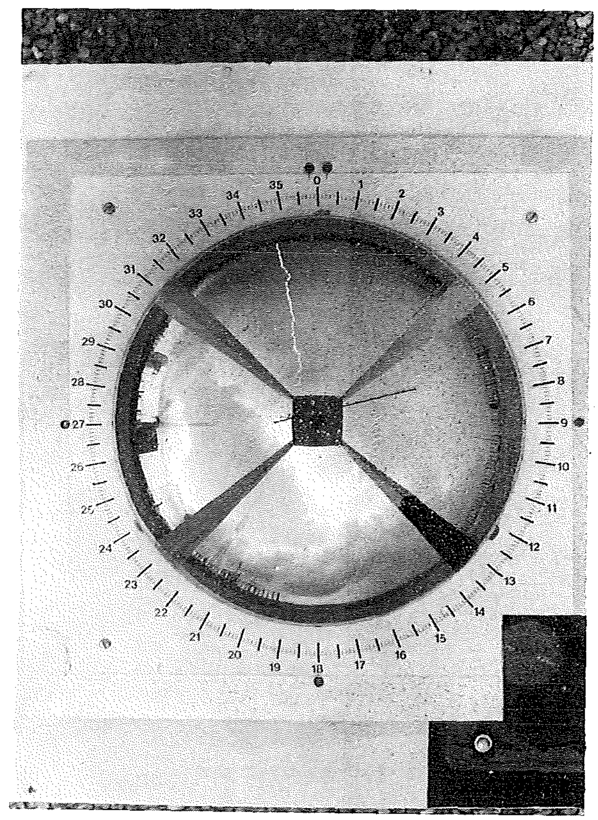
FIGURE 7. Modified Lightning Flash Detector



(a) Receiving Antenna and Housing



(b) Electronics Access



(c) Lightning Strike

Figure 8. Optical Lightning Locator

Also shown in Figure 8(c) are the LEDs used for nighttime photography situated at 0, 90, 180 and 270 degrees with two at 0 degree. The LEDs are used to align an azimuth template for night photographs since the azimuthal grid does not photograph in the dark.

Several significant problems were encountered in the development of the optical lightning locators. One unit was fabricated and deployed atop the four-story library building on the SwRI campus. Tests were begun on this prototype during the fall 1978 storm season in San Antonio. Initially high contrast copy film was used to ensure that the azimuthal grid was included in the photograph. After two storms it was concluded that the film speed was too slow to register lightning flashes. Thus, TRI X-400 was substituted.

Experience with the flash counter indicated that the device was false triggering on intracloud discharges. As a result of this finding, the receiver sensitivity was significantly decreased so that the higher threshold would trigger on the higher energy cloud-to-ground discharges. It was also determined that the central flash detector was triggering the camera while the storm was at a large distance from the camera site. A switch was added to inhibit the camera trigger until the lightning was within 10 miles range of the camera.

After these improvements were made, the system photographed 26 lightning flashes in 34 exposures during one storm. Several of these photographs contained as many as three active lightning channels. This performance was realized during the spring 1979 (April-May) storm season.

2. Detonator Simulation

a. Detonation Characteristics

A detailed description of modern blasting technology is given by Johansson and Persson (1970). The summary given here is a paraphrase of the work offered by Berger (1977). The primary initiator for high explosives is the electric detonator (blasting cap), consisting of a metal shell loaded with several powder charges and an electrical ignition system attached to a pair of insulated "leg" wires. A drawing of a typical detonator is given in Figure 9. In most cases, the explosive charges consist of a base load of high explosive, a primer and ignition load. The electrical ignition element is imbedded in the ignition load and consists of a short piece of high resistance wire welded between the leg wires. A rubber plug is used to form a watertight assembly and to hold the bridgewire in place in the center of the ignition load.

When sufficient energy passes through the electrical system, the bridgewire becomes hot and ignites the ignition load, resulting in ignition of the primer and base charges. In heating the bridgewire, long duration low power input is within the limits imposed by the rate of conduction of heat away from the bridgewire as effective as short duration high power input to initiate detonation.

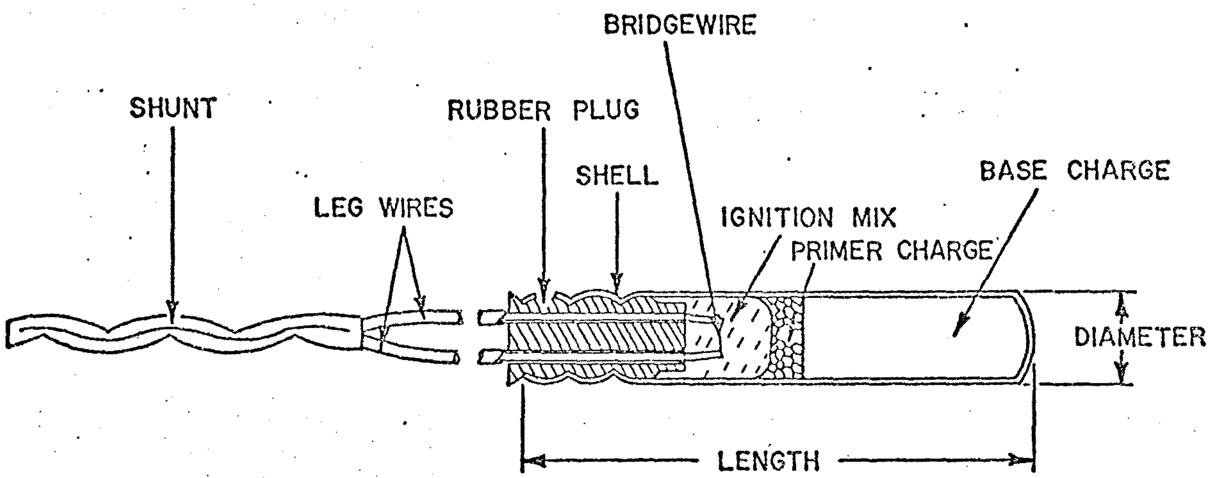


FIGURE 9. - Diagram of a Typical Electric Detonator

There exists a wide variety of explosive detonators differing in physical size, case material, high explosive base charge, and electrical characteristics. The energy output obtained from the detonator is a function of the base charge used. The electrical characteristics are generally quoted as the "all-fire" and "no-fire" currents. The all-fire current is the approximate minimum current which will guarantee that all detonators function. The no-fire current is the approximate maximum current for which no functioning detonators are expected. Table 4 presents the characteristics of several typical electrical blasting caps.

Exploding Bridgewire (EBW) is another basic type of detonator coming into common use. To initiate an EBW, the electric current must be applied rapidly enough to heat the bridgewire to vaporization and explosion. Typically currents of 800 amperes are required to initiate an EBW. No ignition or primer loads are required because the wire explosion is intense enough to initiate the base explosive directly. Ordinary detonators are initiated when the bridgewire becomes hot enough to ignite the ignition load regardless of the rate of bridgewire heating. EBWs require high intensity, short-duration ignition enrgy.

At least three mechanism exist for detonation of electric blasting caps by electrical storms. The most obvious is a direct lightning strike. The second, and most probable, is the induction of current impulses in the cap by nearby cloud-to-cloud or cloud-to-ground lightning. Third, massive electric potentials can occur through large static buildups during electrical storms. These large electric fields can build to the point of flashover, causing a spark to the cap's leads which in turn cause detonation. It is highly unlikely however that large static buildups could cause detonation of a blasting cap directly because no potential could build across the cap terminals themselves. The resistance of electric blasting caps typically is on the order of one ohm, prohibiting such a potential buildup.

There is certainty of detonation by a direct lightning strike; however, detonation by either of the other two processes depends upon the pulse response of the blasting caps.

Data is available on the maximum continuous DC current which safely may be applied through blasting caps. However, sufficient data has not been available to fully establish the firing characteristics when exposed to very short electrical impulses and combinations of impulses such as those experienced during electrical storms.

b. Detonation Simulation

SwRI recently conducted extensive tests under another program on the pulse response of blasting caps. Data were obtained relating to: (1) the mechanism of detonation by short electrical pulses, (2) the firing characteristics during pulsed conditions.

TABLE 4. - Typical Electrical Detonator Characteristics

Product No.	Shell Material	Base Charge (Grains)	Resistance (ohms)	All Fire Current (amps)	No Fire Current (amps)
E-83	Aluminum	13.5 PETN	1.16	0.4	0.1
E-86	Bronze	3.0 Lead Azide	2.3	0.4	0.1
E-2B	Bronze	5.0 RDX	1.1	0.5	0.3
E-108	Aluminum	3.2 PETN	0.44	0.6	0.2
E-321K	Aluminum	8.0 Tacot	1.1	0.7	*
X-884A	Aluminum	6.5 RDX	49-60.3	0.8	0.2
E-109	Brass	5.0 RDX	45-63	0.8	0.2
E-92	Bronze	1.8 Lead Azide	0.12	3.0	1.5
E-107	Bronze	5.0 PETN	0.39	4.0	1.0

The series of tests conducted to explore the mechanism of detonation by short pulses revealed that detonation is a function of the energy content of the pulse determined by the applied voltage, the blasting cap resistance, and the pulse length. For uniform pulses, these factors are related by

$$E = \frac{V^2 t}{R} , \qquad (4)$$

where

E = energy in joules,

V = voltage across cap terminals,

t = length of pulse, and

R = resistance of cap.

Tests showed that it is the energy product described by equation 4 which governs detonation.

Detonation tests were conducted with precisely controlled microsecond duration unipolar rectangular pulses. Blasting caps from different manufacturers and even different types of caps from the same manufacturer exhibit markedly different responses to pulsed electrical excitation. However, the firing energies of all the electric blasting caps tested fell in the range of 2.5 millijoules to 10 millijoules, a 4:1 range.

These values of firing energies and the relation described by equation 4 are valid only for short electrical pulses. As the time duration of the applied pulse becomes greater than a few hundred milliseconds, the current required to detonate approaches that stated by the manufacturer. Typical firing currents are on the order of 500 milliamperes.

Another series of tests under the previous program defined thermal decay characteristics of blasting caps. This data relates to the cumulative heating effects of two or more sub-detonating pulses. A cap excited by a sub-detonating electric pulse tends to retain the heat generated by that pulse for one millisecond to 100 milliseconds after termination of the pulse. After 100 milliseconds, most caps have dissipated the heat from a sub-detonating pulse to negligible proportions.

Ambient temperature has a mild effect on the firing energy of a cap under pulsed conditions. Typically, increasing the ambient temperature by 20°F will cause a 10 percent reduction in the firing energy necessary for detonation. Because the mechanism of cap detonation is simple joule heating and the heat of detonation is considerably hotter than the ambient, nominal changes in the ambient temperature will only weakly effect detonation characteristics.

Two modes of premature detonation of blasting caps were simulated in the lightning warning system evaluation: (1) bridgewire heating, and (2) bridgewire to case arcover. Figure 10 shows the bridgewire modeled using a 1 ohm resistor. The resistor is connected to an external 1000 foot perimeter loop of 22 guage copper wire laid on the ground. Since firing lines are generally twisted pair, the open loop wire represents a worst case condition. The lower portion of the circuit is a pulse generator used to calibrate the output. The two energy levels of particular interest are the no-fire (2.5 millijoules) and the all-fire (10 millijoules) levels.

Figure 11 shows the bridgewire to case arcover simulator. The input was connected to an external linearly extended 600 foot length of #22 copper wire which was grounded at both ends. The calibrate input was used to establish a 2 kV level on the output constituting the breakdown threshold voltage.

The output of both these circuits was continually recorded to determine when a premature explosion would have occurred, and to correlate this data with the warning indications of the lightning warning systems.

3. Test Site Selection

The primary considerations used in the selection of three sites were: (1) relative isoceraunic levels (i.e. thunderstorm day statistics), (2) availability of support facilities, (3) terrain features, and (4) facility cost. Initial deployment was selected to be on the SwRI campus. This test was scheduled to be conducted during the spring 1979 storm season (1 April 1979-15 May 1979). Using the Weather Bureau thunderstorm day statistics (1952), Figure 12 indicates that during the months of April and May, one can expect 10 thunderstorm days. The thunderstorms active during the spring in San Antonio, Texas are due to the movement of large air masses, and hence, are of the frontal type or squall line.

Deployment at SwRI was desirable also because it presented an opportunity to establish test procedures without the attendant problems of operating in a remote environment. The site provided familiar support facilities at minimal cost. The testing schedule at SwRI used the period 15 May 1979 - 1 June 1979 to evaluate the test procedure, make any required modifications, and move to a second site.

The second scheduled test was 1 June 1979 - 15 July 1979. As shown in Figure 13, the area with the highest level of thunderstorm activity is the mid-Florida peninsula. The terrain in Florida is conducive to the convective type thunderstorm cell caused by local surface heating. Considerations of support facilities and cost led to the choice of the Kennedy Space Center complex. Since NASA had supported previous atmospheric electricity experiments, this site was ideally suited to provide support for this experiment.

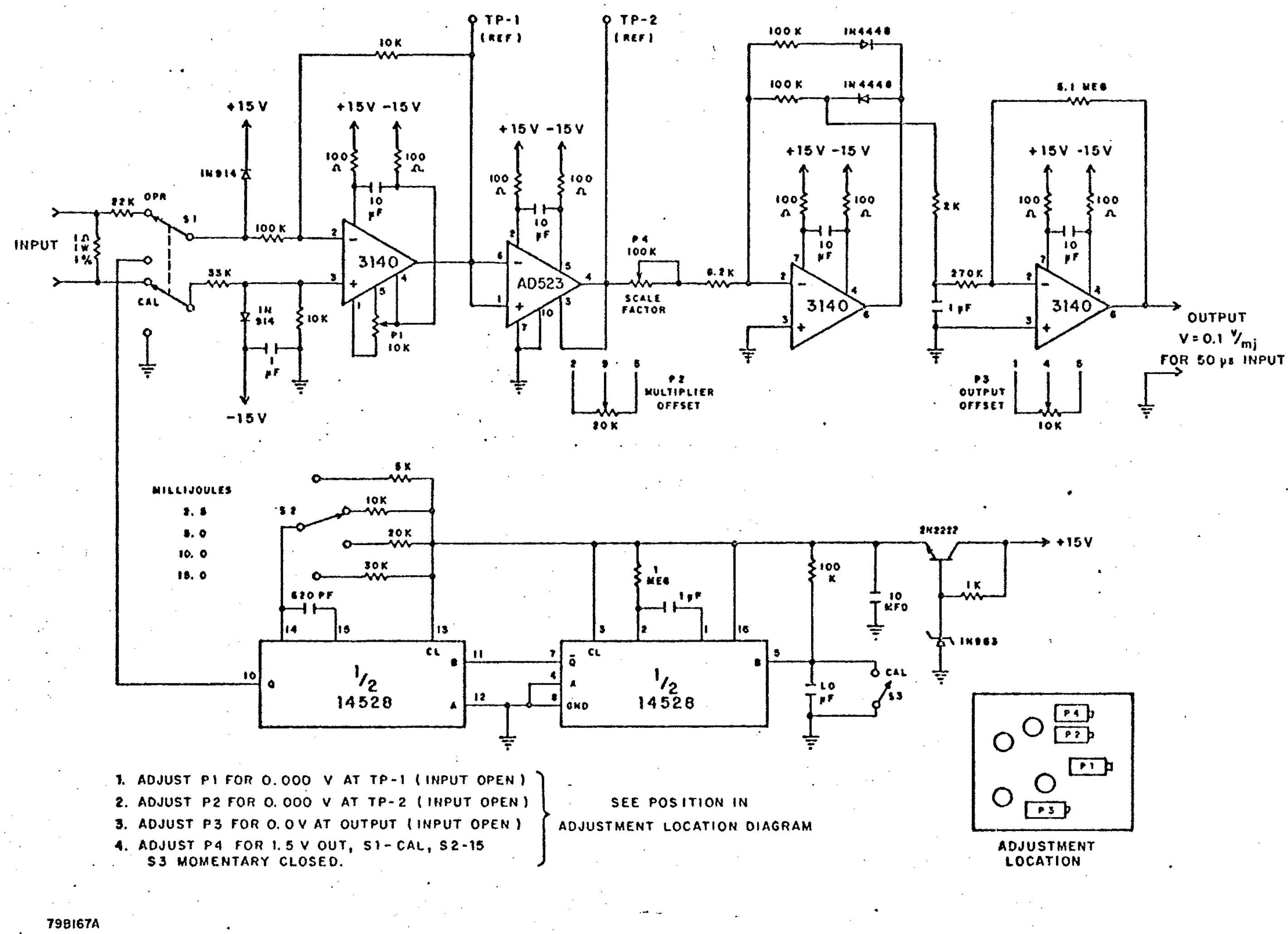
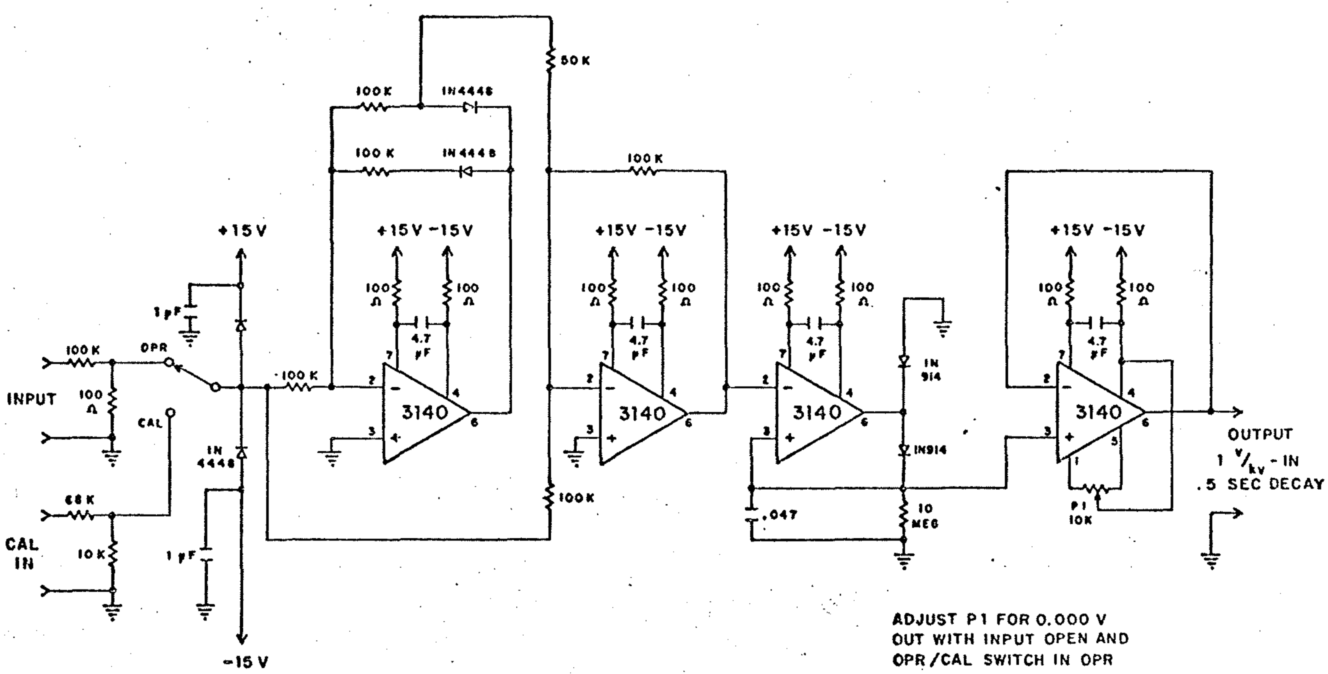


FIGURE 10. - Bridgewire Monitor



PEAK VOLTAGE MONITOR

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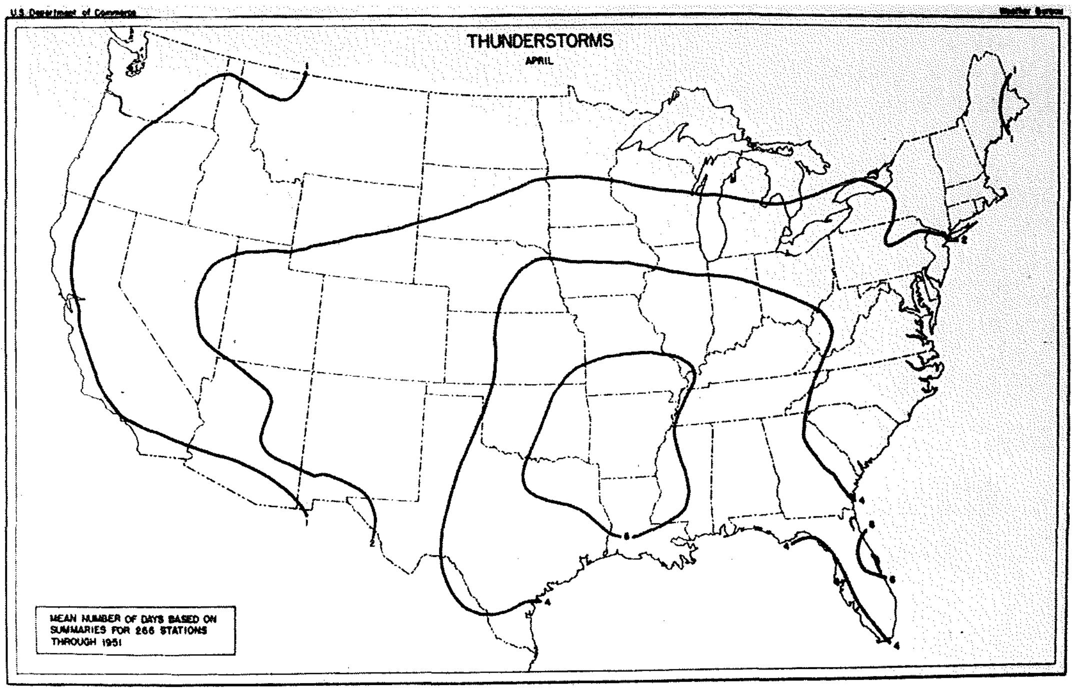
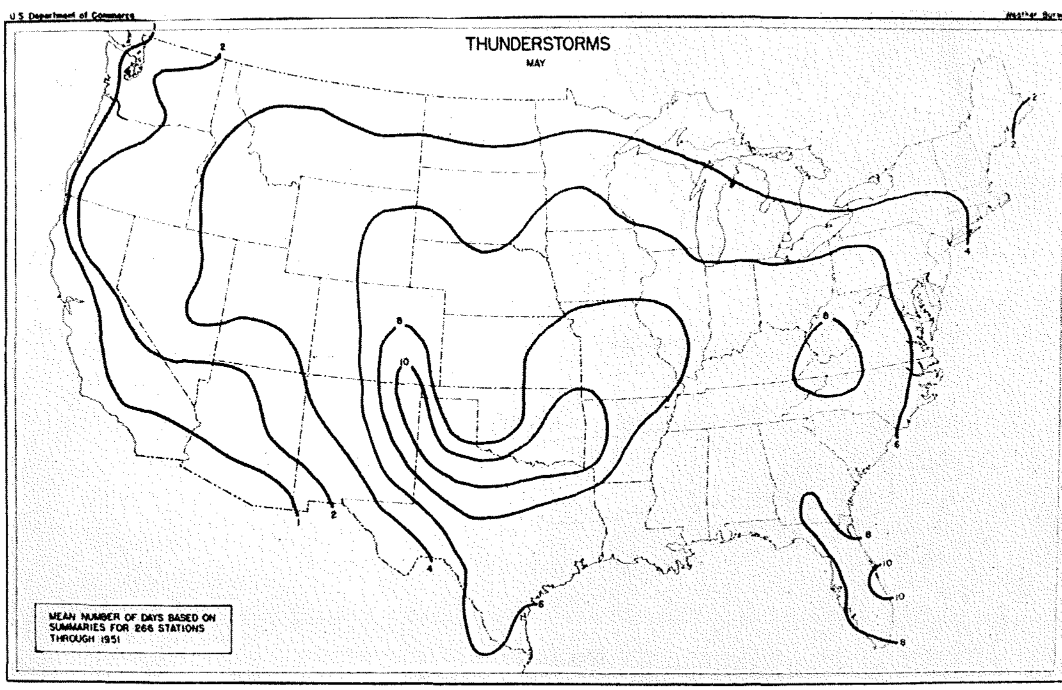
FIGURE 11. - Case to Bridgewire Monitor

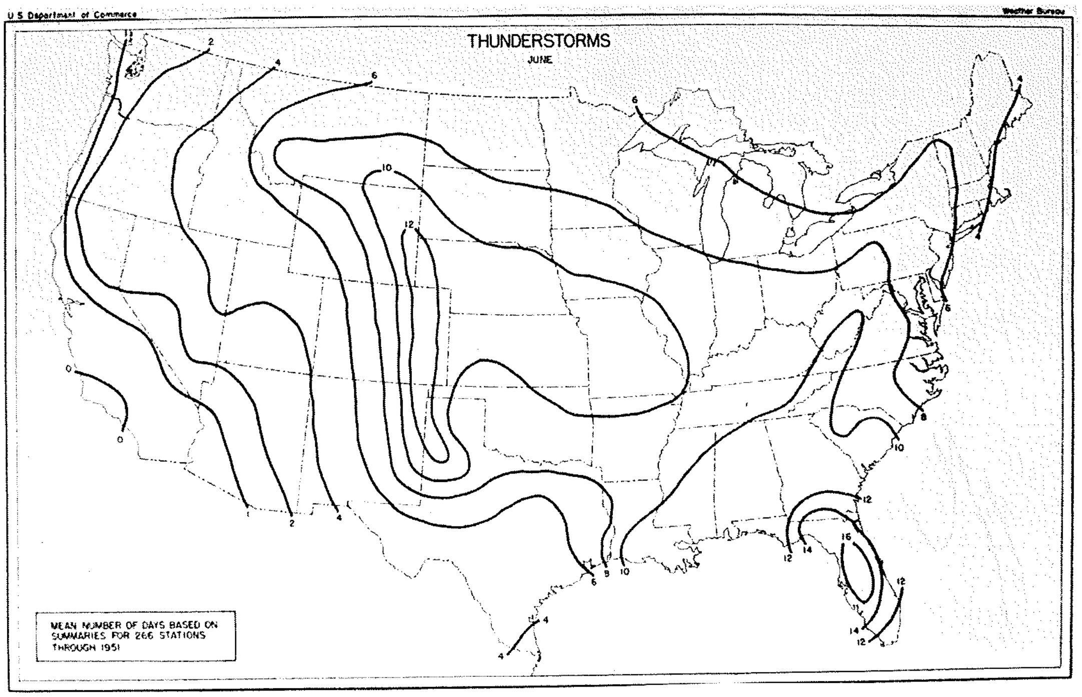


(a) ISOCERAUNIC LEVELS FOR APRIL

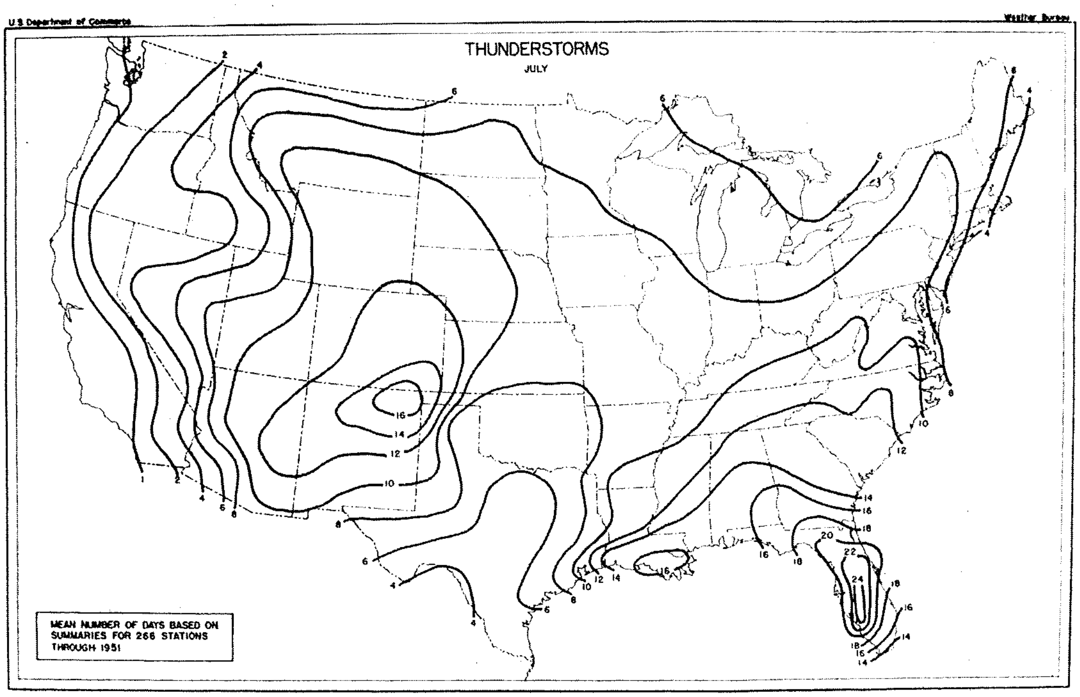


(b) ISOCERAUNIC LEVELS FOR MAY

FIGURE 12. SPRING ISOCERAUNIC LEVELS



(a) ISOCERAUNIC LEVELS FOR JUNE



(b) ISOCERAUNIC LEVELS FOR JULY

FIGURE 13. EARLY-MID SUMMER ISOCERAUNIC LEVELS

The third test used the period 15 July 1979 - 31 August 1979. A review of Figures 13(b) and 14 indicates a high level of activity in northern New Mexico. A site in the mountains of New Mexico was particularly desirable to permit inclusion of mountainous terrain (orographic) effects in the evaluation study. After considering support facilities and cost, a site was chosen at Langmuir Laboratory near Socorro, New Mexico. The laboratory is owned and operated by New Mexico Institute of Mining and Technology. Facilities were readily available to support this evaluation. The laboratory is located at an elevation of 10,500 feet and has been a primary center of study of atmospheric sciences since the early 1960s.

SwRI TEST SITE

SwRI is located on the western city limits of San Antonio, Texas. The city is situated in the south-central portion of Texas. Northwest of the city the terrain slopes upward to the Edwards Plateau and to the southeast it slopes downward to the Gulf Coastal Plains. Soils are blackland clay and silty loam on the Plains and thin limestone soils on the Edwards Plateau. The west field site at SwRI is 750 ft above sea level.

San Antonio is situated between a semiarid area to the west and the coastal area of heavy precipitation to the southeast. Precipitation is fairly well distributed throughout the year with heaviest amounts during May and September. Precipitation from April through September usually occurs with thunderstorms, fairly large rainfall occurring in short periods of time. Hail of damaging intensity seldom occurs but light hail is frequent in connection with springtime thunderstorms. This report of climatological data is a summary of that described by NOAA (1977).

The field deployment of the lightning warning sensors at SwRI is shown in Figures 15 and 16. The mobile laboratory is a 25-ft trailer as shown in Figure 17(a). Mounted atop the trailer are wind speed and wind direction sensors. The platform extending from the rear roof of the trailer is the azimuth/range location system. An interior view of the mobile laboratory is shown in Figure 17(b). Illustrated in Figure 18 is the deployment of the sensors as viewed toward the east and toward the west.

During the evaluation period, 1 April - 15 May 1979, 10 thunderstorm events were monitored over a cumulative period of 36 hours. All storms were frontal type thunderstorms, initiated by the movement of large air masses.

KENNEDY SPACE CENTER TEST SITE

The Kennedy Space Center (KSC) complex is located on the Atlantic Ocean, with the Banana and Indian Rivers running through the complex. Terrain in the area is flat, soil is mostly sandy, and elevations in the area range from

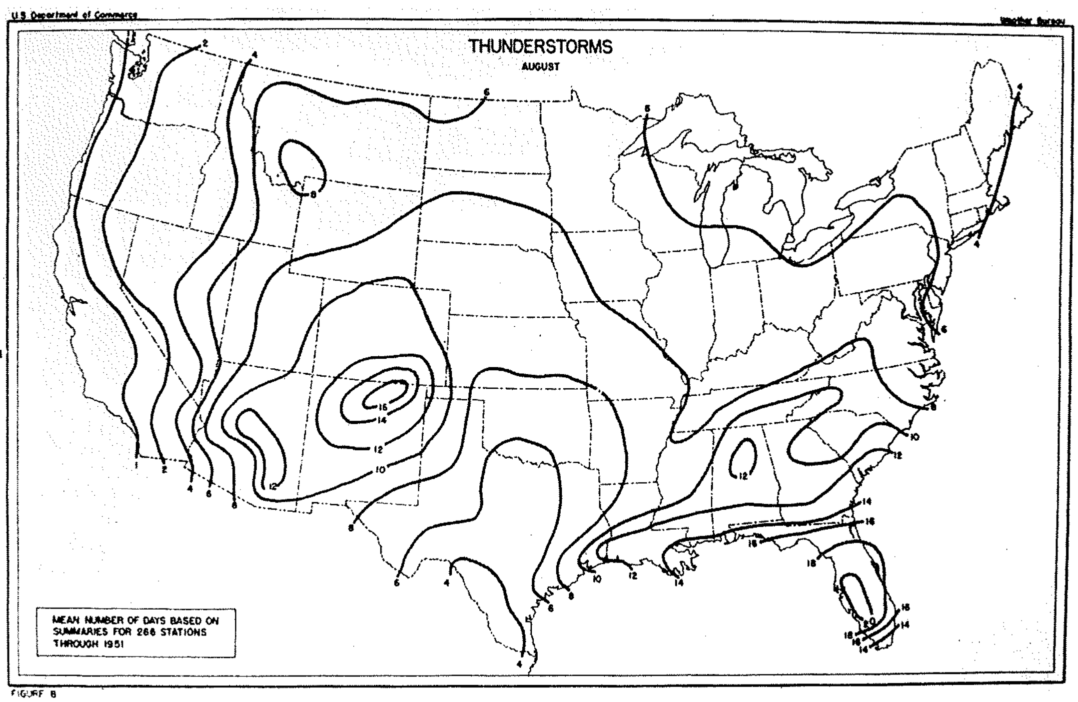


FIGURE 14. ISOCERAUNIC LEVELS FOR AUGUST

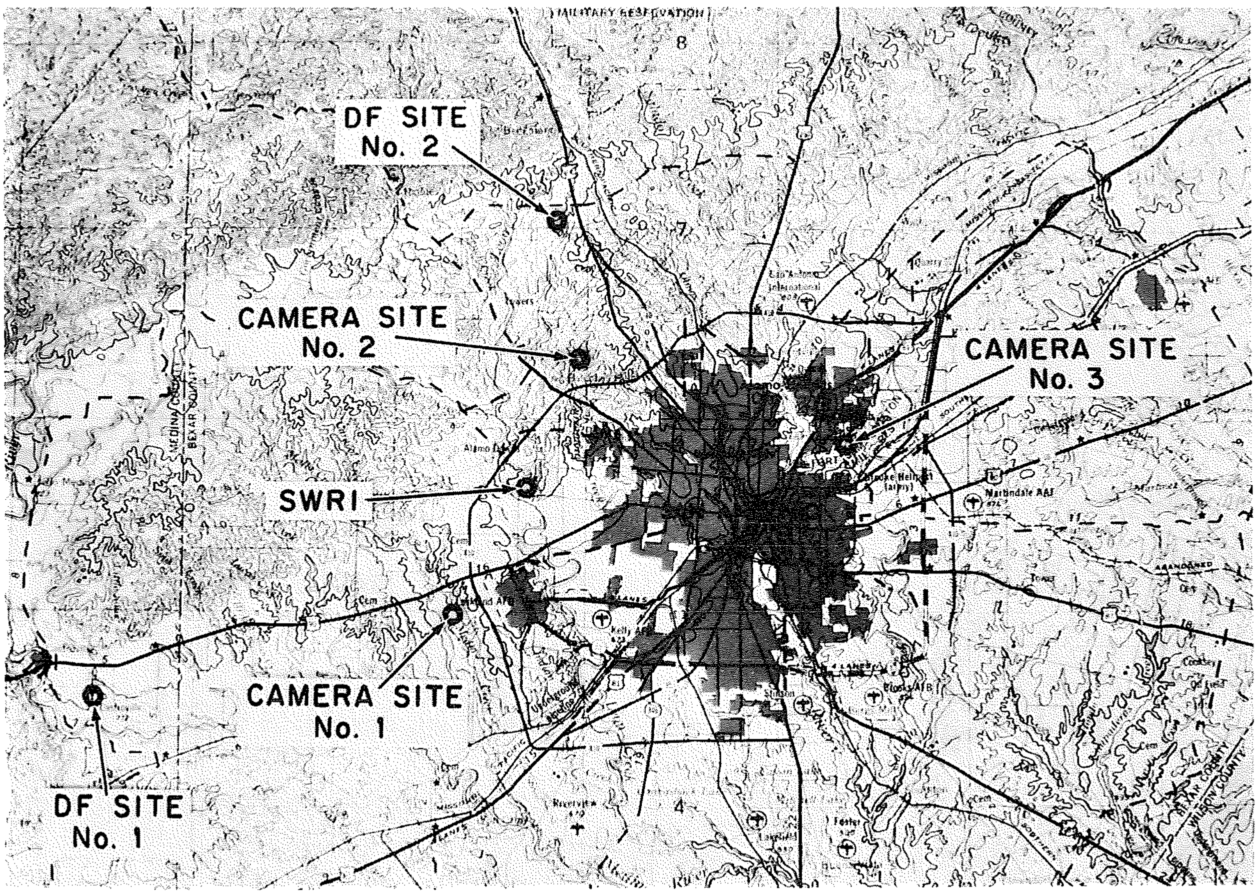


FIGURE 15. SwRI DEPLOYMENT IN SAN ANTONIO

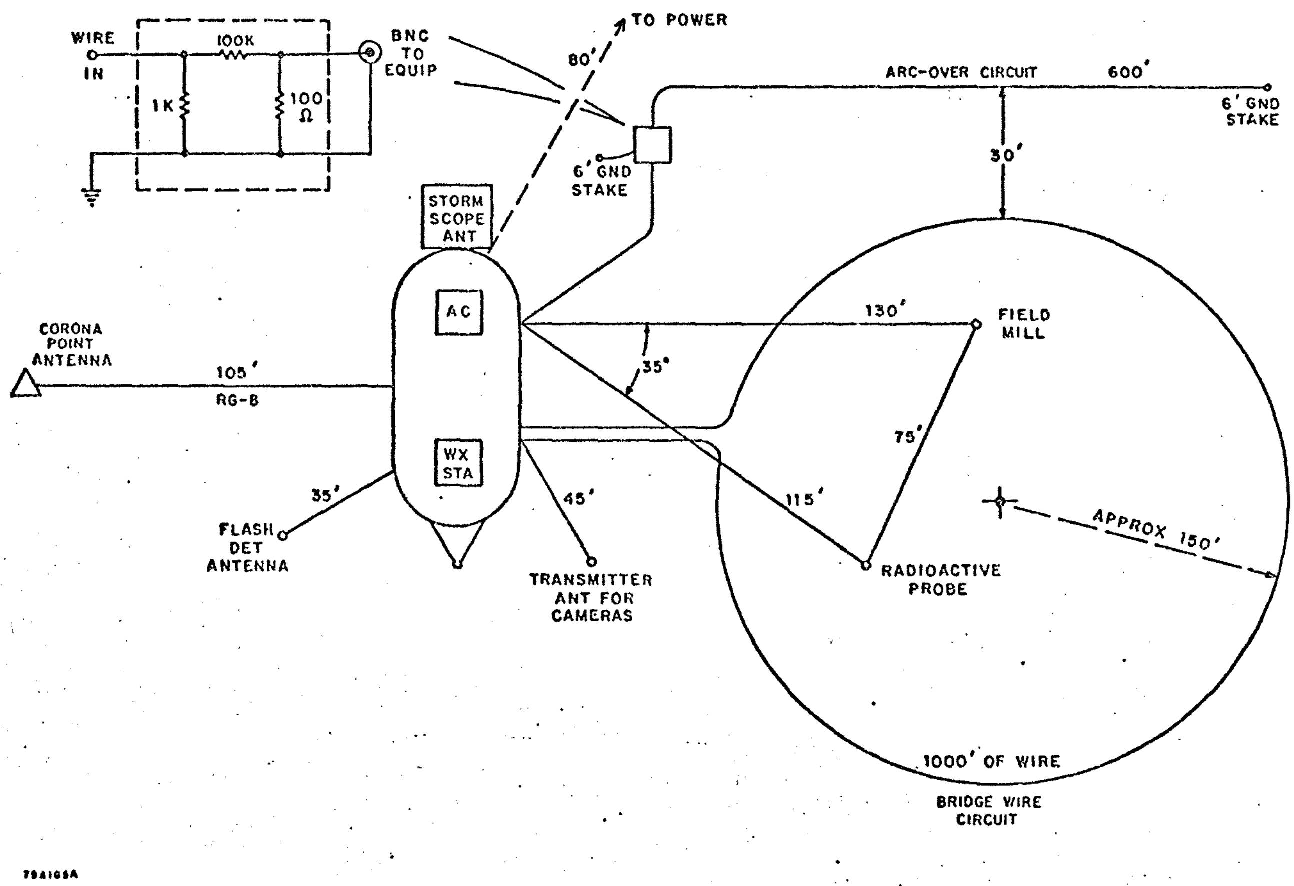
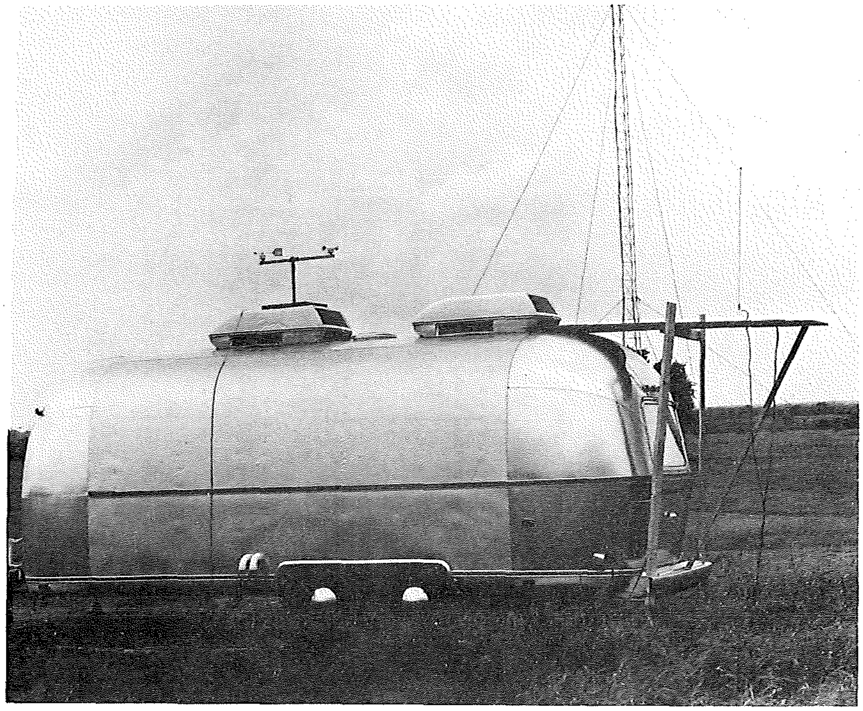
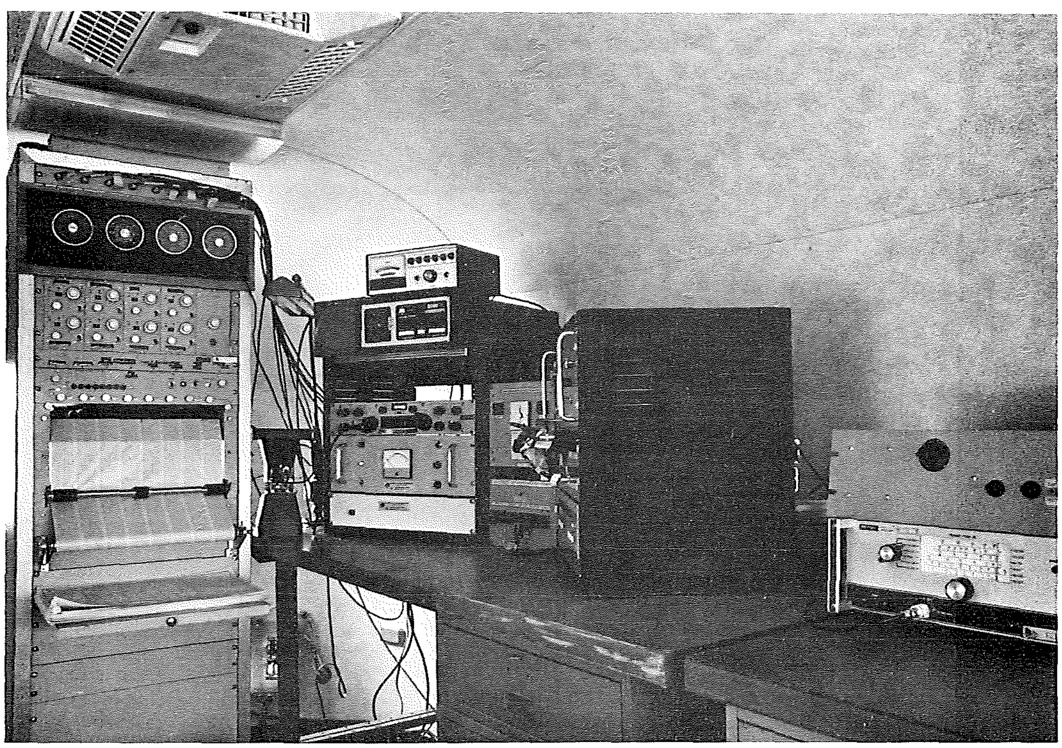


FIGURE 16. - SwRI Site Layout - Overhead View

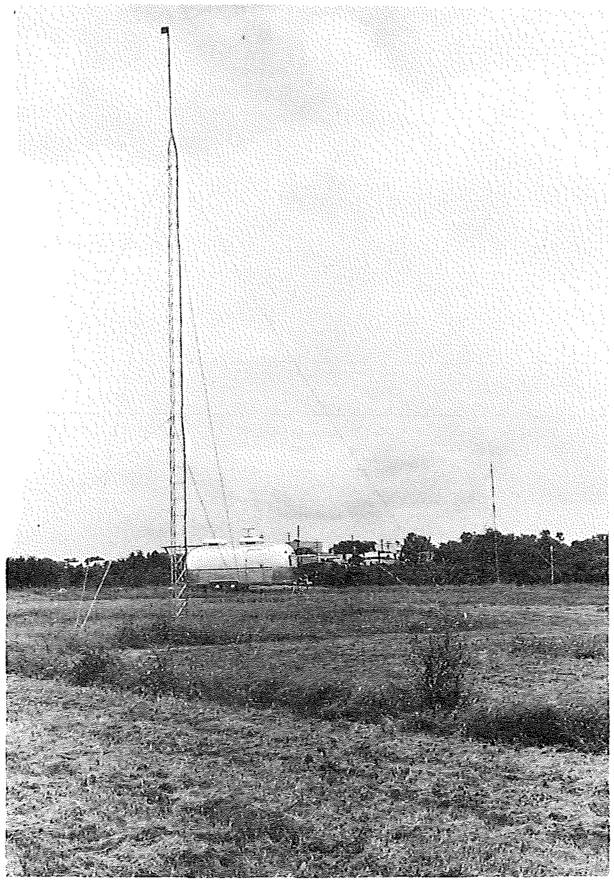


(a) SwRI Mobile Laboratory

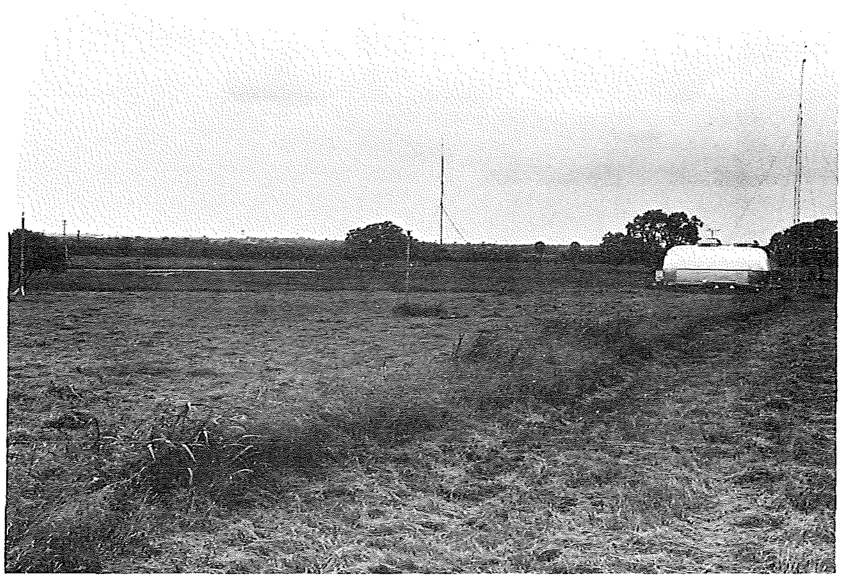


(b) Interior View of Mobile Laboratory

Figure 17. Central Field Facility at SwRI



(a) SwRI Field Site Looking East



(b) SwRI Field Site Looking West

Figure 18. Sensor Array at SwRI Site

3 to 15 feet above sea level. In the summer, while maximum temperatures reach 90 degrees or above during the late morning or early afternoon, the number of hours of 90 degrees or above is relatively small due to the beginning of the sea breeze near midday and the occurrence of local afternoon convective thundershowers which lower the temperature to the 80s.

The "rainy season" from June through mid-October produces 60 percent of the annual rainfall. The major portion of the summer rainfall occurs in the form of local convective thundershowers. These showers are occasionally heavy and produce as much as two or three inches of rain. This report of climatological data is a summary of that described by NOAA (1977).

A map of KSC is shown in Figure 19 showing the deployment of the mobile laboratory, the three optical locator sites and two direction finding sites used for the triangulation location system. A plane view of the mobile laboratory site is shown in Figure 20. Illustrated in Figure 21(a) is a view of the site looking toward the north and 21(b) is a view of the site looking south. As is readily apparent from Figure 21, the mobile lab is situated atop an elevated camera site with an unobstructed view in all directions.

Figure 22 illustrates the three camera locations--22(a) near pad 39A, 22(b) atop the operations and control building, and 22(c) atop the Pass and ID building.

Figure 23 shows the two direction finding sites-23(a) near pad 39A and 23(b) near the meteorological rocket launch site. The electronics were housed in the buildings and shelter shown adjacent to the antennas.

During the test period at KSC, 1 June - 15 July 1979, 22 thunderstorm events were monitored over a cumulative period of 43 hours. The triggering mechanisms for these storms was: (1) movement of frontal air masses, (2) localized convection due to surface heating, and (3) nearby passage of a tropical depression.

LANGMUIR LABORATORY TEST SITE

The Irving Langmuir Laboratory for Atmospheric Research provides a base for the study of cloud processes that produce lightning, hail, and rain. The laboratory is located 10,631 feet above sea level near South Baldy Peak in the Magdalena Mountains of the Cibola National Forest. It is approximately seventeen air miles southwest of Socorro, New Mexico. The Magdalena Mountains were chosen for the location of the laboratory because thunderstorms are initiated by the mountains. The storms are often isolated, stationary, and relatively small.

The weather patterns that produce frequent cumulus cloud development and thunderstorms over the laboratory during July and August each year are closely related to the physical features of its location. In the arid, southwestern

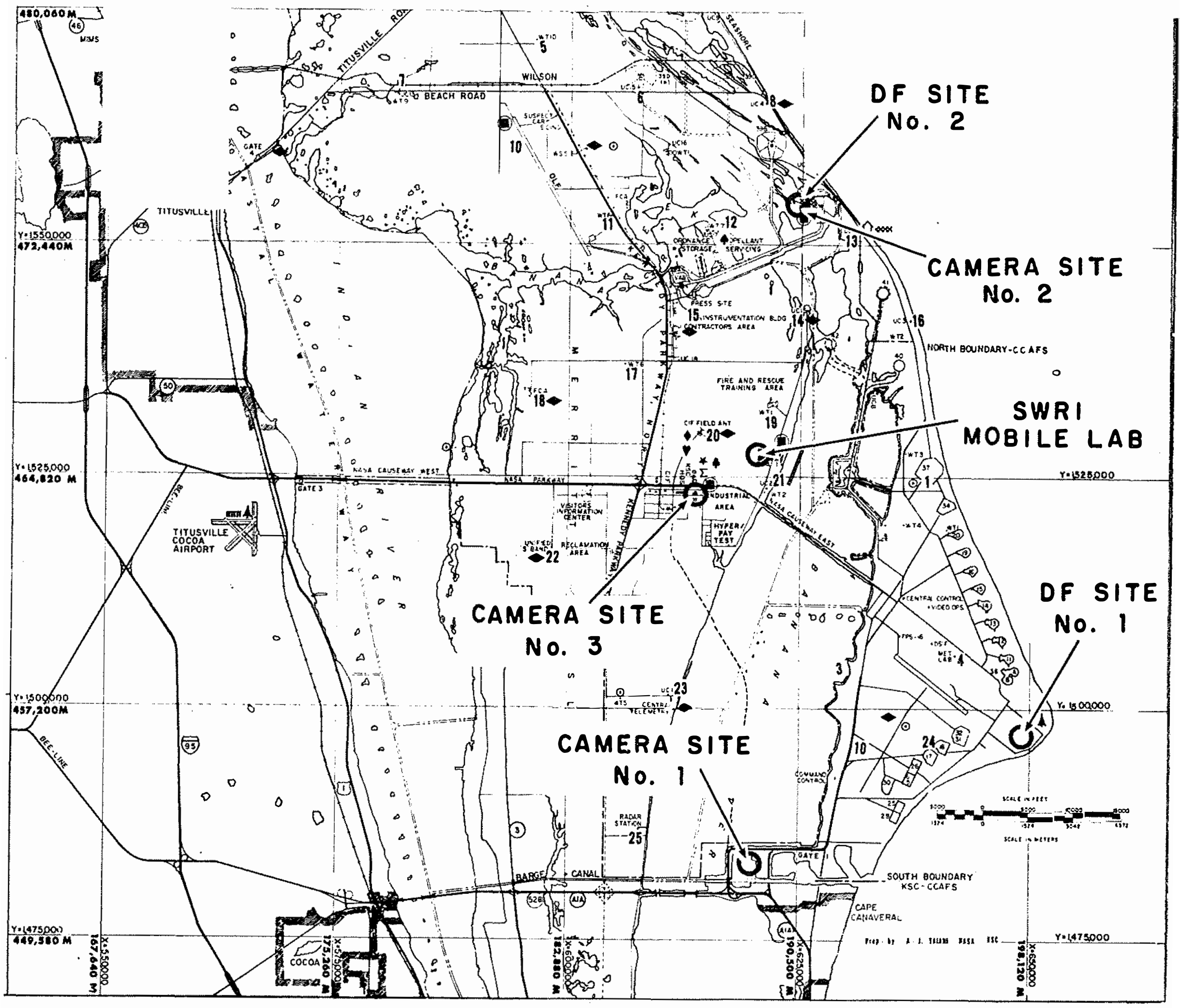


Figure 19, Kennedy Space Center Deployment

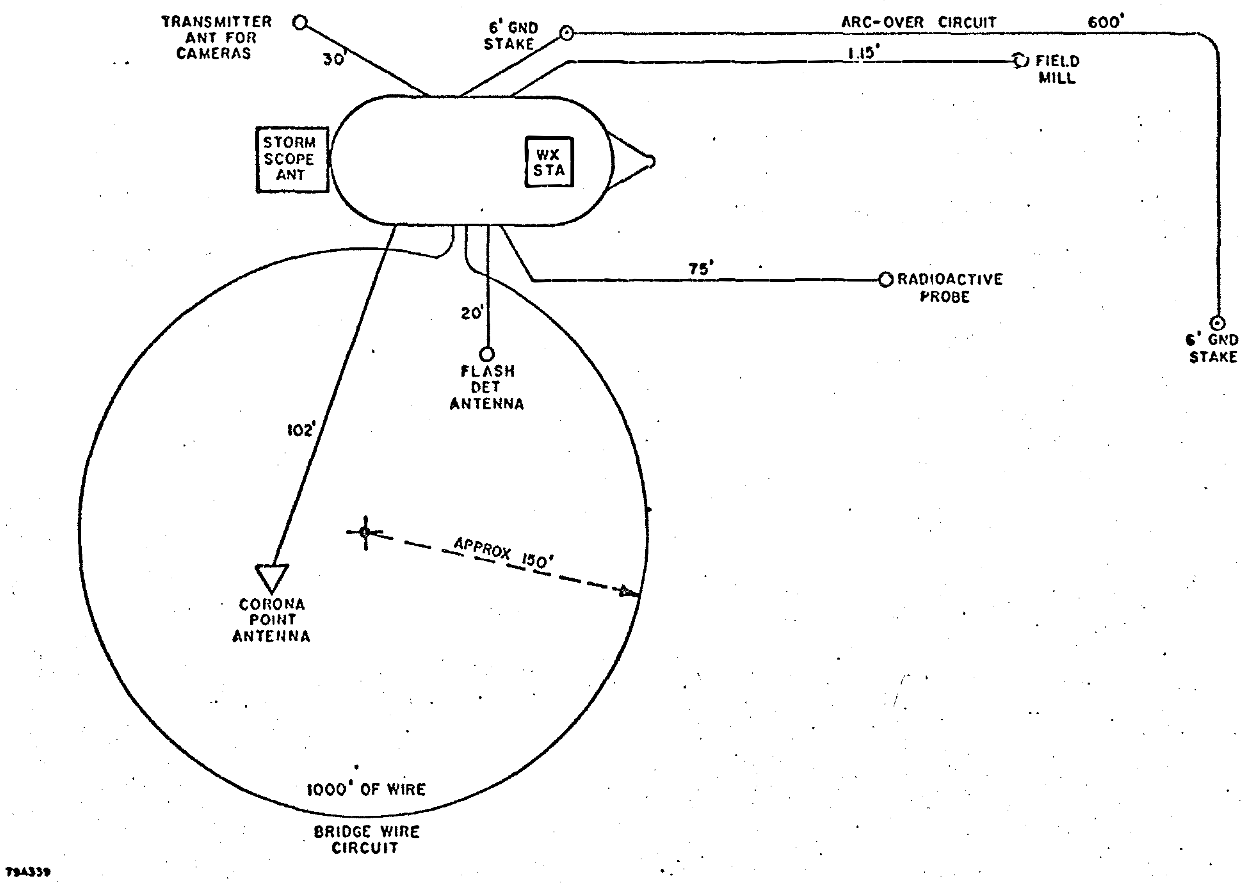
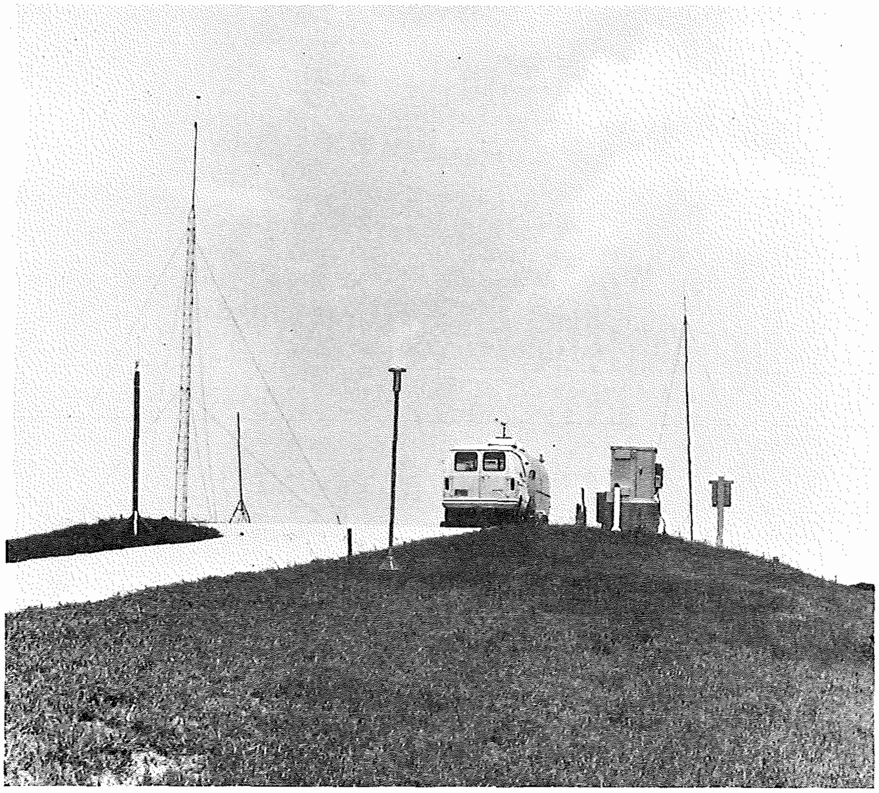
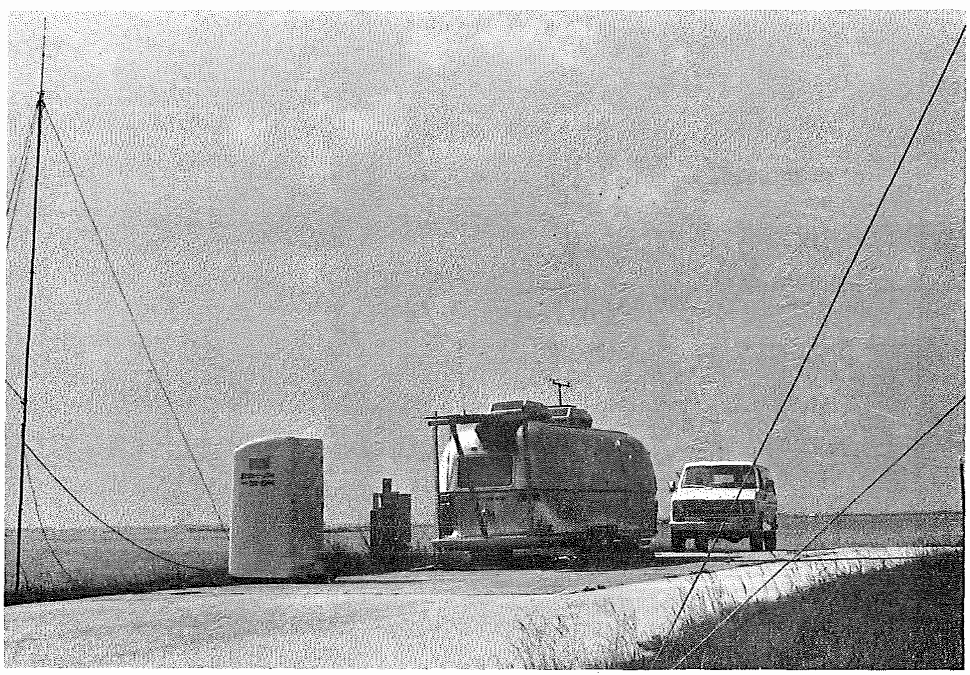


FIGURE 20. - Kennedy Space Center Site Layout - Plane View

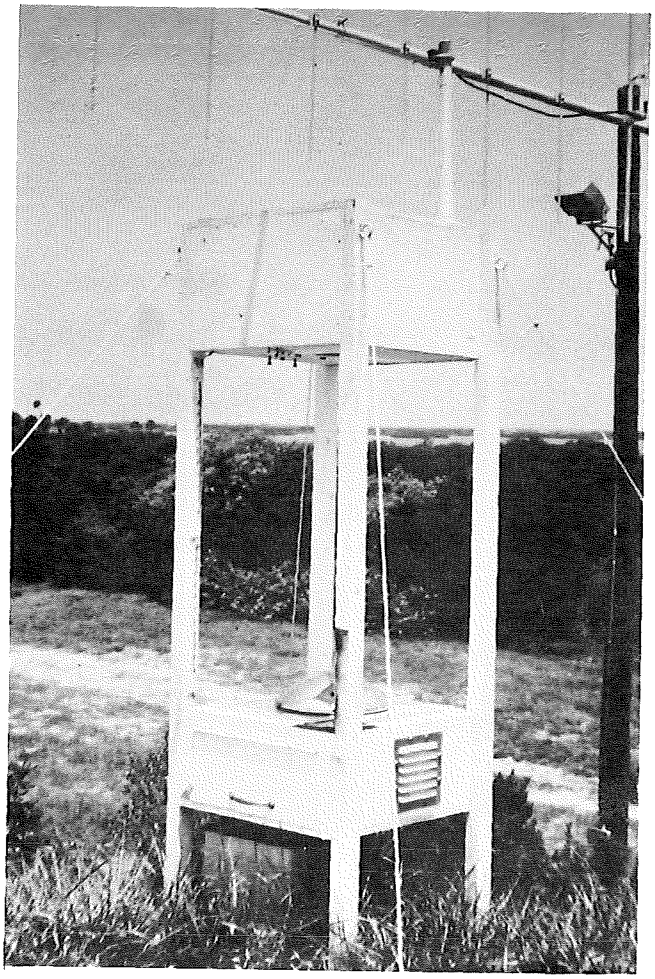


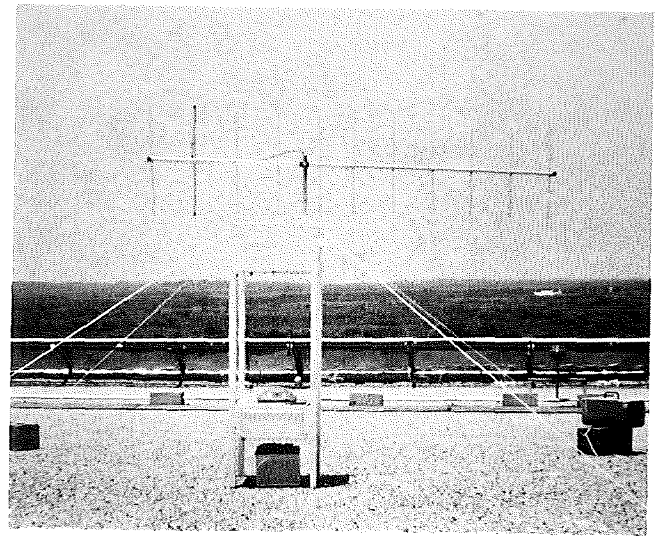
(a) KSC Site Looking North



(b) KSC Site Looking South

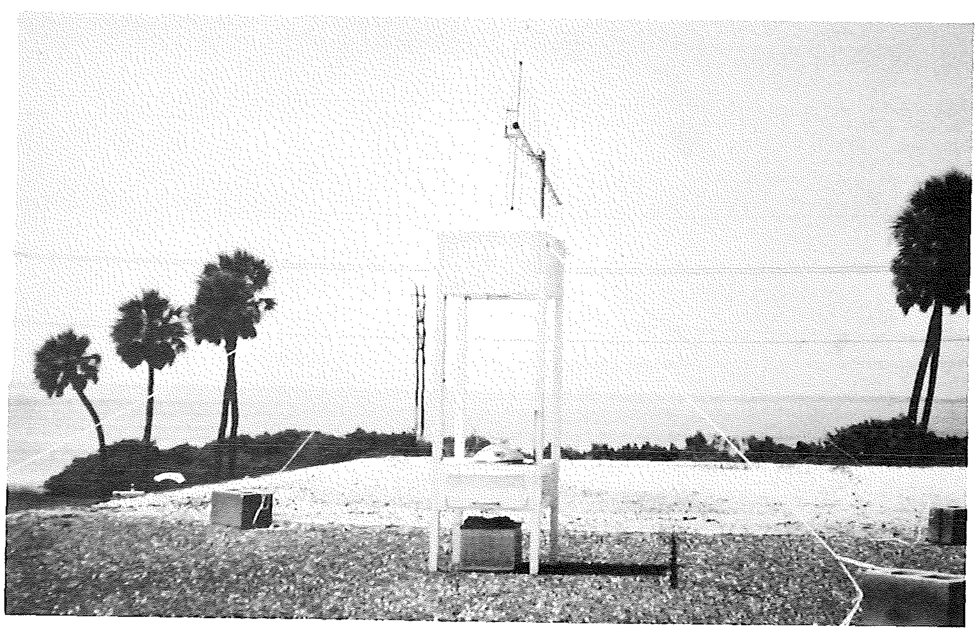
Figure 21. Mobile Laboratory Site at Kennedy Space Center





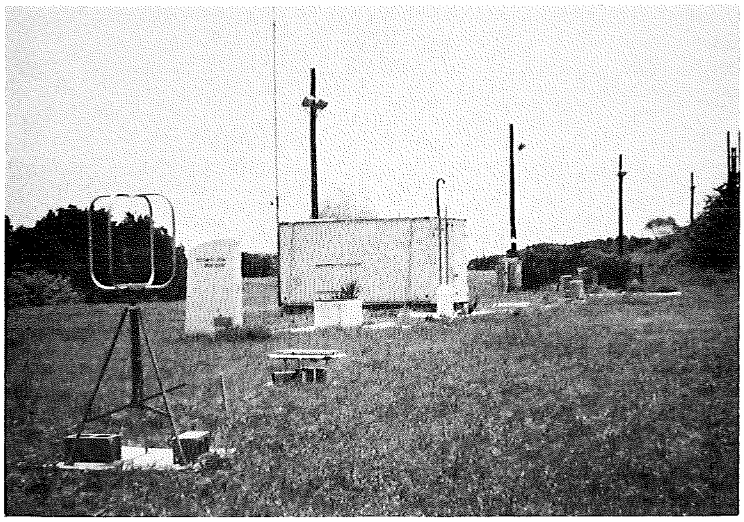
(b) Camera Site Atop the O & C Building

(a) Camera Site Near Pad 39A

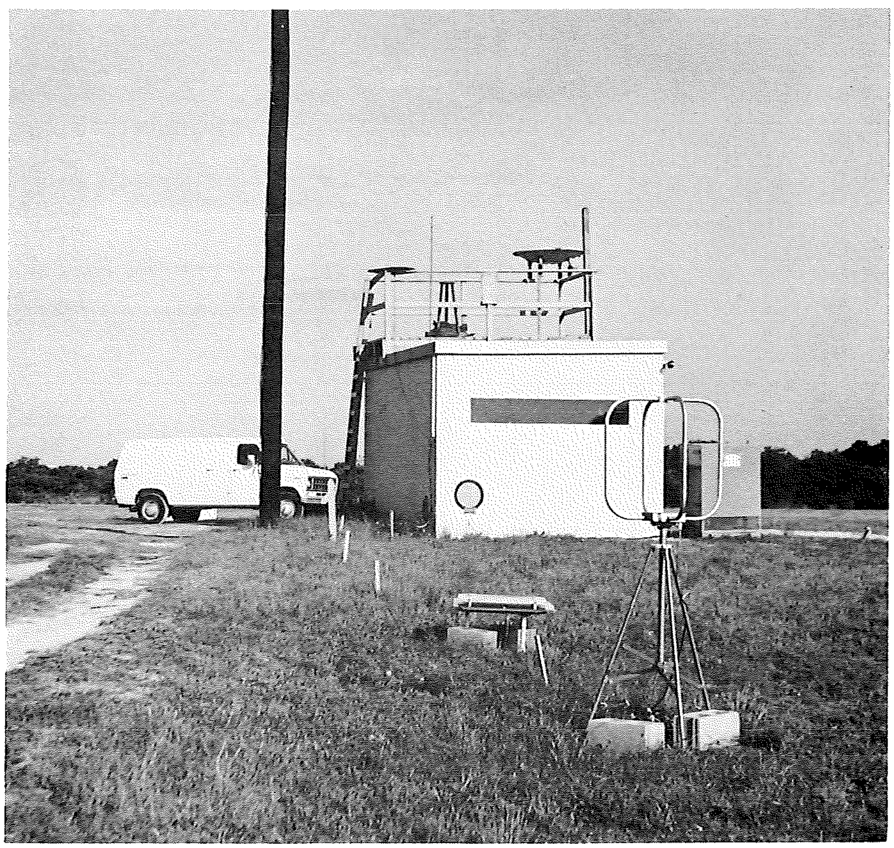


(c) Camera Site Atop the PID Building

Figure 22. Optical Location System Deployed at Kennedy Space Center



(a) Location Sensor Near Pad 39A



(b) Location Sensor Near Met Rocket Launch Pad

Figure 23. Triangulation Location Deployment at Kennedy Space Center

United States, the intense solar heating during the summer months causes the Sonoran "heat low" which is a semipermanent feature of the summer weather map. The "heat low" induces a gentle monsoon of warm, moist air to flow slowly toward the northwest from the Gulf of Mexico. Solar heating on the mountains of this area causes localized updrafts each day so that convective clouds form over these elevated regions. When the winds are gentle, these clouds often go through their entire life cycle--from the first condensation to full development producing lightning, rain and hail--and then dissipate over the mountains where they first formed. This report of climatology is that given by the brochure describing Langmuir Laboratory (1977).

Figure 24 shows the deployment of the triangulation locator system and the SwRI mobile laboratory. Illustrated in Figure 25(a) is the sensor atop the U. S. Forestry Service building in Magdalena, New Mexico. Figure 25(b) shows the sensor atop the U. S. Bureau of Reclamation building south of Socorro. The central facility was located in Workman Center on the New Mexico Tech campus. The central facility was operated remotely from the SwRI mobile laboratory since there existed no land line links to the mountain site.

Figure 26 is a plan view of the sensor deployment at the Langmuir Laboratory site. The deployment is shown pictorally in Figure 27. The optical location system was deployed as shown in Figure 28.

During the test period at Socorro, 21 July - 20 August 1979, 16 thunderstorm events were monitored. The cumulative time of observation was 37 hours. While a thunderstorm was in progress on 7 August 1979, lightning struck the corona point device and severely damaged the electronics as shown in Figure 29. Concurrent with the strike, a transient on the AC power line resulted in a failure of the power supply in the field mill electronics. The bridgewire and arcover measurement electronics were also damaged.

The bridgewire and arcover electronics were repaired. Since the corona point and field mill devices could not be repaired nor replaced within the test period, the second half of the New Mexico test was conducted without these systems.

SYSTEM COMPARATIVE PERFORMANCE

Three criteria have been chosen as fundamental benchmarks for estimating the safety effectiveness of the Lightning Warning Systems (LWS) tested: (1) Prior warning in time to evacuate the blasting area, (2) Electrical dissipation of 10 millijoules in a simulated detonator (all-fire condition) and (3) 2 KV bridge to case arcover threshold in the simulated detonator. 30 minutes warning before a given cell is overhead is provided at 10 nmi radius from the site.

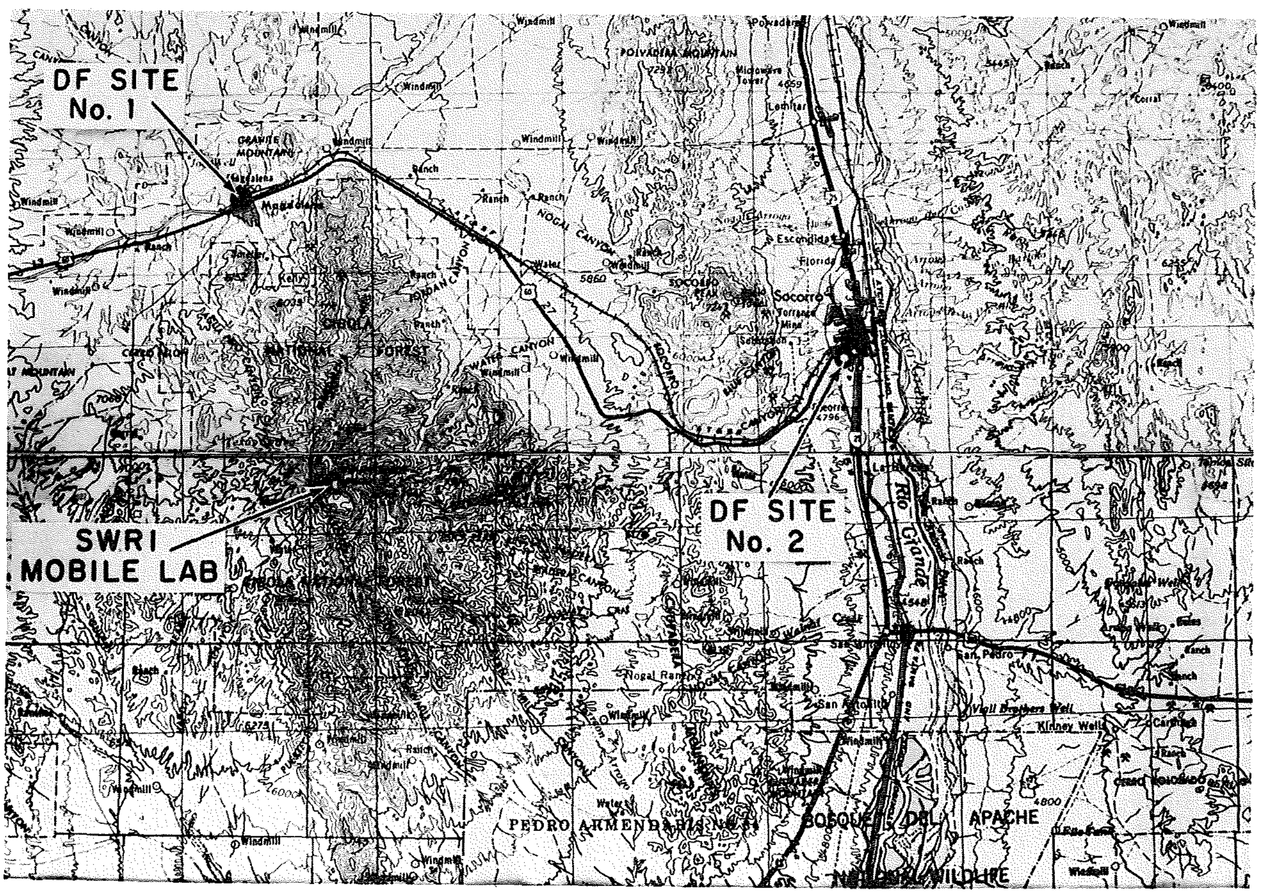


FIGURE 24. SOCORRO, NEW MEXICO DEPLOYMENT

(a) Magdalena Ranger Station Site

(b) Bureau of Reclamation Site

FIGURE 25. TRIANGULATION LOCATOR DEPLOYMENT IN NEW MEXICO

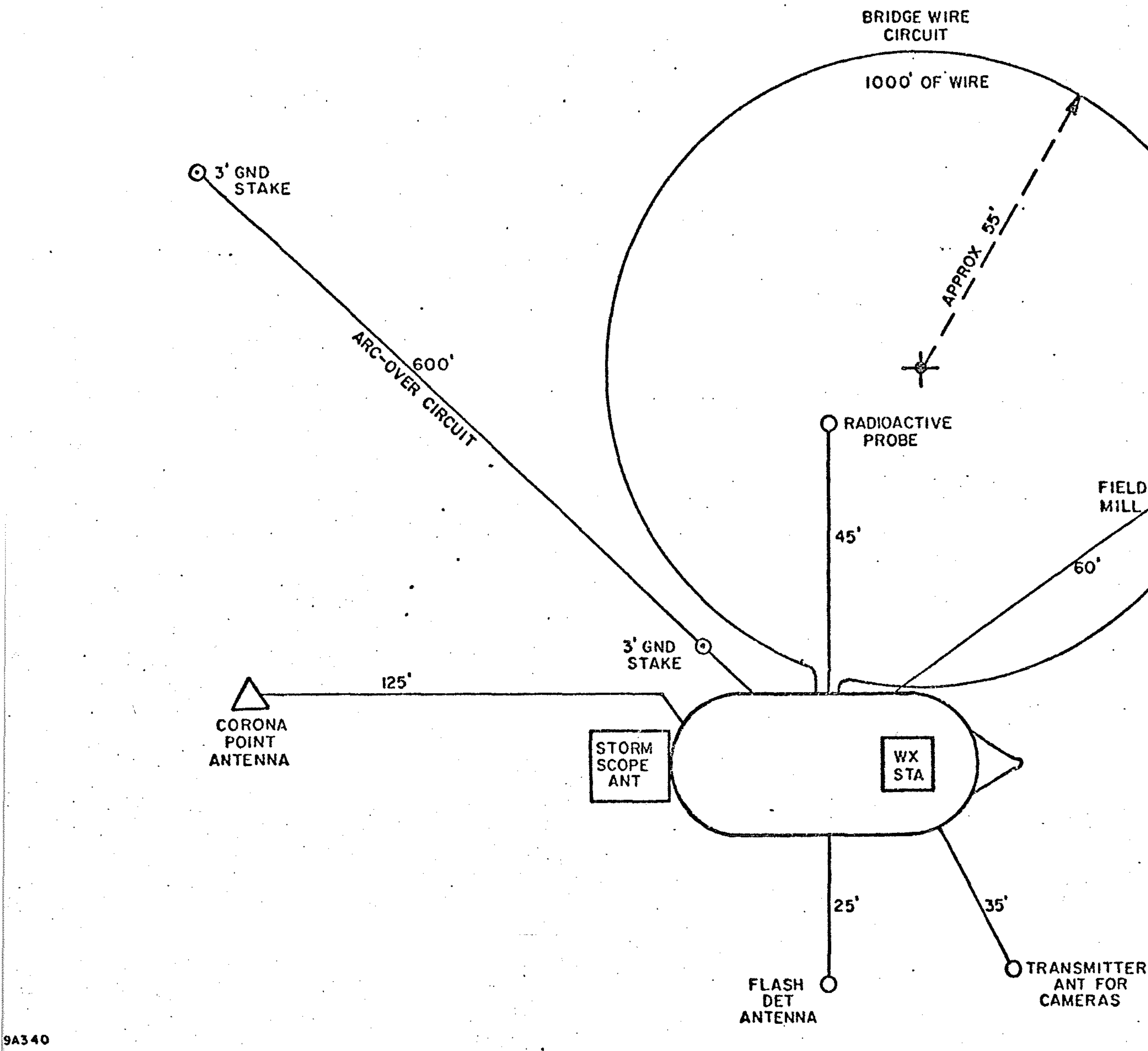
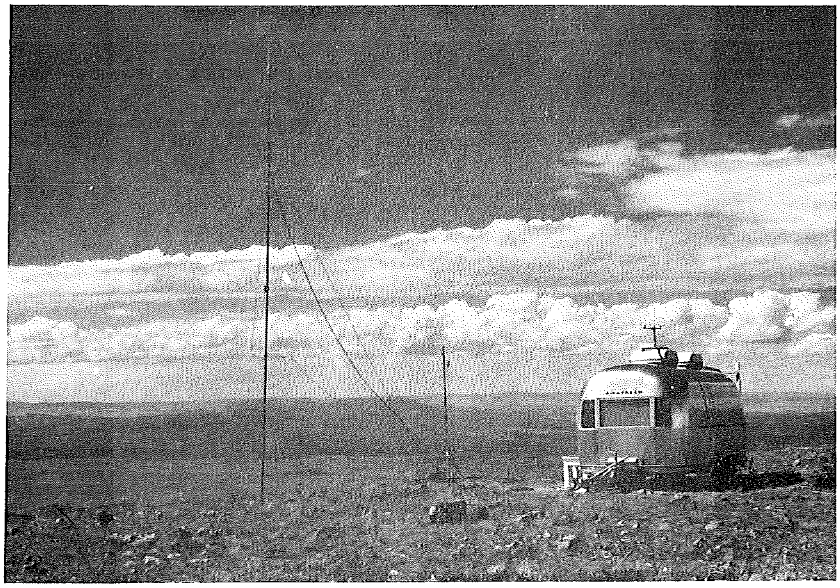
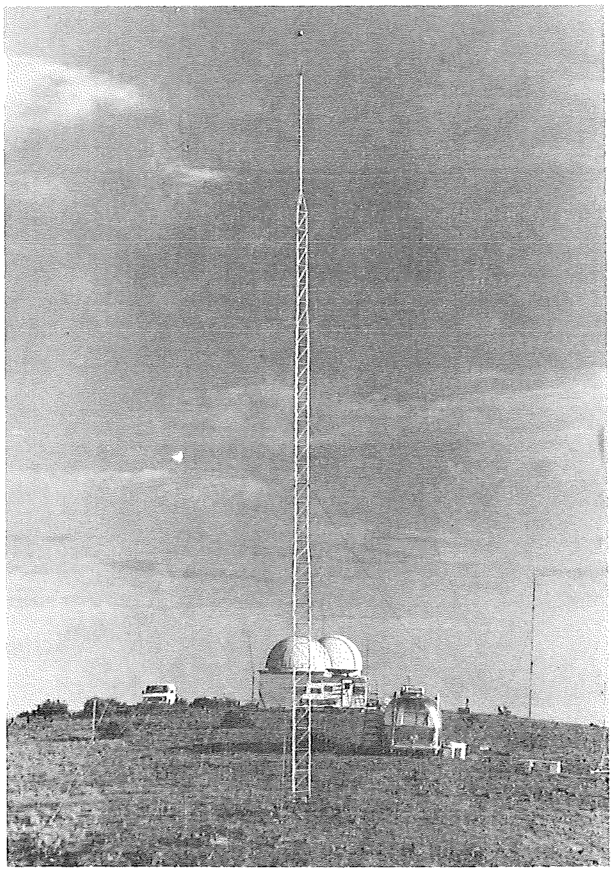


FIGURE 26. - Langmuir Laboratory Site Layout - Plane View

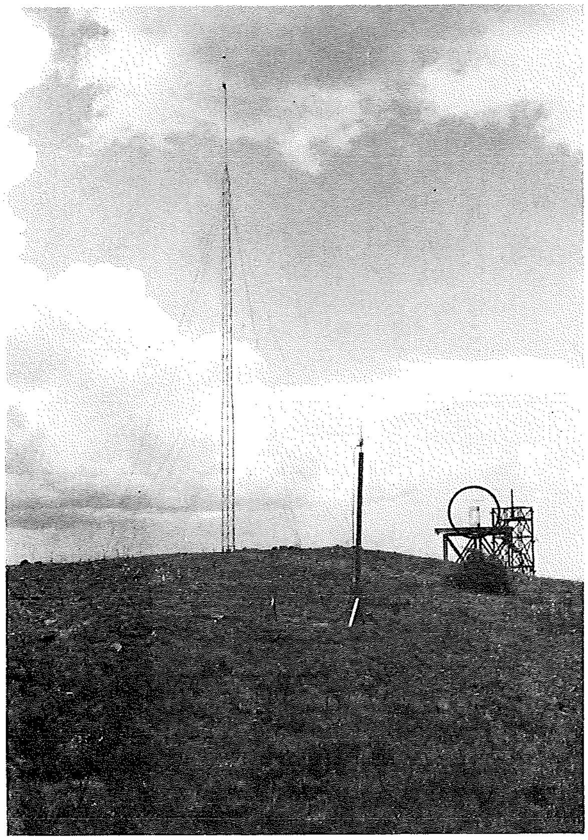


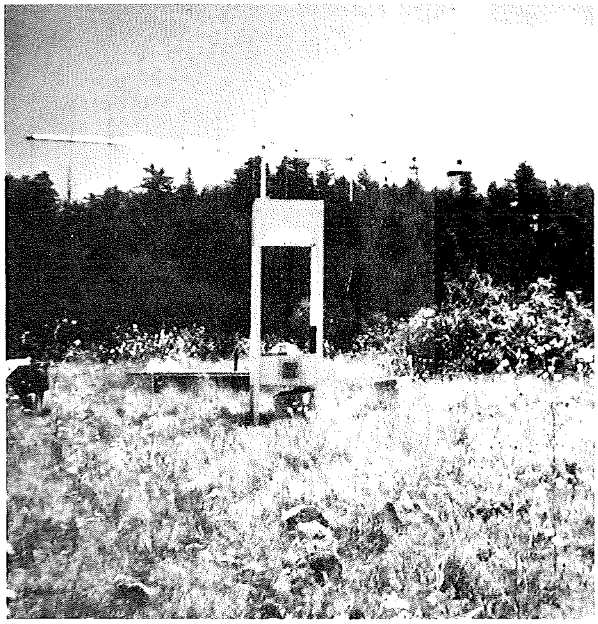
(a) Langmuir Laboratory Site Looking North



(b) Langmuir Laboratory Site Looking South

Figure 27. Langmuir Laboratory Sensor Deployment





(b) Camera Located at Base of Langmuir Laboratory

(a) Camera Located North of Mobile Laboratory

(c) Camera Located on Western Knoll

Figure 28. Optical Locator System Deployment at Langmuir Laboratory

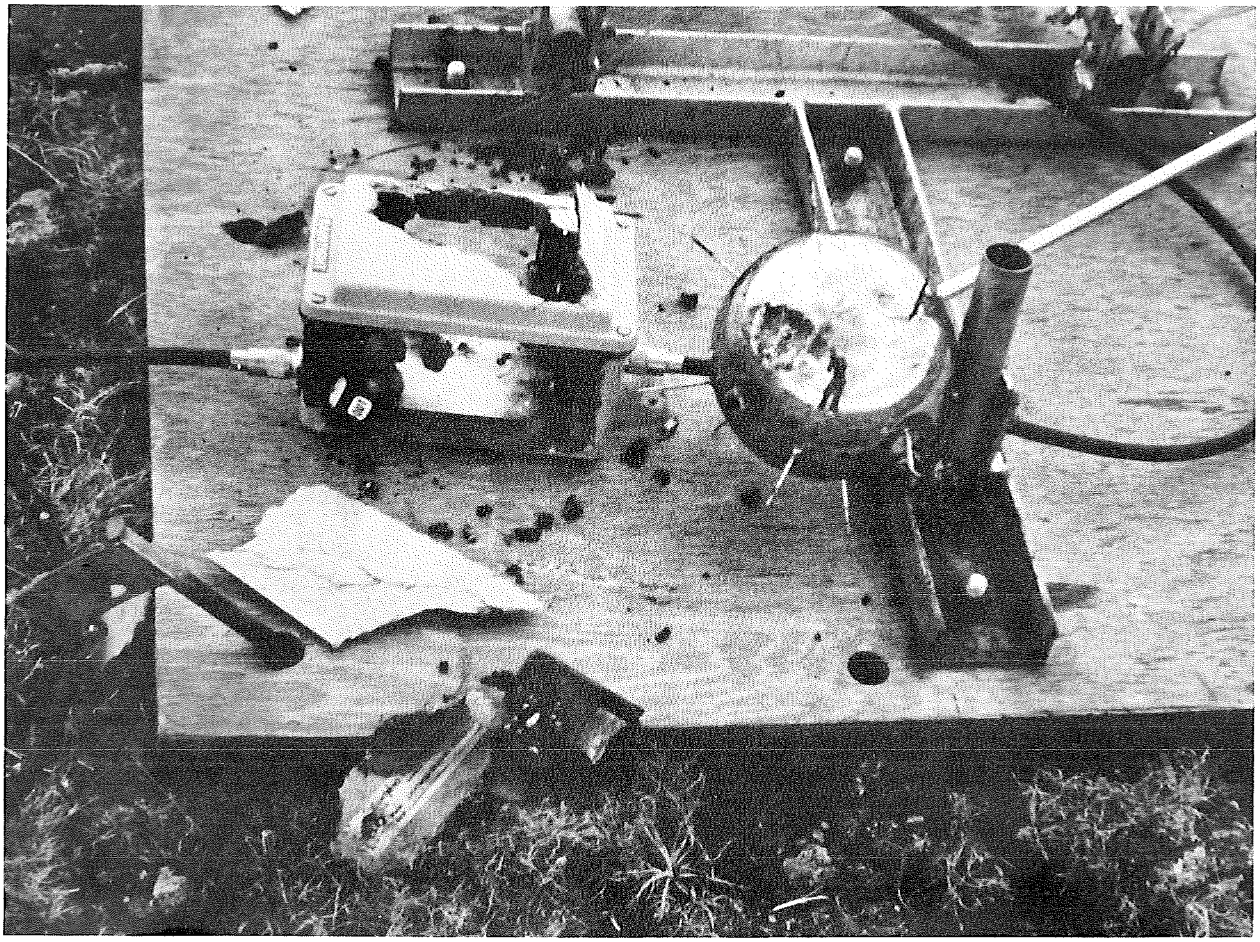


Figure 29. Corona Point Device Following Lightning Strike

To determine the radial coverage of interest which ensures timely mine evacuation, a study was made of simulated premature detonations versus distance to the lightning strike as recorded by the triangulation locator. These data are shown in Figure 30. There were ninety incidences of the all-fire condition, 150 instances greater than the no fire threshold. As shown on the graph, when a premature detonation occurs, the probability is 80 percent that the lightning strike was at 10 nmi range or less. This curve cannot be used to infer the probability of premature detonation as a function of distance. Rather, the curve indicates the probability that the strike was within a given distance or less from the sensors given a premature detonation has occurred.

The 10 nmi warning radius for evaluation of LWS appears reasonable, since the bridgewire simulation is open loop (representing worst case) as compared with the conventional twisted wire which couples less energy into the detonator. Thus, both measures of safety (i.e. 30 minute warning and simulated detonation) suggest a 10 nmi warning radius or greater. The LWS performance parameters were evaluated at 10 nmi radius from the sensors. Methods used to determine the range from the LWS sensors to lightning activity are briefly reviewed below.

WEATHER RADAR AND RADIOLOCATION SYSTEMS

National Weather Service (NWS) radar data archived on 16 mm film in Asheville, NC provided one method of locating storm activity. A systematic comparison was made between the "heavy" echoes (Video Integrator Processor, or VIP, level 3) and lightning location data reported by the radio triangulation locator under test. The radio triangulation data were highly correlated with the "heavy" (VIP level 3), "Very heavy" (VIP level 4), "intense" (VIP level 5) and "extreme" (VIP level 6) radar storm indications. In the case of "light" (VIP level 1), and "moderate" (VIP level 2), there existed no consistent correlation. The radio triangulation data were used for ground truth in those instances where lower VIP levels were recorded by radar, but lightning activity was indicated. This occasionally occurred in the presence of a building thunderstorm or during the decay stage. Also, the triangulation data were used extensively in New Mexico since no NWS archive exists for that area. The other sources of ground truth in New Mexico were operator observations and the detonator simulations.

Thus, the criterion used for potential electrical storm hazard at 10 nmi range during the SwRI and KSC tests was an NWS echo rated "heavy" (VIP level 3) or greater. Additionally, the operator made an entry into the data log if thunder was heard at the site or if lightning was observed.

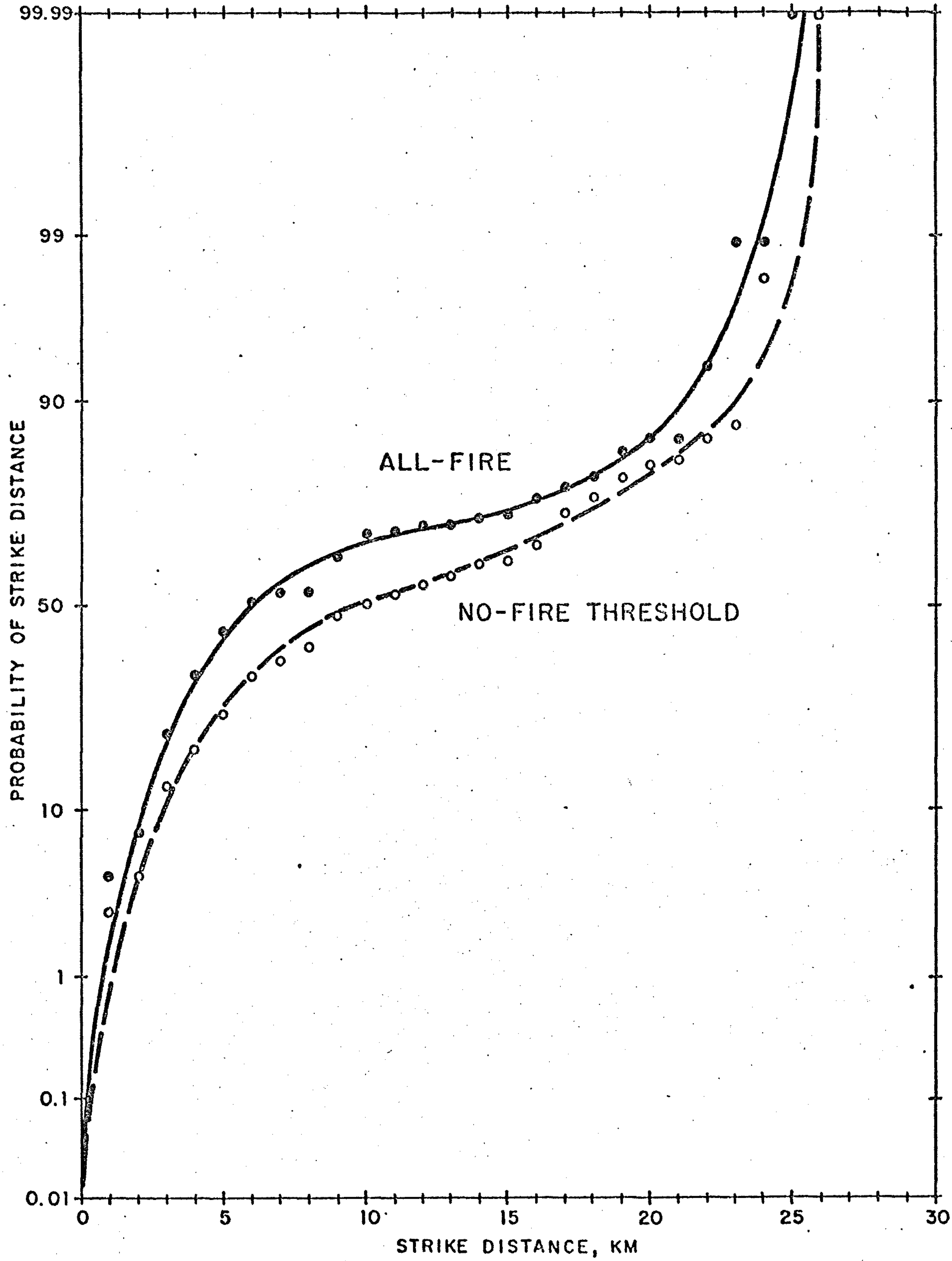


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FIGURE 30. - Lightning Strike Distance on Predetonation

OPTICAL LOCATOR PERFORMANCE

The three all-sky locator cameras did not provide the consistent lightning location data anticipated for the tests. After the initial development and success with one camera at the SwRI site, it was expected that the system would produce useful location results routinely whenever electrical storms were within viewing range of at least two cameras.

Based on primarily mid to late afternoon activity at KSC, neutral density filters were acquired to overcome problems of daytime/nighttime exposures. In addition, separate development mixtures for daytime and for nighttime exposures provided twenty four hour capability. Daytime and nighttime photographs taken at KSC demonstrated this approach was viable.

During testing at KSC, however, the inexpensive, relatively broadband camera trigger receivers were found to be vulnerable to the high density interfering signal environment at KSC. Consequently, the camera system continually false triggered. As a result of variable and persistent interference, only four two-camera correlated lightning photographs were obtained during the six week test period at KSC.

In the test period 15 July 1979 to 22 August 1979 at Langmuir Laboratory, radio frequency interference problems persisted but with less catastrophic results than at KSC. The principal difficulty at New Mexico was the placement of the cameras in accessible locations where film cartridges and batteries could be replaced. The cameras were deployed on approximately one mile baselines in an equilateral triangle at roughly the same elevation on the saddle area between South Baldy peak and Langmuir Laboratory.

While the logistics of this camera deployment were manageable, the area of coverage and consequently the probability of photographing lightning strikes within the viewing range of two or more cameras was significantly diminished. The optical locator system recorded five two-camera correlated lightning photographs during the New Mexico test period.

Although use of an optical lightning location system is a good approach, experience in these tests shows improved camera trigger receivers with significantly less vulnerability to radio frequency interference are required. In addition, at least two more cameras should be deployed in the network to enhance the probability of lightning strike location for baselines of the order of seven to ten miles in the presence of overcast and obscurity due to rain encountered under field conditions.

SYSTEM EVALUATION PARAMETERS

The performance parameters of the LWS's from which comparative performance is derived are the following:

(1) Mean Warning Time: The time elapsed between first warning and storm arrival at 10 nmi radius. Positive time implies time before reaching 10 nmi. Negative time implies time after the storm reaches 10 nmi radius. Zero mean warning time means alarm first occurred when the storm was at 10 nmi radius.

(2) Percent Incidence of False Alarm: The percentage of total alarms for which an alarm was given when no storm event was observable.

(3) Percent Incidence of Failure to Alarm: The percentage of total storm events within 10 nmi range for which no alarm was given.

(4) Percent Valid Alarms: Percent of alarm events for which storm activity was within 10 nmi range.

(5) Mean Time to Clear: Time after storm events passed beyond 10 nmi range to clear the alarm condition of the LWS.

The sum of false alarm and valid alarm percentages encompass all alarm events and adds to 100 percent. From a safety standpoint, the failure to alarm parameter is of greater significance than the false alarm value. A false alarm is a relative nuisance, but reaction to a false alarm does not necessarily increase probability of an accident. Failure to alarm, however, can result in an accident in which no prior warning is given.

The average warning time of each system is determined as follows: Based upon a 10 nmi radius about the site, a hazard exists when (1) a radar echo of "heavy" (VIP level 3) or more has entered the periphery, (2) thunder is reported by the operator, (3) lightning has been observed, or (4) premature simulated detonation has occurred and 30 minutes is subtracted. The various alarm conditions were determined as follows: (1) radioactive probe - using an inverse distance cubed law of propagation, a dense pattern of field changes within 10 nmi or a 2 KV/m field strength was indicated, (2) field mill device - an alarm of yellow or red as indicated on the front panel of the electronics, (3) corona point - 15 μamperes threshold was exceeded, (4) flash counter - the internal alarm was triggered on the 10 nmi range setting after the device had been initially calibrated according to manufacturer's instructions, (5) triangulation locator - lightning strikes registered on or within the perimeter of interest, and (6) azimuth-range locator - a dot on the display indicating lightning activity within a 10 nmi radius.

The time to clear was determined by recording the time at which (1) radar echoes of "heavy" (VIP level 3) or more had left the 10 nmi circle, (2) thirty minutes had transpired since the last premature detonation or (3) the operator was able to visually ascertain that no hazardous condition existed within the area of interest.

RESULTS

1. Frontal Type Thunderstorms (San Antonio, Texas Test)

Typical frontal activity which occurred during the test period 1 April 1979 to 15 May 1979 in San Antonio, Texas consisted of two types: (1) a stalled cold air mass overrun by moist Gulf air, triggering a line of thundershowers in the area of interest, and (2) a moving cold air mass pushing a line of thundershowers ahead in the form of a squall line. The average storm event duration creating hazardous conditions was three hours and six minutes.

A typical strip chart record is shown in Figure 31. The strip chart shows eight channels being recorded as well as two edge tracks. The lower edge track records one minute time markers. The lower channel is the E-field measurement of the radioactive probe and the adjacent channel is a recording of the field change measurements of the radioactive device. The third and fourth channels, proceeding upward, record the field mill measurement of flash count and of electrostatic field respectively. The fifth channel is the corona current measurement and the sixth channel is the output of the flash counter which has a voltage level proportional to the integrated number of lightning flash observations. The seventh channel is the output of the arcover circuit and the eighth channel is the output of the bridgewire simulator. The edge track uppermost in the figure is a trigger marker indicating that the optical location system has sensed a lightning event and the cameras were activated.

These data were recorded during the passage of a nearby storm cell, and the E-field records on channels one and four indicate an average field of the order of 200-300 V/m. The corona point device appears to be responding to a sliding average of the field changes, rather than a corona current measurement, since the indicated field strength is below corona threshold.

Table 5 is the summary data for the performance of the six systems under frontal storm conditions. The table shows that the corona point device and azimuth/range locator were generally unsuitable for warning. The corona point device indicated warning on the average of twenty minutes after the hazardous conditions were in effect. The device also indicated a clear condition nineteen minutes prior to the return of a "safe" condition. Had the alarm threshold been decreased to, say, 10 μamperes, the already high false alarm rate of 27 percent would have significantly increased.

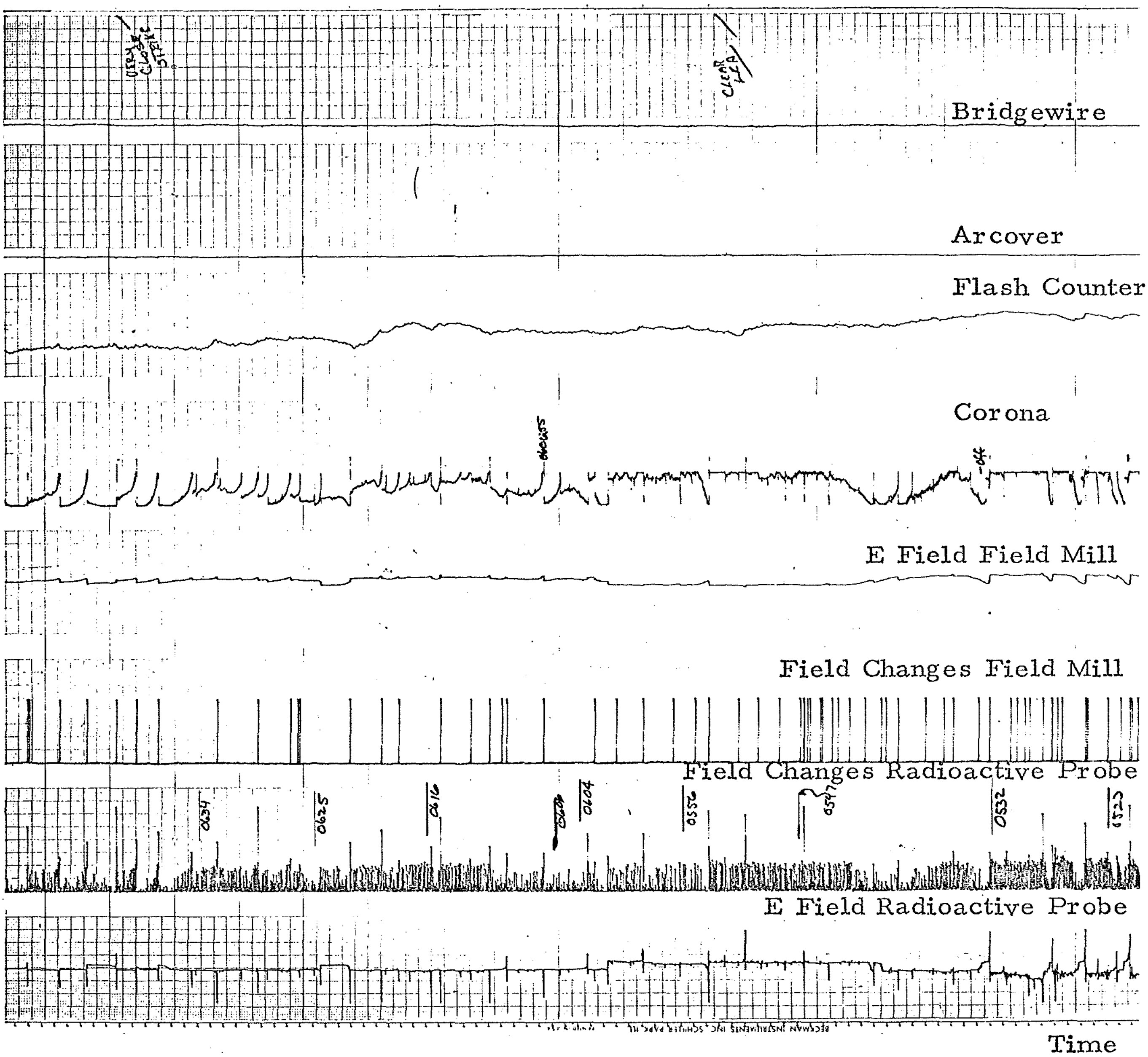


FIGURE 31. - Strip chart recording taken at SwRI test site

TABLE 5. - Frontal Type Storm Summary

DEVICE	Average Warning (Minutes)	False Alarm Rate	Failure To Alarm Rate	Alarm Reli-ability	Time To Clear (Minutes)
Radioactive	33	9%	9%	91%	15
Field Mill	40	18%	9%	82%	22
Corona Point	-20	27%	55%	73%	-19
Flash Counter	35	0%	9%	100%	44
Triangulation Locator	21	0%	9%	100%	5
Azimuth/Range Locator	121	73%	0%	27%	109

In the case of the azimuth/range locator, the ranging algorithm produced 73 percent false alarms which reduces its effectiveness for use as a warning device in terms of the criteria for this program.

The performance of the remaining four devices is relatively similar with the field mill system exhibiting a somewhat higher false alarm rate than the other four.

2. Convective Type Storms (KSC Test)

Thunderstorms observed during the period 1 June 1979 to 15 July 1979 at KSC, Florida were predominantly primarily frontal passages during the early part of the experiment and predominately convective (due to local surface heating) throughout the remainder of the period. The convective cells generally formed south of KSC and moved toward the northwest during their lifetime. The average duration of electrical storm hazard was one hour and forty two minutes.

A strip chart record is shown in Figure 32. The time scale on this recording is the same as was shown in Figure 31. The lower edge track records one minute time markers. This recording was data acquired while a cell was passing directly overhead. Of particular interest is the $\pm$ 4 KV/m field excursions recorded by the radioactive probe (channel 1) and field mill (channel 4). The corona point device (channel 5) appears to have entered into a saturated condition. The radioactive probe field change measurement (channel 2) reveals little activity while the field mill flash count (channel 3) indicates moderate activity. The flash counter device output (channel 6) reflects extremely intense electrical activity.

The summary data for the six systems are shown in Table 6. These data reflect alarm conditions during the period when the test operator was present at the site. The operator received storm information from the Air Weather Service at Cape Canaveral on a 25 nmi alert radius. Data acquisition was initiated when the operator arrived on site. Continual observations as in the San Antonio test were not feasible. Bias (if any) in these data tends to underestimate the false alarm rate and mean alarm times.

Throughout this test, the corona point device exhibited erratic behavior, particularly regarding the lengthy time to reach cleared status. (For example, due to causes unknown this device constantly false alarmed between approximately 7 and 11 p.m. throughout the test). This is primarily attributed to the poor ground provided by the sandy soil at the site. The performance of the flash counter was less favorable than in the San Antonio test. This device required continual adjustments in sensitivity due to its high susceptibility to radio frequency interference. During the experiments at KSC, flash counter false alarm rate measurements were vitiated by the high incidence of coupled extraneous noise and interference.

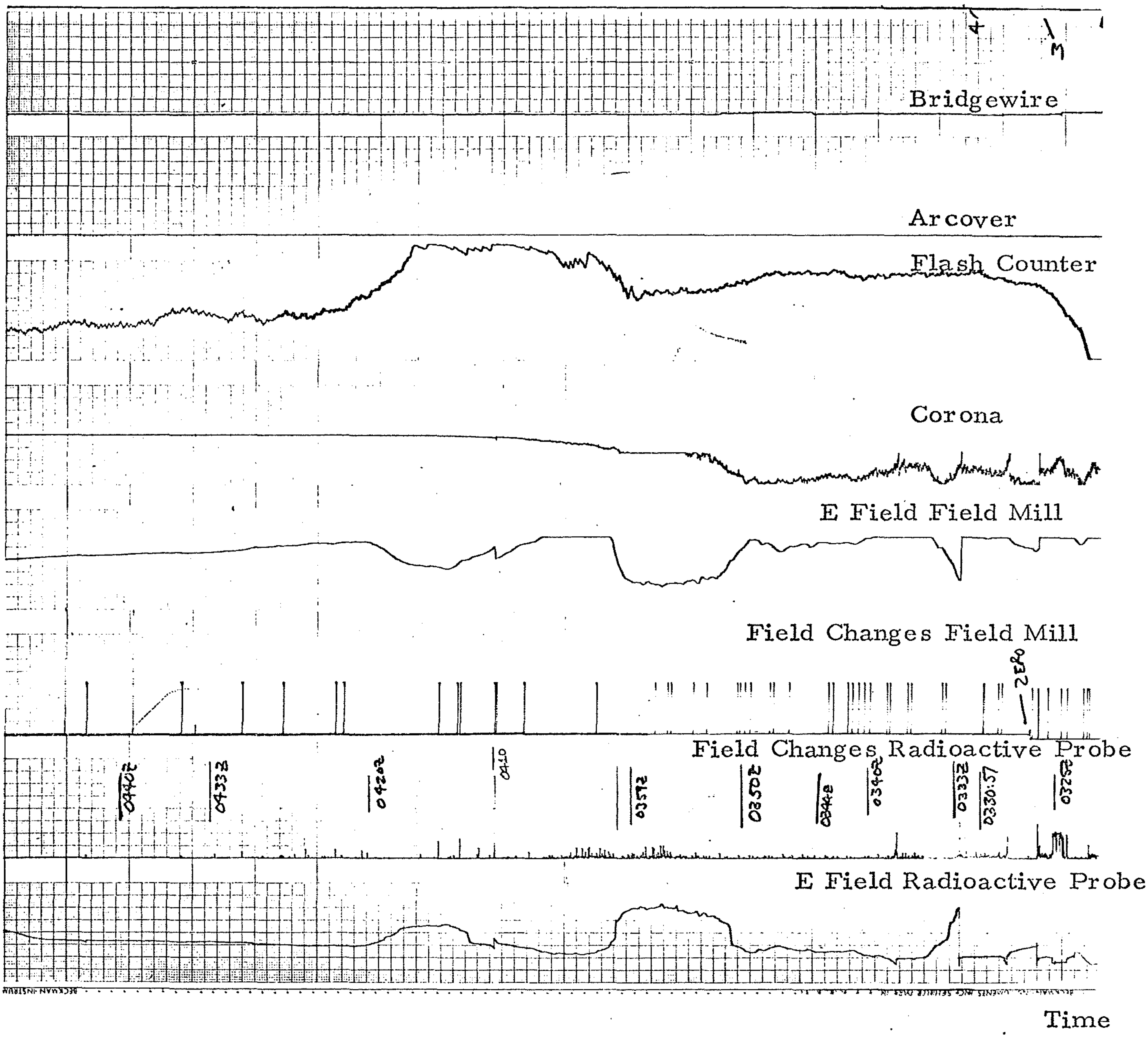


FIGURE 32. - Strip chart recording taken at KSC test site

TABLE 6. KSC Storm Summary

DEVICE	Average Warning (Minutes	False Alarm Rate	Failure To Alarm Rate	Alarm Reli-Ability	Time To Clear (Minutes)
Radioactive	28	0%	10%	100%	-8
Field Mill	27	0%	15%	100%	9
Corona Point	-15	0%	80%	100%	22
Flash Counter	32	0%	55%	100%	-18
Triangulation Locator	21	0%	6%	100%	-4
Azimuth/Range Locator	39	0%	5%	100%	17

The three systems exhibiting conventional warning performance during this test were the (1) radioactive probe, (2) field mill device and (3) triangulation locator.

3. Mountainous Type Storms (New Mexico Test)

Thunderstorms observed during the period 20 July 1979 to 20 August 1979 at Langmuir Laboratory, New Mexico were convective type cells initiated by mountainous terrain. The cumulous buildup generally started over the mountain ridges and was swept eastward or remained stationary over the mountain tops. The average storm hazard duration was one hour and thirty minutes.

A strip chart record is shown in Figure 33. The time scale recording is the same as was indicated in Figures 31 and 32. Of particular interest is the bridgewire detonations which were recorded on channel eight. This particular recording was taken during a period of extremely intense electrical activity.

Shown in Table 7 is the summary of system performance for mountainous terrain. The site was operated on a twenty four hour basis. The measured data for the azimuth/range locator is more representative of system performance regarding false alarms than reported in Table 6. In this case the systems which revealed best overall performance were the radioactive probe, the field mill device and the triangulation locator.

The observations revealed two significant phenomena not observed at the lower altitude test sites: (1) atop the mountain, E fields of 15-20 KV/meter were common; maximum electrostatic fields measured at low altitude were of the order of 1-5 KV/meter, (2) eighty percent of all simulated detonations occurred at the New Mexico site as compared with the two previous sites. This occurred in spite of the fact that numerous cloud-to-ground strikes were observed in close proximity (less than 2 nmi) at both of the other sites.

COMPARISON

Table 8 compares the performance of each LWS under conditions of frontal, convective, and orographic storms. The units generally provide 30 ± 10 minute warning time prior to storm location at 10 nmi range with the exception of the azimuth/range locator and the corona point device. The azimuth/range locator tends to warn one hour or more in advance of 10 nmi range. This is apparently due to the variability of received signal strength and the assumed mean amplitude at the given ranges. As a result, range is underestimated with apparent 10 nmi range locations one hour before the storm reaches this radius.

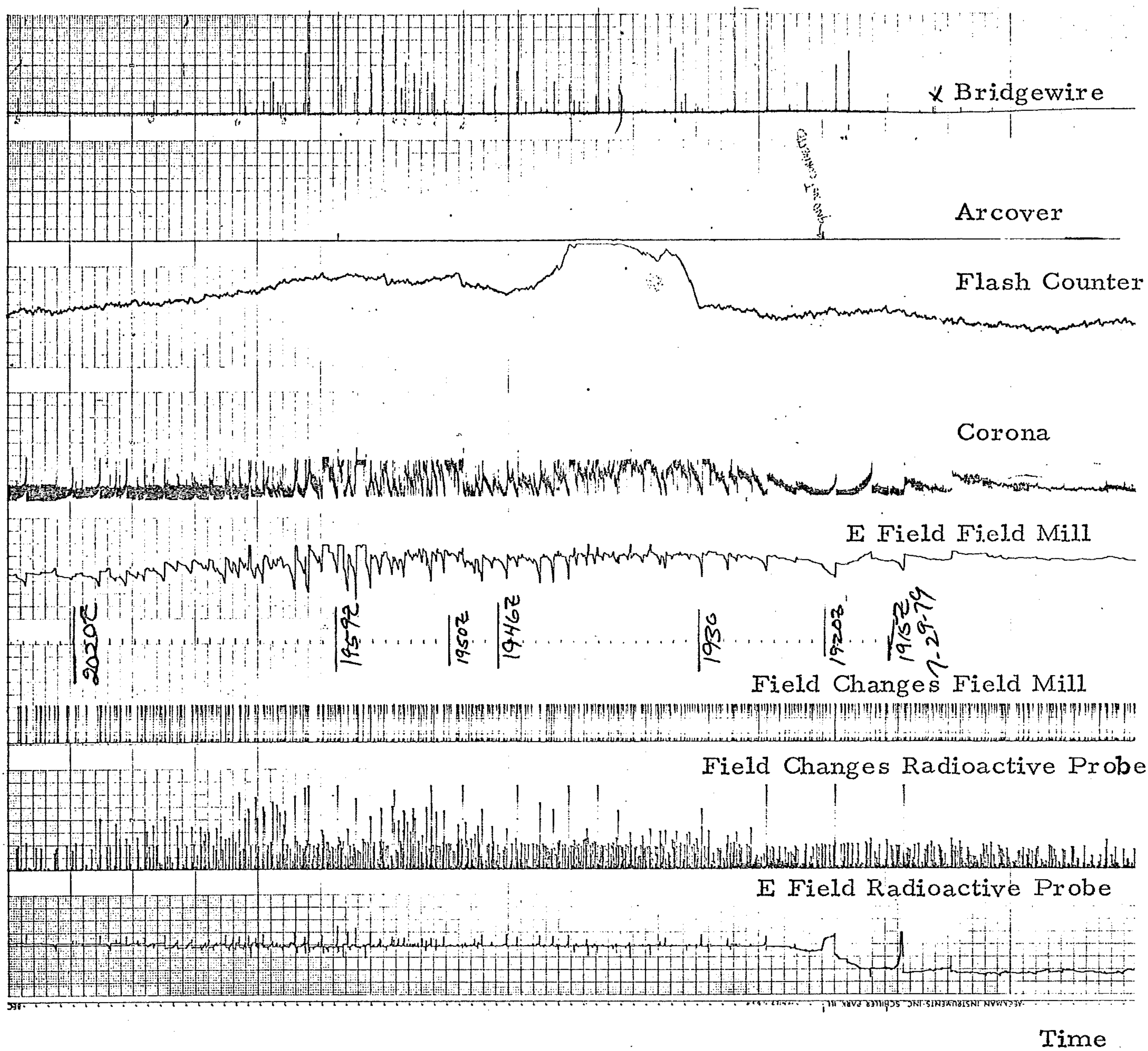


FIGURE 33. -Strip chart recording taken at New Mexico test site

TABLE 7. Mountainous Type Storm Summary

DEVICE	Average Warning (Minutes)	False Alarm Rate	Failure To Alarm Rate	Alarm Reli-ability	Time To Clear (Minutes)
Radioactive	21	0%	27%	100%	33
Field Mill	50	0%	20%	100%	67
Corona Point	-20	0%	80%	100%	40
Flash Counter	-4	0%	64%	100%	23
Triangulation Locator	20	0%	9%	100%	0
Azimuth/Range Locator	101	82%	0%	18%	117

TABLE 8. - Lightning Warning System Comparison by Warning Parameter

Warning Parameter	Radioactive Probe			Field Mill Device			Corona Point Device			Flash Counter			Triangulator			Az/Range Locator		
	Front	*Conv	*Mount*	Front	Conv	Mount	Front	Conv	Mount	Front	Conv	Mount	Front	Conv	Mount	Front	Conv	Mount
Mean Warning Time in Minutes	33	28	21	40	27	50	-20	-15	-20	35	32	-4	21	21	20	121	39	101
False Alarm Incidence Percentage	9	0	0	18	0	0	27	0	0	0	0	0	0	0	0	73	0	82
Failure to Alarm Incidence Percentage	9	10	27	9	15	20	55	80	80	9	55	64	9	6	9	0	5	0
Incidence of Valid Alarm Percentage	91	100	100	82	100	100	73	100	100	100	100	100	100	100	100	27	100	18
Mean Time to Clear After Hazard Passed in Minutes	15	-8	33	22	9	67	-19	22	40	44	-18	23	5	-4	0	109	17	117

* Front - Frontal
Conv - KSC
Mount - Mountain

The corona point device on the other hand typically alarms 15 to 20 minutes after storms have reached the 10 nmi range. This results in warning given approximately 10 minutes before a storm of mean velocity is expected over the site.

False alarm incidence of all units varies from 0 to 18 percent with the exception of the azimuth/range locator and corona point device. Because of the significant range underestimation of the azimuth/range device, false alarms are produced with 70 to 80 percent probability, i.e. the unit estimates lightning range less than 10 nmi when it is greater than 10 nmi range 70 to 80 percent of the time.

The false alarm rate of the corona point device was measured at 27 percent for frontal activity. This is caused by extraneous noise/interference not caused by lightning.

The more hazardous condition of failure to alarm shows 5 to 27 percent incidence for the units with the exception of the corona point and flash counter devices. These units showed upwards of 50 percent failure to alarm, indicating warning was missed more than half the time. This level of failure to alarm indicates the units are more likely not to provide warning than to provide it.

The incidence of valid alarms is high for all units with the exception of the azimuth/range device. A high valid warning percentage means that of all the warnings given, the majority were valid, i.e. storms were actually within 10 nmi radius. The azimuth/range device produced a high incidence of false alarms. Consequently the percent of valid alarms was relatively low for frontal and mountainous storms.

The mean time to clear after storms passed beyond 10 nmi range varied from 9 to 67 minutes. However, four of the systems showed at least some incidence of clear conditions 8 to 19 minutes before actual clearing had occurred. The azimuth/range device showed clear approximately 1-1/2 hours after storms were past the 10 nmi radius.

SUMMARY

Of the six devices, the azimuth/range locator and corona point device showed generally unacceptable performance as lightning warning systems. The one hour or more warning and clear times plus the high false alarm rate are the disqualifying features of the azimuth/range device. The late warning time and high probability of failure to alarm are the primary disqualifying features of the corona point device.

The remaining four units are:

(1) The triangulation systems which showed overall best performance of all the systems tested in all performance categories.

(2) The flash counter which suffered from a high probability of failure to alarm.

(3) The radioactive probe using static field sensing and measures field changes.

(4) The field mill device using static field plus flash counting and radio noise criteria for alarm indication.

1. Radioactive Probe

When the device was working properly, its sensitivity in the 100 V/m to 1 KV/m was particularly useful in predicting storm movement. This sensitivity was not present in the other devices tested.

The primary failure of this device was the inability of the splash shield to maintain a high impedance coupling with the space charge in the vicinity of the probe. Moisture accumulation on the probe produced zero electrostatic field indication while the field mill and the corona point devices indicated significant electrostatic fields were present. When this condition occurred, the device continued to give a warning indication by measuring the electrostatic field changes which is done independent of the electrostatic field measurement.

2. Field Mill Device

This unit combined field mill, flash counting, and radio background noise to produce a warning. As such it is a well conceived system. The lightning flash detector in this device was initially set at an extremely sensitive threshold. This was changed with the approval of the manufacturer due to interference from a military radar near SwRI which produced an alarm indication on each scan. The field mill showed little sensitivity to field changes in the $\pm$ 1 KV/m range and requires a relatively high degree of maintenance to ensure that the conducting plates are cleared of corrosion and debris.

3. Corona Point Device

Due to the sensitivity of the measurement parameter, the high gain electronics at the input sensor results in a high degree of susceptibility to extraneous noise. An additional problem results from the fact that the amount of corona current is a function of height of the point (shown in equation 1, page 14). The height requirement provides a vulnerability to lightning strikes. During the New Mexico test, the device suffered a direct strike and the consequential damage made repair impossible to complete before the end of the test period.

4. Flash Counter

As was shown in the New Mexico data, this device produces no warning for the storm which develops overhead. This device is also highly susceptible to extraneous noise. In particular, it was found that heavy equipment operating in the vicinity of the antenna would trigger an alarm condition due to coupled ignition noise. It was also found that the range setting required recalibration prior to each storm due to the variability of ambient atmospheric noise.

5. Triangulation Locator

Overall this system proved to be the most reliable indicator of cloud-to-ground electrical activity. This device, like the flash counter, produces no warning for the storm which developes overhead. A second problem was found to exist when a storm was in progress along a line between the two remote antennas. In these cases, the system plots a series of strikes along a parabolic line, external to the remote sites. There is a relatively high cost associated with leasing land lines for communication links between the remote sites and the central facility.

6. Azimuth/Range Locator

This device consistently indicated the correct movement of major centers of electrical activity in a storm system; however, the underestimation of proximity produced intolerable false alarm rates. The utility of this device appears to be in the area of lightning avoidance rather than lightning warning.

DISCUSSION

This study of lightning warning technology indicates that four alternatives may be pursued in implementing an effective electrical storm safety program. These are: (1) to encourage the use of common sense safety practices, (2) to use one of the lightning warning systems tested, (3) to develop a system which meets the unique needs of the mining industry, and (4) to develop a device independent safety specification in terms of electric field strengths, number of lightning events, etc. In the following discussion these alternatives are considered.

1. Common Sense Safety Practices

One approach in reducing exposure to lightning hazards is to exploit a knowledge of the local climatology. At KSC, for example, peak summertime thunderstorm activity occurs around 4100-5100 p.m. local time. To ensure minimum downtime and reduce the possibility of accidental predetonation, blasting schedules can be adjusted accordingly.

Also a broadcast receiver can be tuned to a frequency which is not used by a transmitting station, and one can listen for static crashes to estimate if lightning is occurring in the area. This information coupled with visual observations of cloud formations has been used extensively to forecast potentially hazardous lightning conditions.

A major concern in the common sense approach is the lack of exact knowledge about the location of lightning events and the consequent use of subjective judgement. As was demonstrated in the test results, significant errors in the estimates of lightning locations by the flash counter contributed in large part to its poor performance. While the common sense approach is extremely appealing from cost considerations, the incurred risk may be substantial. As a tradeoff among the various safety alternatives, this approach represents minimum cost and maximum risk.

2. Lightning Warning System Evaluation

An alternative approach to preventing lightning induced predetonation is the use of one of the devices tested. An effective automatic lightning warning system has the following advantages over relying on weather observations:

a. On overcast days warning is provided when storm system buildup cannot be seen from the ground.

b. Operations can continue until evacuation is initiated based on storms detected within a predetermined hazardous range.

c. Operations can resume when lightning passes beyond the hazardous range.

d. Warning is provided when the entire crew is engaged in operations.

An automatic lightning warning system which provides the above capability is required to ensure maximum safety in blasting operations. Of the devices evaluated in this study, three evidenced unacceptable performance. The flash counter proved to be unacceptable because of its noise susceptibility and it required continual recalibration of the alarm threshold. The corona point sensor also evidenced a high degree of noise susceptibility and a vulnerability to direct lightning strikes. The false alarm rate observed in the performance of the azimuth/range locator was determined to be intolerable.

Acceptable techniques among the devices tested were the field mill, radioactive probe and the triangulation locator. The field mill device (which measures electric field strength, flash rate and ambient background noise level) exhibited failure-to-alarm rates which were of concern; however, as a cost tradeoff this device appeared to be cost effective as an off-the-shelf single point sensor in comparison to the triangulation locator. Closely comparable in performance to the field mill was the radioactive probe which measures potential gradient and changes in the gradient. This system also had a relatively high failure-to-alarm rate and exhibited probe saturation effects which may require a development effort to correct. The overall best performance was obtained from the triangulation system; however, this system is ineffective against overhead lightning hazard buildup since it reports only cloud-to-ground lightning flashes.

Based upon the results of this evaluation study, the system presently available commercially which technically best satisfies mining safety requirements is the triangulation location system.

3. Triangulation System Deployment

To implement a lightning warning system (within a realistic budget) using the triangulation locator device, a network of the sensors could be deployed throughout a large mining area such as has been done by the Bureau of Land Management in the Western United States for the detection of lightning caused forest fires.

The crossed loop direction finders provide coverage of approximately 400 km radius. Through the deployment of twenty two remote sensors, the BLM acquires lightning location data for the portion of the United States west of the continental divide. A cost sharing program by the mining industry would incur lower operating expense (for a network providing area coverage) than comparable coverage by individual systems located at each mine site.

Each mining operation would have access to the network lightning location data by telephone dial-up. The digital data could be obtained over voice quality lines and automatically plotted on an area map so that lightning hazard regions could be readily identified. The approximate cost to deploy a network of twenty sensors to provide coverage of the eastern United States is expected to be less than $500,000. Monthly operating costs would be of the order of $5,000.

4. Single Point Lightning Warning System Development

This evaluation has shown that certain lightning warning techniques have the capability to warn with stated effectiveness when lightning reaches 10 nmi range. However, instrumental warning thresholds are not effectively set by the manufacturer prior to delivery. The units provide meter indication of certain atmospheric electricity phenomena, but the setting of warning thresholds must be made by the user based on his warning criteria and the site at which the unit is installed. The systems are often delivered with red/yellow indicators, but this does not eliminate the need for system adjustments specific for each site and for the storm conditions prevalent at the time of hazard.

An effective single point automatic lightning warning system must warn against (1) static storm buildup overhead, such as with an electrostatic field probe, and (2) distant storms using a fast field change, i.e. sferic, counting/detection technique. Finally, the system must (3) adjust its warning threshold to the variable ambient sferic background and the field intensity variations at the site, and (4) incorporate design to eliminate the effects of radio frequency interference.

The field mill device tested herein combines electrostatic field, sferic burst, and background measurements. Its shortcomings appear to be derived from engineering design rather than system concept. Figure 34 shows a simplified system block diagram incorporating three major engineering changes respecting the field mill device, viz.,

a. The electrostatic field probe is a radioactive device providing sufficient sensitivity at ranges beyond 5 nmi. Improved splash shielding is necessary over the radioactive probe device tested.

b. A microprocessor is incorporated to scan the output of a flash counter and very long integration time sferic background sensor.

c. Improved RF circuitry to reduce effects of interference from noise and signals.

Software is required to take into account the flash count above background, the relative flash frequency, the altitude/orographic characteristics of the site to generate warning/alarm indication.

This approach synthesizes relevant capability of present technology and performance based on the tests reported herein. The adaptive threshold is considered necessary to reduce the failure to alarm probability to near zero. Experience shows that a fixed sensitivity threshold is often set too high (failure to alarm) or too low (false alarm) to encompass the variation of storm conditions. Automatically adjusted thresholds are required to eliminate the need for skilled personnel adjustments to the device.

5. Device Independent Safety Specification

A fifth alternative approach in developing a mining safety specification is a characterization of hazard criteria in terms of atmospheric electrical parameters, e.g. proximity of lightning, static field potential, etc. These criteria are generally lacking at present. However, lightning warning for mining safety represents a relatively controlled problem, compared to the much less controlled problems of refueling hazards, explosive manufacture, etc. The energy dissipation in the detonator is the critical hazard parameter which offers a relatively tractable parameter for manufacture, etc. Blasting operation warning of lightning hazard is generally limited to the fire condition of the detonator.

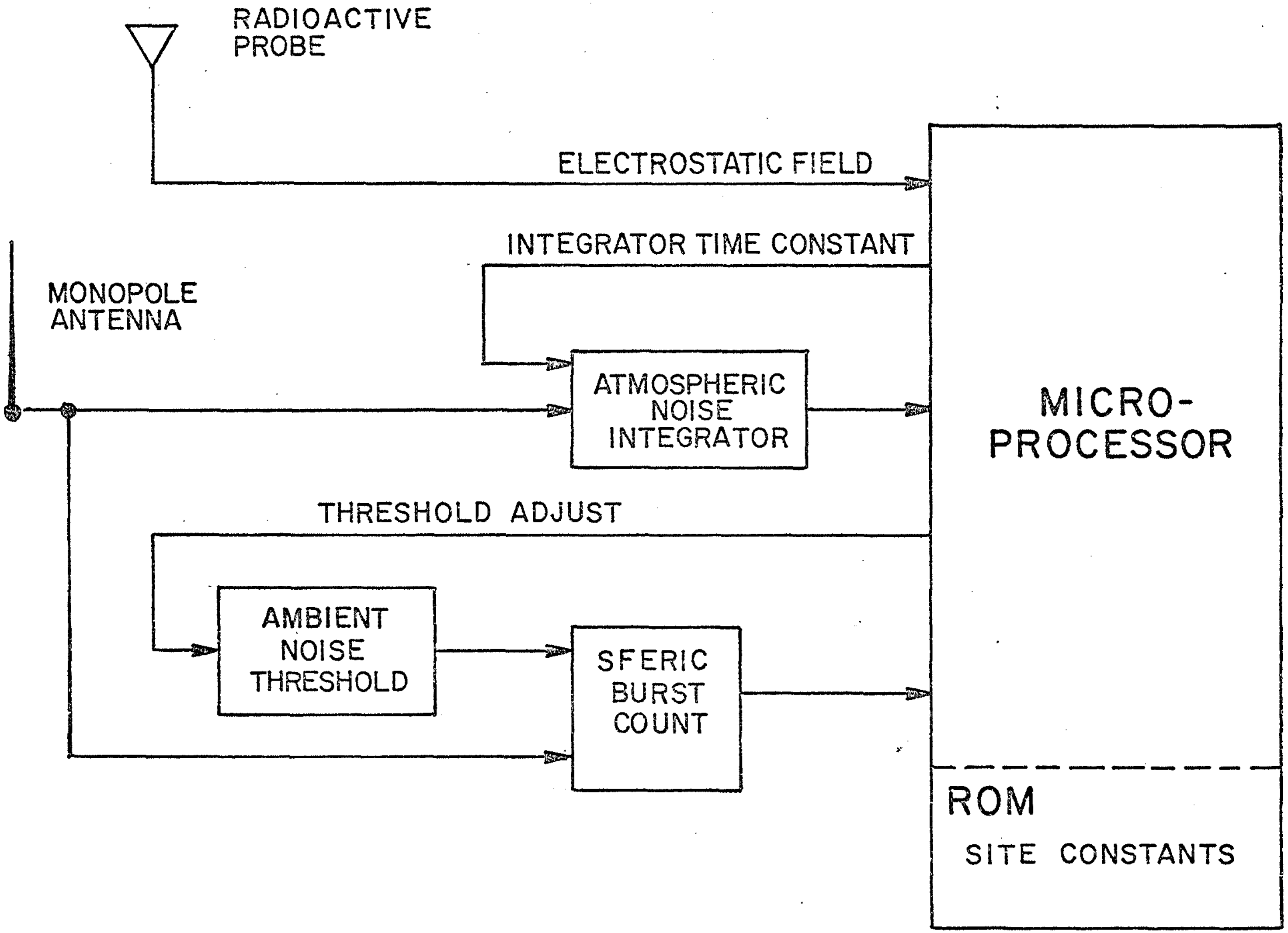


FIGURE 34. - Adaptive Lightning Warning System

An approach to the definition of this problem was begun under this program by the use of simple detonator fire simulation, viz., bridgewire and arcover circuits. Using detonator simulation circuits, the incidence of simulated detonation is highly dependent on terrain. Simulated detonations were extremely rare on flat terrain, i.e. San Antonio and KSC; whereas simulated detonations were common in mountainous terrain. It is believed that the mechanism which accounts for this phenomenon is due to the fact that at low altitudes the primary energy coupled is from the ground wave field component. Since the simulated firing line is a large horizontal antenna, little if any of the vertically polarized ground wave will be coupled into the circuit. At higher altitudes, the closer proximity of the cloud results in a direct wave which contains sufficient horizontal polarization to cause premature detonation. Other hypotheses which should be considered are (1) higher incidence of positive ground strokes, (2) close proximity to the cloud base and consequently streamer processes, and (3) close proximity to intercloud activity.

Most importantly, the observed simulated detonations suggests that practical warning criteria may be established:

1. specifically for different mining terrains and

2. independent of warning device or sensing technique.

If such criteria could be established, then lightning warning system performance for mine safety could be specified, independent of present and future technology. Lightning warning criteria could be based on actual explosive hazard, e.g. in low lying terrain safe warning might be closer to the site than the 10 nmi apparently required in mountainous terrain.

To achieve the goal of objective lightning warning criteria, the technique of this evaluation can be used to perform an improved detonator simulation experiment at a number of sites in different terrains. Using a radio triangulation system to locate lightning and a calibrated field mill, the atmospheric parameters which cause simulated detonation would be obtained as a function of terrain type.

As an example, the New Mexico results show the following: given a simulated detonation, 95 percent of simulated detonations occurred with lightning at 15 nmi range or less. A resulting lightning warning specification would be derived as follows: (Sample)

"A lightning warning system shall be deemed suitable for mine safety in mountainous regions when the system provides:

1. Zero failure to alarm with lightning activity at 15 nmi range or less.

2. 30 minutes warning prior to the first lightning event within 15 nmi of the site.

3. A false alarm probability of 5 percent or less.

4. Indicates clear conditions within 15 minutes after lightning events have crossed within 15 nmi radius of the site."

Such specifications could be derived for other terrains and mining conditions, given sufficiently reliable atmospheric electricity observations using conservative detonation simulation tests.

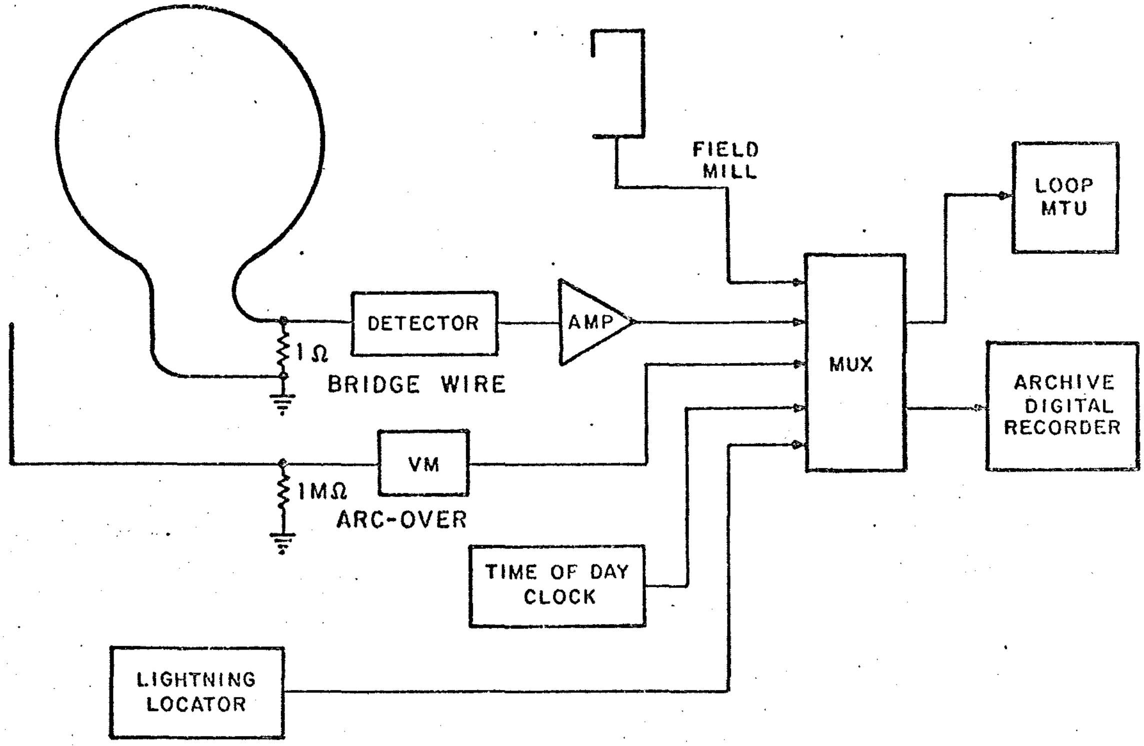
The detonation simulation tests required to derive lightning warning criteria can be performed using simple equipment as shown in Figure 35. The detonation simulation equipment would operate unmanned for extensive periods with data reduced automatically to ensure all statistical parameters are obtained at minimum cost. The experiment could be used to derive two types of information: One result needed is the range dependence of premature detonation for mountainous versus flat terrain. Specifically, given a simulated detonation, determine the probability of occurrence as a function of range. Figure 36 illustrates two probability density functions. The first is of the type observed in mountainous terrain. The second is a simulated density function based on the flat terrain tests reported. The difference in probability versus range for flat versus mountainous conditions equates to the difference in permissible blasting operations down-time for the same safety hazard. If established, this difference would result in greater productivity and efficiency of operation for the same level of explosive risk.

The second type of information required is the atmospheric electricity parameters 30 minutes prior to the first fire condition. This data would be used to generate warning criteria based on atmospheric electricity parameters known to be present in the 30 minutes prior to an explosive hazard. The loop tape recorder shown in Figure 35 would continously record the sensor outputs on a 45 minute loop. Upon a simulated fire, the recorder would dump the analog record of the previous 30 minutes to the archive digital recorder. If two simulated fires occur within 30 minutes, the system would archive the fire/location data. The parameters recorded up to 30 minutes before the first fire would be analyzed to determine warning thresholds.

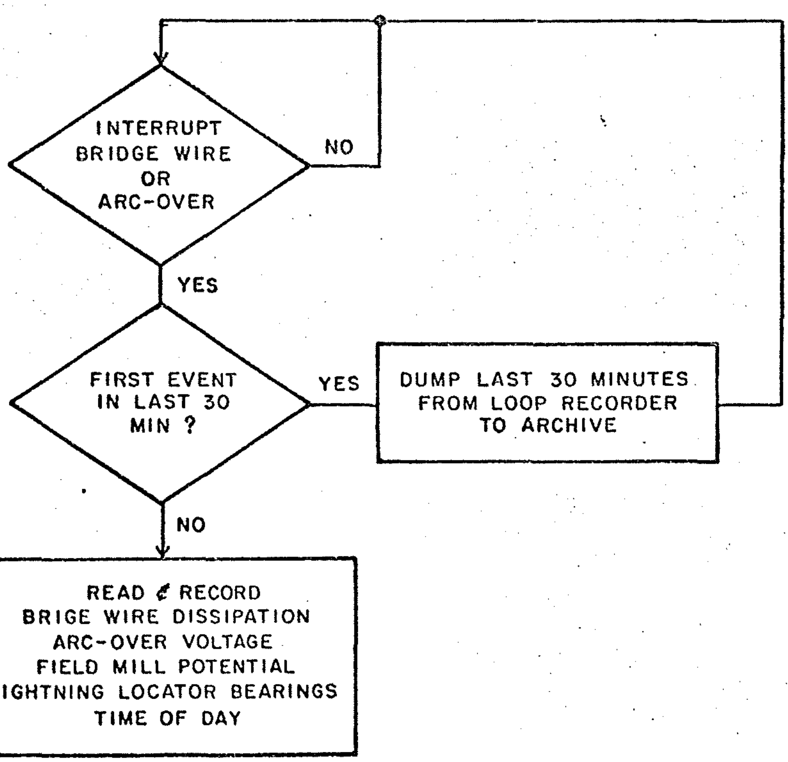
Such experiments run for 3 to 6 months or a year in different terrains could then be evaluated in terms of deriving device-independent warning effectiveness criteria.

CONCLUSIONS

1. The evaluation study has revealed three viable alternatives exist for the development of a mining safety program:



(a) Automated Sensing Instrumentation



(b) Recording Protocol

FIGURE 35. - Lightning Warning Parameter Instrumentation

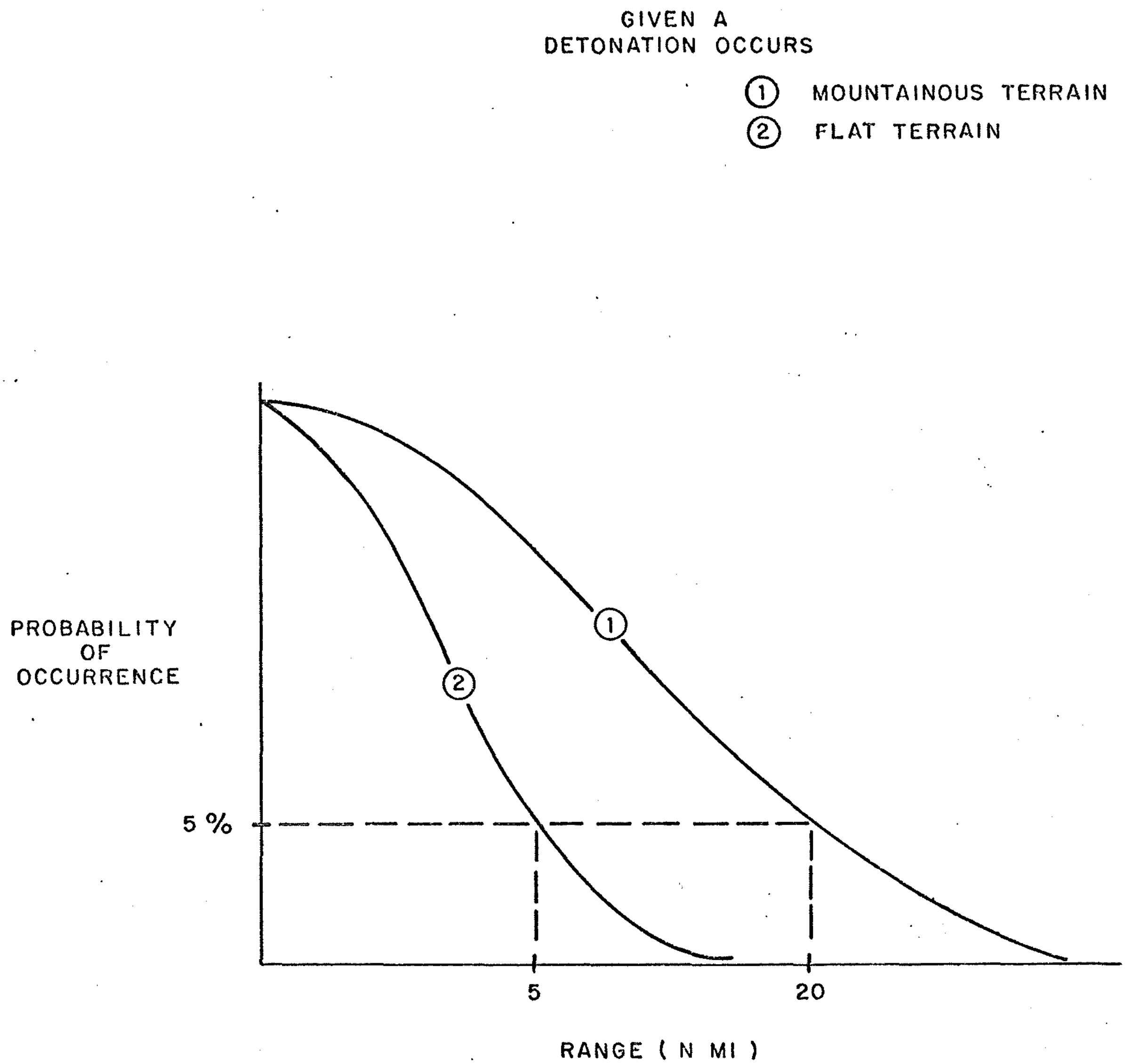


FIGURE 36. - Speculated Differences in Explosive Hazard vs Range for Different Terrains

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a. Development of a device independent safety specification.

b. For the near term, use a triangulation lightning location network.

c. Develop an improved single point hazard sensing device.

2. The experimental techniques used in this study can be adapted to derive device independent warning criteria based on actual explosive hazards. Tests in various terrains using improved detonator simulation equipment are required to provide needed data. Unfortunately warning criteria cannot be derived from the data acquired since the recorded data are specific to the devices under test.

3. Using present technology, the triangulation lightning locator system presents best performance statistics. Deployment of a network of these sensors could be made on a cost sharing basis among the various mining company users. Lightning location plots would be available to individual operations as required.

4. Data obtained in this study can be used to develop an improved single point hazard sensing device.

a. The evaluation study has revealed that a truly automated, single site lightning warning system must have the capability of measuring at least three parameters to be effective to 10 nmi range. The parameters are: (1) electrostatic field, (2) electrical discharge rate (sferics), and (3) atmospheric noise background level. System design must take into account physical and radio frequency environmental factors.

b. The single most important lightning warning statistic requiring improvement is the failure to alarm rate. Improved performance is possible by incorporating an adaptive threshold capability in the warning system.

c. Performance failures of the flash counter and corona point sensor tested outweigh their potential usefulness as a lightning warning system.

d. The azimuth/range locator tested is not considered to be a useful lightning warning system due to the high false alarm rate. Moreover, this concept is not considered to be useful in the development of an improved device due to the inaccuracies in range estimation and the angular directional errors induced by horizontal components in the crossed loop.

e. Using present technology, single point lightning warning can be provided by combining a radioactive probe or field mill, flash counter and background noise sensing device capable of adaptive warning threshold adjustment.

RECOMMENDATIONS

The following recommendations are proposed to reduce the incidence of lightning caused blasting accidents:

1. Based on the terrain dependent predetonation hazard observed in this work, it is recommended effective mine safety lightning warning system performance specifications be developed independent of sensor technology and based on actual explosive hazard. An extensive survey should be performed to determine incidence of simulated detonation versus terrain for the development of this specification.

2. In the event sufficient interest exists among the mining industry users, a network of triangulation lightning location sensors should be deployed to provide lightning mapping data to concerned mining operations. The deployment and operational expenses of the network can be prorated through a moderate subscription rate of shared cost by the individual users. Initial outlay will be approximately \$500,000 with monthly operating costs near \$5,000 for a 20 station net in the eastern United States. The western United States may benefit from the existing Bureau of Land Management lightning location network.

3. If the mining industry prefers single point sensors at each mining site, then an adaptive lightning warning system should be developed to reduce the failure to alarm rates of existing devices. It is anticipated than an adaptive system could be developed and marketed in production quantities at a cost comparable to existing moderately priced devices, say \$5,000 - \$7,000 (1979 dollars).

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APPENDIX A

SYNOPSIS OF APPLICABLE ACCIDENT REPORTS

1. Date: 28 September 1949

Source: DoD Explosive Safety Board

MSHA ID: Not Applicable

Type of Mine/ Activity: Surface Explosive Disposal

Fatalities: 0

Injuries: 0

Mine Activity Name: U. S. Army Ordinance

Location: Unknown

Description of Terrain: Unknown

Description:

Twenty-six charges using electric blasting caps were set to dispose of surplus explosives. Upon approach of thunderstorm, the area was evacuated. Upon the return of the crew, it was found that 20 charges had detonated with six unfired charges scattered in the area. Lightning is listed as the cause. The report mentions a similar incident earlier in the month.

2. Date: 31 May 1962

Source: Explosive Safety Board

MSHA ID: Not Applicable

Type of Mine/ Activity: Tunnel Construction

Fatalities: 1

Injuries: 6

Mine Activity Name: Potomac Sewer Tunnel

Location: Great Falls, VA

Description of Terrain: Unknown

Description:

Work on preparation for blasting operations was stopped during a thunderstorm and resumed when the storm appeared to be over. Two of twenty dynamite charges prematurely detonated resulting in one death and six injuries. The cause is believed to be a surface lightning strike which traveled into the tunnel to the blasting area along a tram track. Electric blasting caps were reported grounded for safety.

3. Date: 5 July 1969

Source: District Office - Metal & Non-Metal Safety Eastern District; Pittsburgh, PA

MSHA ID: New Number: 60010-0-33-005; Old Number: 3174-33-005-14220

Type of Mine: Surface Limestone Mine

Fatalities: 1

Injuries: 0

Mine Activity Name: Plant No. 1; Diamond Stone Quarries, Indiana

Location: Albany, Athens County, Ohio

Description of Terrain: Nominal elevation is 750 ft with flat terrain and low rolling hills

Description:

Twenty-two of 23 holes in an overburden blasting operation were loaded using electric blasting caps. This job was being performed on a bimonthly basis. Drilling of the 23rd hole was proceeding. Two bulldozers were in the pit. One was moved while the victim was sitting on his bulldozer 30ft. from the face. A sudden thunderstorm resulted in a lightning strike which caused a premature explosion. The victim was crushed by a falling boulder.

4. Date: 30 June 1973

Source: District Office - Metal and Non-Metal Safety
Western District

MSHA ID: 02-00136

Type of Mine Activity: Surface Copper Mine

Fatalities: 0

Injuries: 0

Mine Activity Name: Twin Buttes Operation ANAMAX Mining Company

Location: Sahuarita, Pima County, Arizona

Description of Terrain: Mine elevation estimated at 3600 ft. in foothills of a 6000 foot mountain range 10 miles west.

Description:

Eighty-six holes were loaded using electric blasting caps. Detonation was delayed to permit time to clear the area of all workers. During this period lightning from a storm detonated all charges.

5. Date: 9 July 1973

Source: Sub-district Office - Metal and Non-Metal Safety
Rolla, MO

MSHA ID: 23-00008

Type of Mine / Activity: Surface Limestone Mine

Fatalities: 0

Injuries: 0

Mine Activity Name: Ash Grove Limestone Quarry and Mill; Ash Grove Cement Co.

Location: Springfield, Green County, MO

Description of Terrain: Elevation estimated at 1300 feet. Terrain is relatively flat.

Description:

Loading of 12 holes (using electric blasting caps) was initiated. Trouble with the loading machine delayed completion of the charging. At 1:pm the 3-man blasting crew evacuated upon the approach of a thunderstorm. Lightning caused detonation of 9 of the charged holes.

6. Date: 8 June 1974

Source: District Office - Coal Mine Health and Safety, Southeastern District

MSHA ID: (Not on Report)

Type of Mine/ Activity: Surface Coal Mine

Fatalities: 0

Injuries: 1

Mine Activity Name: Splashdown No. 2 Strip Mine, Clinchfield Coal Co.

Location: Haysi, Dickenson County, VA

Description of Terrain: Very hilly. Elevation of mine estimated at 2400 feet with 4000 foot mountains within 20 miles.

Description:

Drilling and charging of 60 holes was started using electric blasting caps at 8:am. Work was delayed because required explosives were not on the job. By 4:45pm, charging of the sixty holes which were being wired in series had begun. Three of the four-man crew evacuated the area and took shelter upon observing an overhead thunderstorm. Lightning caused detonation of 48 of the 60 charged holes. The drill operator who did not leave the area was injured.

7. Date: 8 July 1974

Source: Southeastern District Office, Metal and Non-Metal Mine Safety

MSHA ID: 40-00079

Type of Mine / Activity: Surface Limestone Mine

Fatalities: 0

Injuries: 0

Mine Activity Name: Algood Quarry and Plant; Mid-South Pavers Inc.

Location: Algood, Putnam County, Tennessee

Description of Terrain: Low rolling hills with elevation approximately 1450 feet.

Description:

At 9:am, four mine company employees supervised by powder company employees began charging 52 holes using electric blasting caps. A thunderstorm moved into the area at 1:30pm but work continued with the last holes charged at 1:45pm with nearby visible lightning. During wiring and testing stray currents were noted. The area was evacuated at 2:pm. During the evacuation a truck ran into a ditch 600 ft. from the blasting area. While the truck was being towed out of the ditch at 2:10pm, lightning caused detonation of all 52 charged holes. Three employees near the truck avoided falling rock by taking shelter underneath the truck.

8. Date: 27 August 1974

Source: Southeastern District Office - Metal and Non-Metal Mine Safety

MSHA ID: 40-01289

Type of Mine/ Activity: Surface Limestone Mine

Fatalities: 0

Injuries: 0

Mine Activity Name: Signal Mountain Mine and Mill
Vulcan Materials Company

Location: Jasper, Marion County, Tennessee

Description of Terrain: Exact mine location not known. Terrain in the area is very hilly with elevation variation from 600 feet to 2000 feet.

Description:

A blasting crew consisting of three powder company personnel and three mine company employees began charging a round of 40 holes at 8:30am using electric blasting caps. Charging of the round was suspended at 9:45am because a thunderstorm moved into the area and resumed 12:45pm. Charging was completed at 3:45am. After the round was wired, installation of the blasting line was started. Because of heavy rain all personnel took shelter in their vehicles some 150 ft. from the charged round. At 5:10 , a lightning strike caused all 40 holes to detonate. Minor damage was caused to one vehicle by falling rock.

9. Date: 6 August 1975

Source: Northeastern Office - Metal and Non-metal Safety

MSHA ID: 30-00644

Type of Mine/
Activity: Underground Metal Mine

Fatalities: 0

Injuries: 0

Mine Activity
Name: Willsboro Mine and Mill; Interspace Corp.

Location: Willsboro, Essex County, New York

Description
of Terrain: Mine elevation at approximately 250 feet in river valley 4000 feet; 4000 ft. mountains 15 miles west and 25 miles east.

Description:

A 200-hole round was charged on the fourth level face of this underground mine using electric blasting caps. Blasting operations were performed during non-working hours. The round was to be fired around 10:pm. At 7:pm workers began to evacuate when a thunderstorm was heard. An arc from a water pipe was observed as the workers moved moved through the fourth level. After the storm a large percentage of the holes was found to have detonated. Lightning struck a tree and traveled to the blasting area via a water pipe. The report states a similar premature explosion occurred at this mine on June 26, 1964. No formal report was found on this event.

10. Date: 7 May 1976

Source: Southeastern District (District No. 7)
Coal Mine Health and Safety

MSHA ID: 01-00627

Type of Mine/
Activity: Surface Coal Mine

Fatalities: 0

Injuries: 0

Mine Activity
Name: Flat Top Strip, The Drummund Company

Location: Graysville, Jefferson County, Alabama

Description
of Terrain: Location of the mine not known. Terrain in the area varies from 400 to 600 feet with low rolling hills.

Description:

The report and a letter on the accident are brief. Lightning apparently caused a premature explosion of charged holes on a high wall. Personnel had evacuated the area on the approach of a thunderstorm. Electric blasting caps were being used.

11. Date: 1 August 1977

Source: District 2 - Coal Mine Health and Safety

MSHA ID: 36-02732

Type of Mine/
Activity: Surface Coal Mine

Fatalities: 1

Injuries: 3

Mine Activity
Name: Jones and Braque Strip; Jones and Braque Mining Co.

Location: Morris Run, Tioga County, PA

Description
of Terrain: Mine location unknown. Terrain in the area very hilly with a nominal elevation of 2200 feet.

Description:

Following a 6:am rainshower with lightning, charging of a large number of holes had taken place. This work continued through intermittent rainshowers. At approximately 2:30pm, the two blasters found they had an open circuit and visually inspected the wiring. While they were attempting to test portions of the circuitry, a five minute rain shower occurred. The rain shower was followed by lightning which detonated all but three of the charged holes. One blaster was killed while the other was seriously injured. Two other nearby personnel were injured, one seriously.

12. Date: 10 August 1977

Source: District Office (District 6) MESH Pikeville, KY

MSHA ID 15-09618

Type of Mine / Activity: Surface Coal Mine

Fatalities: 2

Injuries: 1

Mine Activity Name: Lackey Branch Mine; Addinton Brothers Mining, Inc.

Location: Van Lear, Johnson County, Kentucky

Description of Terrain: Area is moderately hilly with elevation variations from 600 to 1000 feet.

Description:

During a normal work shift, the drill and blasting crews were instructed to drill and charge holes using electric blasting caps. At 4:30pm the crew withdrew from the area on the approach of an electrical storm. At 5:15 pm when the rain ceased, work was resumed. Lightning struck 800 feet from the work area detonating sixty charged holes. Two workers were killed and a third seriously injured.

13. Date: 21 June 1978

Source: Northeastern District Office, Metal and Non Metal Safety

MSHA ID: 44-01921

Type of Mine/
Activity: Underground Metal Mine

Fatalities: 0

Injuries: 0

Mine Activity:
Name: Austinville-Ivanhoe Mine and Mill; The New Jersey Zinc Co.

Location: Austinville, Wythe County, VA.

Description
of Terrain: Mine location not known. Terrain in the area is very hilly varying from 750 feet to 3700 foot mountains.

Description:

Two workers began drilling holes at 7:00 a.m. At 12:30 p.m., they called to the surface to check weather conditions and were given the OK to charge the holes. After charging 14 holes (using electric blasting caps) and completing wiring except to blasting machine, the two men began work at 1:55 p.m. in another area. At 2:10 p.m. they heard an explosion. A hoist man reported a severe electrical storm with a lightning strike near the mine. An electrician reported unexplained electrical arching at another underground level at the time of the explosion.

APPENDIX B

COMMERCIAL SUPPLIERS OF ELECTRICAL STORM WARNING SYSTEMS

Commercial Suppliers of Electrical Storm Warning Systems

Atlantic Scientific Corp.
P. O. Box 3201
Indiatlantic, Florida 32903

AUL Instruments, Inc.
1400 Plaza Avenue
New Hyde Park, New York 11040

Bendix Avionics Division
2100 Northwest 62nd Street
Fort Lauderdale, Florida 33310

Edmund Scientific
Edscorp Building
Barrington, New Jersey 08007

Electrofields, Inc.
1811 S. W. 98th Avenue
Miami, Florida 33165

Electro-Photo Products Co.
Lutz Road, Box 52
Glidden, Wisconsin 54527

GCA Corporation
GCA Technology Division
Bedford, Massachusetts 01730

Lightning Elimination Associates
12412 Benedict Avenue
Downey, California 90242

Lightning Location and Protection, Inc.
2030 Speedway Blvd, Suite 120
Tucson, Arizona 85719

Meteorology Research, Inc.
464 West Woodbury Road
Altadena, California 91001

Montgomery-Wards
Catalogue #83 C 1654

Ryan Stormscope
4800 Evanswood Drive
Columbus, Ohio 43229

Safety Devices, Inc.
7208 Lockport Place
Lorton, Virginia 22079

Sears
Catalogue #9H57088

B. K. Sweeney Manufacturing Co
6300 Stapleton South Avenue
Denver, Colorado 80216

VME-Nitro Consult Inc.
1732 Central Street
Evanston, Illinois 60201

Weather Information Systems Corp.
2345 West Mill Road
Milwaukee, Wisconsin 53209