





# EVALUATION OF PROXIMITY WARNING DEVICES

**Prepared for**

**United States Department of the Interior  
Bureau of Mines**

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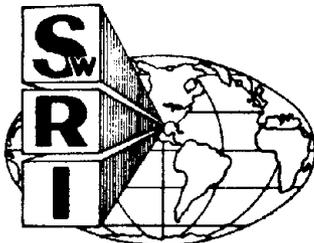
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29 September 1978 to 30 November 1979**

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Evaluation of Proximity Warning Devices**

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**SOUTHWEST RESEARCH INSTITUTE  
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| 16. Abstract (Limit: 200 words)<br>Three electrostatic field sensing proximity warning devices were tested using full-scale cranes and powerline systems, a scaled model facility, environmental testing facilities, and theoretical-numerical analysis. The design objective of each device is to assist in safe crane operation near overhead powerlines. Several design deficiencies were noted, including inadequate overlap in sensitivity ranges, utilization of vacuum tubes and electromechanical parts, temperature sensitivity, and inaudible alarms. In addition, the testing showed major device limitations including sensitivity to boom orientations and length, polarization-dependent responses, and unreliable operation in the presence of multiple powerline circuits. The multiple powerline circuit problem is intrinsic to electrostatic sensing devices. The remaining deficiencies and limitations are correctable within a state-of-the-art design. |  |                                    |                                                                               |                                                        |
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## FOREWORD

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## I. INTRODUCTION

The necessity for mobile cranes to work in the vicinity of overhead power lines frequently results in severe hazards, jeopardizing the safety of the equipment operator and nearby personnel. Present federal regulations (77.807-2 and 77.807-3, Title 30, CFR) specify that equipment of this nature should not be operated within ten feet (or more depending on the line voltage) of an energized power line. However, minor accidents, operator misjudgment, and other unforeseen eventualities occasionally result in equipment extensions coming in contact with energized overhead power lines. Although accidents of this nature account for only a small fraction of all electrical accidents, they do account for a significant fraction of the total deaths by electrical accident. In an effort to decrease the likelihood of such accidents, a number of states have enacted laws requiring the use of insulating safety guards around boom extensions and insulating safety links on load lines to isolate heavy equipment hooks and the hoisting equipment itself. These devices provide a margin of safety to the operator and others working directly with the heavy equipment, but do nothing to prevent actual contact with the energized power line.

As an aid to avoiding equipment contact with energized power lines, several warning devices are marketed that are designed to detect proximity of equipment extensions to overhead power lines and provide both a visible and audible warning to the operator.

The Phase I objectives of this contract were to perform a thorough search to locate and purchase all commercially available power line proximity warning devices and to conduct extensive comparative testing on each device. Three proximity warning devices manufactured in the U.S. were identified and purchased. All of the devices tested operated on the principle of detecting the electrostatic field intensity for determining proximity to the power lines. The performance of these devices was tested using full-scale cranes and power line systems, a scaled model facility, environmental testing facilities, and theoretical/numerical analysis. Besides providing a qualitative comparison between the three units, these tests monitored performance variation resulting from such factors as power line configuration, crane configuration, sensor placement, conducting structures, and environment.

## II. EXECUTIVE SUMMARY

The goal of a proximity warning device for installation on cranes\* is to assist in safe crane operation near overhead power lines. To accomplish this, a proximity warning device would ideally give an alarm when (and only when) any portion of the crane boom (or equipment extension) is closer than some specified fixed distance to an energized power line. However, in practice, the problem is made complex by distortions in the electrostatic field environment and significant variations in the configuration, reliability, and effectiveness of commercially available proximity warning devices. The primary purpose of Phase I of this contract was to purchase three proximity warning devices and test these devices under a wide variety of simulated and actual working conditions. Comparison to theoretically predicted performance was also performed.

This study is not intended to evaluate the safety aspects or policy of utilizing proximity warning devices. Rather, the purpose is to determine the performance characteristics of such devices in relation to the criteria specified in proposed MSHA regulations 77.805-4, i.e., the devices must alarm at a distance of 10 feet from the power line. Furthermore, this study is limited to the evaluation of proximity warning devices operating without interaction with other safety systems.

The three proximity warning devices tested during this contract were the Electro-Alarm Model ECA-X, the Sigalarm,\*\* and the SR Instruments PD-102.\*\*\* As a minimum, each device consists of an electrostatic field probe, a master control unit, and an audible alarm. Typically, the electrostatic field probe is installed near the boom tip. The master control unit is installed within convenient reach and view of the crane operator, and includes a sensitivity adjustment that is necessary for operation around various power line circuit configurations. The procedure for adjusting the sensitivity of each device is to first position the crane boom at the minimum safe working distance and then adjust the sensitivity to establish alarm threshold at that boom position.

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\*In principle, the proximity warning devices studied under this contract could also be applied to other heavy equipment with extensions. However, the analysis performed under this contract was limited to the specific application of proximity warning devices for installation on cranes.

\*\*The Sigalarm unit tested during this program was manufactured by Sonobond Corporation of West Chester, Pennsylvania. At the time of this writing, the manufacturing rights for the Sigalarm have been sold to another company. The Sigalarm unit manufactured by Sonobond is no longer available.

\*\*\*Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding and does not imply endorsement by the Bureau of Mines.

Each of the devices tested was found to perform repeatably, in that alarming typically ceased when the crane boom moved away from the power line and then reactivated when the crane boom moved back into the initial position. However, the tests also monitored the reliability to properly activate the alarm when the crane is brought back into the vicinity of the power line after changing the boom height (simulating actual operation conditions). In general, the power line-to-boom distance causing alarm activation varied with changes in the boom height. For all three devices tested, the nature of the line-to-boom distance variation with boom height changed with changes in power line configuration, with sensor placement on the boom, with boom orientation toward the power line, and with the presence of additional adjacent power line circuits.

The Sigalarm proximity warning device uses a probe that is distributed along the entire length of the crane boom, thus providing inherent protection along the entire length of the boom (on one side of the boom). However, by nature of the distributed sensor, the Sigalarm system demonstrated sensitivity variations with boom extension and with the boom orientation toward the power line.

The SR Instruments device uses a small "point" sensor providing essentially a sphere of coverage centered around the sensor and does not provide adequate protection for the more remote portions of the boom. However, since the SR Instruments device uses a point sensor, the distance between the sensor and the power line required to initiate alarming remains essentially invariant with changes in boom length and boom orientation.

The Electro-Alarm proximity warning device also uses a point sensor, providing protection only in the vicinity of the sensor itself. However, the Electro-Alarm system provides, as an option, several sensors for installation along the length of the boom to increase the boom protection coverage.

Because each of the devices detects the proximity of an energized power line by measuring a component of the electric field strength produced by the power line, each device is influenced by the nature of the total electric field in its vicinity. For example, in the presence of multiple power line circuits,\* the electric field components in the vicinity of the crane may combine to cancel and produce field nulls. Under such circumstances, neither of the three devices nor any device operating on electrostatic field detection principles alone can operate reliably. Each of the three devices responds with maximum sensitivity to electric field vector components oriented in a direction preferred by the sensor/boom configuration, and produces a minimum (or even null) response for electric field orientations orthogonal to that preferred direction. As a consequence, each of the three devices experienced

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\*In a multiple circuit configuration, each power line circuit may have a different line voltage, string of utility poles, and right of way.

gross sensitivity variations due to variation in electrostatic field vector orientation. Each of the three devices also displayed a shadowing phenomenon, whereby the sensor was shielded by the crane boom whenever the crane boom position was such that the sensor and the power line were on opposite sides of the crane boom.

In addition to the above physical limitations in the operational characteristics, the three devices displayed several design differences. The Electro-Alarm had the least usable range of detectable power line voltages, showed regions of power line voltages in which operation was completely unreliable, used fragile vacuum tube circuitry, did not provide means for adjusting the signal cable length as the boom extension was changed, and failed completely at temperatures below 30° Fahrenheit. The Sigalarm proximity warning device had the greatest dynamic range of detectable power line voltages, had very adequate overlapping sensitivity ranges, used solid state circuitry exclusively, operated well in temperatures from -60° Fahrenheit to +160° Fahrenheit, and provided capability for conveniently adjusting the signal line length as the crane boom length was changed. The SR Instruments proximity warning device was also solid state, and while it operated over a wide temperature range, it displayed unacceptable sensitivity variations with temperature, had an inaudible alarm, and did not provide means for adjusting the cable length as the boom length was changed.

The investigations performed during Phase I of this contract produced the conclusion that of the three devices tested, the Sigalarm device was the most reliable and effective unit. However, all of the devices tested and, in fact, any proximity warning device based only upon electrostatic field sensing will fail to alarm reliably under certain configurations of multiple power line circuits. The other deficiencies of the commercial devices tested, i.e., the sensitivity to electric field orientation, to boom shadow effects, and to boom orientation can be minimized by more sophisticated design. The recommended design would utilize multiple point sensors located on all sides of the boom and along the length of the boom, with each sensor being separately monitored to report an alarm whenever its output exceeds a preset threshold. The electronics would use a microprocessor for self-calibration and more complex alarm/logic analysis.

### III. TECHNICAL DISCUSSION

#### A. Proximity Warning Device Performance Goal

To assist the crane operator in complying with federal regulations and to allow safe operation, a proximity warning device would ideally give an alarm when (and only when) any portion of the crane boom is closer than some specified fixed distance to an energized power line. A less ideal, but still desirable performance goal would result in an alarm activation whenever some chosen point (e.g., the boom tip) is closer than the specified distance. This concept is illustrated in Figure 1, which shows the cross section of a power line conductor (the nearest conductor) and a danger zone around the conductor. The alarm contour is defined in accordance with proposed MSHA Regulation 77.805-4 and is the locus of all boom positions where the device is at the threshold of alarm activation. Whenever the crane boom penetrates the alarm contour, the alarm activates. The vertical portion of the ideal alarm contour is required, since the crane's extended work cable is closer than the specified safe distance when the crane boom tip passes through the vertical line.

Any departure from the ideal performance described above either jeopardizes the safety or the productivity of the crane operator and surrounding personnel. Obviously, whenever the proximity warning device allows the crane boom to encroach into the danger zone shown in Figure 1, personnel safety is compromised. However, whenever the proximity warning device alarm activates for boom positions that are not in the danger zone, either the crane productivity is sacrificed, or the alarm is viewed with less confidence and is perhaps ignored. Finally, since the boom position at which alarm sensitivity is to be adjusted may unknowingly be chosen at a position of minimum sensitivity, any departure whatsoever from the ideal alarm contour potentially allows the crane boom to enter the danger zone.

#### B. Proximity Warning Device Literature Search

During the process of searching for commercially available proximity warning devices, product descriptive information was requested from the manufacturer of each device. In addition, a search of U.S. patent literature was performed to provide auxiliary information about devices for this application, and the principles on which they operate. Finally, literature describing tests that have been performed on proximity warning devices was collected and studied. The product descriptions, test reports, and a list of most relevant U.S. patents are presented in Appendix A.

#### C. Methods of Energized Line Detection

An energized power line generates both electric and magnetic fields in the vicinity of the electric wires. Consequently, the presence of an energized power line may be detected by measuring either the electric field strength or the magnetic field strength. The intensity of the

Ideal Alarm Contour  
(Dividing line between alarm  
activation and no alarm condition)

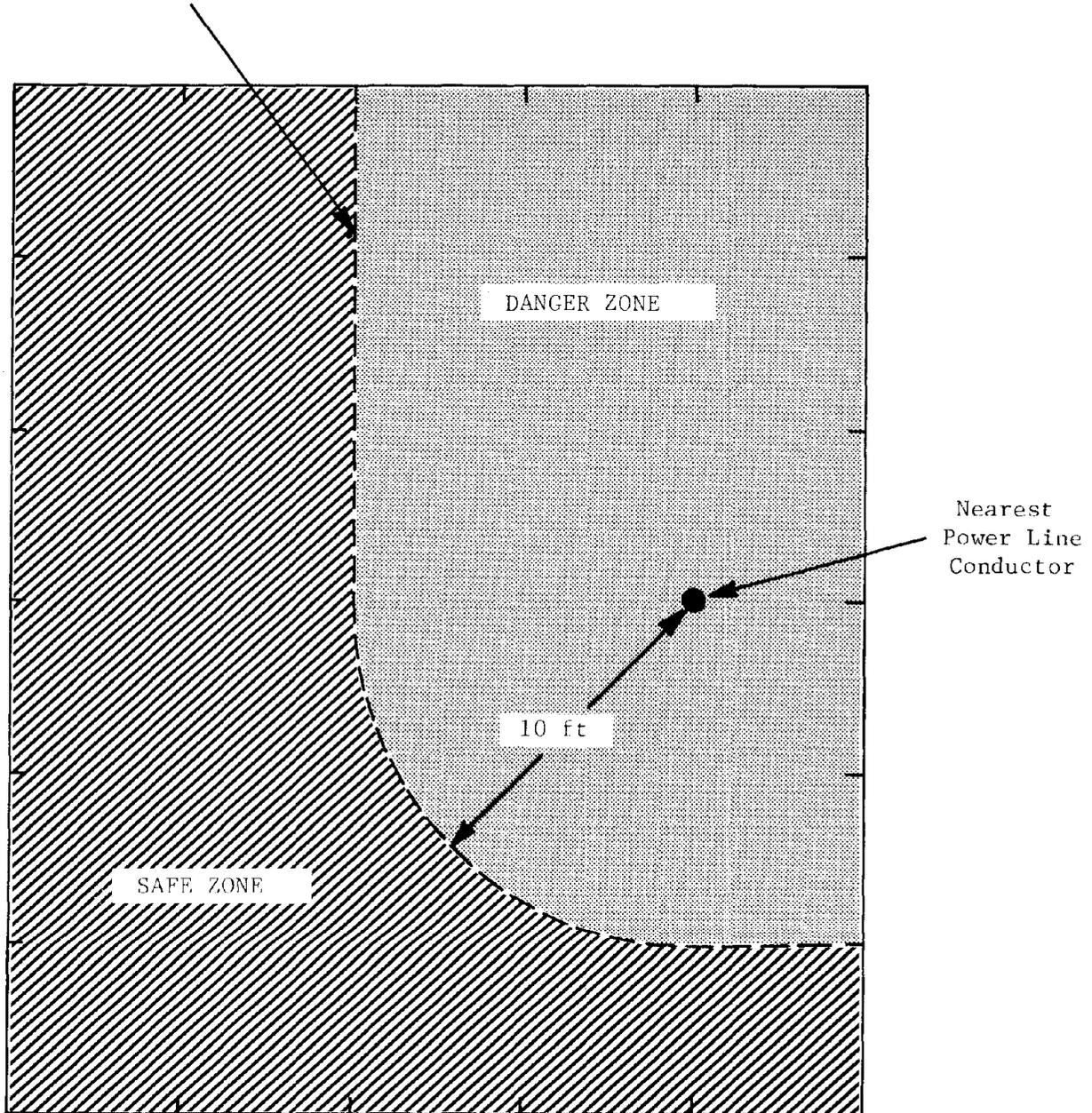


FIGURE 1

ALARM CONTOUR FOR IDEAL PROXIMITY WARNING DEVICE  
MEETING PROPOSED MSHA REGULATION 77.805-4

generated magnetic field at any point around the power line is a function of the power line geometry and of the current that is being carried by the power lines. Since the power line current varies with the electrical demand that is placed on the power system, the magnetic field strength varies with the electrical loading conditions. Thus, although detection of the magnetic field strength is an indication of an energized power line, it cannot reliably be used to give information about distance to the power line.

In contrast, the electric field generated by an electric power line is a function of the transmission line geometry and of the voltage at which the transmission lines are maintained. All of the relevant parameters that determine the electric field strength distribution are fixed for a specified power line configuration, and measurement of the electric field strength may therefore be used as a more reliable indicator of distance to an energized power line.

#### D. Proximity Warning Device Descriptions

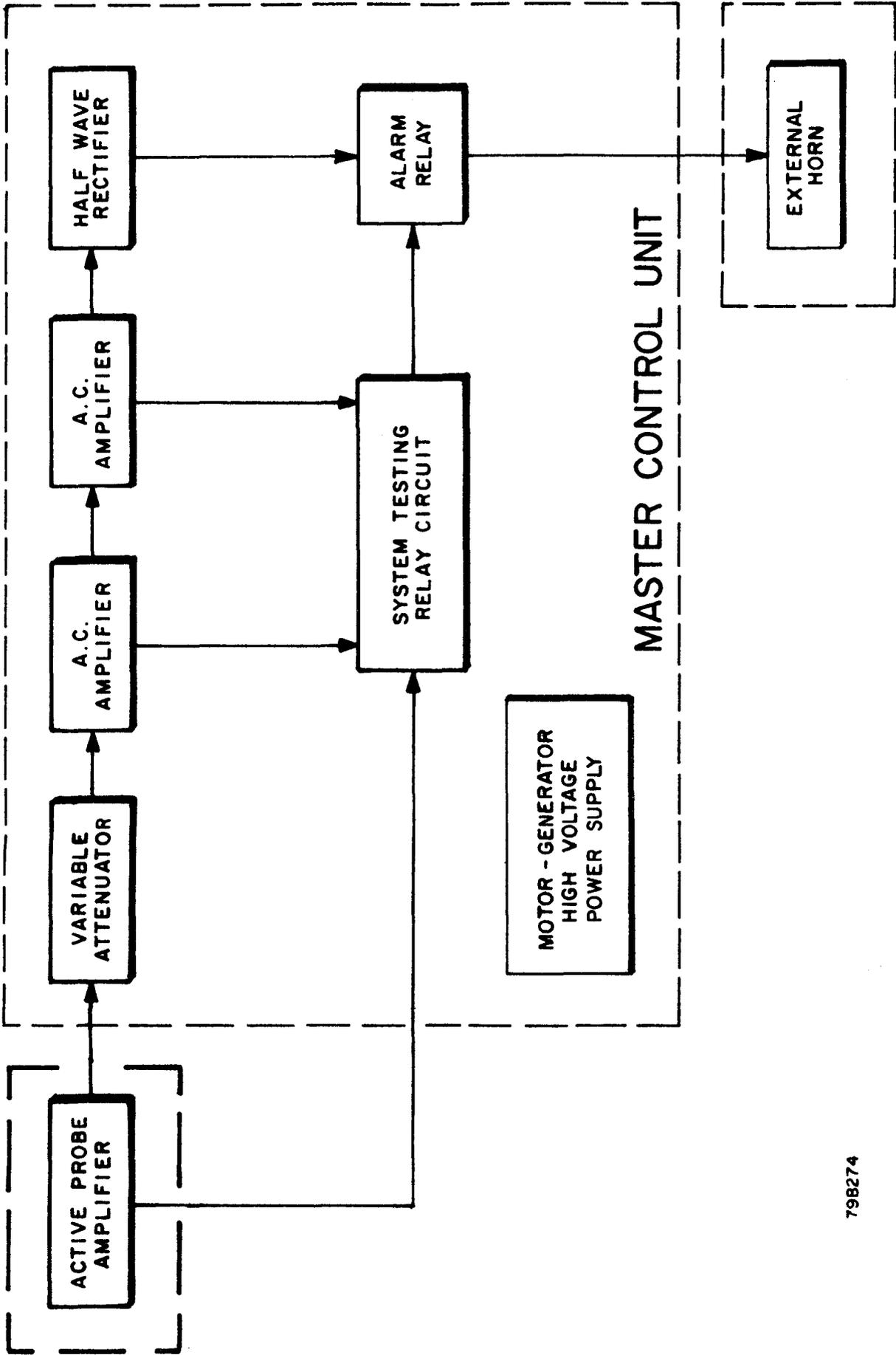
Three different proximity warning devices, each operating by detecting the electric field, were purchased for evaluation as part of this contract. As a minimum, each device consists of a probe, a master control unit, and an audible alarm. Typically, the probe is installed near the boom tip and the master control unit is installed within convenient reach and view of the crane operator. The master control unit for each device includes a coarse sensitivity adjustment, a continuously adjustable fine sensitivity control, alarm lights, and circuit monitoring lights. Each device monitors the 60 Hz electrostatic field at the device probe, and amplifies and rectifies the resulting 60 Hz signal to produce a dc level proportional to the 60 Hz signal. Whenever the dc voltage exceeds a fixed threshold, an audible and visible alarm circuit is activated. Whenever the dc voltage falls below the threshold level, alarming ceases. The procedure for adjusting the sensitivity of each device is to position the crane boom at the minimum safe working distance and adjust the sensitivity to establish alarm threshold at that boom position. The distinguishing features of the three devices are described below.

##### 1. Electro-Alarm

Figure 2 is a photograph of the Electro-Alarm model ECA-X proximity warning device manufactured by Electro-Alarm Corporation of Fresno, California. Figure 3 is a block diagram of the basic Electro-Alarm system consisting of a probe module, a master control unit, and a warning horn. The Electro-Alarm is also designed to permit the installation of multiple probe units. The probe module consists of (1) a 57" length of protective rubber hose enclosing the electrostatic field sensor wire and (2) a 3" x 4" x 6" metal box containing a signal preamplifier. A shielded three conductor signal/feed cable, connected between the control unit and the preamplifier, supplies dc power to the preamplifier and carries the 60 Hz signal to the master control unit.



FIGURE 2. ELECTRO-ALARM PROXIMITY WARNING DEVICE



798274

FIGURE 3. ELECTRO-ALARM PROXIMITY WARNING DEVICE BLOCK DIAGRAM

The Electro-Alarm proximity warning device uses vacuum tube circuitry in both the master control unit and the probe preamplifier. The plate supply voltage is produced from a dynamotor, which is a dc motor-driven generator. The logic circuits use electromechanical relays.

The Electro-Alarm coarse sensitivity adjustment is provided by a two-position toggle switch giving a "high volts" and a "low volts" range. Under alarm activation conditions, the relay logic repetitively flashes the alarm light and sounds the horn at about one second intervals. A system self-test circuit continuously monitors the operating conditions of each vacuum tube and the feed cable. If a failure is detected, the test circuit turns on a separate warning light.

## 2. Sigalarm

Figure 4 is a photograph of the Sigalarm proximity warning device, manufactured by Sonobond\* Corporation of West Chester, Pennsylvania. Figure 5 is a block diagram of the basic Sigalarm unit, consisting of a probe wire, a master control unit, and a warning horn. Sonobond Corporation also offers exterior horns, exterior warning lights, and various accessories, including manual or automatic antenna sensor reels for adjusting the sensor length as the crane boom length varies. The probe wire consists of ordinary two-wire, jacketed ac line cord. One conductor is connected to the alarm circuitry and the other is connected through a test switch to a signal injection circuit. At the remote end of the probe cable, the conductors are connected together to complete the signal injection path. The sensor cable is typically installed underneath the crane boom with about two feet extending free near the boom tip. Installed in this manner, the entire length of the sensor wire extending from the master control unit is sensitive to the electrostatic field produced by the power line. By switching on the signal injection circuit, a test signal is routed through the sensor into the master control unit, activating the alarm circuit and verifying the operational integrity of the sensor, electronics, and horn. The Sigalarm uses solid state circuitry exclusively and requires only a single relay to activate the horn and alarm light. The Sigalarm coarse sensitivity adjustment is provided by a six-position rotary attenuator switch. At threshold conditions for alarm activation, the horn and light operate repetitively at about one second intervals. As the 60 Hz input signal increases, the repetition rate increases correspondingly, alerting the operator that the crane movements are bringing the boom into even stronger electrostatic fields.

Manufacturers information describing the Sigalarm is presented in Appendix A.

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\*At the time of this writing, the manufacturing rights for the Sigalarm have been sold to another company. The Sigalarm unit manufactured by Sonobond is no longer available.

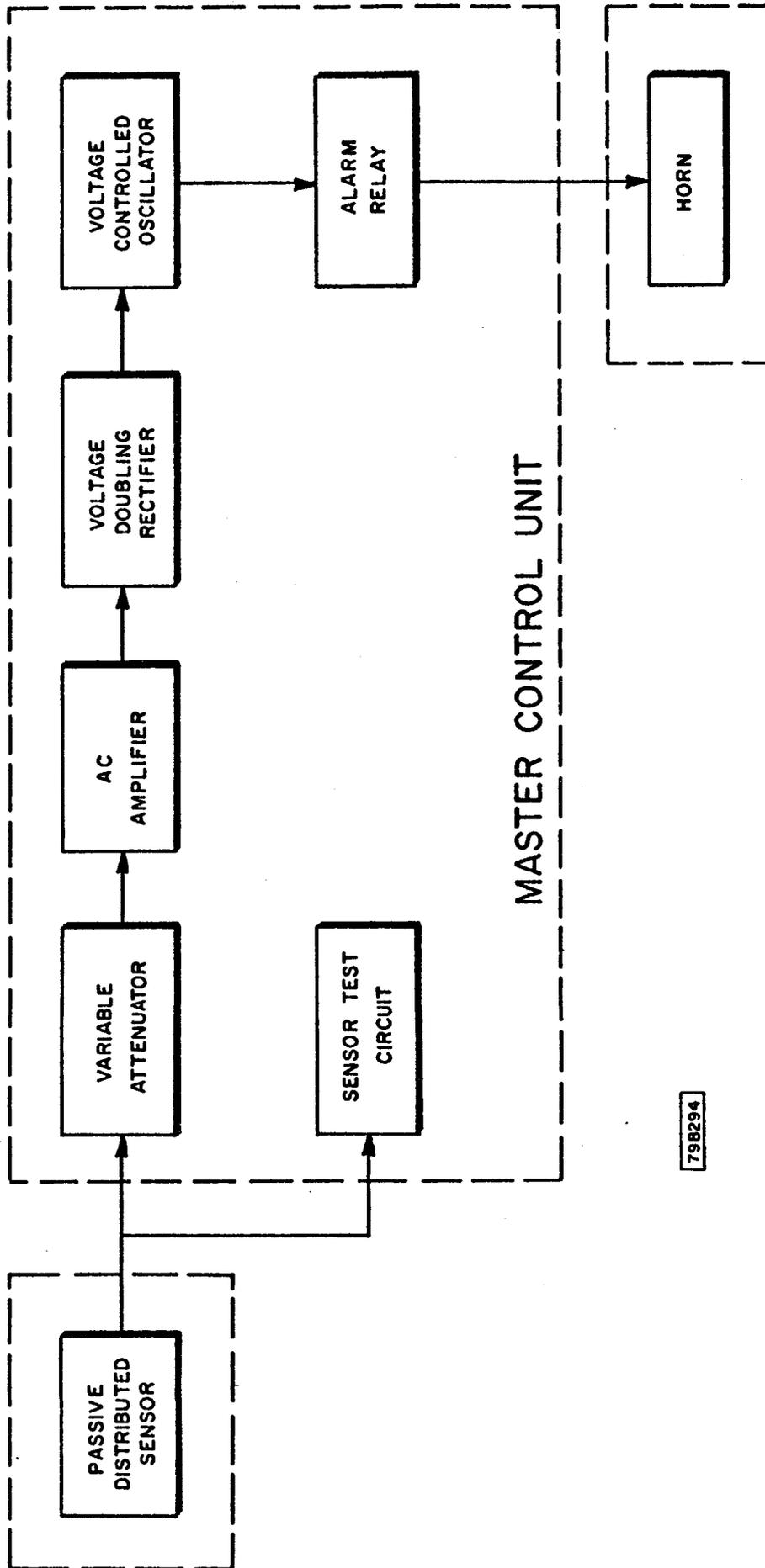
ANTENNA SENSOR REEL

HORN

CONTROL UNIT



FIGURE 4. SIGALARM PROXIMITY WARNING DEVICE



798294

FIGURE 5. SIGALARM PROXIMITY WARNING DEVICE BLOCK DIAGRAM

### 3. SR Instruments

Figure 6 is a photograph of the PD-102 proximity warning device manufactured by SR Instruments of North Tonawanda, New York. Figure 7 is a block diagram of the PD-102, consisting of a preamplifier probe module and a master control unit. Both the probe module and the master control unit use solid state circuitry exclusively. The probe module consists of a 1" x 1" x 2" metal block, housing the preamplifier, and a nine-inch rigid probe. The probe module is connected to the master control unit by a shielded two conductor cable. Since the shielded cable is insensitive to the external electrostatic fields established by a power line system, the PD-102, like the Electro-Alarm ECA, is essentially a point sensor system. The audible alarm of the PD-102 is a small Sonalert™ mounted to the chassis of the master control unit. The PD-102 coarse sensitivity adjustment is continuously adjustable. Under alarm activation conditions, the alarm light and the Sonalert™ are activated continuously, in contrast to the pulsating alarms of the Electro-Alarm and Sigalarm units. A test circuit in the SR Instruments unit continuously monitors the dc operating point in the active sensor module and extinguishes a light if an open or short circuit condition occurs in the shielded cable.

#### E. Electrostatic Field Distribution Around an Overhead Power Line

The primary geometrical factors that determine the electrical field strength in a power line system are the diameter and separation of the various phase conductors in the power line. The distance between the conductors and ground level is also a factor, but can usually be neglected since the conductor height above the earth is typically larger than the conductor spacing. By neglecting the ground plane, discussions of horizontally separated power line conductors are also relevant to vertically separated power line conductors. The accuracy of the resulting model is compromised to the degree that either the line separation or the observation point distance (i.e., 10 to 15 feet) from the power line becomes greater than the power line height above ground. For interpretational simplicity and contractual efficiency, the majority of the theoretical and experimental analysis was performed with single phase power line systems. A limited amount of three phase system analysis was performed to verify that alarm performance characteristics are similar for both three-phase and single-phase power lines.

Figure 8 is a cross-section of a single-phase horizontal power line geometry. The electrostatic potential distribution  $\phi$  that is forced by such a configuration may be described\* as

$$\phi(x,y) = \frac{V_0}{4 \cosh^{-1} (d/R)} \ln \left[ \frac{(x-a)^2 + y^2}{(x+a)^2 + y^2} \right] \quad (1)$$

\*W. Ramo, J. R. Whinnery, and T. Van Duzer, Fields and Waves in Communications Electronics, New York, Wiley, 1965.

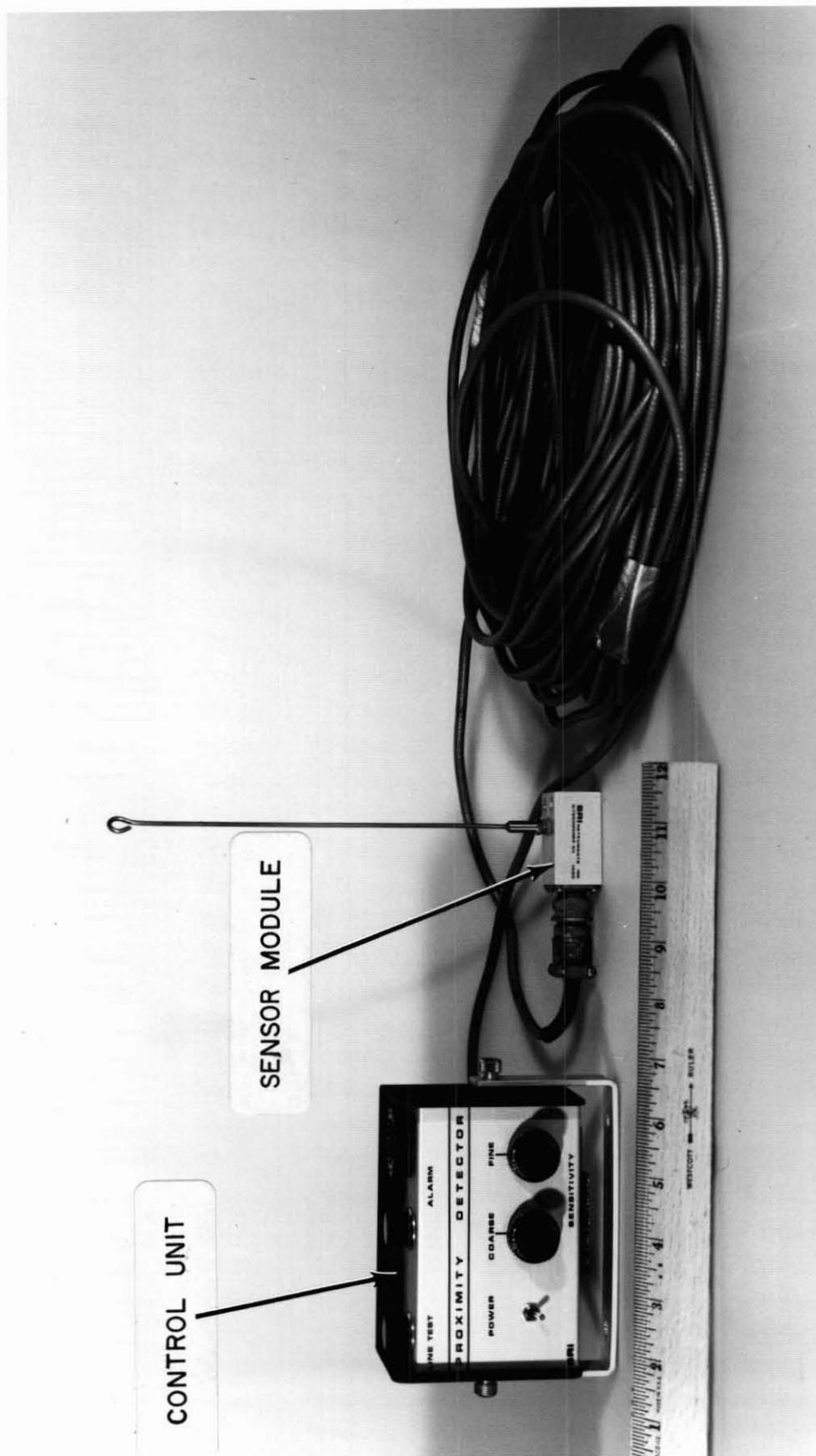


FIGURE 6. SR INSTRUMENTS PROXIMITY WARNING DEVICE

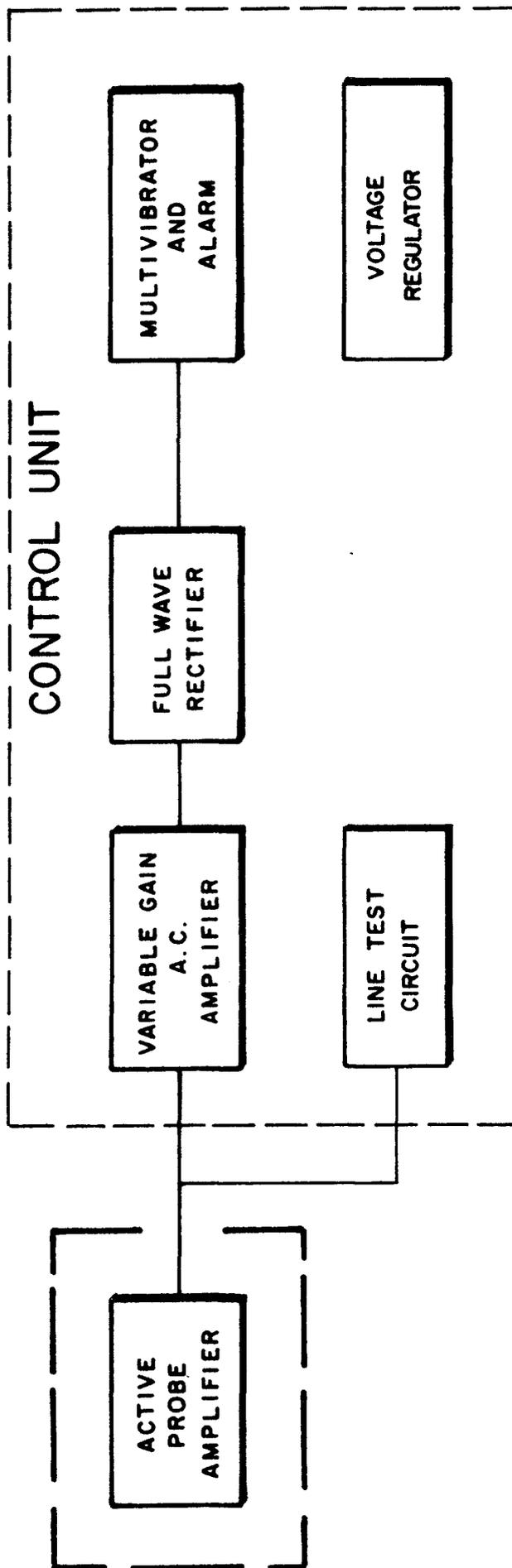


FIGURE 7. SR INSTRUMENTS PROXIMITY WARNING DEVICE BLOCK DIAGRAM

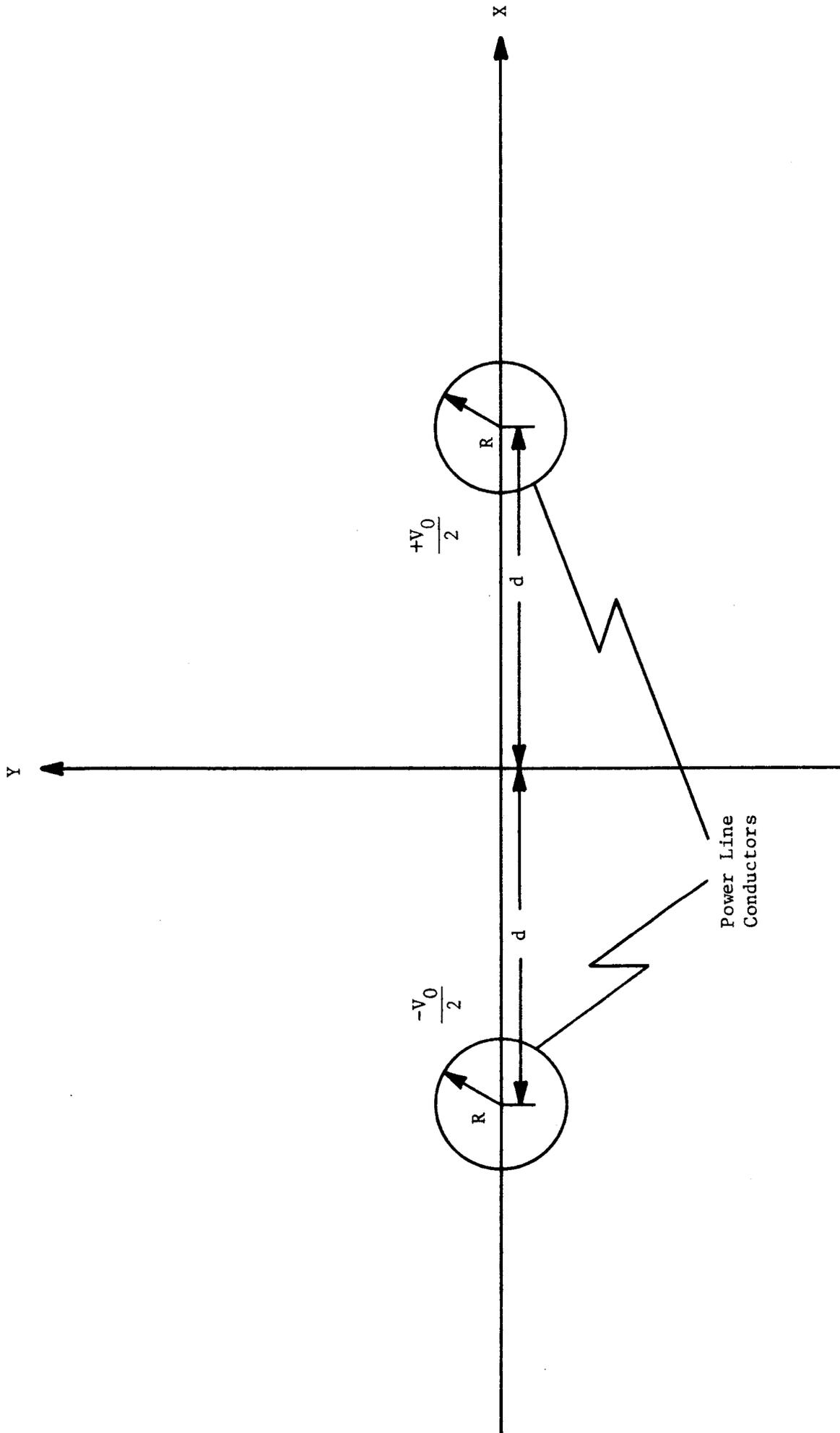


FIGURE 8. CROSS SECTION OF ENERGIZED POWER LINE

Where

$(x,y)$  = Rectangular coordinate location of observation point at which  $\phi$  is desired.

$V_0$  = Power line voltage.

$2d$  = Conductor separation.

$R$  = Conductor radius.

$$a = \sqrt{d^2 - R^2}$$

The electric field vector, which is more relevant to discussion of proximity warning devices, is determined from the gradient of the electrostatic potential distribution

$$\begin{aligned} \vec{E} &= -\nabla\phi \\ &= \frac{aV_0}{\cosh^{-1}(d/R)} \frac{(x^2 - a^2 - y^2) \hat{a}_x + 2xy\hat{a}_y}{\left[ (x - a)^2 + y^2 \right] \left[ (x + a)^2 + y^2 \right]} \end{aligned} \quad (2)$$

where  $\hat{a}_x$ ,  $\hat{a}_y$  are unit vectors in the x and y directions.

Equation (2) is an expression for the electrostatic field variation as a function of position. As can be seen from Equation (2), the electrostatic field distribution is a function of line geometry (conductor separation and conductor radius), line voltage, and position. For a fixed power line configuration and power line voltage, the electrostatic field distribution is a function only of position, thus forming the basis for an electrostatic sensing device to be used as a proximity warning detector. However, neither the amplitude nor the orientation of the electrostatic field vector is a function of mere distance from the power line and thus cannot provide the basis for exact compliance with the ideal proximity warning device performance. In addition, the electrostatic field distribution given by Equation (2) is valid only for an undisturbed power line and is significantly altered by the presence of the crane boom. Experimental measurements and theoretical discussions will form the basis for discussing these discrepancies in the following sections.

#### F. Experimental Testing Program

The three purchased proximity warning devices were tested to determine performance characteristics and severity of anticipated difficulties for various operating conditions. The difficulties investigated

include performance variation with changes in power line geometry, false alarms due to large grounded metal objects, performance degradation due to multiple power line circuits, false alarms from nearby thunderstorms, minimum detectable distribution voltages, the effect of the boom configuration, susceptibility to environmental conditions, and response to out-of-band interference. These tests were conducted using a scaled model laboratory facility, full-scale cranes and power lines, environmental test facilities, and a field mock-up of a crane boom.

In both the scaled model testing and the full-scale crane testing, the primary procedure for measuring variations in proximity warning device performance was to record the alarm contour (i.e., the locus of all boom tip positions for alarm initiation) under various operating conditions. The typical procedure for determining the alarm contour was to first move the crane towards the power line to a reference position where the crane boom tip is at a point representing 10 feet from the nearest conductor. If the proximity warning device meets the ideal performance goal, the reference point (at a 10-foot spacing) may be chosen in any direction from the power line. There is no basis for choosing a reference point in any particular direction from the power line unless there is a prior knowledge of the actual alarm contour for the particular combination of device, sensor installation and power line configuration in question. Normally, the reference position during these tests was arbitrarily chosen at a point on the same horizontal plane as some selected power line conductor. In a few instances, the basis for choosing the reference point depended on other criteria. For example, at the Alcoa mine site, the crane boom was restricted to maintain a minimum distance of 10 feet from the power line. In some of the Alcoa tests, the above arbitrary reference point criteria would have resulted in the majority of data points being unavailable, since they would have been closer than 10 feet to the power line. Consequently, the reference points at Alcoa were chosen by trial and error to be near the point of least alarm sensitivity, thus allowing a maximum number of alarm positions to be recorded at a distance greater than 10 feet.

At the reference position selected, the alarm sensitivity was adjusted (or in the case of scale model measurements the power line voltage was adjusted) so that alarming was initiated. With the alarm sensitivity thus established, the crane boom height would be changed by a known increment and the crane moved either closer to or farther from the power line to a position where the device was again at the threshold of alarm activation. The location of the boom tip at the new point was recorded and plotted. The process of changing the boom height, moving the crane to a new point of alarm activation threshold, and recording the data was repeated until sufficient data had been gathered to describe the alarm contour around the overhead power line. (For reference, Figure 1 shows the ideal alarm contour.)

## 1. Scaled Model Laboratory Tests

Scaled models were used for the laboratory testing to provide the wide range of flexibility necessary to test the above conditions in a variety of combinations. The scaled laboratory tests were supplemented by a limited set of validation tests performed on actual cranes with overhead power lines.

### a. Theoretical Basis

Since the power line proximity alarm responds to electrostatic field component amplitudes, a properly scaled power line system is representative of an actual power line system and the two systems produce the same electric field vectors at corresponding geometrical locations. The electric field vectors are preserved by applying identical scale factors to the system voltage and the system geometry. To demonstrate that this is true, consider again Equation (2) which describes the electric field from a parallel wire transmission line

$$\vec{E}_A(x,y) = \frac{aV_0}{\cosh^{-1}(d/R)} \frac{(x^2 - a^2 - y^2) \hat{a}_x + 2xy\hat{a}_y}{[(x-a)^2 + y^2][(x+a)^2 + y^2]}$$

Now apply an identical scaling factor  $\alpha$  to each of the geometrical parameters  $x$ ,  $y$ ,  $d$ ,  $R$ , and consequently  $a$ . Also apply the same scaling factor  $\alpha$  to the voltage  $V_0$ . The resulting electric field strength for the scaled system is

$$\begin{aligned} \vec{E}_S(\alpha x, \alpha y) &= \frac{\alpha^2(aV_0)}{\cosh^{-1}[(\alpha d)/(\alpha R)]} \frac{\alpha^2 \left[ (x^2 - a^2 - y^2) \hat{a}_x + 2xy\hat{a}_y \right]}{\alpha^2 \left[ (x-a)^2 + y^2 \right] \alpha^2 \left[ (x+a)^2 + y^2 \right]} \\ &= \frac{aV_0}{\cosh^{-1}(d/R)} \frac{(x^2 - a^2 - y^2) \hat{a}_x + 2xy\hat{a}_y}{[(x-a)^2 + y^2][(x+a)^2 + y^2]} \\ &= \vec{E}_A(x,y) \end{aligned}$$

### b. Equipment Description

Figure 9 is a sketch of the 1:10 scaled model system used to test the proximity alarms. The system includes a variable transformer cascaded with a high voltage transformer to allow system voltages to be varied from 0 to 7.5 kV. The separation and height of the power line conductors were adjustable to simulate a wide variety of power line configurations. The height of the power line was adjustable from near 0 to 5 feet, representing an actual power line system height of up to 50 feet. Likewise, the spacing of the power lines was adjustable from near 0 to approximately 4 feet allowing simulation of power lines having up to 40 feet conductor separation.

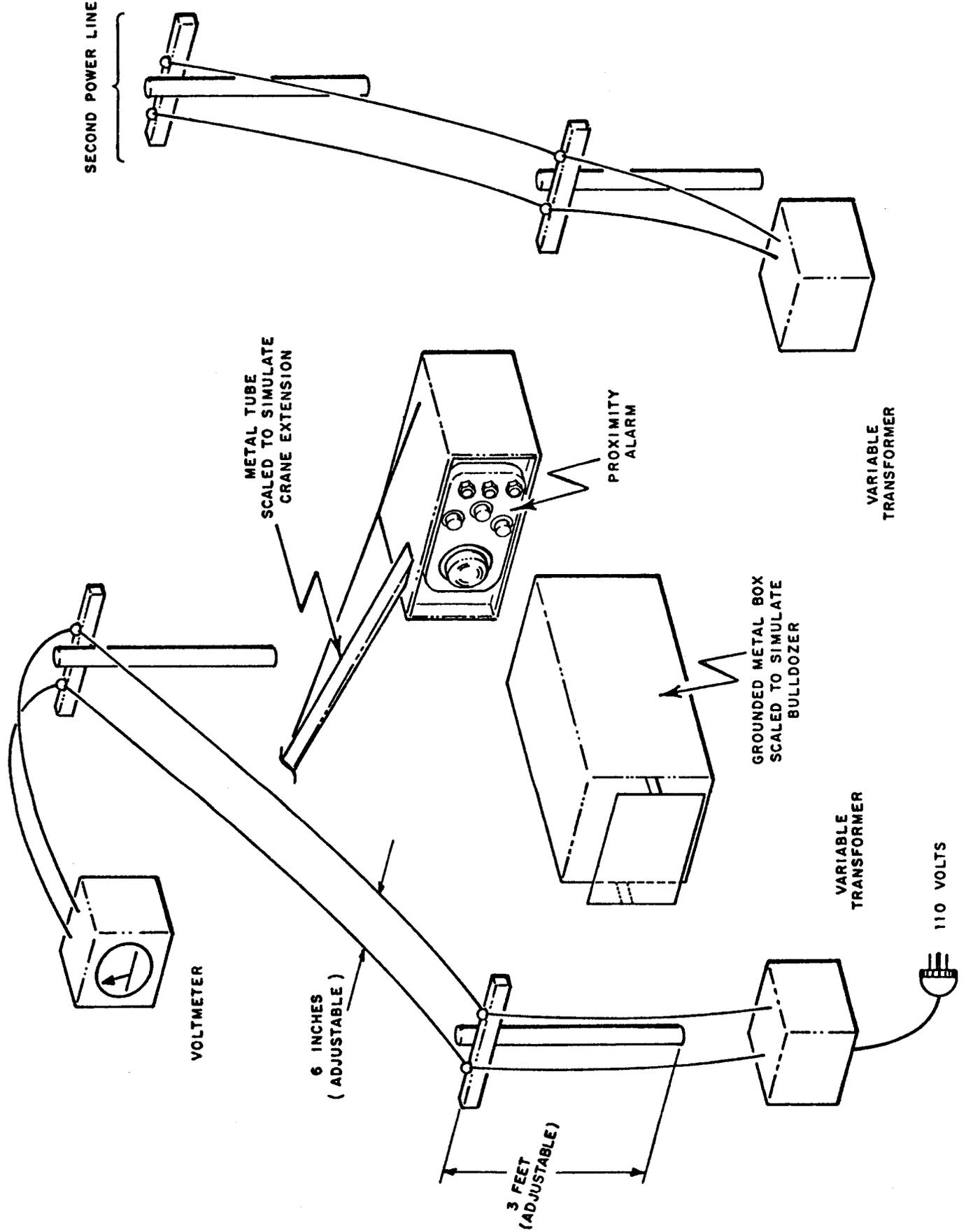


FIGURE 9. LABORATORY SCALED MODEL SYSTEM FOR TESTING PROXIMITY WARNING DEVICES

Figure 10 is a photograph of the scaled model crane, which is an approximate model of a Galion 150. A nonconducting wooden handle was added to the scaled model to facilitate crane movement with a minimum of electrostatic field disturbance by the technician. A small 12 volt battery to operate the proximity alarms was stored inside the rear compartment of the scaled model crane. As shown in Figure 10, the proximity alarm master control units were individually mounted on the rear compartment of the scale model crane. A 1:10 scale model of a D9 bulldozer was also part of the scaled model system and was used to test the influence of nearby large metal grounded objects that might be present in a mining environment. Finally, a second scaled model circuit was included to test the effect of multiple power line circuits. Figure 11 is a photograph of the laboratory scaled model system showing one of the power line circuits, an earlier scaled model crane, the D9 bulldozer, transformer and voltmeter.

For laboratory personnel safety, high voltage test lead wire rated at 5 kV and tested at 29 kV was used for the power line conductors. In addition, a neon sign transformer, having a low output current capability was used for the high voltage transformer.

## 2. Full-Scale Tests

Scaled model testing of the proximity warning devices was supplemented by full-scale testing using actual cranes and full-scale power lines. These tests were conducted to (1) verify the scaled model test results, (2) perform testing that was not practical with the scaled model facility, and (3) gain experimental data in an actual mining environment under MSHA regulations. The boom tip position in the full-scale crane tests was determined occasionally by estimation, but most often by measuring the horizontal and vertical displacement of the extended work cable.

### a. City Public Service System

A number of tests was performed using the Sigalarm proximity warning device installed on a City Public Service crane operating near a single-phase power line. The purpose of these tests was to establish the validity of the scaled model tests being performed in the laboratory. Figure 12 is a photograph of one of the CPS test sites with the CPS crane. Figure 13 shows the sensor wire of the Sigalarm installed along the boom of the crane. After the CPS data had been recorded and analyzed, the CPS power line configuration and the CPS crane boom configuration with Sigalarm sensor wire were modeled and the CPS tests were simulated on the scaled model system. A first series of tests, in which the CPS tests were only loosely simulated in the laboratory, failed to show satisfactory comparison. However, when additional details (i.e., boom shape and elevation angle) were modeled in the laboratory, the agreement between the CPS test results and the laboratory scaled model test results was very good. Figure 14 shows the comparisons between tests performed with a vertically configured single phase power line and the crane oriented perpendicular to the power line.

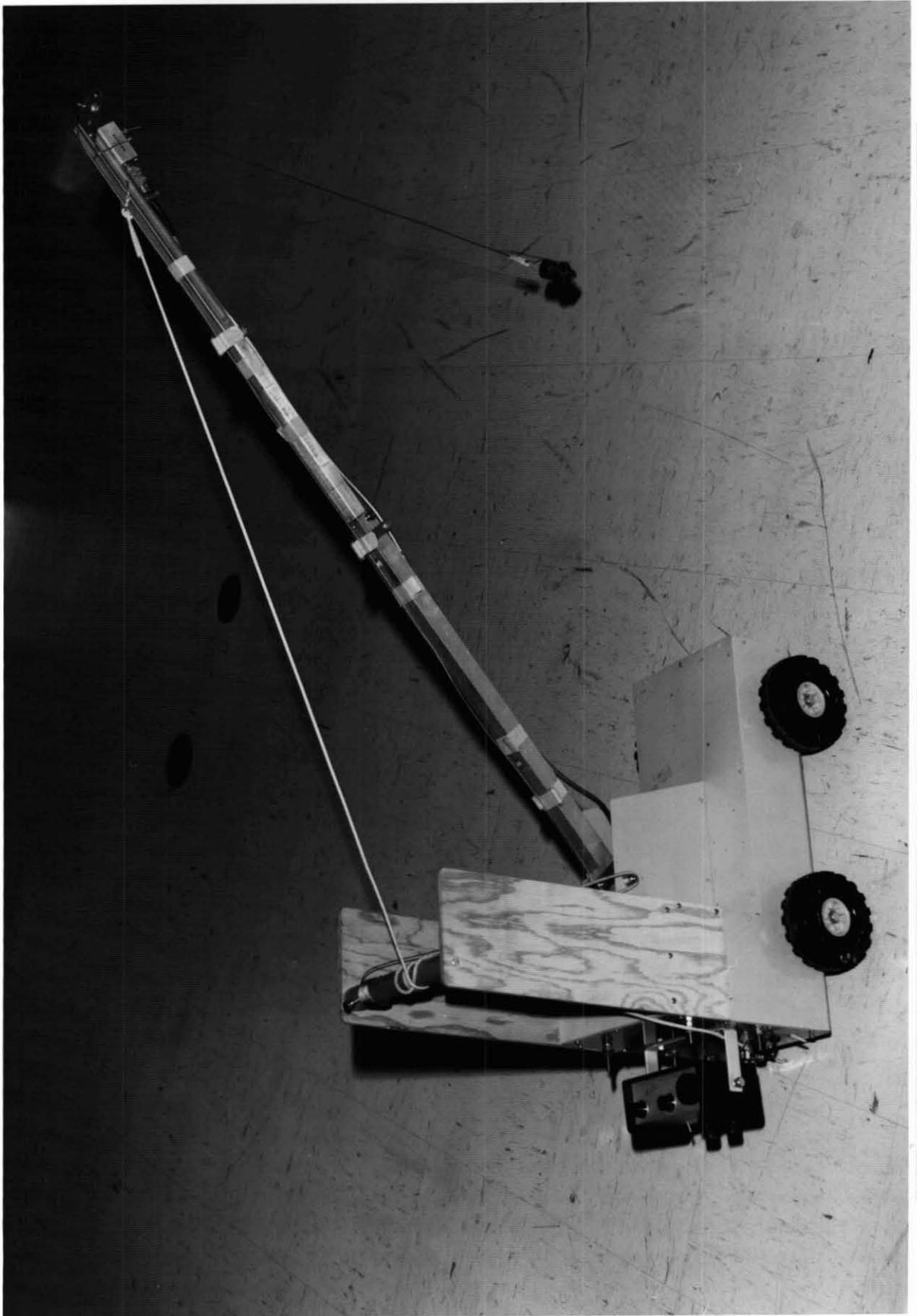


FIGURE 10. LABORATORY SCALED MODEL OF GALION 150 CRANE



FIGURE 11. LABORATORY SCALED MODEL SYSTEM



FIGURE 12. PROXIMITY ALARM TEST WITH CITY PUBLIC SERVICE CRANE



FIGURE 13. CPS CRANE BOOM WITH SIGALARM SENSOR MOUNTED BENEATH BOOM

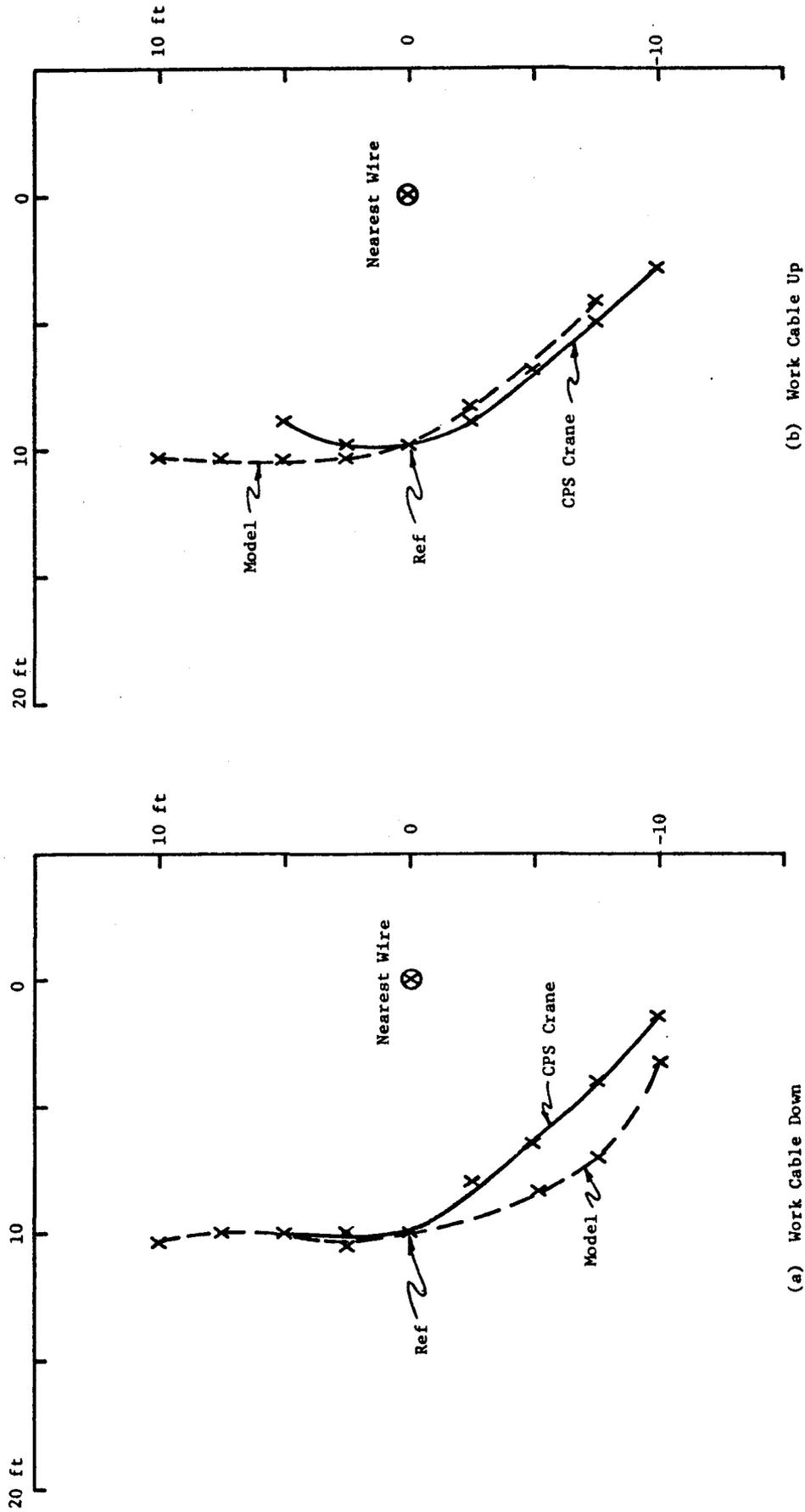


FIGURE 14. COMPARISON OF FULL-SCALE AND SCALED MODEL ALARM CONTOURS

Analogous tests that were performed with the crane oriented parallel to the power line did not show such good agreement as that shown in Figure 14. The disagreement was attributed to the inability to accurately control the pivot point in the scaled model crane as compared to the actual full-scale model. Both laboratory and field tests have verified that the alarm performance is influenced by the orientation of the crane boom with respect to the power line and the consequent failure to control the pivot point of crane cab rotation would produce discrepancies between compared tests. The agreement shown in Figure 14 was deemed sufficient to confirm the validity of the scaled model tests.

b. Full-Scale Testing on the SwRI Campus

Approximately one week of full-scale testing was performed on the SwRI campus using a 16-ton Bucyrus Erie crane. The primary objective of the SwRI full-scale tests were to perform tests that could not adequately be performed on the scaled model facility. These tests included evaluation of the Electro-Alarm proximity device, since its large physical size, weight, and power consumption would not allow testing on a 1:10 scaled model. In addition, tests were run to provide a direct comparison between the sensitivities and the dynamic ranges of the three devices. Figure 15 shows the Bucyrus Erie crane with the Electro-Alarm installed. The sensor hose for the Electro-Alarm is projecting from the extreme tip of the crane boom. The master control unit of the Electro-Alarm was mounted temporarily on the right front fender of the crane and the combination signal return/power supply line for the active probe is mounted underneath the crane boom. The power line shown in Figure 16 was an existing 500-foot run of telephone poles and conductors that had been used for previous experiments at SwRI. The conductors were temporarily connected through a single phase neon sign transformer to a 110 volt variable transformer for this test.

c. Alcoa Mining Site

The third set of full-scale tests was performed at the Alcoa mining site near Rockdale, Texas. The performance of the Sig-alarm, the Electro-Alarm, and SR Instruments proximity warning devices was evaluated under typical mine site operating constraints. The crane and crane operating crew were provided by Texas Power and Light (TP&L). Figure 17 is a photograph of the crane, an 18-ton Grove Crane, leased by TP&L for a utility construction project at that site. Figure 18 shows a closer view of the boom tip with the SR Instruments probe and two non-conducting "hot sticks" orthogonally installed on the boom. The hot sticks were installed with exactly 10 feet extending beyond the boom tip and provided a capability for precisely positioning the boom at 10 feet below or beside a power line conductor.

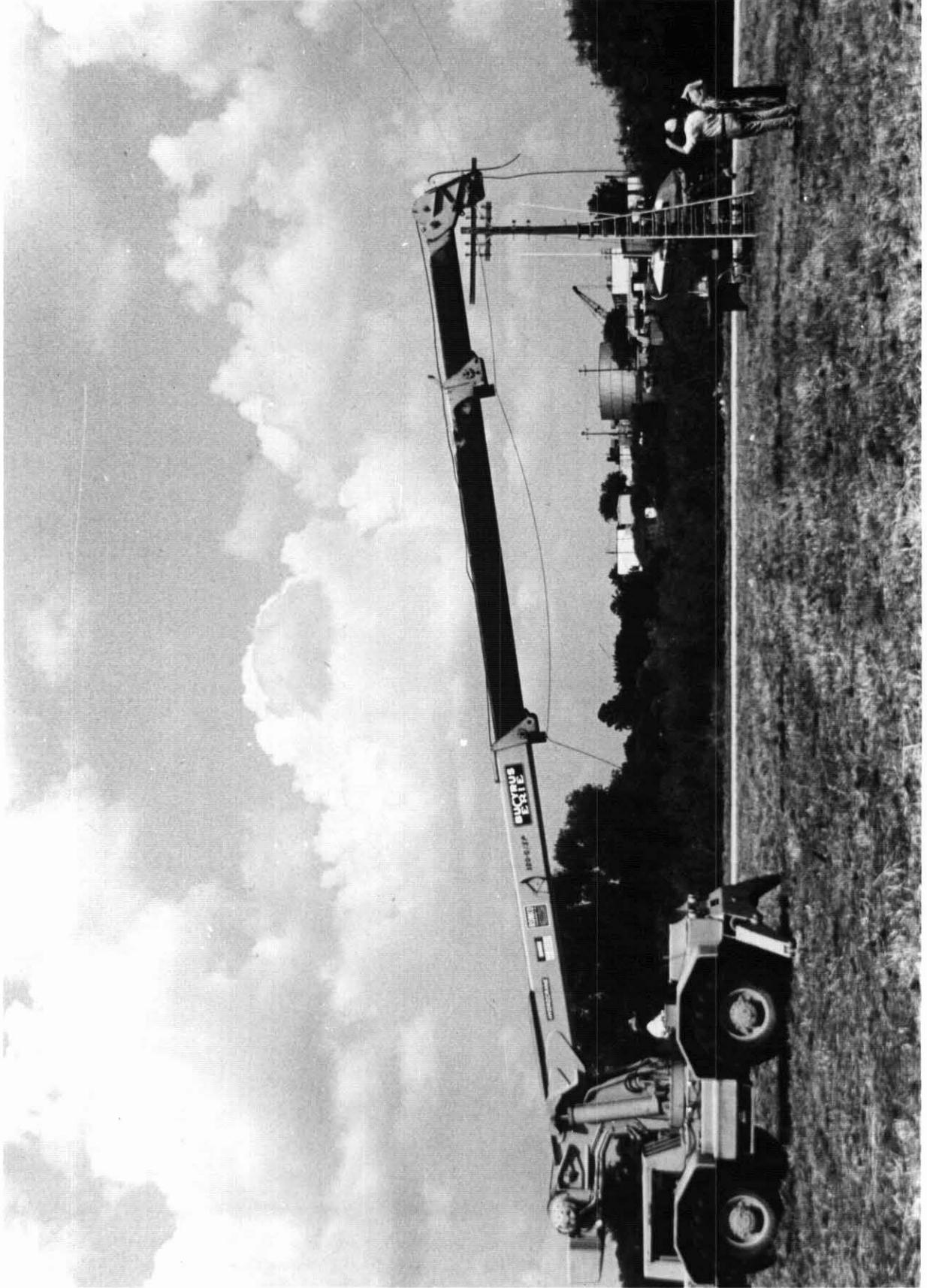


FIGURE 15. BUCYRUS ERIE CRANE AT SWRI FIELD SITE

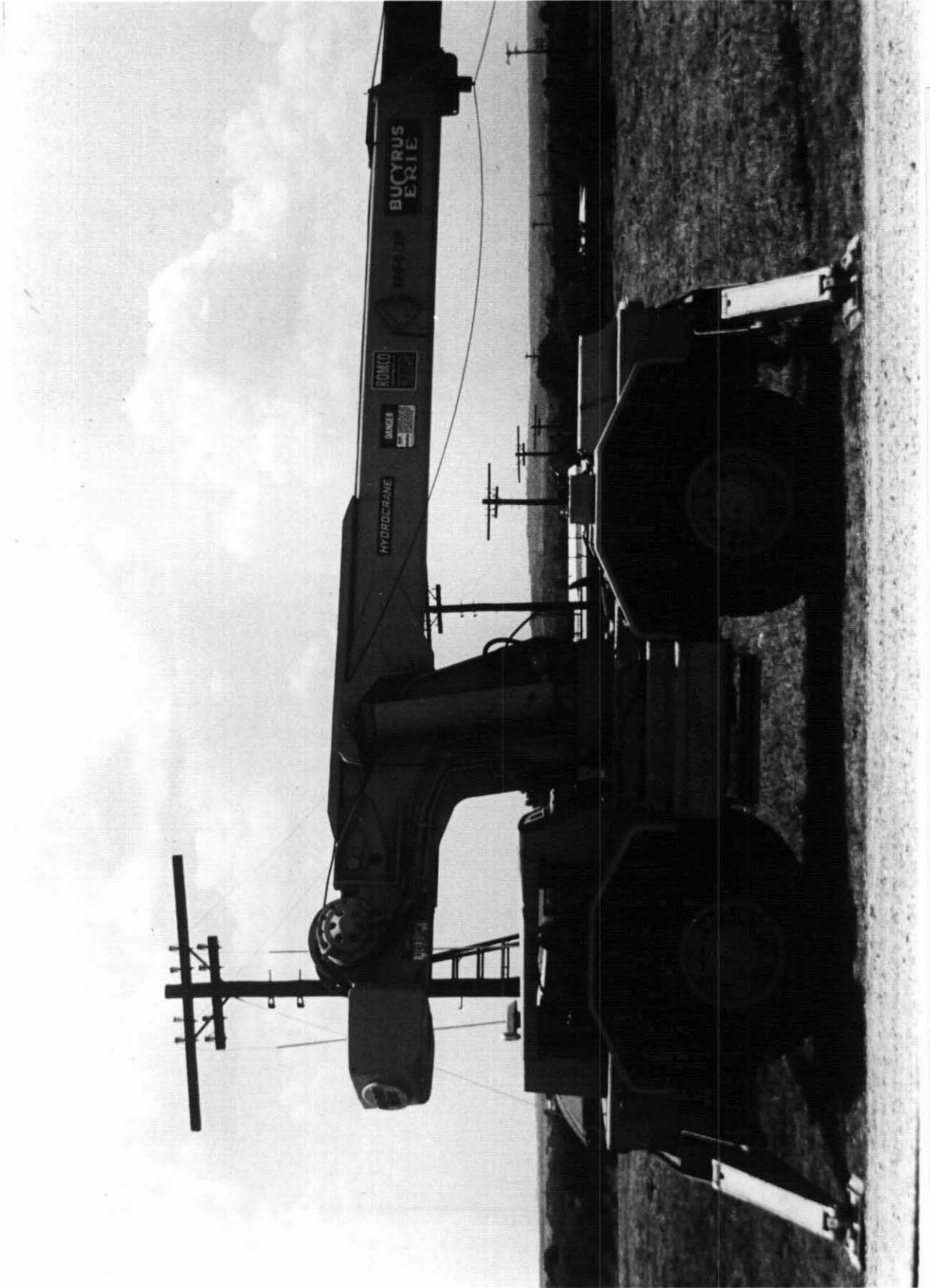


FIGURE 16. SWRI FIELD TEST SITE



FIGURE 17. ALCOA MINE TEST SITE



FIGURE 18. CRANE BOOM WITH HOT STICK EXTENSIONS

The evaluation tests were similar to those using the scaled laboratory model and those using the CPS crane. However, the mine site tests were conducted in accordance with MSHA and TP&L safety regulations, and care was taken not to bring the crane boom closer than 10 feet to an energized conductor. Furthermore, the crane remained grounded with outriggers extended during the test periods. All tests performed were performed with the objective of setting the alarm sensitivity to allow operation of the crane to within 10 feet without alarm activation.

Two areas were selected at the Alcoa mining site for performing the tests. The first site was a single three-phase 33 kV circuit with the neutral and three-phase conductors arranged at the four corners of a square.

The second site consisted of a 12 kV circuit passing under a 33 kV circuit at an approximate angle of 60°. The four conductors of the 12 kV circuit were arranged in a horizontal configuration. This site was chosen to evaluate proximity warning device performance in the vicinity of multiple circuits.

### 3. Field Tests for Thunderstorm Induced False Alarms

The proximity warning devices were tested to observe their susceptibility to thunderstorm induced false alarms. Each device was installed on a simulated full-scale crane boom at an SwRI field site and monitored continuously for several weeks. The crane boom was simulated by a 30-foot metal mast with a four-inch diameter cross-section erected at an angle of about 30° with respect to earth. The alarm electrical output of each device was connected to a 1 mm/min strip chart recorder to monitor alarm events vs time of day.

### 4. Environmental Tests

Each proximity warning device was subjected to a set of standard controlled tests to determine the durability of the device with respect to moisture, temperature, shock, and vibration conditions simulating the extreme range of these parameters expected in a mining environment. A high temperature test was performed to determine the susceptibility of the proximity devices to elevated temperatures encountered during typical service life for both operating and storage conditions. Similarly, a temperature test was performed to demonstrate the effects of low temperatures on the devices during storage and service conditions.

Humidity tests were executed to observe the device susceptibility to the effects of a warm, highly humid atmosphere.

A drip-proof test was implemented to determine whether falling drops of liquid or solid particles cause operational problems in the proximity device.

Finally, each device was subjected to vibration and shock tests to determine if the device construction would withstand anticipated dynamic vibrational and shock stresses without performance degradation.

#### 5. Frequency Response Tests

To validate the corona RFI rejection capability of the proximity alarm devices, the devices were subjected to a series of tests describing the circuit sensitivity vs signal frequency. The measured alarm sensitivity provided a quantitative measure of the device rejection to out-of-band signals, i.e., those signals not confined to the frequency band near 60 Hz. The tests were performed with signal generators connected directly to the sensor input port of each device.

#### IV. ANALYSIS RESULTS

The above described tests were performed to evaluate the relative performance of each proximity warning device and to provide an understanding of the device limitations. A large class of performance deficiencies is common to all of the devices and principally arises from the physical limitations of the basic operational principles. A second class of deficiencies varies from one device to another and is in general due to individual design limitations within the various devices.

##### A. Limitations Arising from Operational Principles

Each of the three tested devices operates by detecting a component (or components) of the electrostatic field distribution around an energized overhead power line. Consequently, the reliability of each device is influenced by variations in the electrostatic field distribution. The electrostatic field distribution around an energized overhead power line is influenced to varying degrees by the interfering electrostatic fields from adjacent power line circuits, by the electrostatic field disturbance from the conductive crane boom, by the power line configuration, or by large conducting nearby objects. In addition, the reliability of the device operation is influenced by interactions between the device sensor and the crane boom and by the device sensitivity to the electrostatic field vector orientations.

Table 1 is a list, presented roughly in decreasing order of importance, of physical factors that influence the reliability of proximity warning device operation. These limitations are discussed in the following paragraphs, both from their physical bases and from experimentally observed results. The discussion of the physical limitations of the devices is also augmented by numerically calculated results based upon Equation (2). Except where explicitly discussed, the experimental and numerically generated results assume a single-phase line.

The importance of the experimental results to be described lies not in their detailed descriptions, but rather in the classes of performance deficiency that they illustrate. Indeed, the presented results are influenced by configuration details in the power line, the crane, and the device installation, and are not necessarily valid in quantitative detail for modified configurations.

##### 1. Electrostatic Field Distortion from Multiple Power Line Circuits

In the vicinity of multiple power line circuits, an electric field sensing proximity warning device responds to the total electric field being produced at the point of the alarm sensor. The total electric field at the point of the alarm sensor is a vector superposition of the electric fields from the various power line circuits. The reliability of the proximity warning device is compromised whenever the

TABLE 1

## INFLUENCING FACTORS FOR PROXIMITY WARNING DEVICE RELIABILITY

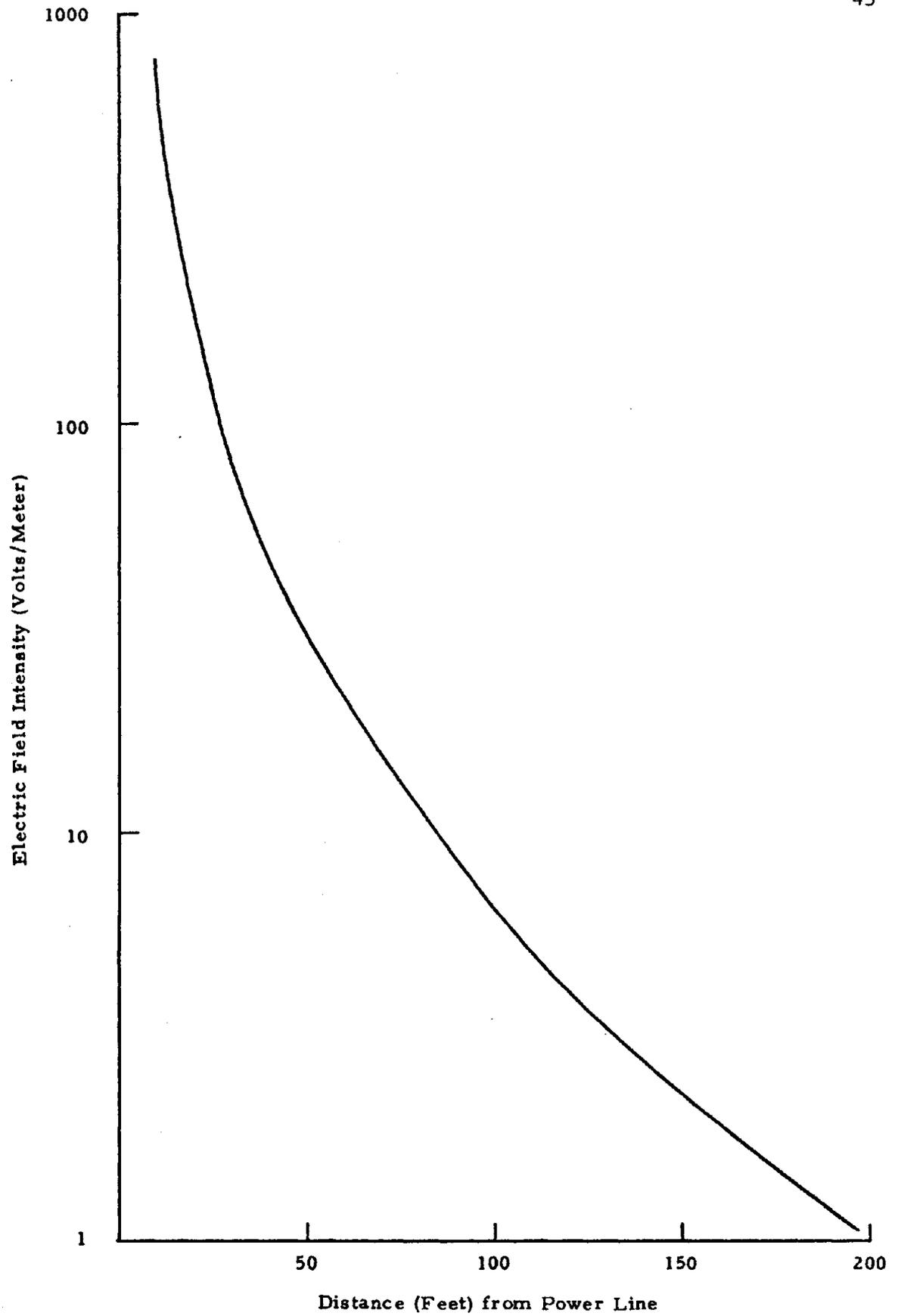
1. Electrostatic field distortion from multiple power line circuits
2. Sensitivity variation with electrostatic field orientation
3. Sensor-boom interaction
  - a. Sensor shading by boom
  - b. Sensor placement
  - c. Sensor shading by work cable
4. Boom orientation with respect to power line
  - a. Azimuth
  - b. Elevation
5. Power line configuration
  - a. Line spacing
  - b. Line height
  - c. Vertical vs horizontal
  - d. Three-phase vs single-phase
  - e. Location of neutral
  - f. Voltage
6. Nearby objects

electric fields from the more distant power lines are of the same order of magnitude or greater than the electric field of the nearest power line at safe working distances.

Figure 19 is a numerically generated curve of the electric field strength amplitude as a function of distance from a 35 kV power line having 500 mcm conductors separated by six feet and located 30 feet above ground level. At the minimum safe working distance from a 220 volt power line, the maximum electric field strength is calculated to be about 1.5 volts per meter. Consequently, if a crane operator were to adjust the sensitivity of his proximity warning device to alarm as his boom passes the minimum safe distance from a 220 volt power line of this class, his device would alarm whenever he came within 175 feet of the 35 kV line. For reliable alarm operation near the 220 volt power line, the operator must remain well in excess of 200 feet from the 35 kV power line. Figure 20 shows the numerically calculated electric field strength around the safety zone of a 30-foot high 220 volt power line that is separated from the 35 kV power line by 200 feet. Even at this distance, the distortion of the electric field strength around the 220 volt power line is of such a magnitude as to severely compromise the utility of an electrostatic proximity warning device. The device could not operate in the region between the two power lines because of the heavy contribution of the distant 35 kV line. For example, if the device sensitivity were set to alarm at 1.44 V/m (corresponding to 10 feet distance horizontally toward the 35 kV line), the alarm would sound for all horizontal positions corresponding to 20 feet above ground (at a level 10 feet below the power line) between the two power lines, since at that height the field strength does not go below 1.75 V/m. At the surface of the safety zone on the more distant side of the 220 volt power line, the resulting distortion is still so severe that the total electric field strength varies by a factor of almost 4:1, thus limiting alarm reliability.

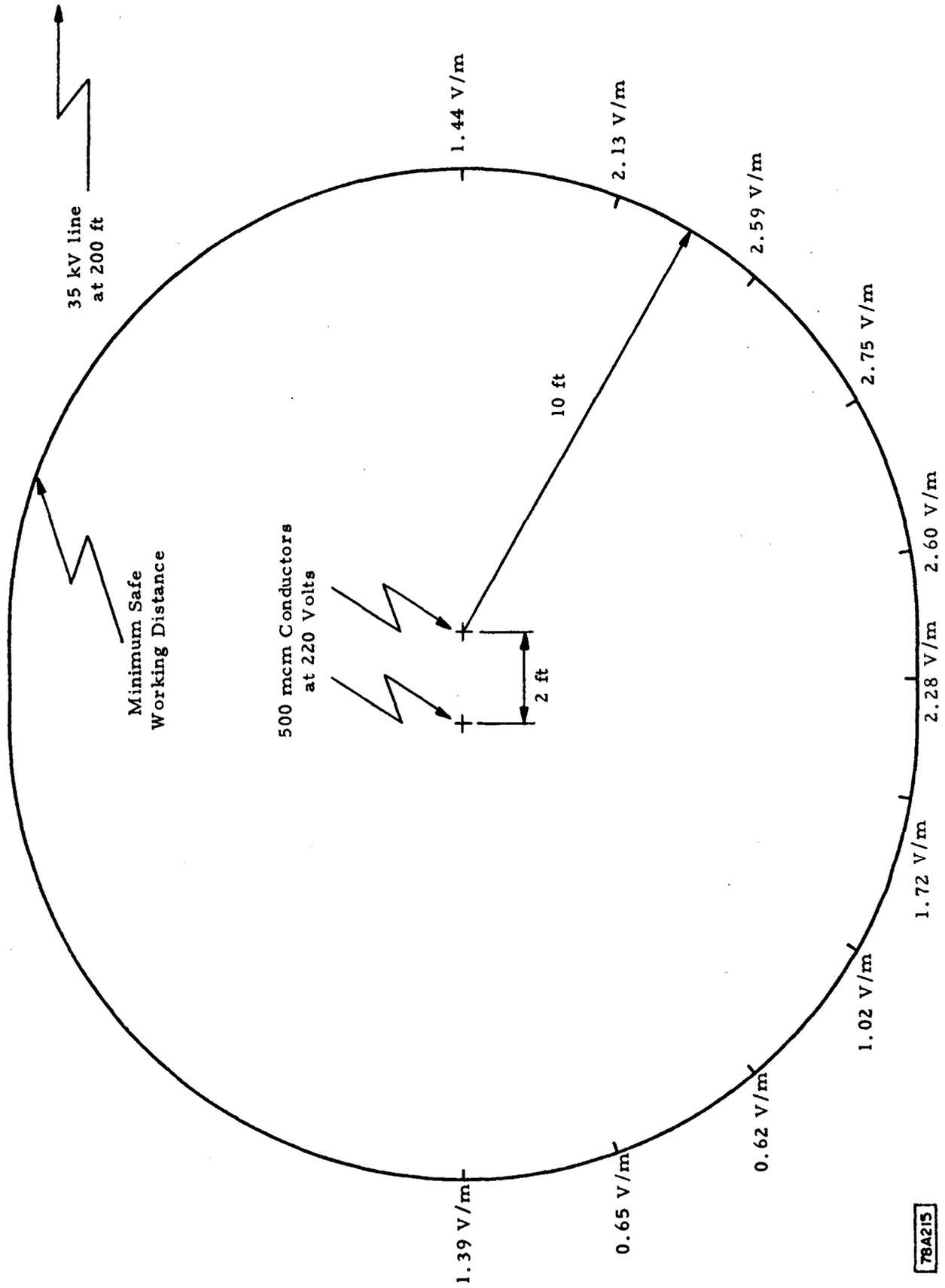
The combination of a 35 kV primary distribution line and a 220 volt secondary distribution line is admittedly an extreme combination, but does emphasize the difficulty of operating safely in a region of multiple power line circuits. Similar but lesser difficulties would be anticipated for a 7.2 kV power line near a 35 kV line, but separations between the two lines could be much closer before alarm reliability would be compromised.

Figure 21 shows a plan view of the testing configuration at Site #2 at the Alcoa mining site at Rockdale, Texas. In Figure 21(a), the alarm sensitivity was established with the tip of crane boom operating at 10 feet underneath the 12 kV power line at a point that was roughly 35 feet from the 33 kV power line. With the sensitivity established at that point, the crane boom was rotated along the arc shown in Figure 21(a). Figure 22 is the resulting alarm contour produced by the Sigalarm proximity warning device and demonstrates the loss of reliability when operating in a multiple circuit environment. The Electro-Alarm and the SR Instruments device performed similarly. Only by moving to the position shown in Figure 21(b), which is about 70 feet from the 33 kV power line, would the proximity warning devices operate in the normal manner around the 12 kV power line.



78A217

FIGURE 19. THEORETICAL VARIATION OF ELECTRIC FIELD INTENSITY FROM DISTANT 35 kV PRIMARY DISTRIBUTION LINE



78A215

FIGURE 20. THEORETICAL DISTORTION OF ELECTRIC FIELD INTENSITY AROUND 220 VOLT SECONDARY DISTRIBUTION LINE AS INDUCED BY 35 kV LINE 200 FEET AWAY

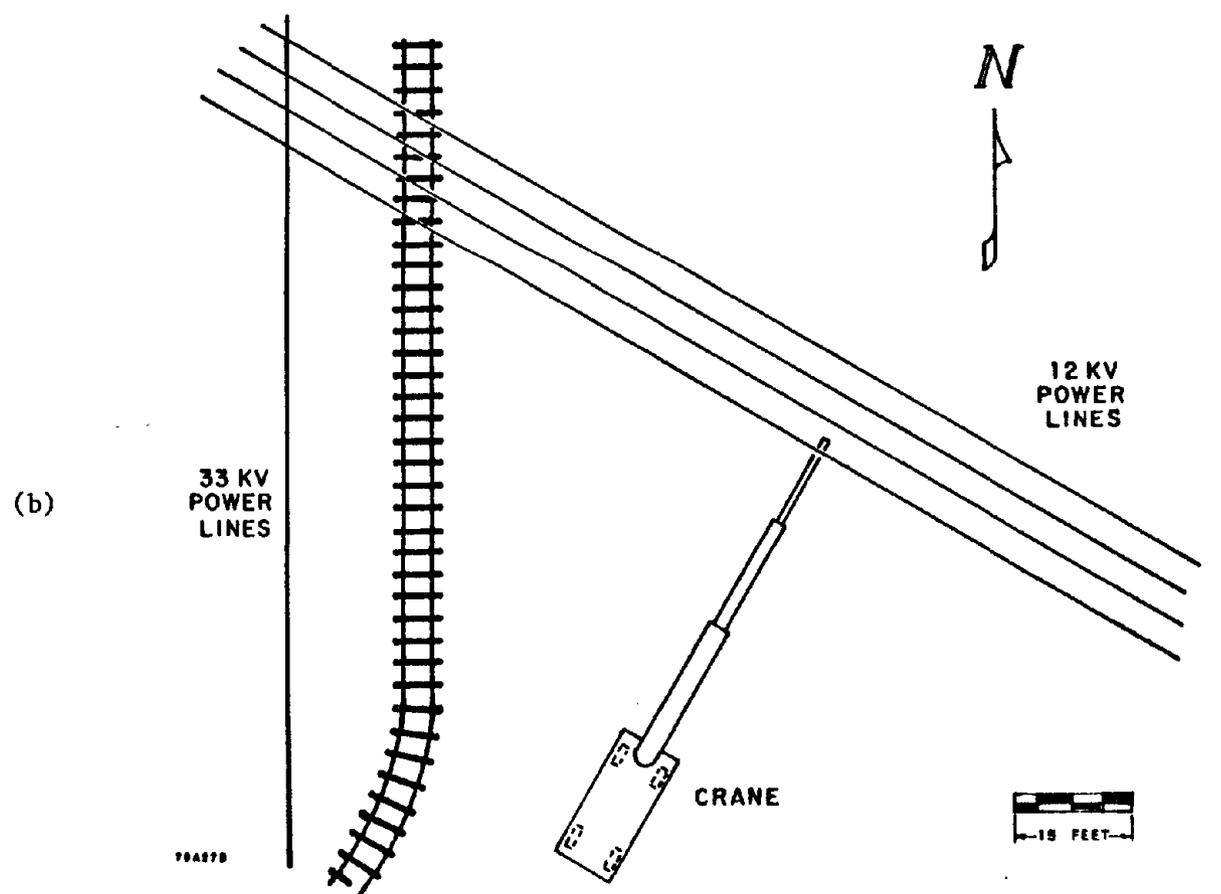
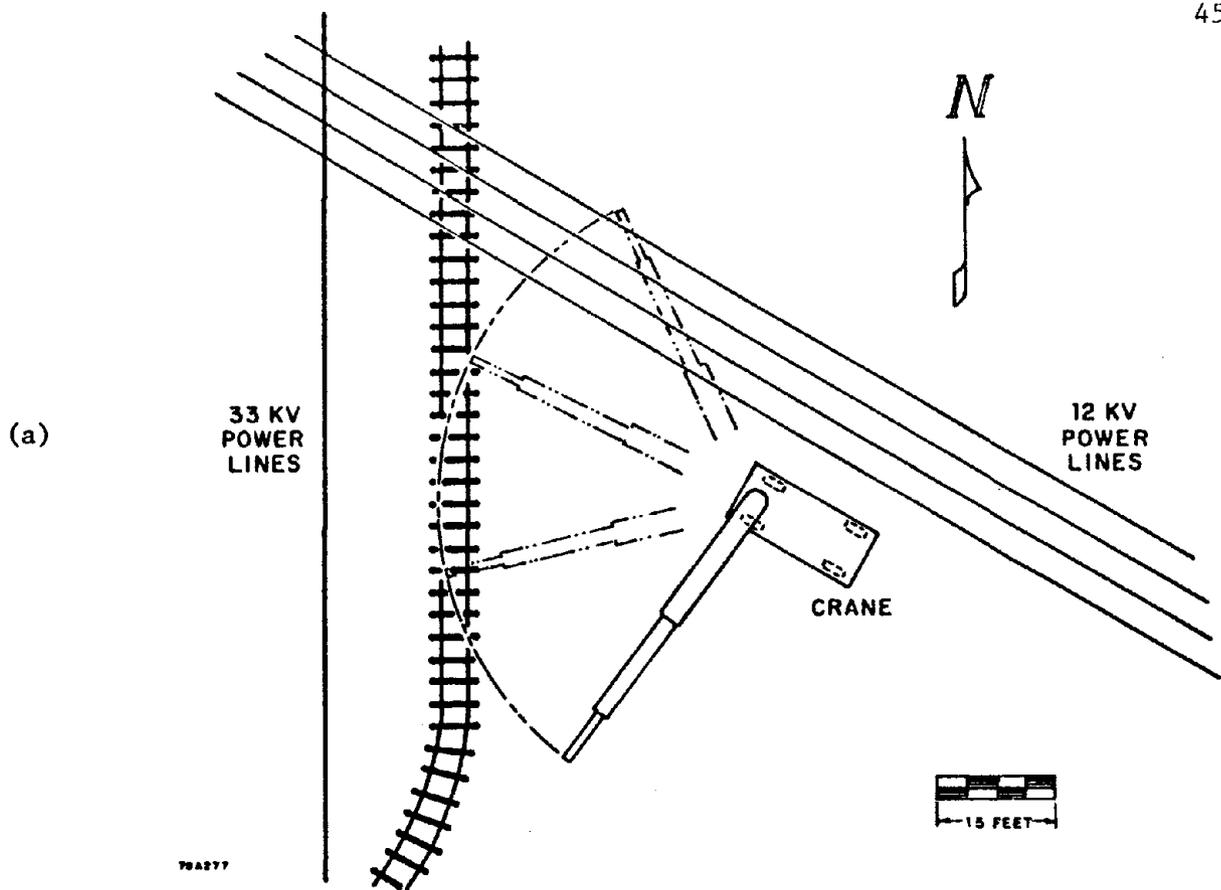


FIGURE 21. MULTIPLE CIRCUIT TEST SITE AT ALCOA MINE



A number of scaled model tests were also performed to observe the influence of multiple power line circuits. Some of the most pronounced effects of field cancellation were conducted with two circuits mounted on the same pole, such as shown in Figure 23. Circuit #1 consisted of two conductors in a vertical configuration with an equivalent full-scale spacing of 45 inches. A single-phase, three-conductor (i.e., two "hot" wires and a neutral) circuit was mounted in a horizontal configuration 45 (equiv) inches below the lower wire of circuit #1. The horizontally configured circuit #2 was equivalently 30 feet above the earth's surface.

To demonstrate worst case effects of multiple circuits, the line voltages were adjusted one at a time to provide an equal alarm response at the reference point. Then both circuits were switched on and alarm contours were measured. The field distortion from the multiple circuit configuration was so extensive that dead zones were created wherein the crane could actually move toward the power line and alarm activation would cease. Figure 24 is an alarm contour plot using the SR Instruments device, and shows a dead zone on the same level as circuit #2. The dead zones are a result of electric fields from the two circuits canceling each other, producing abnormal field component nulls in the near vicinity of the two circuits.

## 2. Variation of Polarization with Position

Each proximity warning device responds to the voltage gradient, i.e., the electric field component, between the probe and the crane boom. Consequently, the variation of electric field polarization around a power line can produce severe sensitivity variations in the proximity warning device. The presence of the crane boom significantly alters the electric field distribution in its vicinity. However, a very rough first order description of polarization influences on proximity alarm performance can be gained by considering the action of a small, isolated electric field probe in the undisturbed electric field distribution of an energized power line.

As described in Equation (2), the individual vector components of electric field strength vary as separate functions of position. Since the two vector components vary as different functions of position, the orientation of the electric field vector at any point also varies with position. Figure 25 is a numerically generated\* plot showing the amplitude and orientation of the electric field vector at various points along the minimum safe working distance boundary for a 35 kV horizontal power line configuration. Thus, for the horizontally configured line, the electric field in any given quadrant varies from completely horizontal to completely vertical and back to completely horizontal again. Since an electric field probe responds only to a single

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\*The Fortran listing of program COMPONENT used to generate the points for Figure 25 is presented in Appendix B.

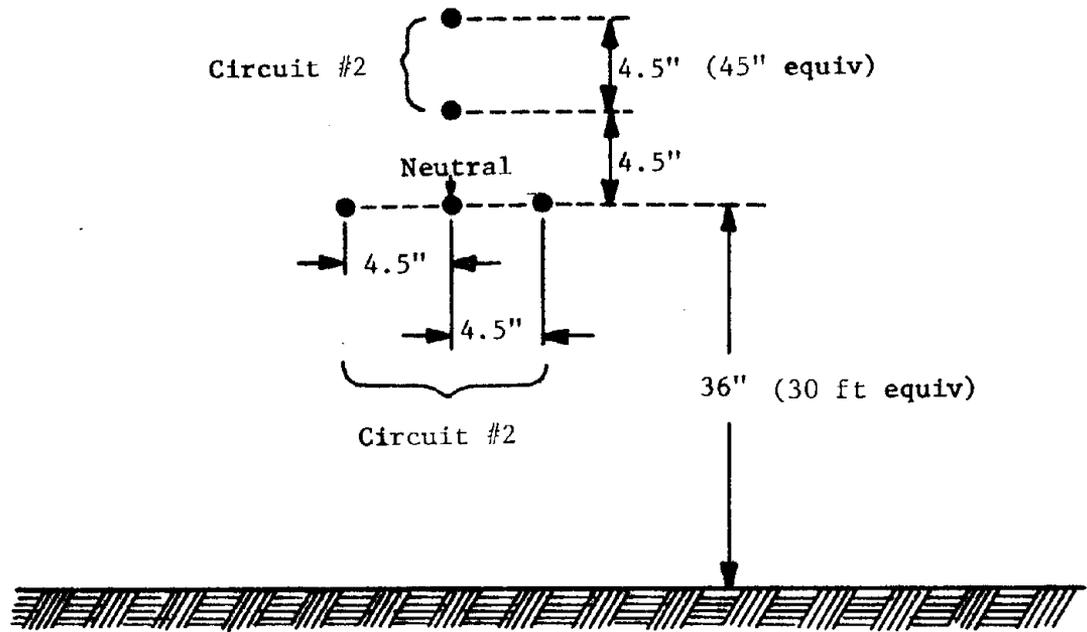
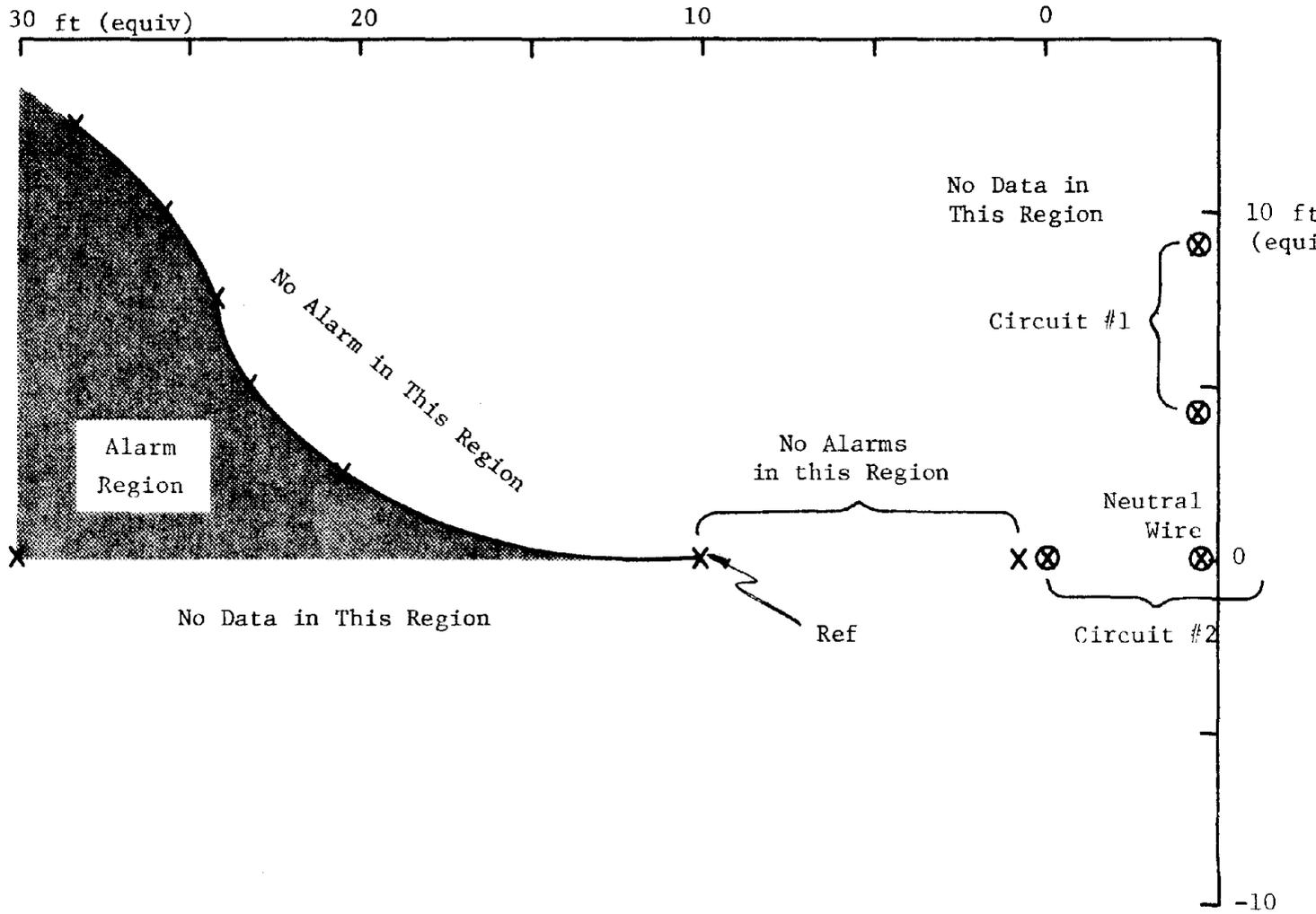


FIGURE 23

SCALED MODEL LINE GEOMETRY FOR MULTIPLE CIRCUIT TESTS



SR Instruments Proximity Warning Device  
Scaled Model Measurements  
Two Power Line Circuits, Single Phase  
Crane Boom Perpendicular to Power Line

FIGURE 24

SCALED MODEL ALARM CONTOUR DISTORTION  
IN PRESENCE OF MULTIPLE CIRCUITS

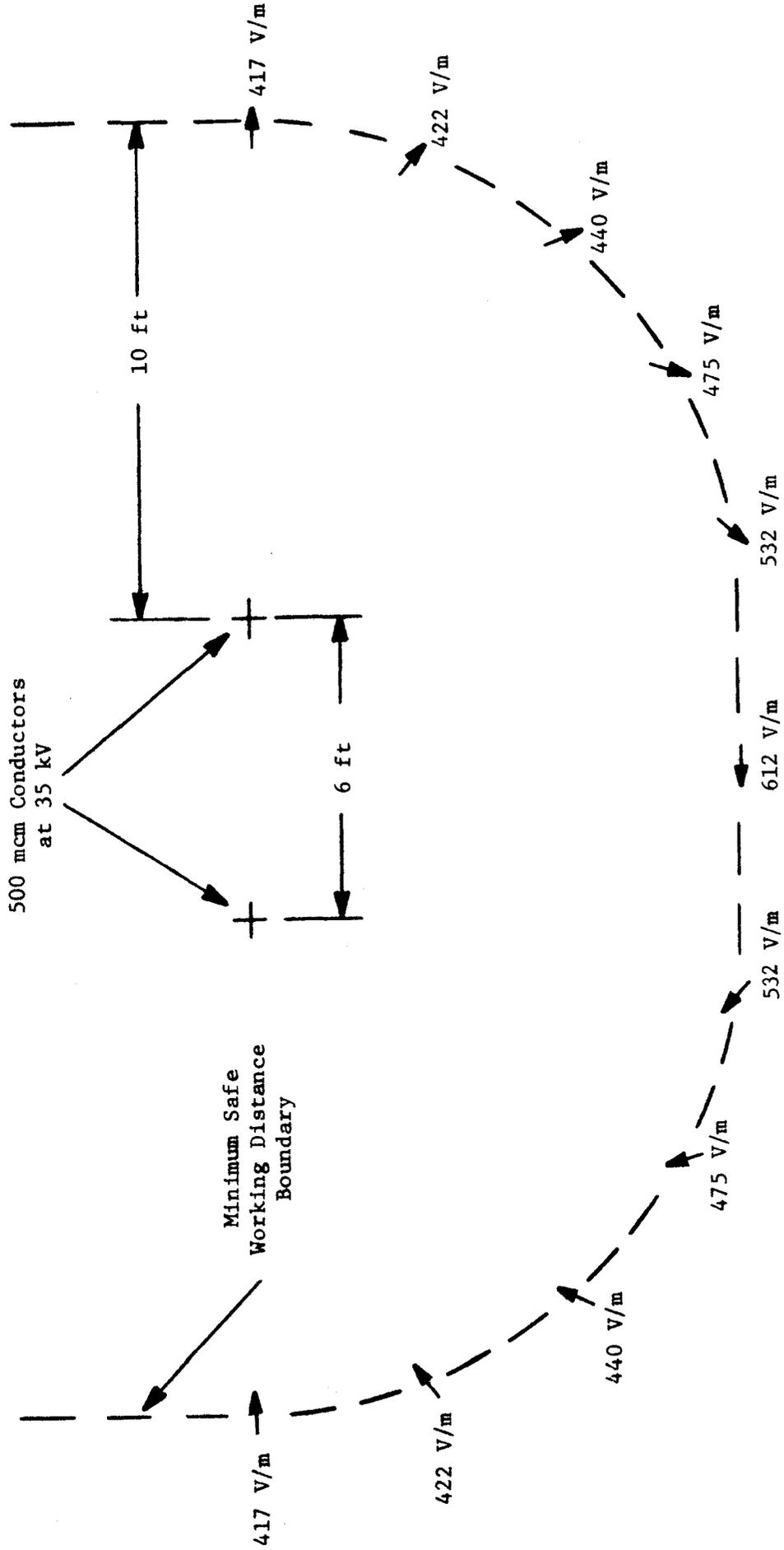


FIGURE 25. THEORETICAL VARIATION OF ELECTRIC FIELD VECTOR AROUND MINIMUM SAFE WORKING DISTANCE BOUNDARY

component of electrostatic field, a fixed orientation electric field probe experiences nulls as it moves along the minimum safe working distance boundary. Figure 26 shows the two conductors of a horizontally configured power line and several numerically generated loci of points producing constant electric field probe outputs. Each locus of points in Figure 26 assumes a small electric field probe oriented in a fixed direction and passing through a point 10 feet to the side of the nearest conductor. To the extent that the effect of the crane boom disturbance can be ignored, Figure 26 approximates alarm contours for various probe orientations, and predicts a significant departure from the ideal alarm contour described in Section II.A.

The contours shown in Figure 26 assume a point sensor with no distortion introduced by the crane boom. Figure 27(a) is an experimentally measured alarm contour recorded with the SR Instruments proximity warning device probe mounted on the extreme tip of a Bucyrus Erie 16-ton crane. Since the small probe was mounted at the boom tip, the alarm responded primarily to electric field components oriented along the boom axis. The boom was long compared to the power line height, and remained essentially horizontal. Consequently, the alarm was responding primarily to horizontal electric field components. Another factor, simplifying this particular example, was that the probe was between the power line and the entirety of the boom structure. As a result, the boom introduced a minimum of field component distortion in the neighborhood of the small probe. Consequently, the experimental alarm contour in Figure 27(a) compares very closely with the numerically synthesized curve for the horizontal probe shown in Figure 26. In general, the field distortions introduced by the presence of the crane boom are very significant and cannot be ignored, so that typical alarm contour curves do not match so closely with the undisturbed field loci shown in Figure 26. However, the occurrence of polarization nulls was observed for all three devices during both full-scale and scale model tests, and for both single-phase and three-phase systems.

In contrast to the SR Instruments and Electro-Alarm probes, the sensor wire of the Sigalarm extends along the entire length of the crane boom. This feature produces a net alarm response that is a collective effect from all points along the entire sensor wire and minimizes the influence of electric field polarization at any single point. Consequently, the Sigalarm typically displays less severe polarization nulls than do the two "point sensor" alarms. However, Figure 27(b) does show one example of a Sigalarm sensitivity null from polarization phenomena around a vertically configured three-phase scaled model system.

Figure 27(c) shows a polarization null as experienced by the Electro-Alarm operating under a horizontally configured three-phase power line at the Alcoa mine site near Rockdale, Texas.

### 3. Crane Boom Influence

The output voltage from each proximity warning device probe is the average of the voltages distributed along its length. The massive conducting crane boom causes a significant distortion in the

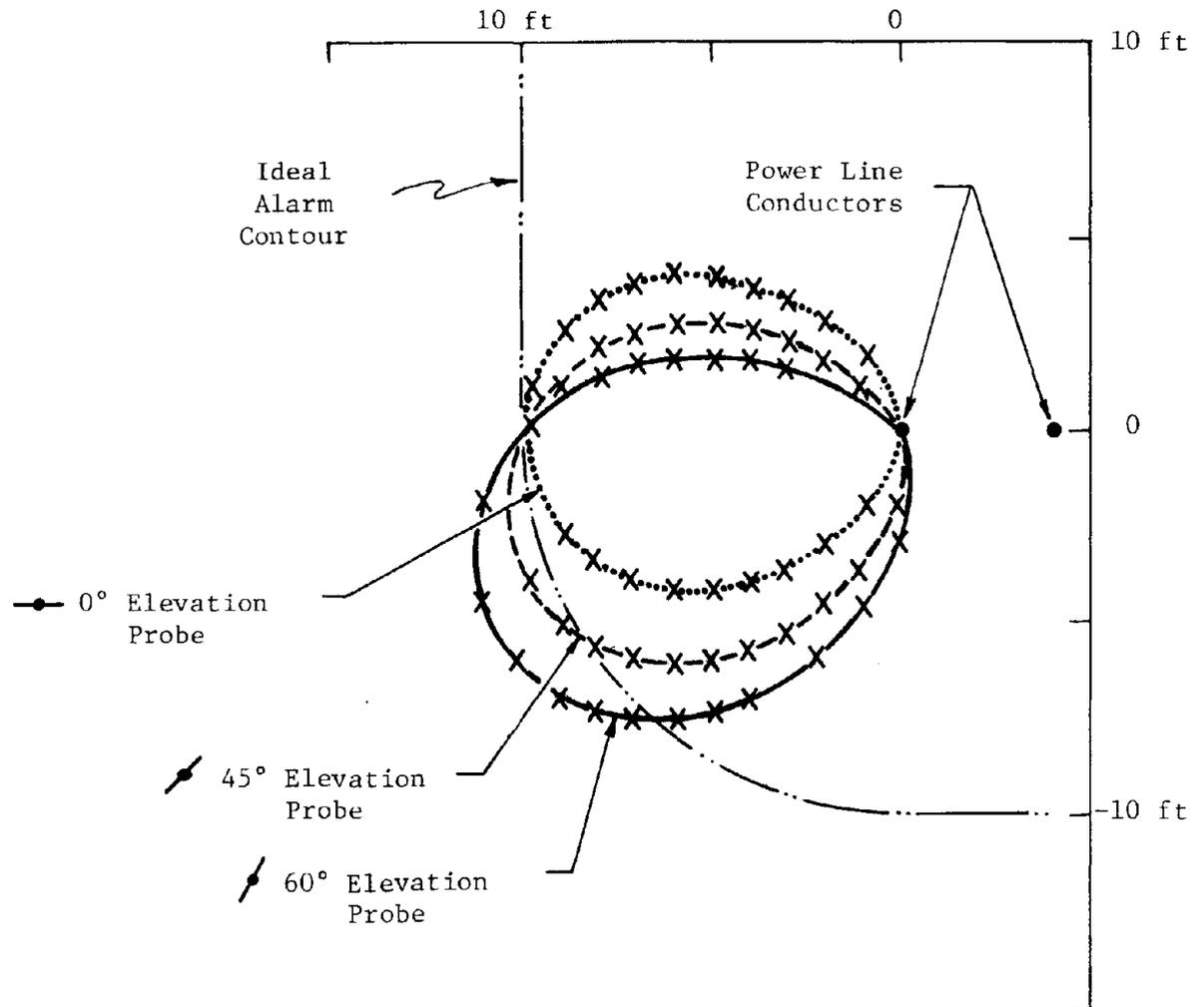
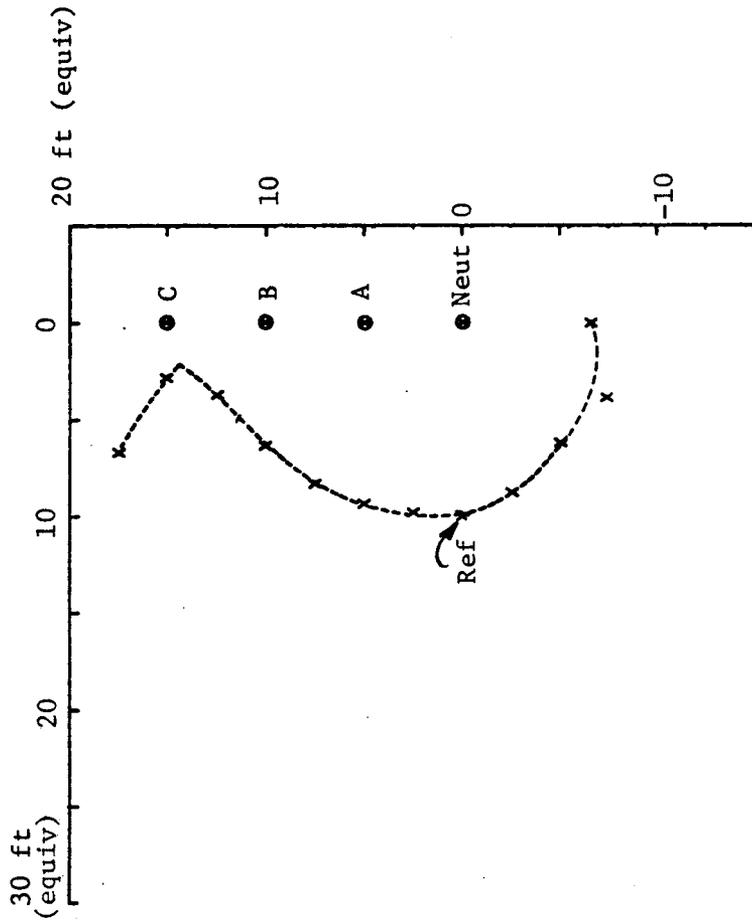
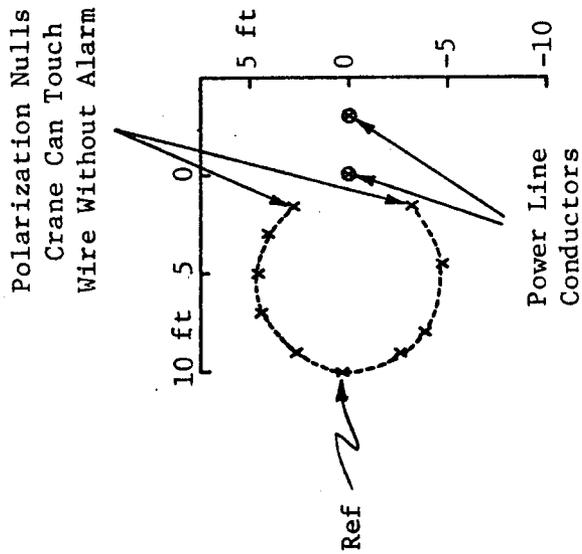
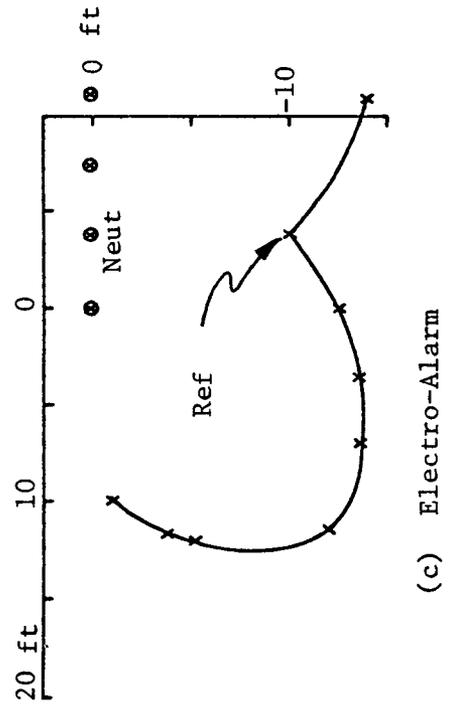


FIGURE 26

THEORETICAL LOCI OF CONSTANT OUTPUT SIGNAL FOR  
 VARIOUS ISOLATED ELECTRIC FIELD PROBE ORIENTATIONS



(b) Sigalarm



- (a) SR Instruments Proximity Warning Device  
Full-Scale Measurements  
Single Phase, Horizontally Configured Power Line  
Crane Boom Perpendicular to Power Line
- (b) Sigalarm Proximity Warning Device  
Scaled Model Measurements  
Sensor Wire Below Boom  
Three Phase, Vertically Configured Power Line  
Crane Boom Perpendicular to Power Line
- (c) Electro-Alarm Proximity Warning Device  
Full-Scale Measurements  
Three Phase, Horizontally Configured Power Line  
Crane Boom Perpendicular to Power Line

FIGURE 27. EXPERIMENTAL DEMONSTRATION OF PROXIMITY WARNING DEVICE POLARIZATION DEPENDENCE

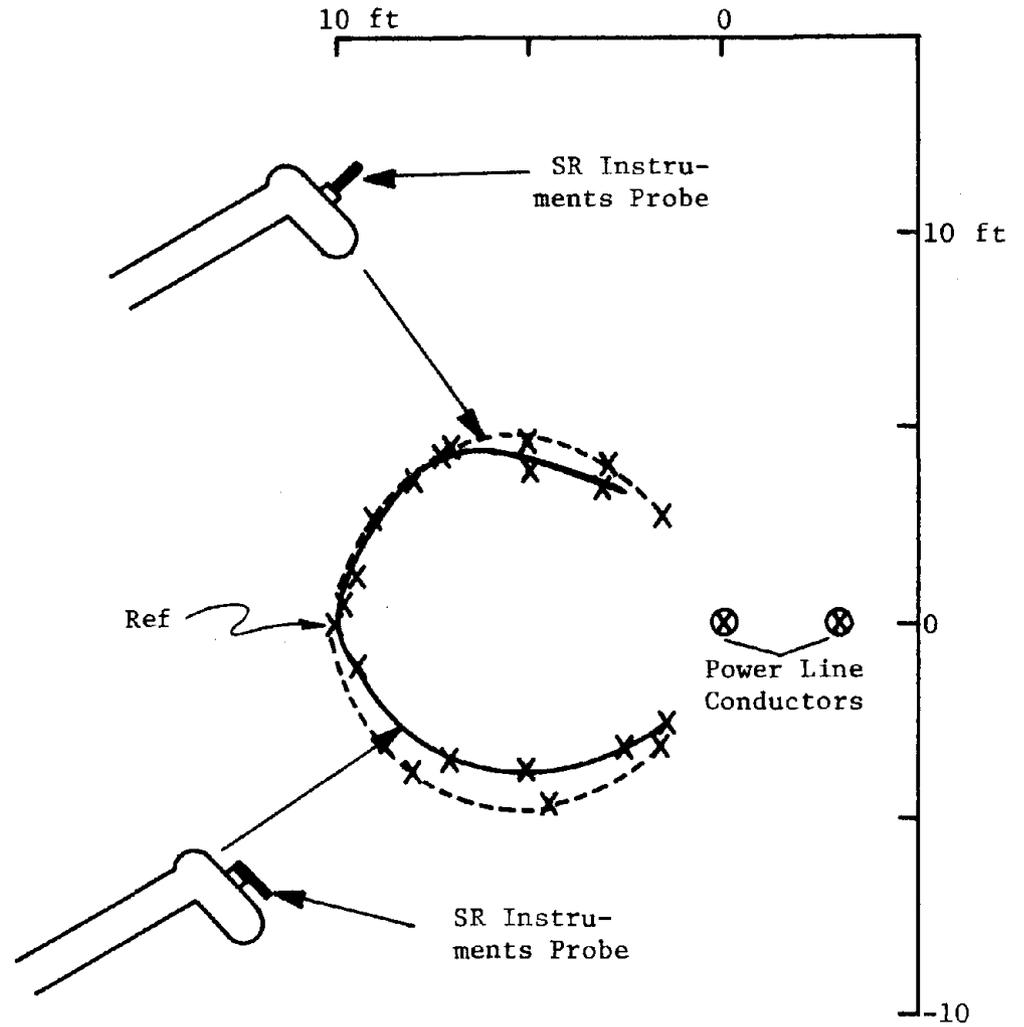
electrostatic field distribution around the energized power line establishing its own surface as a surface at zero volts. Consequently, rather than measuring the voltage gradient of the undisturbed field distribution around the power line, the proximity warning device sensor provides a measure of the average resulting voltage gradient between the sensor and the crane boom.

Figure 28 shows two alarm contours for two different orientations of SR Instruments sensor at the same location on a Bucyrus Erie crane boom. Within experimental measurement error, the two curves are identical. The close agreement for orthogonal sensor orientations is in strong contrast to the distinctly different loci shown in Figure 26 for differently oriented isolated electric field probes. The close agreement for the two curves shown in Figure 28 is because the probe is not functioning as an isolated electric field probe, but rather is responding to the voltage gradient (i.e., the electric field component) between the sensor and the crane. Even though the alarm contours shown in Figure 28 did not change with sensor orientation, the alarm system sensitivity did change. Since the electric field in the very near vicinity of a perfectly conducting surface is always perpendicular to that surface, the alarm system sensitivity is greater when the probe is likewise oriented perpendicularly to that surface.

Because of the strong boom influence on the alarm sensor response, the performance characteristics are significantly influenced by the sensor position on the crane boom. The manufacturer's recommended installation procedure for the Sigalarm proximity warning device suggests mounting the sensor wire inside or underneath the crane boom. Various other mounting positions were investigated both to provide insight into sensor/boom interaction, and to determine if other positions might provide operational advantages. Figure 29 shows a comparison of alarm contours for the Sigalarm sensor mounted below and above the crane boom. The two contours of Figure 29 demonstrate that sensor placement definitely influences the performance characteristics of a proximity warning device.

Figure 29 also demonstrates sensor "shading" or shielding by the crane boom. Whenever the alarm sensor and the energized power line are on opposite sides of the crane boom, the boom shields the sensor from the source of the fields, lowering the alarm sensitivity. Consequently, in the lower half of Figure 29, the bottom mounted sensor is in the boom "shadow" and is less sensitive and therefore allows the boom to come closer to the energized power line before activating the alarm. Correspondingly, in the upper half of Figure 29, the top-mounted sensor is in the shadow zone of the boom, and allows the crane boom to come closer to the power line. As shown in Figure 30, the shadowing effect can be so complete as to allow the crane boom to be raised into actual contact with the power line without activating the alarm.

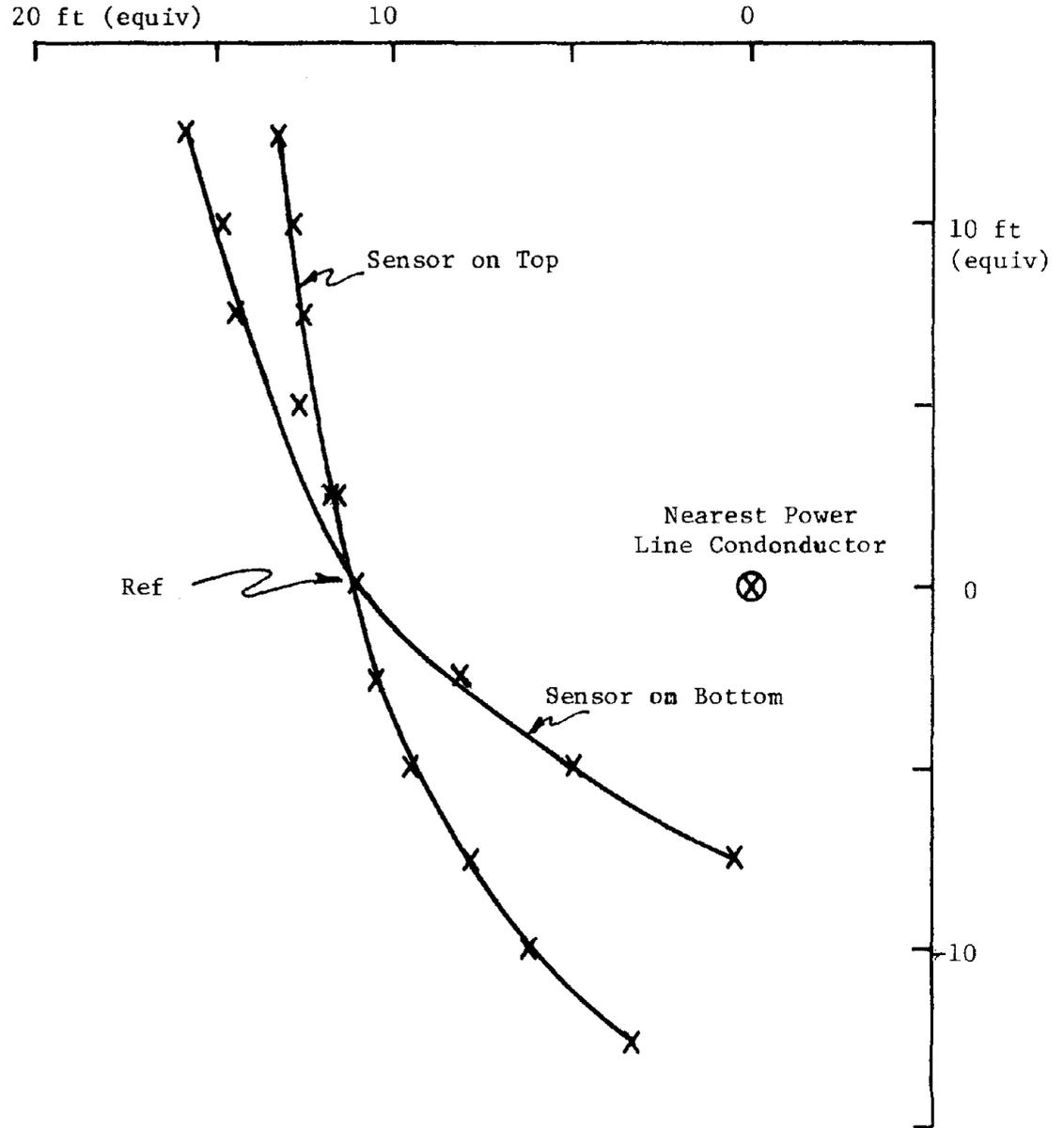
Various scaled model tests were performed comparing open simulated grid work booms with solid tubular booms, but no changes in sensitivity or alarm contours were observed to result from that aspect alone.



SR Instruments Proximity Warning Device  
Full-Scale Measurements  
Single Phase, Horizontally Configured Power Line  
Crane Boom Perpendicular to Power Line

FIGURE 28

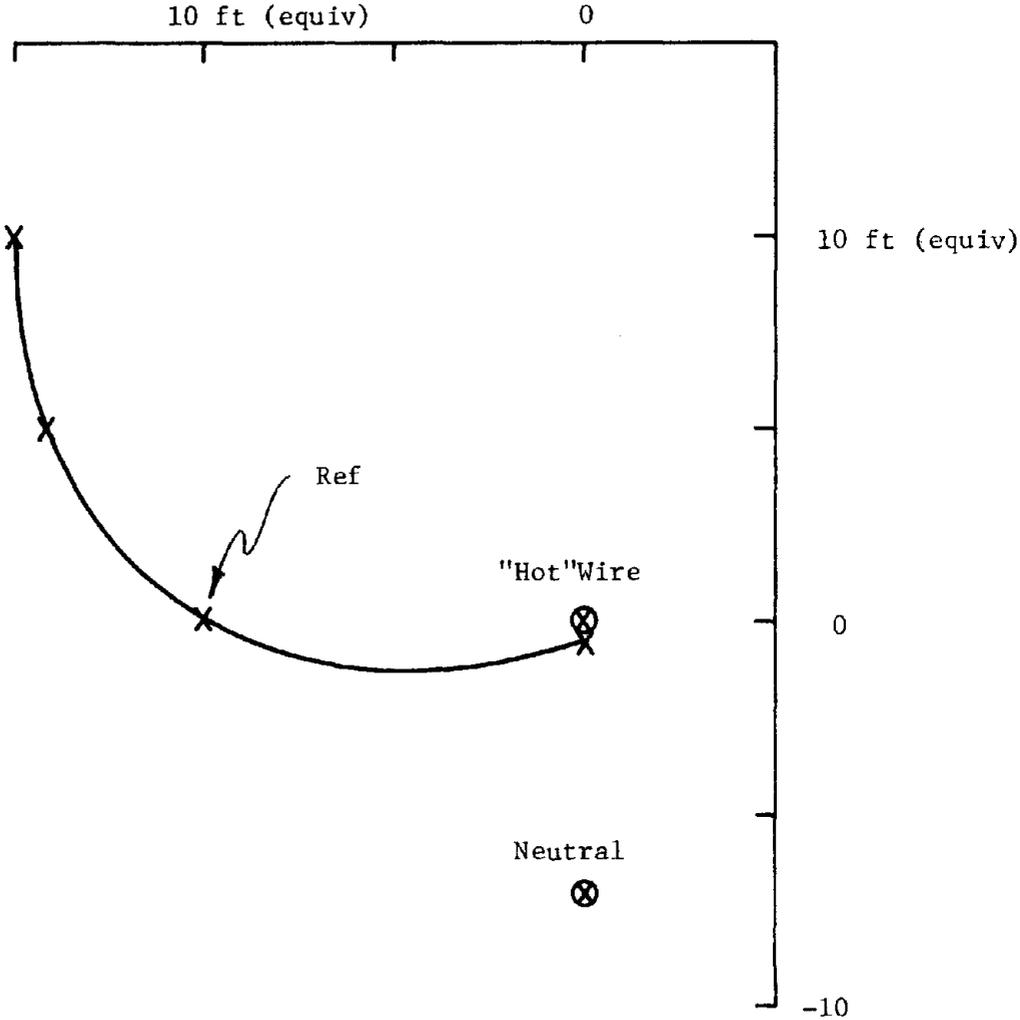
ALARM CONTOUR INSENSITIVITY TO PROBE ORIENTATION



Sigalarm Proximity Warning Device  
Scaled Model Measurements  
Single Phase, Horizontally Configured Power Line  
Crane Boom Perpendicular to Power Line

FIGURE 29

ALARM CONTOUR DEPENDENCE ON SENSOR POSITION



Sigalarm Proximity Warning Device  
Scaled Model Measurements  
Sensor Wire Below Boom  
Single Phase, Horizontally Configured Line  
Crane Boom Parallel with Power Line

FIGURE 30  
BOOM SHIELDING EFFECT FOR CRANE PARALLEL TO POWER LINE

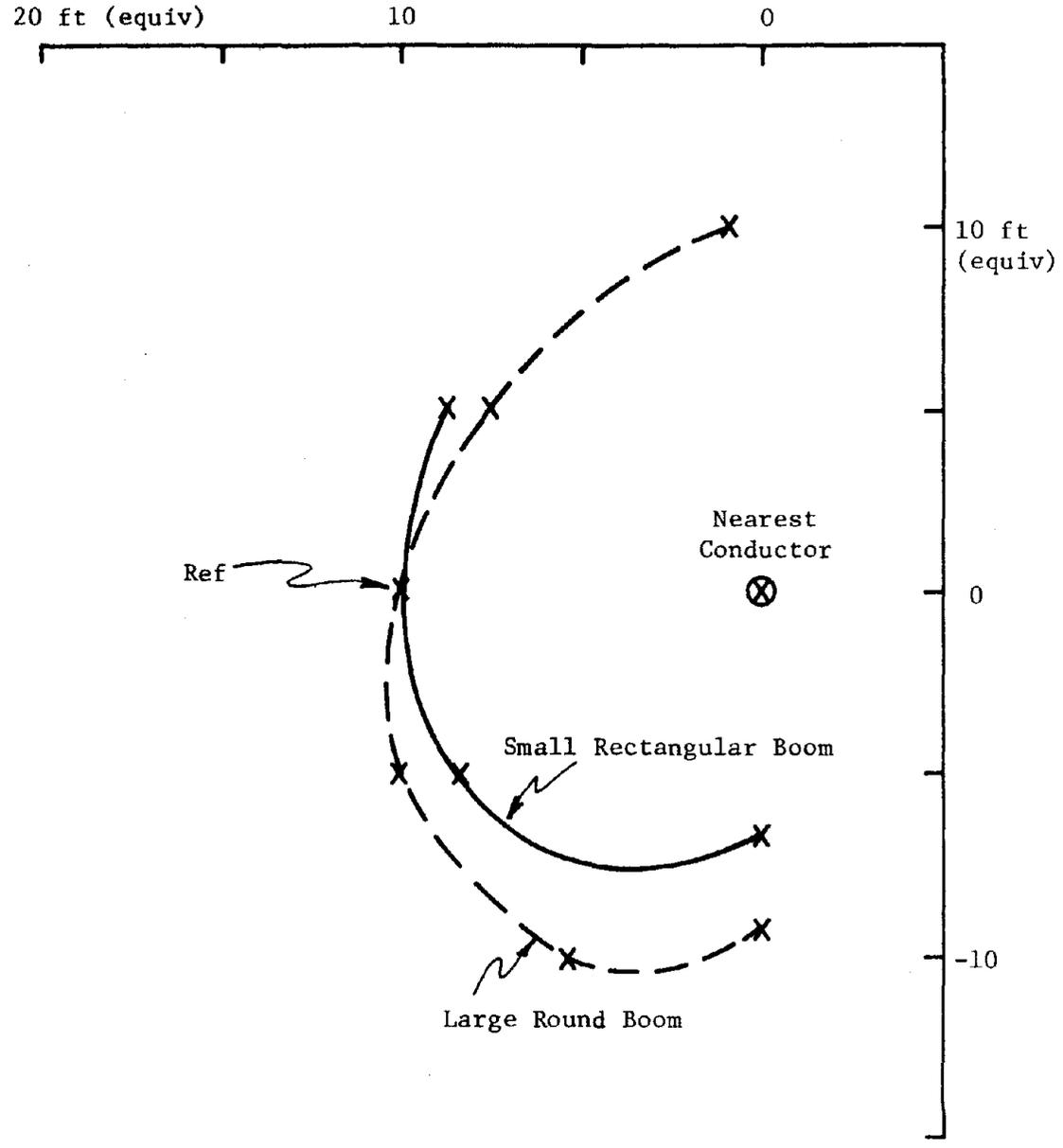
However, Sigalarm recommends routing the sensor wire inside of, instead of under, an open framework boom. Mounting the sensor wire inside the boom effectively shields the enclosed portion of sensor wire, leaving only the recommended two-foot extension near the boom tip to be sensitive to the electrostatic fields produced by the power line. This mounting procedure reduces the Sigalarm sensor to the identical performance characteristics of the short sensor probes used by the SR Instruments and Electro-Alarm systems. To the extent that the Sigalarm sensor wire is fastened directly to the crane boom, it is also shielded by nature of its close proximity to the boom.

Figure 31 demonstrates that boom cross section also influences the shadowing effect of the proximity alarm device. To produce the two contours in Figure 31, the Sigalarm sensor wire was mounted along the top of a 2" diameter round scaled model boom, and then along the top of a 1" x 1/2" rectangular scaled model boom. As illustrated in Figure 31, the more massive boom produces a greater reduction in sensitivity at the higher positions.

Boom length also causes a variation in the performance characteristics of the Sigalarm, if the boom is being extended and retracted during operation. The Sigalarm response variation with boom length occurs because the entire length of the Sigalarm sensor is typically sensitive to the electrostatic field. Consequently, as the boom length changes, the sensor length and thus the system sensitivity changes. A related difficulty is that the sensor wire slack changes as the boom length changes. Increased slack in the sensor wire causes increased distance between the sensor and the boom, and results in increased device sensitivity.

A large number of tests was also performed with and without lowered work cables on the crane. Usually, the alarm response for the two work cable configurations agreed within experimental error. However, for higher boom elevation angles, the work cable hangs closer to the alarm probe and reduces the sensitivity. Consequently, the presence of the work cable produces decreased sensitivity with increased elevation, becoming more pronounced at higher elevation angles. Figure 32 is an extreme case, showing a comparison between Sigalarm responses with raised and lowered work cables for operation with a City Public Service crane.

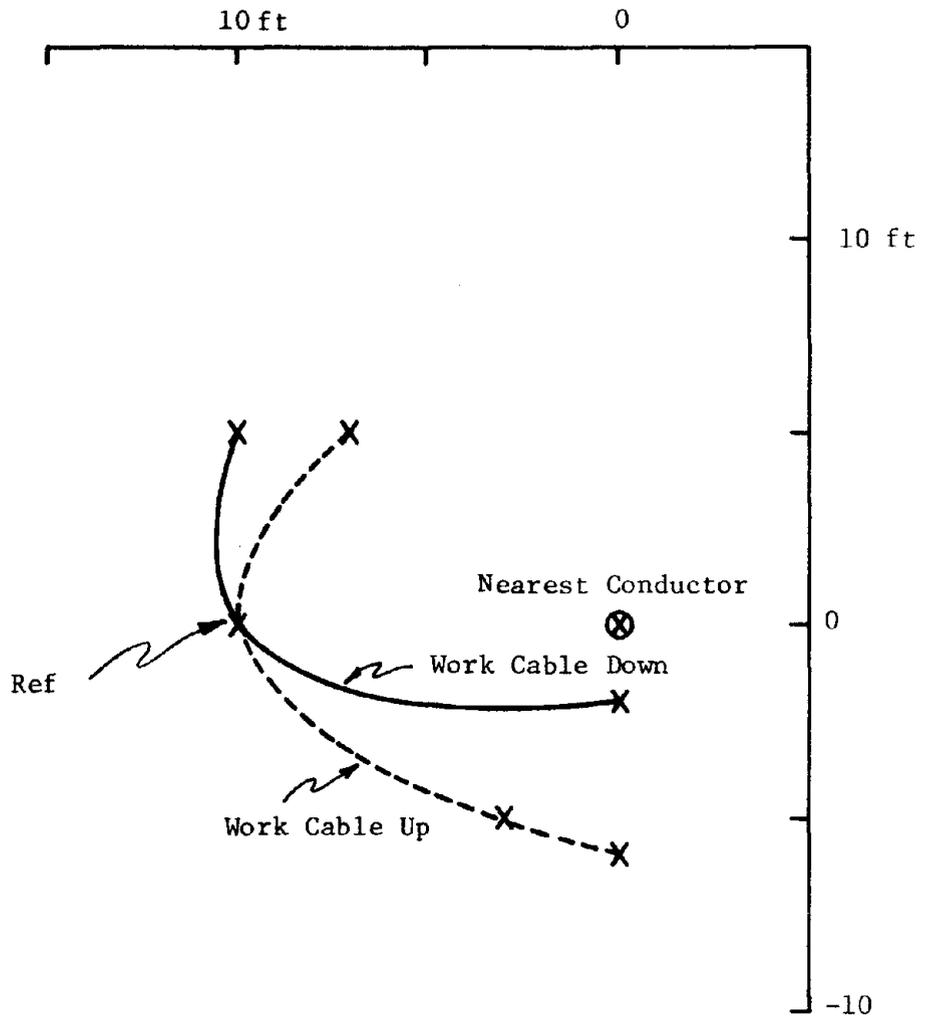
To the extent that the proximity warning devices can be considered isolated point sensors, the azimuthal orientation of the crane boom with respect to the power line has only a minor effect. The influences of boom/sensor interaction does prevent the proximity warning device from exactly performing as an isolated point sensor and consequently produces some contour variations as the boom azimuth is varied. Whenever a distributed sensor is utilized, the effect of azimuth orientation becomes much more significant. Figure 33 shows the parallel and perpendicular alarm contours for the Sigalarm with the sensor wire mounted above the boom. Conceptually, if a crane were to rotate about



Sigalarm Proximity Warning Device  
Scaled Model Measurements  
Sensor Wire Above Boom  
Single Phase, Horizontally Configured Power Line  
Crane Boom Perpendicular to Power Line

FIGURE 31

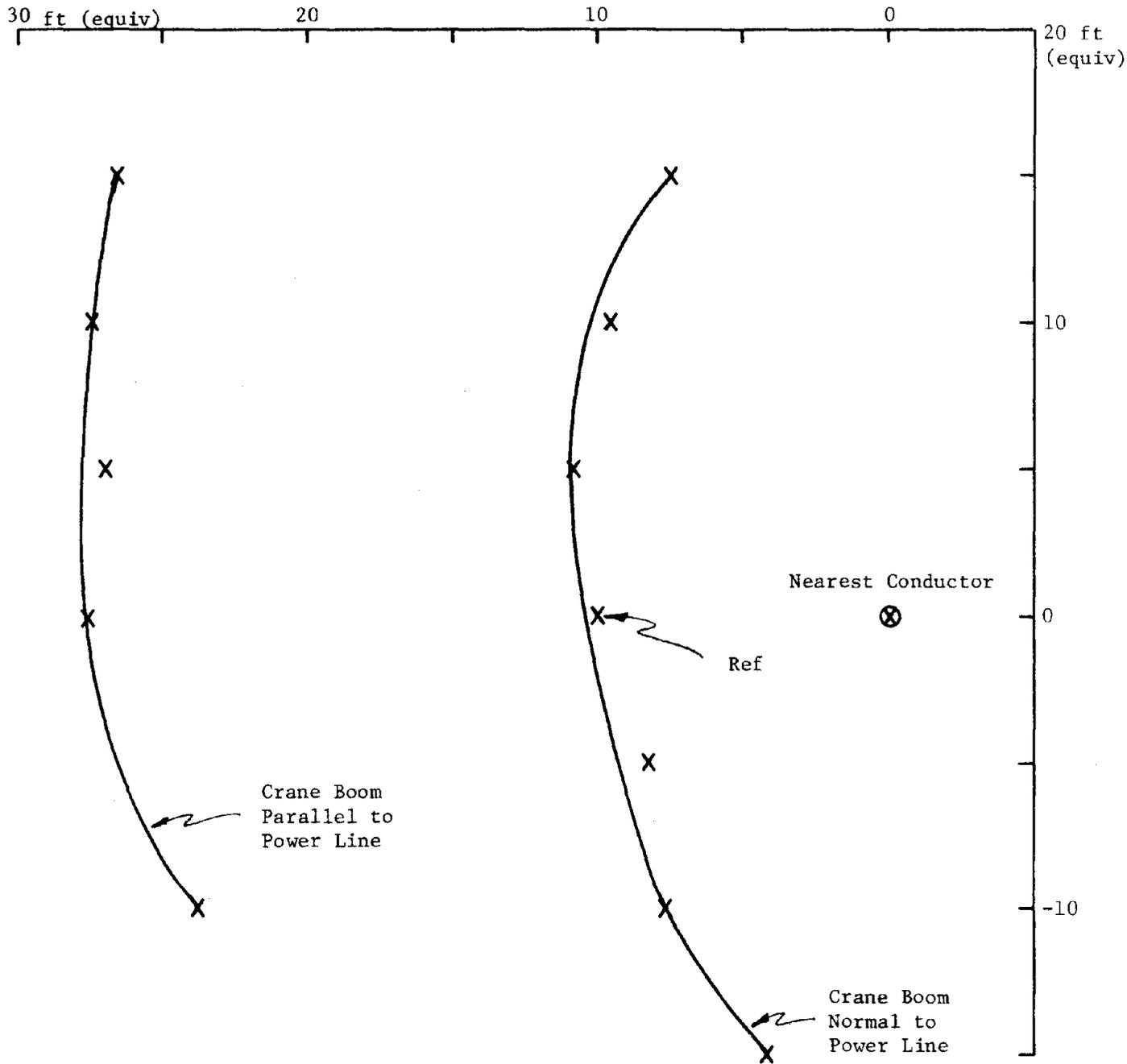
EFFECT OF BOOM CROSS SECTION ON ALARM CONTOUR



Sigalarm Proximity Warning Device  
Full-Scale Measurements  
Sensor Wire Below Boom  
Single Phase, Horizontally Configured Power Line  
Crane Boom Perpendicular to Power Line

FIGURE 32

EFFECT OF WORK CABLE ON ALARM CONTOUR



Sigalarm Proximity Warning Device  
Scaled Model Measurements  
Sensor Wire Above Boom  
Single Phase, Horizontally Configured Power Line

FIGURE 33

INFLUENCE OF CRANE ORIENTATION ON ALARM CONTOUR

the boom tip, the portion of sensor between the tip and the cab would be farthest when the boom is perpendicular to the power line and closest when the boom is parallel to the power line. Consequently, the distributed sensor system is more sensitive when the boom is parallel to the power line, as demonstrated by the more distant alarm contour for the parallel orientation of the boom.

The performance of the proximity warning device also changes with boom elevation angle, since the orientation of the probe polarization null and the probe maximum response rotate with crane boom elevation angle. In addition, the previously described phenomenon of probe shielding by the work cable is elevation dependent, since the work cable moves closer to the sensor probe at higher elevation angles. Finally, if the probe of a point sensor proximity warning device is elevated to a position very much higher (e.g., 20 or 30 feet) than the power line, the crane can conceivably move the lower portion of the boom into actual line contact without activating the alarm.

#### 4. Influence of Power Line Configuration

The physical configuration of the power line also has varying degrees of influence on the operating characteristics of proximity warning devices.

##### a. Proximity Alarm Sensitivity

As expressed in Equation (2), the electric field intensity at all points around the power line is proportional to the term

$$\frac{aV_0}{\cosh^{-1}(d/R)}$$

regardless of position. Consequently, the electric field intensity increases with increased separation ( $a$ ), line voltage ( $V_0$ ), or wire radius ( $R$ ). A uniform increase or decrease in the electric field strength caused by configuration changes leaves the alarm contour unchanged (unless the field strength becomes so small as to become undetectable by the device), if the device sensitivity is adjusted for the changed configuration.

The phenomenon of increasing electric field strength with increasing voltage is obvious, and does not merit discussion.

The occurrence of decreasing electric field strength with decreasing phase separation arises from the increased tendency of the fields generated by the two equal and opposite voltage conductors to cancel each other as the conductors approach each other. An extreme instance of this effect arises whenever the insulated power line conductors are bundled together, a practice commonly employed with 220 volt secondary distribution lines.

The phenomenon of increasing electric field strength with increased conductor radius can be understood by examining the electrostatic potential at a point very near the surface of a large conductor. At a point very near the surface of a larger conductor, the electrostatic potential is essentially the potential that is forced on the conductor itself (i.e., the power line voltage). As the conductor radius is made smaller while maintaining a fixed axis position, the conductor surface moves away from the observation point. With a constant enforced potential on the conductor, the electrostatic potential at the observation point must decrease as the conductor decreases in size, moving away from the observation point. As the electrostatic potential at the observation point decreases, the electric field strength likewise decreases. This effect can be extrapolated from an observation point very near the surface of the conductor to all points in the electric field.

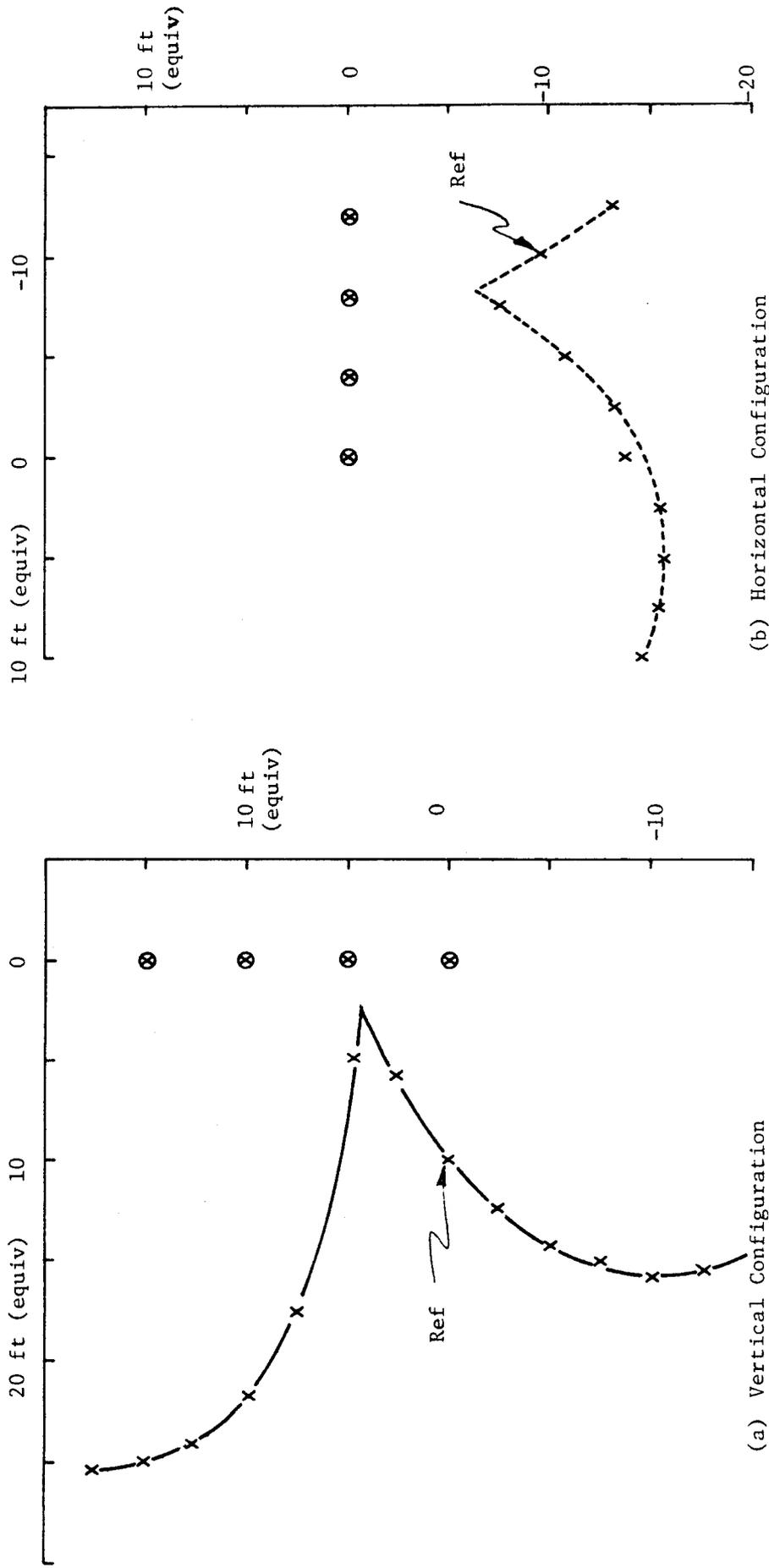
#### b. Proximity Alarm Contour Effects

A vertically configured set of power line conductors produces a distribution of electric field vectors that are rotated 90° from the orientation of electric field vectors produced from an otherwise similar but horizontally configured power line. For this reason, a given crane/sensor configuration will result in distinctly different alarm contours for vertically and horizontally configured power lines. According to the same line of reasoning, multiphase power line configurations not having all conductors in a single plane will produce still different alarm contours.

Figure 34 shows the difference in alarm contours for operation around a vertically configured and a horizontally configured three-phase power line. Both contours were produced with the SR Instruments device. The probe was mounted on the top surface of the scaled model Galion 150 crane.

The location of the neutral wire presents another difficulty for achieving the ideal alarm contour. First, the placement of the neutral wire modifies the electric field distribution, and consequently the alarm contours. Secondly, the neutral wire is at the same electrical potential as the crane boom, and is not a direct source of electric fields. As a consequence, the grounded crane boom can occasionally come into actual contact with the neutral wire without activating the alarm. Figure 35 is an alarm contour around a single-phase 7.9 kV primary distribution line for a Sigalarm installed on a City Public Service crane, operating parallel to the power line. As shown in Figure 35, the crane boom actually extends past the neutral wire to a point midway between the neutral and "hot" wires before the alarm is activated.

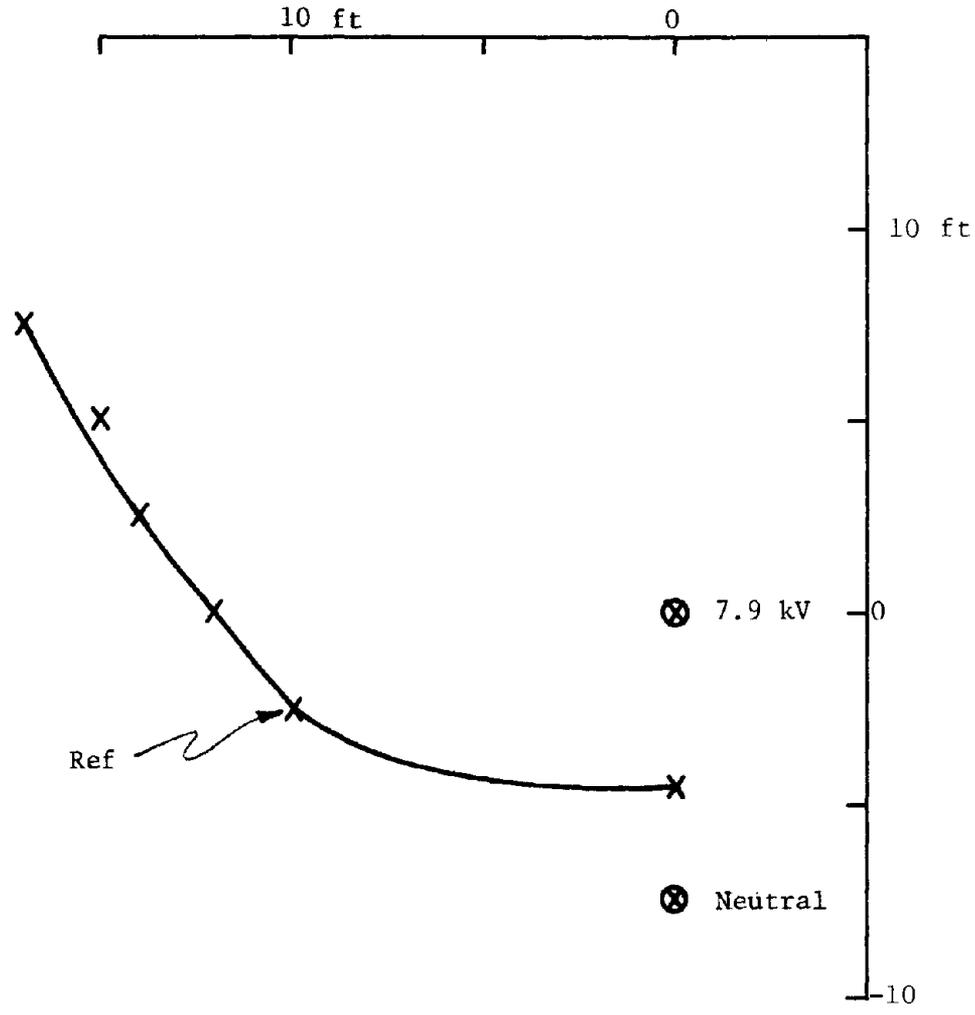
The form of Equation (2) infers that line spacing can influence the distribution as well as the amplitude of electric field vectors. However, within the limits of measurement accuracy, no alarm contour variations for line spacing were observed in either numerical simulations or experimental measurements.



SR Instruments Proximity Warning Device  
 Scaled Model Measurements  
 Three-Phase, Vertically Configured Power Line  
 Crane Boom Perpendicular to Power Line

SR Instruments Proximity Warning Device  
 Scaled Model Measurements  
 Single Phase, Horizontally Configured Power Line  
 Crane Boom Perpendicular to Power Line

FIGURE 34. ALARM CONTOURS AROUND VERTICALLY AND HORIZONTALLY CONFIGURED POWER LINES



Sigalarm Proximity Warning Device  
Full-Scale Measurements  
Sensor Wire Above Boom  
Single Phase, Vertically Configured Power Line  
Crane Boom Parallel to Power Line

FIGURE 35  
PROXIMITY WARNING DEVICE INSENSITIVITY TO NEUTRAL WIRE

Variations in line height have typically demonstrated only a slight influence on the measured alarm contours. However, Figure 36 is a significantly differing pair of measured scale model alarm contours for two different line heights, with all other configuration parameters remaining constant. Since the line spacing is typically small compared to the height above ground surface, the contribution from ground plane images can be ignored. Rather, the variation is interpreted as resulting from the associated variations in boom elevation.

#### 5. Influence of Large Grounded Metal Object

A number of scaled model and full-scale tests were performed to monitor the influence of large grounded metal objects in the vicinity of the crane. Minor variations were occasionally observed upon introduction of the large metal object. However, the variations followed no trend, showing both slight increases and decreases in alarm sensitivity for various configurations.

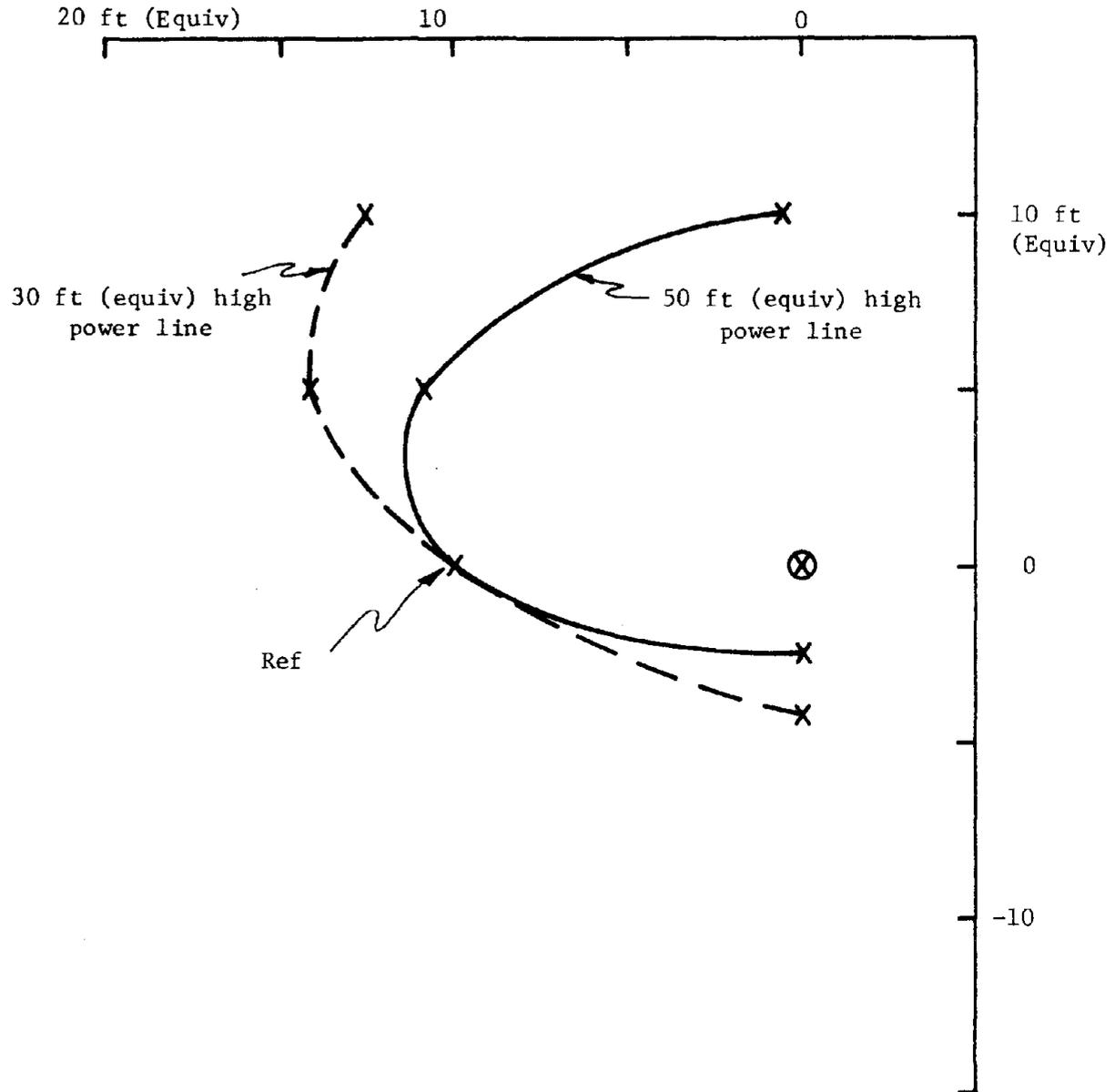
#### 6. Crane Boom/Power Line Contacts

Sufficient scaled model experimental data on the Sigalarm and SR Instruments device was collected to produce more than 150 alarm contours. Each contour characterized the alarm system performance for a different combination of power line, crane, alarm device, and sensor configurations. The configuration combinations were chosen to determine the severity with which various parameters would influence the device operational characteristics. From these contours, a total of 57 contacts between the crane boom and the power line were observed in which no alarm was produced. No actual contacts were recorded for the Electro-alarm device since that unit could not be tested on the 1:10 scaled model. However, the Electro-Alarm, like the other two devices, operates by monitoring the electrostatic field, and it is reasonable to conclude that boom contacts with the power line would have similarly occurred if scaled model tests with the Electro-Alarm had been performed.\*

In interpreting the quantitative distribution of contacts, it is important to realize that the three devices were not always tested under identical conditions. For obvious safety reasons, no boom/power line contacts were allowed during full-scale tests. The wider variations for Sigalarm sensor feed wire mounting positions (e.g., inside the boom, above the boom, below the boom, etc.) prompted a number of tests with the Sigalarm that were not relevant for the SR Instruments device. Finally, since two SR Instruments devices were purchased, whereas only one Sigalarm was available from the manufacturer, some tests involved only the SR Instruments alarm device. Consequently, the actual counts of power line contact presented here should not be interpreted as direct indicators of comparative device performance, but rather as evidence that a number of hazardous operational conditions were simulated in which no alarm was produced.

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\*This conclusion was strengthened during full-scale testing with the Electro-Alarm where seven instances were documented in which the crane boom approached within two feet of the power line without producing an alarm. For safety reasons, the boom was not moved closer to the power line, but it was apparent that boom contact with the power line could have occurred without producing an alarm.



Sigalarm Proximity Warning Device  
Scaled Model Measurements  
Sensor Wire Inside Boom  
Single Phase, Vertically Configured Power Lines  
Crane Boom Perpendicular to Power Line

FIGURE 36

ALARM CONTOUR VARIATION WITH POWER LINE HEIGHT

The 57 contacts between the scaled model crane boom and power lines included a number of variations in crane grounding and work cable configurations. However, the testing performed under this contract indicated that the device performance variations caused by the crane grounding and by the work cable positions were generally negligible. When the grounding and work cable variations are excluded, a total of 39 instances remain in which the crane boom contacted the power line without causing alarm activation. Tables 2 and 3 summarize the system configurations associated with the 39 distinguishable instances of contact.

#### 7. Field Tests for Thunderstorm Induced False Alarms

Results of the field tests for thunderstorm induced false alarms indicate a higher incidence of false alarms during increased thunderstorm activity, regardless of which particular device was being tested. Although a number of the alarm activations could be positively attributed to nearby lightning strikes, very little correlation was observed between alarm activation and independently monitored electrostatic field intensity. All of the alarm events that were directly attributed to thunderstorm activity were transient alarms and as such should be readily distinguishable from alarms due to power line proximity.

#### 8. Proximity Warning Device Settings for Traveling Cranes

In addition to the performance goal of maintaining a minimum safe distance from an energized power line while working in its vicinity, another objective for proximity warning devices is to warn the driver of a traveling crane when he is in the neighborhood of a high voltage power line. Ideally, the device would be switched to a preset, fixed sensitivity for operation in this mode. Since high voltage power lines are common with a wide range of voltages and geometrical configurations, a wide range of alarm distances must be tolerated. Fortunately, however, the electric field decreases much more rapidly than a simple inverse amplitude with distance relationship.

Various geometrical configurations of three-phase high voltage power lines over an ideal ground plane line were numerically\* analyzed to estimate the range of electric field intensities at distances of 50 and 100 feet. The geometrical configurations included vertically and horizontally configured power line circuits and circuits arranged with the four conductors (three phases and one neutral wire) arranged at the four corners of a square. In addition, various placements of the neutral wire were analyzed.

Both the upper and lower extremes of calculated electric field strength occurred for horizontally configured lines. Depending on the placement of the neutral wire, the vertical component of the electric field at 10 feet above the earth can theoretically vary from as much as 80 volts/meter to as little as 35 V/m at 50 feet from a 69 kV line,

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\*The Fortran listing of program MULTI used to predict the electric field strength from three-phase systems is presented in Appendix C.

TABLE 2

SCALED MODEL CONFIGURATIONS WITH THE SIGALARM DEVICE  
 RESULTING IN CRANE BOOM CONTACT WITH POWER LINE

| <u>Antenna Wire<br/>Route Along<br/>Crane Boom</u> | <u>Boom Orientation<br/>With Respect to<br/>Power Line</u> | <u>Power Line Geometry</u>    | <u>Boom Motion<br/>Producing<br/>Contact</u> | <u>Number of<br/>Distinguishable<br/>Configurations<br/>Producing Contact</u> |
|----------------------------------------------------|------------------------------------------------------------|-------------------------------|----------------------------------------------|-------------------------------------------------------------------------------|
| Inside                                             | Perpendicular                                              | Horizontal (Various Spacings) | Lowering                                     | 4                                                                             |
| Inside                                             | Perpendicular                                              | Horizontal (Various Spacings) | Raising                                      | 2                                                                             |
| Inside                                             | Parallel                                                   | Horizontal (Various Spacings) | Swinging                                     | 4                                                                             |
| Inside                                             | Parallel                                                   | Horizontal (Various Spacings) | Raising                                      | 1                                                                             |
| Above                                              | Perpendicular                                              | Horizontal (Various Spacings) | Lowering                                     | 4                                                                             |
| Above                                              | Parallel                                                   | Vertical (Various Spacings)   | Raising                                      | 2*                                                                            |
| Below                                              | Perpendicular                                              | Vertical (Various Spacings)   | Raising                                      | 1                                                                             |
| Below                                              | Perpendicular                                              | Vertical (Various Spacings)   | Lowering                                     | 1*                                                                            |
| Below                                              | Parallel                                                   | Vertical (Various Spacings)   | Raising                                      | 3                                                                             |

\*Contacts with neutral wire.

TABLE 3

SCALED MODEL CONFIGURATIONS WITH SR INSTRUMENTS DEVICE  
 RESULTING IN CRANE BOOM CONTACT WITH POWER LINE

| <u>Boom Orientation<br/>with Respect to<br/>Power Line</u> | <u>Power Line Geometry</u>    | <u>Boom Motion<br/>Producing<br/>Contact</u> | <u>Number of<br/>Distinguishable<br/>Configurations<br/>Producing Contact</u> |
|------------------------------------------------------------|-------------------------------|----------------------------------------------|-------------------------------------------------------------------------------|
| Perpendicular                                              | Horizontal (Various Spacings) | Lowering                                     | 5                                                                             |
| Perpendicular                                              | Horizontal (Various Spacings) | Raising                                      | 1                                                                             |
| Parallel                                                   | Horizontal (Various Spacings) | Swinging                                     | 4                                                                             |
| Parallel                                                   | Horizontal (Various Spacings) | Raising                                      | 5                                                                             |
| Perpendicular                                              | Horizontal (Three phase*)     | Lowering                                     | 1                                                                             |
| Parallel                                                   | Horizontal (Three phase*)     | Swinging                                     | 1                                                                             |

\*A very limited amount of three-phase scale model testing was performed.

and from 4 to 15 volts/meter at 100 feet from the line. Similarly, the electric fields from a 7 kV three-phase line can vary theoretically from 4 to 8 volts/meter at 50 feet and from 0.5 to 1.5 volts/meter at 100 feet. To the extent that the effects of terrain, nearby structures, and other secondary influences can be ignored, a proximity warning system with a preset alarm threshold sensitivity of 4 volts/meter would be expected to alarm at a minimum distance of 50 feet from a 7 kV power line and a maximum of 100 feet from a 69 kV power line. The effects of terrain and nearby structures, as well as power line voltages outside the 7-69 kV range, would result in a corresponding increase in the spread of alarm distances.

## B. Comparison of Proximity Warning Device Characteristics

As discussed in Section A, each of the proximity warning devices displayed limitations resulting from the physical principle of operation. However, during the testing phase, various differences became apparent in the operational characteristics of the three devices. The comparative characteristics of the three devices are summarized in Table 4 and are discussed in the following paragraphs. For completeness, some information already presented will be duplicated.

### 1. Electro-Alarm

The Electro-Alarm, like the SR Instruments and the Sigalarm, operates by detecting the presence of electrostatic fields in the direction preferred by the probe/boom configuration. As a consequence, the Electro-Alarm (like the other two devices) experienced polarization nulls, proved unreliable in the presence of multiple power line circuits, performed differently with different power line configurations, and changed operational characteristics when the sensor placement was changed. The Electro-Alarm displayed a very moderate change in both the sensitivity and the shape of alarm contours when the boom orientation was changed from perpendicular to parallel with respect to the power line wires. Since the Electro-Alarm is basically a point sensor warning device, the device basically offers a "sphere" of protection around the point sensor and does not give protection along the full length of the boom. For example, whenever the probe is mounted near the boom tip and the boom is extended to the full length, the lower part of the crane boom is unprotected by the Electro-Alarm sensor. However, Electro-Alarm does offer multiple probes as an option to be mounted at various points along the boom. The addition of sufficient multiple probes should minimize the problem of "point" coverage. Since the Electro-Alarm warning device is basically a point sensor system and uses shielded signal wire between the point sensor and the master control unit, the system sensitivity (i.e., the distance between the sensor and the power line to produce alarm) is not changed by changing the boom length. However, the Electro-Alarm has no convenient method for adjusting the shielded wire length as the boom length changes.

TABLE 4

COMPARISON OF DEVICE CHARACTERISTICS

| Device Characteristic                                                                 | Electro-Alarm     | Sigalarm            | SR Instruments  |
|---------------------------------------------------------------------------------------|-------------------|---------------------|-----------------|
| Type of sensor                                                                        | Multiple discrete | Single distributed  | Single discrete |
| Reliability degraded by multiple power circuits                                       | Yes               | Yes                 | Yes             |
| Experienced polarization nulls                                                        | Yes               | Yes                 | Yes             |
| Operational characteristics influenced by choice of sensor placement                  | Yes               | Yes                 | Yes             |
| Operational characteristics influenced by power line configuration                    | Yes               | Yes                 | Yes             |
| Operational characteristics influenced by boom orientation with respect to power line | Slight            | Most                | Slight          |
| Full boom protection                                                                  | No                | Yes (one side only) | No              |
| Sensitivity influenced by boom extension                                              | No                | Yes                 | No              |
| Provides convenient means of adjusting signal cable length                            | No                | Yes                 | No              |
| Sensitivity                                                                           | Least             | Intermediate        | Most            |

TABLE 4  
COMPARISON OF DEVICE CHARACTERISTICS (CONT)

| Device Characteristic                     | Electro-Alarm                           | Sigalarm                                              | SR Instruments          |
|-------------------------------------------|-----------------------------------------|-------------------------------------------------------|-------------------------|
| Dynamic range                             | Least                                   | Most                                                  | Intermediate            |
| Overlapping sensitivity ranges            | Poor                                    | Good                                                  | Continuously adjustable |
| Observed saturation                       | Yes                                     | No                                                    | No                      |
| Electronics                               | Vacuum tube, Dynamotor, 6 relays        | Solid state, 1 relay                                  | Solid state             |
| Operable temperature range                | +30°F to 160°F                          | -60°F to 160°F                                        | -60°F to 160°F          |
| Variation of sensitivity with temperature | Minor                                   | Moderate                                              | Excessive               |
| Weight                                    | 26.4 lbs                                | 2.7 lbs                                               | 1.1 lbs                 |
| Power requirements                        | 12 Vdc at 2 amps<br>Approx. 4 amps peak | 11 to 15 Vdc at 200 ma<br>4 amps peak                 | 12 to 15 Vdc at 0.5 A   |
| Alarm rate                                | Fixed at about 1 blast per second       | Blast rate increases as electrostatic field increases | Continuous              |
| Alarm audibility                          | Good                                    | Good                                                  | Poor                    |

During the full-scale crane tests at SwRI, a series of tests was performed to directly compare the basic sensitivity and the dynamic range of the three devices. These tests were accomplished with each device installed on the crane according to the various manufacturer's recommended procedures. The crane boom tip was stationed at a distance of 10 feet from the test power line and the power line voltage was adjusted until alarm threshold conditions were established. The test power line was an 18-foot high, 2-conductor, single-phase line with a 40-inch separation between No. 8 conductors. The maximum sensitivity of each device was within 4 dB of the other two devices. The Electro-Alarm has only two sensitivity ranges, a high volts range and a low volts range with about 10 dB and 20 dB dynamic range, respectively. Furthermore, the two ranges do not provide an overlapping region of reliable operation. If a sensitivity setting midway between the two ranges is required, the low volts switch must be set and the fine adjustment of the sensitivity must be turned down to its minimum setting. However, with this setting, the Electro-Alarm displayed a saturation effect whereby the voltage of the SwRI power line system could be raised to produce alarm activation, and raised still further to result in a cessation of the alarm. The Electro-Alarm also showed saturation during the Alcoa mine tests, first producing the appropriate alarm as the crane approached the power line, and then deactivating the alarm as the crane approached closer to the power line.

The Electro-Alarm circuitry uses vacuum tube electronics with relay logic and a small motor driven generator (Dynamotor) to supply the high voltage required for the vacuum tube operation. Consequently, the Electro-Alarm proved to be the least rugged of the three devices, as evidenced by the results of the shock tests. In addition, because of Dynamotor freezing, the Electro-Alarm would not perform for temperatures below 30° Fahrenheit. However, the variation of the Electro-Alarm sensitivity with changes in environmental temperature was less than the variation of the other two devices. This desirable characteristic was attributed to the vacuum tube design. Finally, the Electro-Alarm weight size and power consumption were each significantly greater than those of the other two units.

## 2. Sigalarm

As described for the Electro-Alarm, the Sigalarm proximity warning device is not reliable in the presence of multiple power circuits, is susceptible to polarization nulls, is strongly influenced by the choice of sensor placement and by the power line configuration. However, since the Sigalarm uses a distributed rather than a point sensor, the Sigalarm device should be less susceptible to polarization nulls than are the other two devices. Also, since the Sigalarm proximity warning device uses a sensor that is distributed along the full length of the boom, it offers intrinsic protection along the full length of the boom (on one side only). However, because of the distributed sensor wire, the Sigalarm shows a significant change of sensitivity with boom extension and with boom orientation toward the power line. On the other hand, only the Sigalarm has provisions for conveniently adjusting the signal wire length as the boom length is changed. The Sigalarm provides (as options) (1) a manually retractable sensor wire on a rotatable drum and (2) a spring loaded drum that automatically reels the sensor wire in as the boom is shortened and releases the sensor wire as the boom is extended.

The Sigalarm uses a rotary switch to provide six sensitivity ranges. By using the fine sensitivity adjustment, each range extends over approximately 20 dB and overlaps the adjacent ranges by about 5 dB. As a consequence, the dynamic range and the overlap in the sensitivity ranges of the Sigalarm are very adequate.

The Sigalarm incorporates a circuit feature which produces an audible alarm blast rate that increases as the electrostatic field increases. Under normal circumstances, this has the advantageous effect of giving the operator information that he is moving in the wrong direction if the blast rate is increasing.

### 3. SR Instruments Device

As was true for the other two devices tested, the SR Instruments proximity warning device operates on the principle of electrostatic field detection and consequently shares several basic limitations with the other two devices. The reliability of the SR Instruments proximity warning device is degraded by the presence of multiple power circuits, and is influenced by the local polarization of the electrostatic field. Likewise, the operational characteristics of the SR Instruments device are influenced by the location of the sensor and by the power line configuration. Since the SR Instruments device is basically a point sensor device, its operational characteristics are only moderately influenced by boom orientation with respect to the power line. However, because of the point sensor, the SR Instruments device basically offers only protection in the vicinity of the sensor itself and may not provide warning that the lower part of the boom is moving into proximity with the power line.

During the SwRI full-scale crane tests to compare sensitivity, the SR Instruments unit responded to about 200 volts on the power line at a distance of 10 feet. This was the minimum required line voltage for alarm excitation of the three devices measured. The SR Instruments unit has about 40 dB of dynamic range controlled by continuously adjustable coarse and fine sensitivity controls.

The SR Instruments device showed very poor stability with temperature variations. During the field tests for evaluating susceptibility to thunderstorms, the SR Instruments device produced false alarms continuously from approximately 4:00 a.m. to 6:00 a.m. each morning, a period during which the ambient temperature was at a minimum. In addition, during a two-hour operational full-scale field test at SwRI, the device sensitivity decreased with increasing ambient temperature and allowed the crane to come significantly closer to the power line than had been originally allowed when sensitivity was first adjusted.

The SR Instruments unit uses a Sonalert™ type audible alarm which, because of typical crane engine noise, cannot be reliably heard by the crane operator and cannot be heard at all by the crane crew.

Like the Electro-Alarm, the SR Instruments device uses a shielded signal wire between the sensor and the master control unit, and the device sensitivity is not influenced by variations in the boom length. However, the SR Instruments has no provision for adjusting the length of the signal wire as the boom length changes.

### C. Environmental Test Summary

Environmental tests were performed on the three proximity warning devices to determine the mechanical vulnerability of the units to harsh environments that might be encountered in mining applications. The results of those tests are only summarized in this section, but a more complete discussion of the environmental tests and test results are presented in Appendix D.

During the low temperature tests, the Electro-Alarm proximity warning device failed, apparently due to the low temperature induced seizing of the dynamotor assembly. Both the SR Instruments and the Sigalarm units operated satisfactorily at  $-30^{\circ}\text{F}$ , but both showed a significant increase in sensitivity as compared to  $80^{\circ}\text{F}$  sensitivity. All three units performed satisfactorily after returning from the extreme cold temperatures to ambient temperature.

All three units performed adequately during and after the high temperature cycle, except that the SR Instruments device displayed a significant decrease in sensitivity at  $120^{\circ}\text{F}$ .

All three units performed well after the humidity tests, with only minor corrosion occurring in each of the three alarms.

All three units performed well after being subjected to a 1.5 g vibration test. A vibration of 1.5 g from 7 to 2500 Hz was injected along all three of the major axes.

During the drip test, the SR Instruments unit showed extensive evidence of moisture collecting throughout the device and the Electro-Alarm showed evidence of water leakage in the sensor device enclosure, but the Sigalarm showed no evidence of internal moisture. All systems responded properly when placed in the operational mode after the drip tests.

Each of the units was subjected to harsh shock tests. The SR Instruments device and the Sigalarm suffered minor packaging damage. In addition, a printed wiring cable was torn in the Sigalarm. The Electro-Alarm was extensively damaged, apparently because the dynamotor broke away from its shock mounts, causing damage to the vacuum tubes and relays inside the master control unit. The SR Instruments unit and the Sigalarm unit responded properly after the shock tests, although the test circuitry in the Sigalarm was inoperative. The damage to the Electro-Alarm was so extensive that even after major repairs some of the electronics components still failed to respond properly.

#### D. Frequency Response Results

The frequency response measurements were performed by connecting a signal generator directly to the sensor input port of each device and observing the signal level required to activate the alarm at various frequencies. This measurement procedure determined the high frequency cutoff frequencies and the rate of sensitivity falloff in the rejection skirts. The measured high frequency cutoff points are 400 Hz for the SR Instruments device, 900 Hz for the Sigalarm, and 5 kHz for the Electro-Alarm.

All three devices showed an effective sensitivity falloff rate of 12 dB per octave above the cutoff frequencies. In addition, the Sigalarm displayed an 18 dB per octave falloff rate beginning at two octaves above the high frequency cutoff point. The measurements also indicated a 6 dB per octave low frequency rejection falloff rate for all the devices, with the low frequency cutoff points being 25 Hz for the Sigalarm, 95 Hz for the SR Instruments device, and 350 Hz for the Electro-Alarm.

Based on these measurements, the high frequency sensitivity would be 60 dB down from the 60 Hz sensitivity at 10 kHz for Sigalarm, 17 kHz for the SR Instruments device, and 640 kHz for the Electro-Alarm. Since the RF fields created by corona discharge are less than the 60 Hz fields at 10 feet from the power line, the high frequency rejection should be very adequate in each of the units.

## V. CONCLUSIONS AND RECOMMENDATIONS

### A. Conclusions

Several design deficiencies were observed in the three commercial proximity warning devices tested under this contract. These design deficiencies, which vary from device to device, include inadequate overlap in sensitivity ranges, utilization of fragile vacuum tubes and electromechanical parts, excessive sensitivity to temperature, inaudible alarms, and lack of provisions for boom length variations. The elimination of these deficiencies is straightforward and within the present state of the art.

In addition, several aspects of the proximity warning device reliability are severely limited by the physical principle (i.e., electrostatic field sensing) on which the devices operate.

Six categories of physical phenomena were observed to produce undesirable performance in the commercially available proximity warning devices. These phenomena included field distortion from multiple power line circuits, electric field polarization effects, sensor shielding by the crane boom, partial boom protection, sensitivity variation with boom orientation, and sensitivity variation with boom extension. The inability of the devices to operate reliably in the presence of multiple power line circuits results from an interaction of the electrostatic field vectors produced by the individual power line circuits and can cause extreme departures from the electrostatic field produced by a single power line circuit. These variations are so diverse and extreme as to render unreliable any device operating on electrostatic field detection principles alone. However, a more sophisticated proximity warning device system can be designed to minimize the above limitations and substantially improve the operational reliability in the vicinity of a single circuit power line.

### B. Recommendations

#### 1. Recommended Design Objectives for Improved Performance

##### a. Minimize Electric Field Polarization Effects

Electric field polarization effects were observed during the tests of all three commercially available devices and arise from the nature of a single sensor/boom configuration to have a maximum sensitivity for a preferred orientation of electrostatic field vector. At positions where the electrostatic field vector is oriented orthogonally to the preferred orientation, the system sensitivity is minimized, allowing the crane boom to be positioned much closer to the power line without producing an alarm. To overcome this difficulty, separately monitored multiple sensors placed on all sides of the crane boom are recommended. In this configuration, even though the electrostatic field vector orientation may be orthogonal to the preferred direction for some sensors, other sensors mounted in positions responding to different preferred field orientations will respond to the electrostatic field.

b. Eliminate Sensor Shielding by the Crane Boom

Sensor shielding by the crane boom was also observed for all proximity warning devices tested. Whenever the electrostatic field sensor and the electrostatic field source (i.e., the power line) are on opposite sides of the crane boom, the massive conducting structure of the crane boom effectively shields the sensor probe, severely reducing its sensitivity. To eliminate this effect, multiple sensors placed on different sides of the crane boom are recommended, making it impossible for all sensors to be simultaneously in the "shadow" of the crane boom.

c. Provide Full Boom Protection

Two of the devices tested, the Electro-Alarm and the SR Instruments, used short (i.e., "point") sensors and gave effectively only a sphere of protection about the sensor. Consequently, with the point sensor placed near the boom tip, the base of the crane boom would not be adequately protected and could come into contact with the power line if the boom tip were raised to a high position above the power line. To overcome this limitation, multiple sensor placement along the entire length of the boom is recommended.

d. Minimize Sensitivity Variation with Boom Orientation

One of the devices, the Sigalarm, used a distributed sensor and displayed significant sensitivity variation with boom orientation. As the boom was rotated from a position parallel to the power line to a position normal to the power line, the sensitivity decreased severely. To minimize the sensitivity fluctuation with boom orientation, point sensors are recommended.

e. Eliminate Sensitivity Variations with Boom Extension

The Sigalarm used a distributed sensor, and by its nature showed decreasing sensitivity with decreasing boom length. To eliminate this variation, point sensors are recommended.

2. Recommended Improved Proximity Warning Device System Design

To incorporate all the features of the above recommended improvements, the improved proximity warning device system must incorporate multiple point sensors distributed around the boom and along the length of the boom. The output of each sensor must be separately monitored to produce an alarm whenever the power line approaches within ten feet (or some other established distance) of that individual sensor. In this way, an approximately uniform distance-sensitivity can be established along the entire length of the boom and on all sides of the boom, regardless of the field orientation, the boom orientation or the boom extension.

In addition, it is recommended that the device incorporate a feature that automatically turns on the device to maximum sensitivity whenever the crane operation begins. This "wake up" sensitivity of the device would be factory adjusted to alarm whenever the crane comes within 50 to 100 feet from a high voltage power line. Such a capability would warn a traveling crane operator that he is coming into the vicinity of a high voltage power line.

To minimize the difficulty of establishing the proper sensitivity at the beginning of operation, it is recommended that the sensitivity adjustment controls be replaced by a single pushbutton switch that activates an automatic sensitivity adjustment.

APPENDIX A  
PROXIMITY WARNING DEVICE LITERATURE

# ELECTRO-ALARM® FREES YOUR OPERATOR FROM POWER-LINE WORRY!

Now your operator can work safely in the vicinity of power-lines . . . swing his boom in a circle-of-safety . . . protected by an automatic, electronic warning device which eliminates operator-error! Let **ELECTRO-ALARM** protect the lives of your workmen — prevent costly destruction to your equipment— sound a warning against possible damage to high-lines in proximity to your rigs.

**SET FOR ANY WORKING DISTANCE** with a single control. Simple adjustment can be made by operator or oiler. Boom is swung within safe distance of transmission line and control advanced till horn sounds. Horn will sound again at any time boom enters this pre-set danger zone.

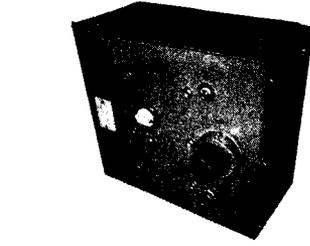
**AUTOMATIC** . . . Electro-Alarm requires no attention. Specialized electronic circuits monitor device and sound warnings the instant boom gets within dangerous proximity of power lines.

**WORKS ON ANY RIG.** Regardless of make, model or size, **ELECTRO-ALARM** furnishes fool-proof, adequate protection against operator-error. Built for years of rough use.

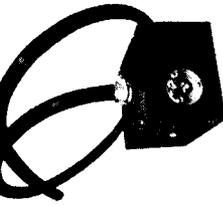
**WORKS ON LOW-POWER OPERATING VOLTAGES.** Requires no special batteries to operate. Runs off starter battery, or lighting circuit from any rig. Can be operated on AC, or DC, 6 to 110 volts. Cannot itself become a source of danger.

**OPERATES AT NIGHT, IN RAIN OR ICE.** Repeated tests in heavy rain-storms proved successful in every way. Hard ice is tapped free of proximity detector before use. Thereafter movement and normal jarring of boom serves to clear it of ice and slush. Boom lights, unless mounted directly in front of proximity detector, do not interfere with action of warning device.

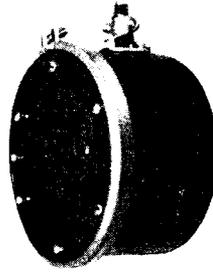
**SIMPLE TO INSTALL.** Proximity detector mounts readily on boom end. Other units mount wherever desired.



**1 MASTER CONTROL UNIT**  
Rugged heart of the proximity warning device is set in operation with flip of a switch. Operation is completely automatic! Sensitivity control can be manually adjusted for desired working distance from hazardous power-lines. Has replaceable fuse, accessible from front panel. Can be mounted anywhere in the cab.



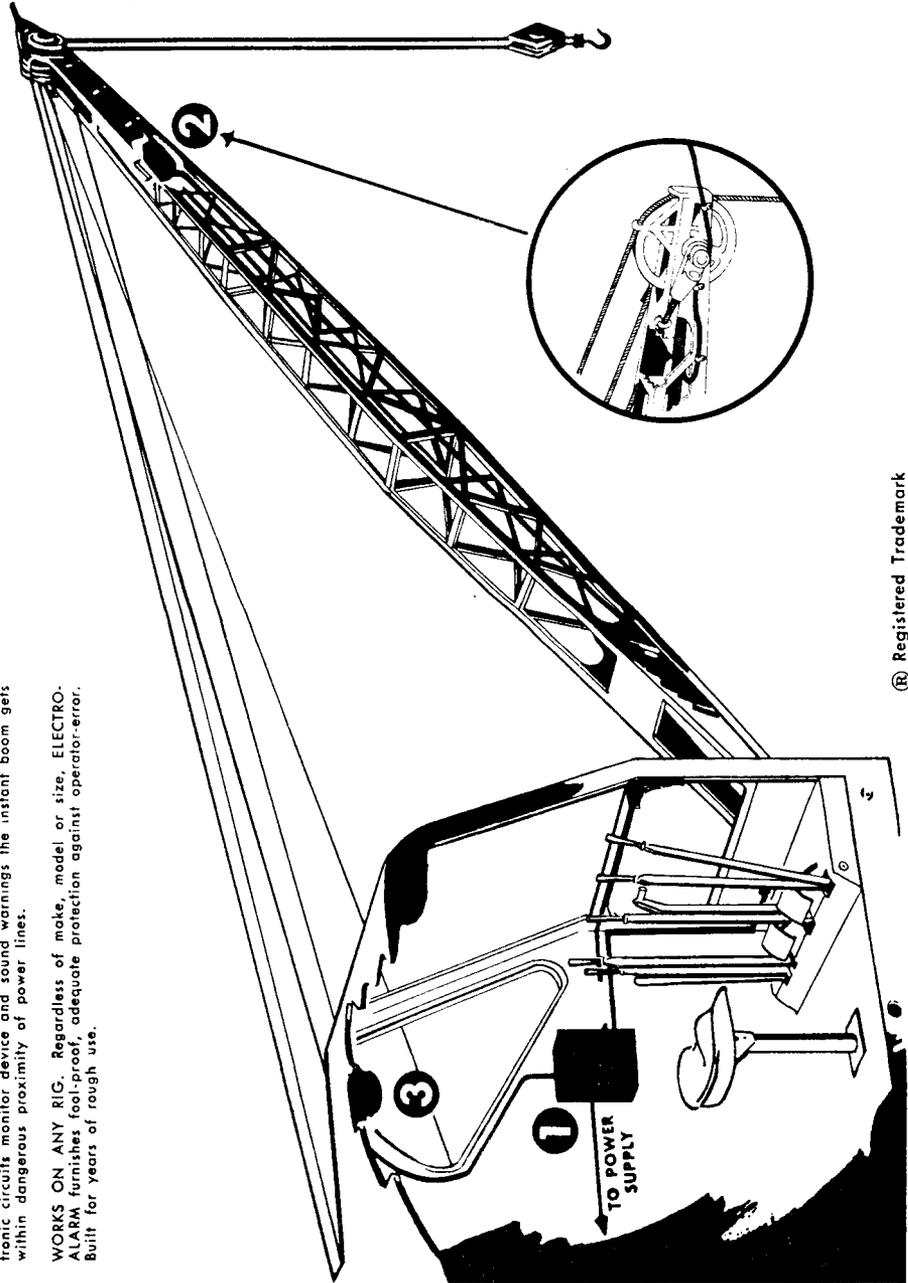
**2 PROXIMITY DETECTOR**  
Sensitive trigger is shock-mounted on the end of the boom. Picks up signals on any nearby AC voltage or DC with ripple component present. Not affected by, and cannot interfere with, radio or television.



**3 PROXIMITY WARNING HORN**  
Voice of Electro-Alarm sounds insistent warning as long as boom remains in vicinity of hazard. May be mounted anywhere convenient. Has adjustable tone-volume control!

## TROUBLE-CHECK FLASHER

Built-in safety device stands alert for any disruption to the warning system itself. Mounted for ready observation by the operator. Instantly warns of snapped or shorted cables, or internal failures. Normally off, it flashes brightly the instant any trouble occurs . . . continuing to do so until trouble is cleared.



# introduction



Power lines have always been a hazard to equipment with booms or extensions, and while contact with overhead high voltage lines represents only 5% of the total electrical accidents, it is responsible for 43.5% of the fatalities. Many of these accidents can be avoided by the installation and proper use of a proximity warning system. This system is now available. It is called SIGALARM.

SIGALARM is a patented, solid state electronic safety system used for detecting the electro-static field of any AC power line. It provides both an audio and visual warning signal to alert the operator of the imminent danger.

Today, with the passage of the Federal Construction Safety Act of 1969 and the Occupational Safety and Health Act of 1970, it is incumbent upon management and safety officials to provide the ultimate assurance of safe working conditions.

# applications

## *Construction*

Heavy equipment such as cranes, power shovels, concrete pumps with booms, etc.

## *Utility Companies*

Aerial towers and platforms.

## *Fire Department*

Snorkel units, aerial towers and platforms, water towers and aerial ladders.

## *Railroads*

Locomotive cranes and railroad wreckers.

## *Aircraft*

For installation on helicopters to alert the pilot that the craft is setting down in the vicinity of high voltage lines.

## *Government*

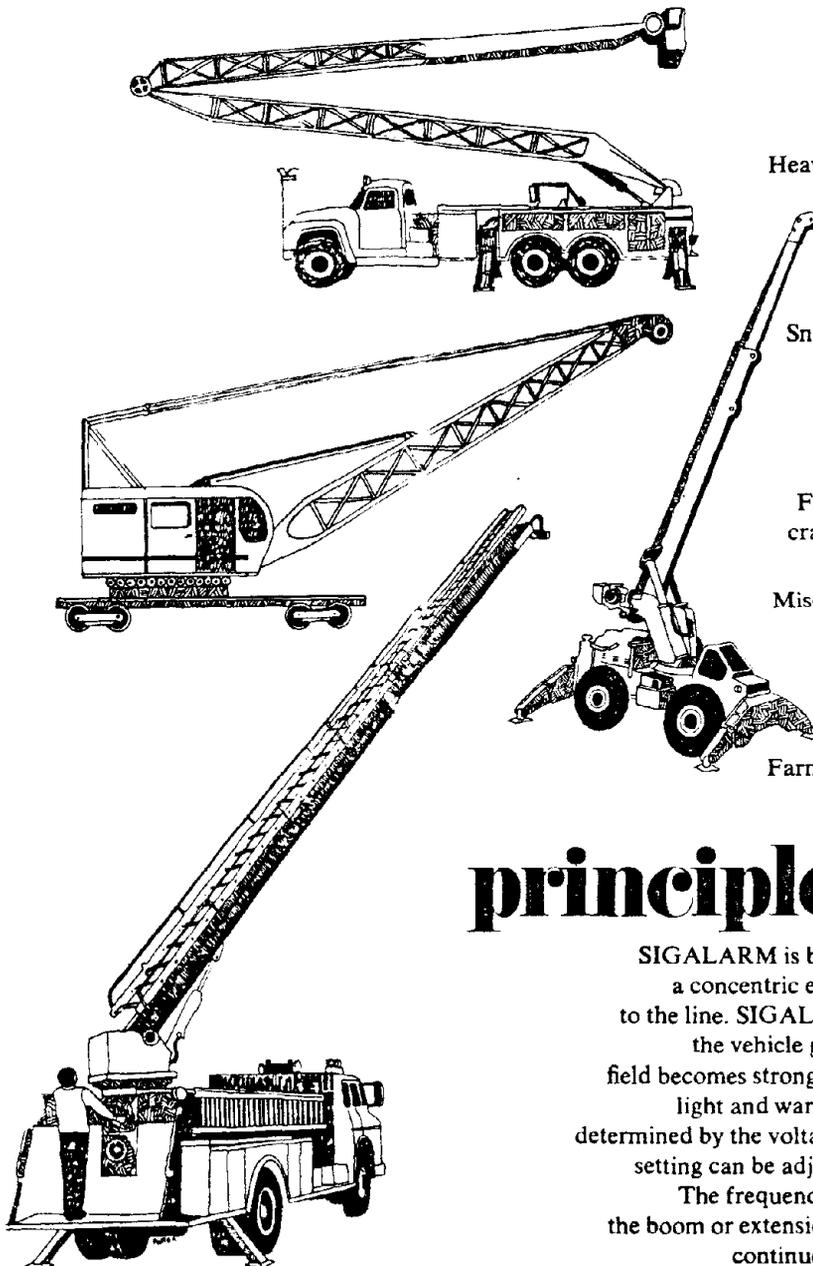
Miscellaneous construction equipment, aerial ladders for street light maintenance, etc.

## *Signs (Billboard)*

Telescoping arms and booms.

## *Other*

Farm equipment, portable drilling rigs, house movers and truck-mounted "A" frames.



# principle of operation

SIGALARM is based on the principle that all live power lines develop a concentric electrostatic field that grows stronger as you get closer to the line. SIGALARM detects and measures this electrostatic field. As the vehicle gets closer to the "hot" power line, the intensity of the field becomes strong enough to trigger a circuit that activates the warning light and warning horn. The distance at which the alarm triggers is determined by the voltage of the power line and the sensitivity controls. This setting can be adjusted from less than one foot to several hundred feet.

The frequency rate of both the audio and visual alarm increases as the boom or extension moves closer to the "hot" power line. The warning continues until the boom is withdrawn from the danger zone.

# features

Mounting brackets securely fasten SIGALARM to interior of cab. No special installation.

Weather-proof, tamper-proof, rugged housing.

Fail-safe, redundant, flashing light and interior howler is activated by proximity to power lines. High reliability, long-life automotive-type light bulb.

Coarse and fine sensitivity control permits adjustment from less than one foot to several hundred feet sensitivity.

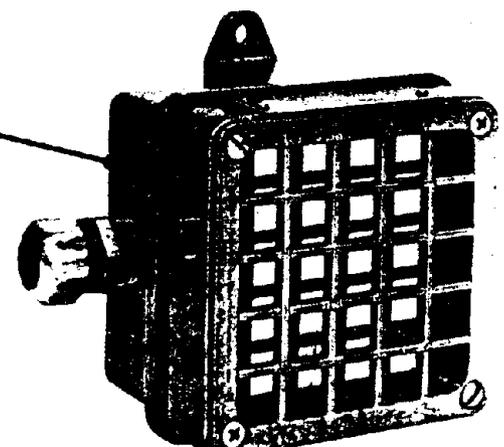
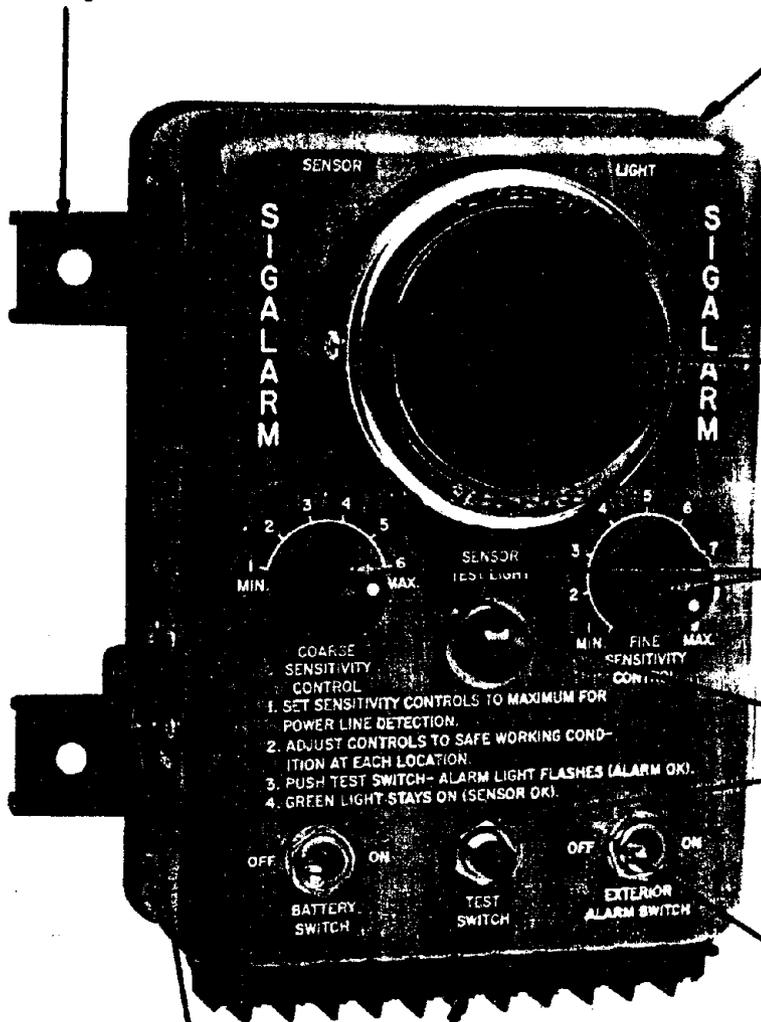
Test button allows operator to test circuitry and antenna sensor. Test light glows green when power is on to indicate proper operation.

Exterior alarm switch activates exterior howler(s).

Threaded cannon-type connector assures positive contact with sensing antenna.

All external and internal alarms connect quickly and positively to terminal strip.

Interior Howler



# accessories

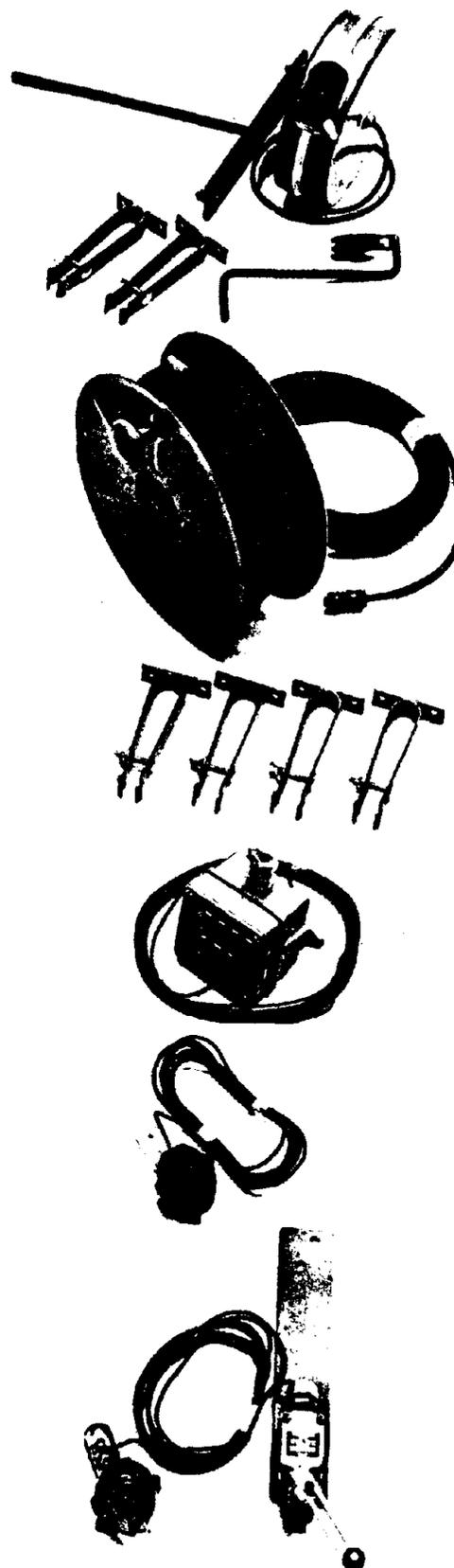
**Automatic Antenna Sensor Reel with 50' of Antenna Sensor:** An automatic reel which will extend and retract the sensor with the operation of telescopic booms and extensions. Required for installation on hydraulic booms, fork lifts and ladder trucks. Reels may be connected in series for extensions longer than 50 feet. Complete with all necessary support hardware and idler wheel.

**Manual Reel with 200' Antenna Sensor:** A manually-operated reel which mounts in the bottom section of the boom, allowing addition or removal of sections in the boom. Recommended where frequent boom length changes are made. Maximum capacity of reel 300'. Complete with all necessary support hardware for complete installation.

**Exterior Alarm Howler:** An audible sounding device for warning operator and ground personnel when SIGALARM is activated. Sound differs from horn signals to avoid confusion. Tone adjustable. Connects to SIGALARM terminal strip with single wire. Single and double projectors to concentrate and direct audio warning signals also available.

**Remote Light:** A single light for mounting in line of sight of operator. Works simultaneously with light on SIGALARM. Connects to SIGALARM terminal strip with single wire.

**Boom Alarm (Visual):** An accessory consisting of a micro-switch and amber light using SIGALARM as its power source. Makes an integral safety system to warn the operator when the crane boom is approaching the boom stops (vertical critical position). Connects to SIGALARM terminal strip with single wire.



# specifications

1. *Primary Power Requirements*

A. Input Voltage: +11 to +15 VDC

B. Input Current:

Standby: 200 ma DC max

Operating: 4 amperes DC peak

2. *Ignition Noise Suppression*

Noise pulses on the internal power bus shall not exceed 0.5 Volts when noise pulses at the input power terminal are 200 micro-seconds or less in duration and 80% or less of the input voltage (Battery voltage) in magnitude.

3. *Operating Temperature*

-29°F to +158°F

4. *Alarm Outputs*

The Sigalarm provides alarm outputs in two forms simultaneously: 1) visual, by means of a flashing red light mounted on the Sigalarm and 2) external, by means of voltage pulses applied to the external alarm terminal through an exterior alarm switch. An alarm is defined to mean one flash of the red light, and simultaneously, one voltage pulse at the external alarm terminal through the external alarm switch.

A. Visual (Red Flashing Light)

Repetition Rate: Proportional to electric field intensity at the sensor cable, up to a maximum of 5 ± 10% Alarms/second.

On Time: During each alarm, the red flashing light shall be on for a duration of 60 to 90 milliseconds.

B. External (External Alarm Terminal to Ground)

Output Voltage Pulse Amplitude to External Alarm Terminals: +10 to +16 volts (same amplitude as input battery voltage) Maximum Output Current: 5 amperes

Repetition Rate: Proportional to electric field intensity at the sensor cable, up to a maximum of 5 ± 10% Alarms/second.

On Time: During each alarm, the voltage pulse at the external alarm terminal shall have a duration of 60 to 90 milliseconds.

5. *Maximum Alarm Response*

2 seconds nominal

6. *Sensing*

Electrostatic Field, 49 to 450 Hertz.

7. *Sensitivity Adjustment*

Front panel controls shall provide means for coarse and fine adjustment of the sigalarm sensitivity. The course control attenuates the sensitivity by 1.0, 10, 100, 1000, and 10,000. The fine control attenuates the sensitivity within

each range set by the coarse control, providing a means of continuous attenuation of sensitivity from zero to the maximum sensitivity set by the coarse control.

8. *Minimum Sensitivity*

The Sigalarm must give a repetitive visual alarm when the sensor cable, short-circuited at the remote end, is subjected to an electric field intensity representative of 121 volts RMS/meter over the frequency range from 49 Hertz to 450 Hertz.

9. *Operational Test*

A single push button shall be provided to test the continuity of the sensor cable and to test the operation of the electronic circuitry and associated visual and external alarms.

10. *Weight*

Gross weight not to exceed 3 lbs.

11. *Size*

7" x 7.55" x 5.30".

12. *Range of Effectiveness*

Depending upon the proximity of the overhead high-voltage line, and its intensity, SIGALARM can be adjusted to actuate the warning alarm at any desired distance from less than one foot to several hundred feet.

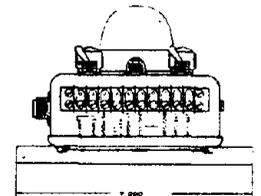
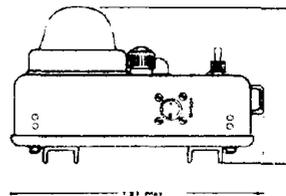
*Range of Effectiveness*

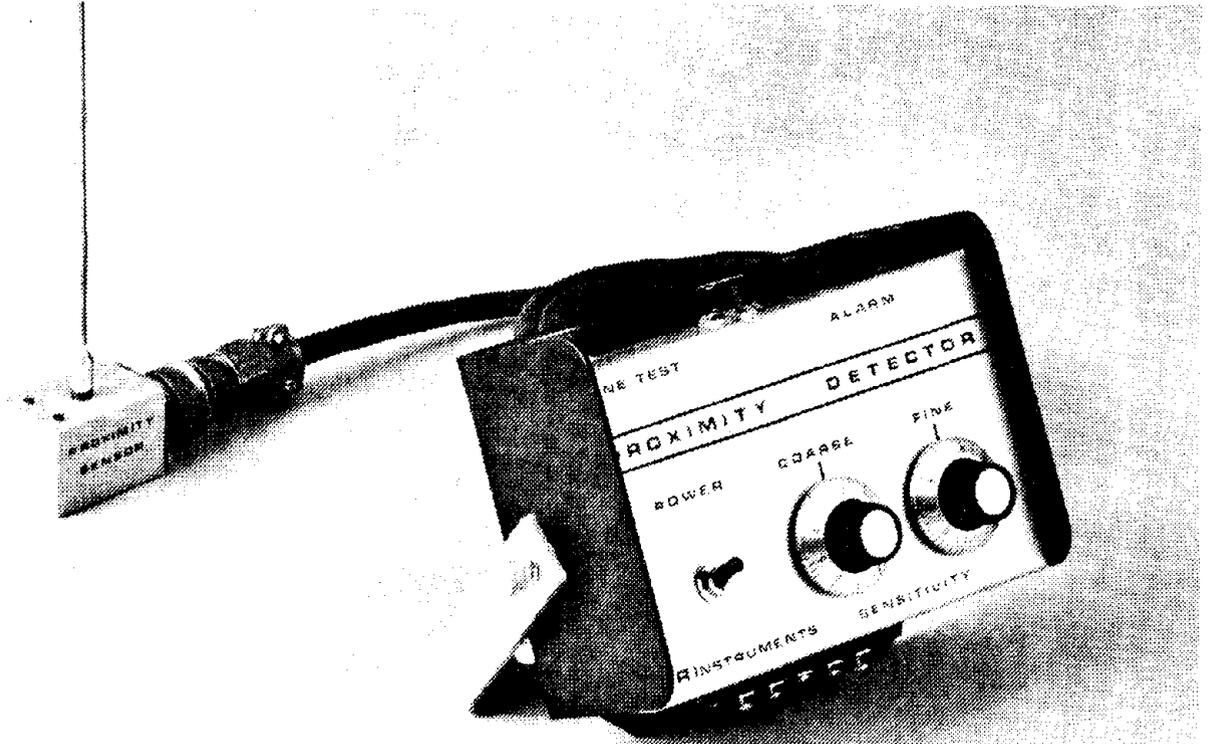
| <i>Volt Line</i> | <i>Approximate Operating Range (feet)</i> |
|------------------|-------------------------------------------|
| 110-115          | 18                                        |
| 12,000           | 200                                       |
| 69,000           | 470                                       |
| 110,000          | 550                                       |

*Howler:*

1. Db Rating: Adjustable from 0-97 Db.

2. Construction: Die cast aluminum housing. Exterior howler (optional) is sealed and weatherproof. Internal howler is non-weatherproof.





## PROXIMITY DETECTOR

Model PD 102

### Description

The S R Instrument Model PD 102 Proximity Detector is designed to detect AC electrostatic fields around power lines and provide audible and visual alarms to safeguard personnel and construction equipment. The unit employs a small sensor with short antenna that is mounted on a crane boom or other equipment whose proximity to power lines is to be monitored. This sensor is connected with a two wire cable to the control module located in the cab or other convenient position. The control module contains a green line test lamp that is lit whenever the cable to the sensor is connected and functioning properly. If the input cable is shorted or open, the line test lamp is extinguished. The sensitivity of the control module is adjusted with fine and coarse knobs to activate the alarm when the sensor is at the nearest position desired relative to power lines. Whenever the sensor is placed closer than this position, a flashing red lamp and pulsing audio tone is activated. This proximity may be adjusted from a few feet to several hundred feet for higher tension lines.

## Specifications

|                         |                 |                                                                                                                                                   |
|-------------------------|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| Range, adjustable       |                 | less than one foot to the following:<br>50 ft for 110 v line<br>300 ft for 12,000 v line<br>600 ft for 69,000 v line<br>750 ft for 110,000 v line |
| Alarms                  |                 | flashing red light, pulsing 2900 Hz tone                                                                                                          |
| Sensor Line Test        |                 | green lamp lights for proper operation<br>lamp extinguishes for shorted or open line                                                              |
| Sensitivity Adjustments |                 | coarse and fine controls                                                                                                                          |
| Power                   | Model PD 102-12 | 12 - 15 VDC .5 A max                                                                                                                              |
|                         | Model PD 102-24 | 24 - 28 VDC .5 A max                                                                                                                              |
| Size                    | Sensor          | 1.5 x 1 x 1" mounts with two #10 screws                                                                                                           |
|                         | Control Module  | 6.5 x 3 x 4" " " " ¼" screws                                                                                                                      |
| Temperature             |                 | -20 to +120° F                                                                                                                                    |

## PROXIMITY WARNING DEVICE RELATED PATENTS

| <u>Number</u> | <u>Title</u>                                                                | <u>Authors</u>                                   | <u>Date</u>      |
|---------------|-----------------------------------------------------------------------------|--------------------------------------------------|------------------|
| 2,615,969     | Electrical Power Line<br>Warning Device for Vehicles<br>with Extended Booms | A. H. Albrecht                                   | 10/28/52         |
| 2,789,282     | Automatic Approach Alarm                                                    | D. R. Winters                                    | 04/16/57         |
| 3,125,751     | Proximity Alarm                                                             | D. R. Winters                                    | 03/17/64         |
| 3,168,729     | Proximity Alarm                                                             | H.W. Volberg                                     | 02/02/65         |
| 3,201,775     | Voltage Proximity Detector                                                  | R. D. Pedersen                                   | 08/17/65         |
| 3,296,494     | Voltage Responsive Devices<br>and Methods of Voltage<br>Detection           | A. Stenger, Jr.                                  | 08/03/67         |
| 3,745,549     | Proximity Alarm                                                             | Richard M. Jepperson<br>C. Warren Simmonds       | 04/19/71 (filed) |
| 4,064,997     | Crane Swing Safety Control                                                  | Eugene Richard Holland<br>Melvin Glynn Schlieman | 12/27/77         |



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# A Practical Review of High Voltage Safety Devices for Mobile Cranes

George S. Allin, Jack T. Wilson, and  
Richard E. Zibolski  
Harnischfeger Corp.

## Society of Automotive Engineers

Off-Highway Vehicle Meeting  
& Exhibition  
MECCA, Milwaukee  
September 12-15, 1977

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# A Practical Review of High Voltage Safety Devices for Mobile Cranes

George S. Allin, Jack T. Wilson, and  
Richard E. Zibolski  
Harnischfeger Corp.

THE USE OF MOBILE CRANES has increased at a rate that parallels the growth of electric power distribution in the United States and the world. Distribution systems using poles and masts to support conductors crisscross both urban communities and rural areas while high voltage transmission lines supported on steel and wooden towers of diverse designs can be seen across the skylines everywhere. One result has been to increase the possibility of accidental contact between crane booms and overhead electrical conductors.

Manufacturers of mobile cranes are concerned with the increasing danger of accidents involving electrical contact with power lines.

This concern has led crane manufacturers to test high voltage safety devices offered by crane auxiliary equipment suppliers in an effort to evaluate their effectiveness in preventing accidents. These devices are designed to either serve as insulators or power line proximity warnings.

One device consists of a cage supported by electrical insulators and

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—ABSTRACT

This paper presents a discussion of insulators and power line proximity warning systems sold by suppliers of auxiliary equipment for use on mobile cranes. These devices are offered as a solution to the problem of crane booms, loads and load lines accidentally contacting electric power lines.

This discussion shows that insulator devices and electronic warning systems do not solve the problem of preventing these accidents.

The number of these accidents will only be reduced when those having administrative and supervisory responsibility of work projects near power lines recognize the hazard and take precautions before work is begun. Effective planning including consulting with power companies to determine precautions is the only dependable solution to the problem.

fitted to a crane boom so as to shield a limited area of the boom. We will call these "insulated boom cages".

Another method uses an electrical insulator or dielectric link inserted in the hoisting line just above the hook or other material grapppling device. These devices are designed to isolate the hook and load in the event the boom or hoist line of the crane comes in contact with a power line so that a person standing on the ground or grounded footing would not be subjected to electric shock should he touch the load. We will call these "insulator links".

A third type of high voltage safety device is an electronic apparatus consisting of an antenna attached to a crane boom and a control box in the operator's cab. This device is designed to give a warning whenever the crane comes within a certain distance of a power line. We shall call these "proximity warning devices".

#### THE INSULATED "BOOM CAGE AND INSULATOR LINKS

THE INSULATED BOOM CAGE - Figure 1 shows this device mounted on a crane for test purposes. It consists of a tubular steel cage provided with fiberglass standoff insulators. It is mounted on the tip of the boom and extends approximately 12 to 15 feet back along the boom pendant lines. The device tested was manufactured by the Saf-T-Boom Corp. of Little Rock, Arkansas and uses standoff electric insulators manufactured by the A. B. Chance Co. The standoff insulators are designed to prevent the charge from being carried from the cage to the crane if the cage makes contact with a power line.

INSULATOR LINKS - The device pictured in Figure 2 is an insulator link manufactured by the E. D. Bullard Co. of Sausalito, California. It consists of a cylindrical block of dielectric material with steel inserts anchored at each end. The cylindrical block is made up of multiple straps of fiberglass impregnated with insulating resins surrounding a core of insulating material. This construction is enclosed in a smooth cylinder which con-

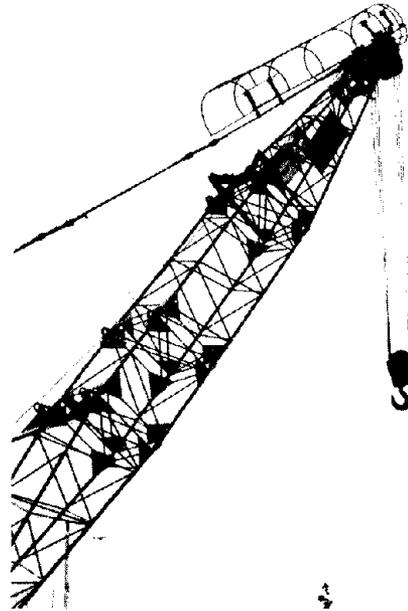


Fig. 1 - Insulated boom cage mounted on crane boom

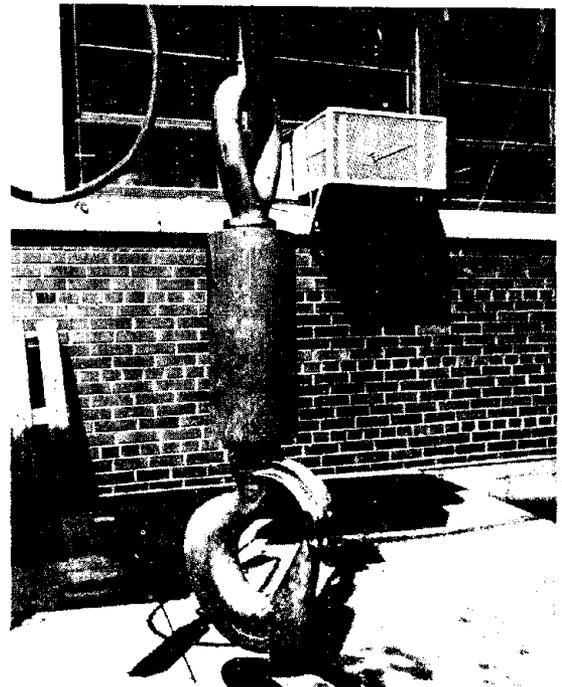


Fig. 2 - Insulator link of the type that places the insulator in tension

tains a solid fill of dielectric resins and fillers. The entire weight of any load carried on this type of hook is sustained by the arrangement of fiberglass and plastic materials. Although no tests were conducted to evaluate the potential hazard, these resins and glass constructions may rapidly age under field conditions resulting in a danger of the link fracturing.

The unit illustrated in Figure 3 is a Miller Swivel Insulated Hook manufactured by S.S.P. Construction Equipment Inc., Pomona, California. The construction of this insulated link includes multiple plates of steel attached to the shanks at each end in such manner that the insulating material is held in compression. In the event of breaking or cracking of the insulating material the metal plates are designed to fall into contact with each other and support the load. The breakage of the insulating material would, however, destroy the effectiveness of the electrical insulation.

All the above devices depend upon insulators to isolate the crane or load from electrical charges which would result from contact with power lines. Because the hazard of current traveling along the surfaces of such insulators is greater than the hazard of it going through the dielectric material, the problem any electrical insulator has performing in a high voltage field is that its performance is absolutely dependent on the surface condition of the insulator. When the surface of an insulator is perfectly clean or has been thoroughly cleaned under laboratory conditions the performance characteristics will prove to be considerably different than they will when the surface has been soiled under typical construction site handling and storage conditions. It is important to note, however, that during electrical testing of the link pictured in Figure 2 current paths were established through the insulator as well as on the surface.

To determine the electrical performance of a clean insulator link, the unit pictured in Figure 3 was taken into the laboratory and placed in a large

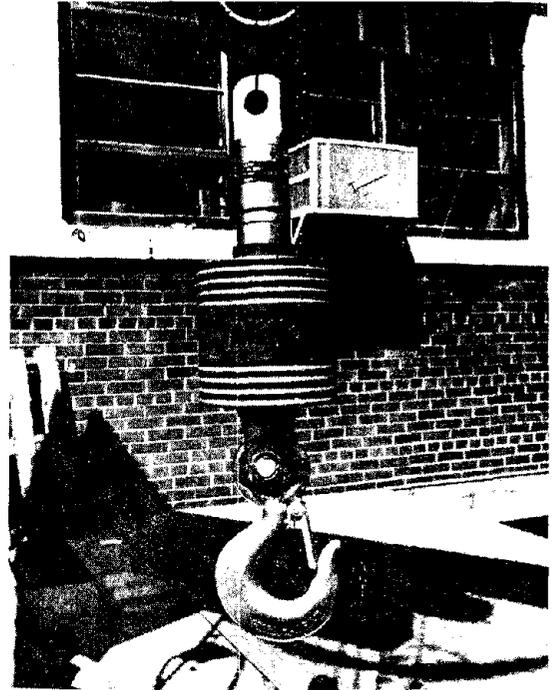


Fig. 3 - Insulator link of the type that places the insulator in compression

sink. Tap water at a temperature of 120° was flowed across the molded rubber insulated section and, after the surface had become thoroughly moistened and warmed, a small quantity of laboratory cleaner was applied with a medium soft bristle brush. This removed all traces of residual oils and greases and produced a clean surface after rinsing. The hook was then suspended for one hour to permit it to dry.

A hook cleaned and dried in this manner performs well even up to 50,000 volts, the maximum voltages for which it is specified. If the hook is contaminated, however, the quality of its performance will be greatly different. In order to be a practical test the hook should carry the amount of surface contamination which would be the result of normal handling in a contractor's plant and in his operations.

To determine how to treat the surface of an insulator to simulate two or more weeks of exposure in a contractor's yard, the following experimental procedures were tried.

The insulator link was placed on the ground in an area where materials

handling trucks are continuously present. Residual salt in the soil is one type of contaminant which readily affects the insulator's surface condition. A garden hose was used to spray tap water on the soil near the hook and the link was allowed to dry carrying whatever residual of spattered soil produced by this treatment. The link was then taken to the laboratory and measured for dielectric strength. It was shown that the salt and other ionizable contaminant produced a conducting surface which caused spark-over at a voltage of 22,000 volts.

When the insulator link was thoroughly cleaned with the laboratory washing powder as described above and tested the dielectric strength had been restored.

The following steps were taken in the second method of testing surface conditions on the insulator:

1. Dust the clean hook with fine clay collected from an area adjacent to a roadway or truck path.
2. Wipe off all excess dust with a shop rag which has been spotted with ordinary crank-case lubricating oil.
3. Dust again with the fine clay.
4. Roll the insulator on bare ground typical of shop and yard areas.
5. Apply a light spray of tap water with a spray bottle.
6. Allow the hook to dry in air and rub the hook gently with clean shop rags to remove apparent traces of contaminants before testing.

The above method seems to be a practical means of duplicating those conditions which may exist with normal storage in a contractor's shop or storage sheds. A hook tested under these conditions broke down electrically at voltages between 16,000 and 33,000 volts.

Testing of insulators from insulated boom cages and insulator links has shown that an accumulation of dust and yard dirt reduces the insulating properties of the safety device to alarmingly low values. Further laboratory tests have shown the accumulation of street salt used in winter to thaw ice and snow will seriously degrade the insulation surface to the point where tracking will be produced across

the insulator surface when exposed to an electrical potential of between 5,000 to 7,000 volts, 60 cycle AC for a period of three minutes.

Current levels were kept low for these tests to avoid unnecessary damage to the insulators and equipment. The electric arcs observed across the soiled insulator surfaces would be capable, however, of sustaining electrical currents of many hundreds of amperes with consequent destruction of not only the insulators but other objects in the electrical circuit. This type of electrical spark-over is one of the greatest hazards associated with the use of any type of the insulator link or standoff insulator block.

#### PROXIMITY WARNING DEVICES

Proximity warning devices of various brand names have been marketed in the United States, Canada and England. They are all similar in that they are electronic devices designed to sense the presence of an electrical charge on a conductor.

The system used in the following field test summary was the Sigalarm Proximity Warning Device marketed by Bower Industries of Orange, California. It includes a control box containing the circuitry connected through terminal blocks to a 12 volt D.C. power supply, the antenna sensor cable and external warning devices.

The controls include coarse and fine adjustment dials, a battery switch and a red signal light which is used as a warning flasher and in circuit performance testing. The control panel also provides a test switch, an alarm switch and a test button to check the operating condition of the signal lamp. The sensor cable is an insulated two-wire electrical conductor strung along the boom and terminating at the tip with an extended section approximately 18 inches long.

This particular device is claimed to be sensitive to electrostatic fields or the voltage gradient between an electrical conductor and the ground or nearest object at an electrical potential different from that of the electrical conductor. Studies of the

circuitry and operating characteristics reveal that the device actually operates as a broad band low frequency radio receiver with a high gain amplifier coupled with a signal pulsing output network.

The impedance of the electrical circuitry has been designed to respond to frequencies ranging from about 50 cycles per second up to and including 480 cycles per second. A system of tuned electrical filters and capacitors is used in the circuit to filter out radio frequencies.

The magnitude of the radiation field into which the sensor cable is exposed along with the adjustment of the sensitivity controls will determine the rate at which the warning light flashes. The triggering threshold produces an intermittent flashing with slow rhythm. As the field strength increases the flashing sequence becomes more rapid. A signal horn is sounded with each flash of the lamp.

Figure 4 shows a crane equipped with a proximity warning device for the test procedures. The outriggers have been extended and the chassis of the crane elevated so that the weight of the machine is no longer supported by the rubber tires. The antenna assembly is mounted on the crane boom as illustrated in Figure 5. The antenna wire terminates in a bracket at the boom tip with a section of the antenna allowed to dangle. A small rubber ball weight at the end of the antenna holds the 18 inch length in approximately a vertical position independent of boom angle.

Figure 6 illustrates the view the crane operator has of the power lines used in the tests. A field lighting transformer is shown on one of the poles. Floodlighting for the parking lot and street lighting fixtures are also shown. The power line assembly is made up of six conductors at the top level supported by crossarms consisting of two sets of 3-phase lines carrying 13,000 volts, 60 cycles A.C., one set on each side of the supporting pole. A crossarm below the six lines supports a 3-phase group carrying 4 kilovolts. Below the 3-wire system



Fig. 4 - Mobile crane equipped with proximity warning device in position for field demonstrations

a crossarm supports the single-phase conductors for a street lighting circuit. A 120/240 volt, single-phase group of conductors is carried below the lighting circuit conductors. A large telephone cable is located below that assembly. The lowest assembly on the poles consists of 240 volt, 3-phase line assembly.

TEST NO. 1 - The first demonstration used the cement truck and concrete bucket shown in Figures 7 and 8. The crane picked up the bucket and then was positioned so the boom was parallel to and a distance of 30 feet from the power lines. The sensitivity adjustment was set so that if the boom was swung toward the power line the signal would trigger when the tip of the boom was 10 feet from the line.

The concrete truck was driven in the lane between the crane and the power line. When the truck was alongside of the crane, the signal stopped sounding. When the boom was moved closer to the power line with the concrete truck remaining stationary, the signal did not trigger until the sen-

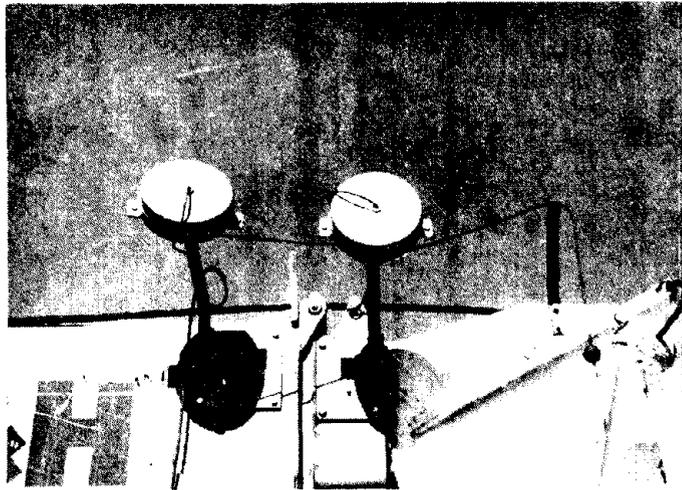


Fig. 5 - Proximity warning device  
antenna and take-up reels mounted on  
crane boom

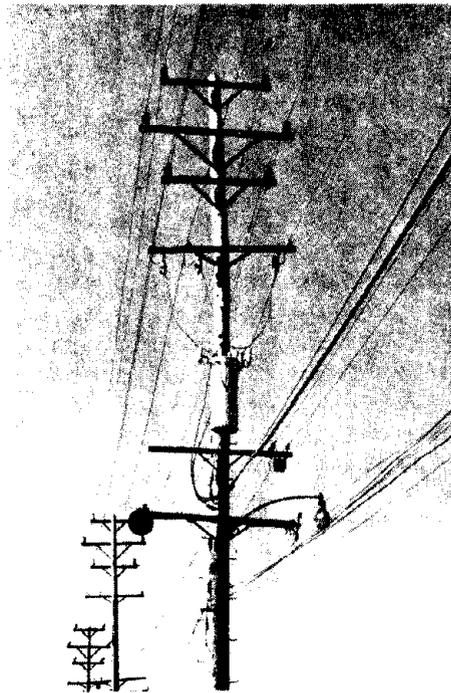


Fig. 6 - Power lines used during  
field demonstrations

sitivity adjustment was advanced to  
the maximum setting.

The boom was swung away from the  
power line to a position parallel with  
the power line and the concrete truck  
driven slowly forward. At several

different positions the alarm would  
begin to sound even though the crane  
boom position was not moved. At other  
positions the alarm would stop sound-  
ing. This test shows that the position  
of a large vehicle between a power line  
and a proximity device may greatly in-  
fluence the response characteristics  
of the detector.

TEST NO. 2 - The second demonstra-  
tion involved the truck shown in Figure  
9 and a bundle of aluminum pipe approx-  
imately 18 feet long which was suspended  
from the crane hook as shown in Figure  
10. A cord was tied to one end of the  
bundle so that it could be swung to any  
azimuth position under the hook. The  
axis of the pipe was adjusted to coin-  
cide with that of the boom with the  
pipe approximately 10 feet off the  
ground. The alarm sensitivity adjust-  
ment was made to trigger slowly at  
this position.

When the axis of the pipe was  
swung through 90 degrees, the alarm  
triggered more rapidly. The trigger-  
ing frequency could be modified from  
slow to fast by adjusting the azimuth  
position of the pipe bundle.

The scrap metal truck was driven  
in the lane between the crane and the  
power line while the pipe was held  
with its axis coinciding with the boom.  
At several different positions of the  
scrap truck the sensitivity of the

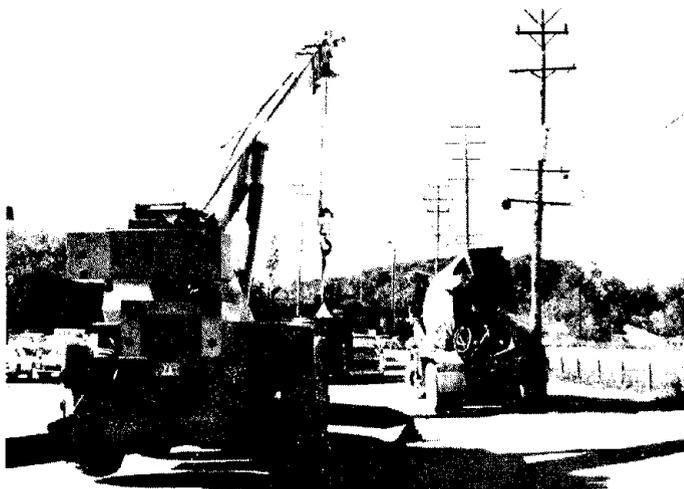


Fig. 7 - Cement truck between power lines and crane lifting cement bucket

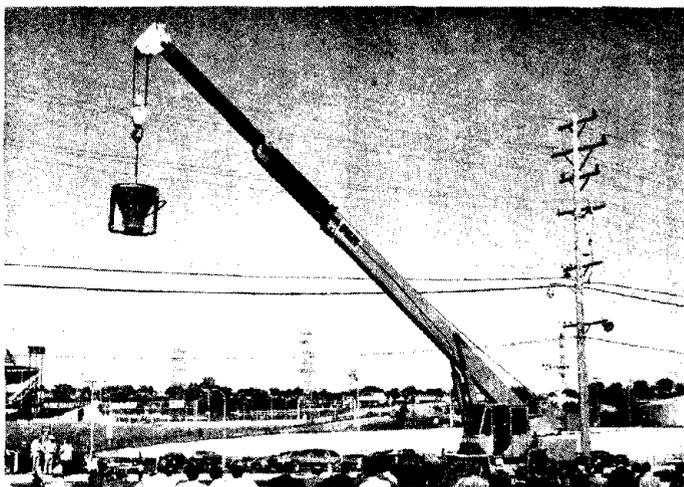


Fig. 8 - Crane lifting cement bucket

detector was greatly diminished, and at one position, the truck could remain stationary and the indicator signal could be triggered or extinguished by changing the angle of the pipe axis.

When the boom angle was elevated and the proximity indicator antenna came into the stronger field of the upper conductors, the position of the truck and the pipe axis had less effect on the sensitivity of the detector.

This test shows that the sensitivity of the detector is affected by the configuration of metallic objects in the vicinity of the crane and that the device requires continued read-

justment of sensitivity if the signals from the detector are to be trusted.

TEST NO. 3 - For the following series of demonstrations the boom sections were extended and the boom angle raised to approximately 45 degrees. At this position the boom tip was at about the same plane as the middle wire of the top group of 3-phase conductors. The sensitivity was adjusted so that the detector flashed slowly when the tip of the boom was about 25 feet from the middle conductor of the top most group.

When the boom was returned to a low angle, the sensitivity of the detector was no longer effective in



Fig. 9 - Material hauling truck used  
in demonstrations

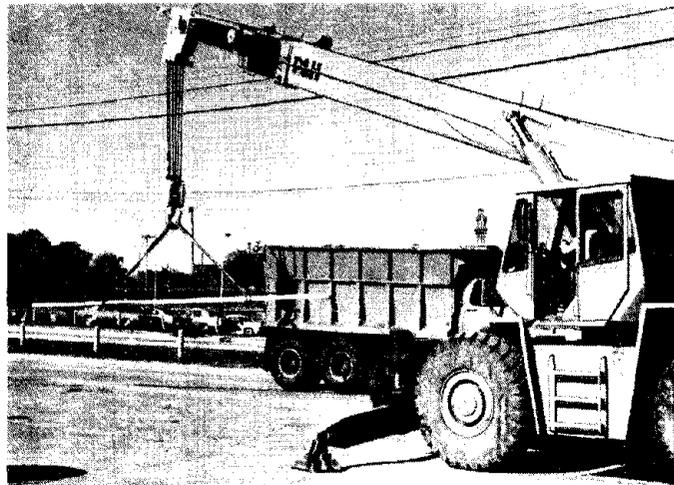


Fig. 10 - Truck between power lines  
and crane lifting pipe bundle

triggering the signal even when the boom was swung within three feet of the lower group of power lines.

It was also observed that the sensitivity of the device was diminished appreciably by the capacitance of the boom when the boom approached the power line with the boom between the antenna and the power line.

TEST NO. 4 - The upper structure of the crane was rotated so the tip of the boom was approximately 10 feet from the nearest power line of the lower group. The controls were adjusted to a slow rate of signal response. The operator then rotated

the boom away from the power lines. As the boom tip moved away from the power lines, the frequency of the detector signal increased and reached a peak when the boom was parallel to the wires. As the boom moved through a large arc the signal frequency diminished and finally stopped altogether. The boom was moved slowly through a full half circle and as it approached the line again the signal became frequent, reached a peak, and, as the boom approached the power lines, diminished.

This observation shows that the array of power conductors precisely

determines the regions where partial cancellation of induced electrical field will occur. For each different configuration, there will be totally different zones of diminished or cancelled induced fields.

TEST NO. 5 - Positioning the boom directly under the power lines revealed some very curious behavior of the proximity warning device. Figure 11 shows the boom directly under and approximately perpendicular to the power lines. When the boom tip was positioned so that the centerline of the power conductors bisected the antenna section supported above the boom by the reel brackets the signal halted. The boom was elevated to within 6 inches of the lowest power lines and the detector device gave no signal even when the sensitivity adjustment was at the highest possible level.

These regions of cancellation are well understood by power distribution engineers. Telephone cables are purposely placed in these regions of cancellation in order to minimize undesirable signals on the telephone system. (A discussion on this subject is presented in Chapter 19 in the ELECTRICAL TRANSMISSION AND DISTRIBUTION REFERENCE BOOK published by the Westinghouse Electric & Manufacturing Company.)

It is important to point out that regions of partial signal cancellation

can be very confusing to the proximity device user. Only the most advanced techniques of analysis of electrical potential gradients would make it possible to plot the highly complex induced electrical force field distribution in the area of a crane and a typical multi-conductor power line. A crane operator could not determine the hazards of depending upon signal triggering as a means for safe guidance in the operation of his crane unless he had carefully plotted regions of field strength in his working area.

TEST NO. 6 - The final demonstration illustrates the behavior of the proximity indicator when the crane is used to transport materials in yard operations.

Figure 12 shows the crane with the concrete bucket lifted, the crane boom parallel to the lines and the outriggers of the crane chassis lifted. The proximity indicator was adjusted so that when the tip of the crane boom was four or five feet from the line the proximity device responded with a rapid signal.

The crane was moved so that the center of the crane chassis was perpendicular to the power lines and approximately 90 feet from their midline. The crane boom was elevated as shown in Figure 13. At this position, the telescoping boom was ex-

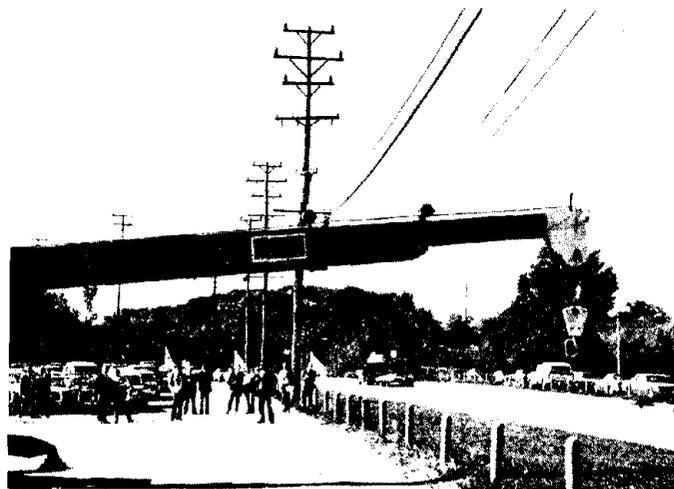


Fig. 11 - Crane boom extended beneath power lines

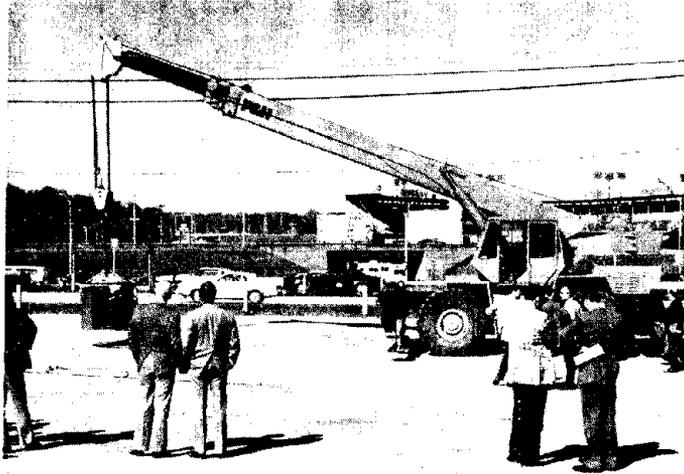


Fig. 12 - Crane with outriggers raised and lifting cement bucket

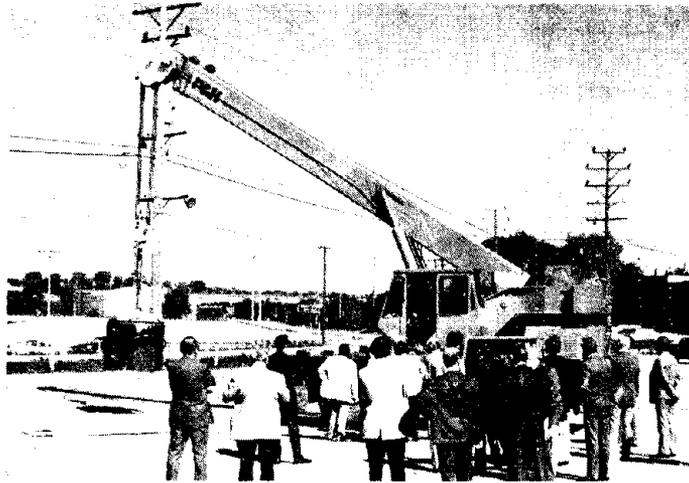


Fig. 13 - Crane driving toward power lines with suspended cement bucket

tended until a slow signal of the proximity warning device sounded.

The angle of boom elevation was increased and the crane was driven toward the power line. When the steel cable supporting the hook came within approximately 20 feet of the power line, the warning signal sounded.

The crane was moved back away from the lines, the warning signal stopped sounding and the boom angle was lowered. Without changing the sensitivity adjustment of the warning device, the crane was moved toward the lines with the boom tip approaching the lower conductors. The warning device did

not sound even though the boom tip came within 30 inches of the lowest conductors.

This demonstration again illustrates that unless the sensitivity controls of the proximity device are readjusted whenever boom angle or the orientation of the crane chassis is changed the crane boom can be dangerously close to power lines without triggering the warning signal.

In order to understand the performance of the proximity warning device it is important to study the behavior of an electric charge in a conductor and to observe what proper-

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ties of a charge may manifest themselves in the area surrounding a conductor.

Most conductors carry alternating current in which the electrical polarity changes 60 times per second. Any such conductor acts as a broadcast antenna transmitting at 60 cycles. It is almost impossible to design and build a dependable proximity warning device because it is very difficult to discriminate between the energy produced by a power line and the random frequencies which are broadcast by many sources. Urban communities and even rural areas are flooded by radio broadcasts and standing waves of broadcast patterns which may confuse any proximity warning device giving it all manner of false triggerings. Sixty cycle signals and signals ranging through 50 cycles up to several hundreds cycles are found in great abundance in areas of construction.

Some years ago gasoline engines in all types of vehicles used DC generators for battery and ignition systems. In modern equipment, however, the DC generator has been replaced with alternator systems which produce radiation signals of variable frequency ranging in value through the region most sensitive to the proximity warning device.

A proximity warning device depends upon an electrostatic or an electromagnetic field of force surrounding power transmission lines. Unfortunately, the distribution of this energy does not occur as a uniform gradient in most cases. Rather, a complex pattern of energy distribution will result from the effect of nearby objects which may be electrical conductors at ground potential or may exhibit large electrical capacitances.

Much research has been completed during the past few years which examines the theory and the actual measurement of electrical gradients surrounding power lines. The computation of voltage gradients at ground level below power transmission lines has been published in great detail. Chapter 8 of the TRANSMISSION LINE REFERENCE

BOOK, sponsored by the Electrical Research Council of the Electric Power Research Institute contains a full discussion of this subject. An important presentation of theory and actual measurement has been submitted for publication in the Transactions of IEEE as paper Code F 76 180-0. This paper, authored by Dr. Don W. Deno, is entitled TRANSMISSION LINE FIELDS.

The above papers concern ultra high voltage power transmission lines in which the space factors and voltage gradients are much larger than would be commonly encountered around moderate voltage power transmission and distribution lines. The techniques of field strength measurement are, however, of great importance to our considerations in this report.

The literature treats extensively the space between the electrical conductor and ground. Since crane booms would normally approach a power line from the side, any study of the problem of detecting the approach of a crane boom to power lines must also carefully consider the field distribution in the areas above and to the side of the conductor.

The electrical field surrounding both single-phase and poly-phase power transmission lines can be predicted. The analysis, however, requires computer technology making the construction of an energy field chart at any given crane operating area totally impractical.

Field strength measuring instruments have been used to compare proximity warning device responses to instrument measurements in an effort to both predict and explain some of the erratic performance of the proximity warning device. Unfortunately, crane operators and their crews have neither the time nor the skills to make instrument measurements on the field strength of electrostatic potentials in the crane working area before beginning a job. Such measurements would require the services of specially trained electronics experts.

#### DISCUSSION

Up to this point we have discussed some of the practical problems

involved in the use of safety devices designed to either insulate workers from power lines or to signal the dangerous proximity of a crane boom to power lines. We will now examine some accepted administrative safeguards designed to completely avoid the hazard of working close to energized power lines.

The prime contractor must accept overall responsibility for work site operating procedures including job-site safety. The construction foreman and the crane operator also have a responsibility to take every possible safeguard to avoid accidental contact with electrical conductors. As soon as a construction site has been chosen it is the responsibility of the contractor to determine the location of all overhead electric power lines and other utilities which may offer a hazard. It is necessary to inspect the work site for the presence of power lines which may not have been shown on the charts or diagrams used in planning the operation. When power lines are present, the means of safeguarding against accidental contact must be carefully planned taking into consideration all national and state laws which govern and control the distances a boom, load cables, or other types of tools may approach electrical conductors.

The local power company must be consulted whenever an operation is planned near power line and must be informed of the nature of the job and the proposed dates for carrying out the work. Planning and coordinating the work with the power company is perhaps the single most important safeguard to be taken by those responsible for crane operations in the vicinity of power lines.

Power companies are anxious to avoid any danger that may be associated with the use of electric power. When informed of an intended operation near power lines, they are eager to assist in planning the job and selecting the safest location for cranes and other equipment. They will supply diagrams designating the clearance requirements specified both by law

as well as by their policies and offer additional safety information concerning work done in the vicinity of electrical conductors.

Many jobs require that the power be cut off from lines in the vicinity. The decision to do this will rest with the power company. In many instances, however, the power company can reroute the power and thus permit a section of the line to be deactivated and grounded. In other instances it is possible to disconnect the power and ground the line for short periods of time. The power company's engineers may choose to use insulating sleeves to cover the electrical conductors in those regions which might accidentally be contacted by booms or load hoisting lines.

The nature of the electric power line itself and the voltages which are carried in the conductors as well as the type of crane work to be performed will determine the specific precautions that should be taken.

#### CONCLUSION

We have briefly described the observed operating characteristics of insulated boom cages, insulator links and proximity warning devices. Mobile crane manufacturers will continue to evaluate these accessories to determine if they contribute to the overall safe use of cranes. At the present time the limitations of these devices are such that they clearly cannot be recommended for general usage.

The boom cage offers no protection for the load lifting cable and only limited coverage of the boom tip. An even greater limit to the dependable performance of this type of device is the hazard of dirt accumulations on the standoff insulators.

The greatest risk in using insulator links is the very real hazard of electrically conductive contaminants accumulating on the surface of the insulator blocks which will produce flashover at typical power line voltages. The mechanical safety of a hook which relies upon resins and fiber-

glass structures to carry loads is also questionable.

In addition to the serious problem of insulator breakdown through surface contamination there are other hazards associated with insulator links because they will only isolate that portion of the load which is carried by the hook or grappling device. In the event of an accidental contact with a power line the steel cable which suspends the load above the insulator would become charged and so would the entire structure of the crane including its mobile carriage. Should a person accidentally contact the carriage or any part of the crane or the load line above the insulator while standing on a grounded surface the insulator link would give no protection against the danger of electrocution.

The electrical proximity warning device does not reliably detect power lines in typical power distribution systems consisting of multiple conductors. All manner of geometric arrays of power lines intersecting at all angles can be found in abundance in modern power line systems. The variety of power line configurations coupled with the movement of trucks, materials and the crane itself tend to confuse or cancel the sensitivity of the detector.

All of these devices tend to give crane operators and working personnel a false sense of confidence in their protection against exposure to electrocution. Such unfounded confidence may cause serious accidents or electrocutions to construction workers which could have been avoided through proper safety procedures providing for strict avoidance of power lines.

Our examination of mechanical insulator devices and electronic warning systems has shown that they do not solve the problem of preventing electrical accidents. The most effective solution to the problem lies in the proper execution of the administrative and supervisory responsibility of a work project. Planning the position of a mobile crane so that no part of it or its load suspending cable can possibly touch an electrical conductor is clearly the safest practice. When close proximity to a power line is unavoidable it is essential that strict safety procedures be developed with the assistance of the power company. If possible, power lines in the area should be disconnected and grounded. No other safety practice is as effective. When human life is at stake the extra effort necessary to take these precautions is mandatory.

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Informational Report 1035

# Field Evaluation of a Proximity Alarm Device

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UNITED STATES DEPARTMENT OF THE INTERIOR  
Thomas S. Kleppe, Secretary

Mining Enforcement and Safety Administration  
Robert E. Barrett, Administrator

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# FIELD EVALUATION OF A PROXIMITY ALARM DEVICE

by

Richard L. Reynolds<sup>1</sup>

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## ABSTRACT

This report examines the use of a proximity warning device on a crane boom to provide a warning when the boom approaches a predetermined safe distance from an energized powerline. The purpose of this study was to determine the sensitivity and ruggedness of the device under field operating conditions.

## INTRODUCTION

In the past, industry as a whole and the mining industry in particular have been faced with the hazard of bare high voltage lines in the vicinity of work areas. These lines were not a hazard until a crane or similar type of equipment containing a boom or mast was brought into the work area. In spite of the efforts of the equipment operators, the boom or masts of their equipment, on occasion, would strike the overhead lines. In the past 2 years the mining industry has experienced four electrocutions from such accidents.

Because of these electrocutions MESA's Coal Mine Health and Safety requested Technical Support to evaluate a proximity alarm device which could give a warning and thus prevent such accidents.

The proximity alarm device, which was evaluated, is known as "Sigalarm."<sup>2</sup> The purpose of the evaluation was to determine--

1. If the device would operate properly in the mining environment for an extended period of time, and
2. If it needed any design changes to produce the margin of safety necessary to prevent future electrocutions resulting from contact of equipment with high voltage lines.

---

<sup>1</sup>Chief, Mine Electrical Systems Group.

<sup>2</sup>Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding and does not imply endorsement by the Mining Enforcement and Safety Administration.

### ACKNOWLEDGMENTS

The assistance of Fred Williams and Lemoyne Morris of Coal Mine Health and Safety, District 8, in conducting this evaluation is greatly appreciated. Thanks are also due to Mr. Henry Gilham of Consolidation Coal Company for providing the crane and manpower for the device installation, and to Mr. Eldon Heither of Heither Associates, Incorporated, for providing the proximity alarm device.

### FIELD TESTS

On October 25, 1973, a "Sigalarm" system was installed on a Bucyrus Erie Hydrocrane for evaluation. The crane was located at the Electric Shop of the Central Division of Consolidation Coal Company. The following people were present during the installation and tests:

#### Consolidation Coal Company

Henry Gilham  
Tom Russiello  
Sam Hartley  
Ivan Coleman

#### Heither Associates, Inc.

Sam Midkiff

#### Bower Industries, Inc.

Arthur C. Gregr

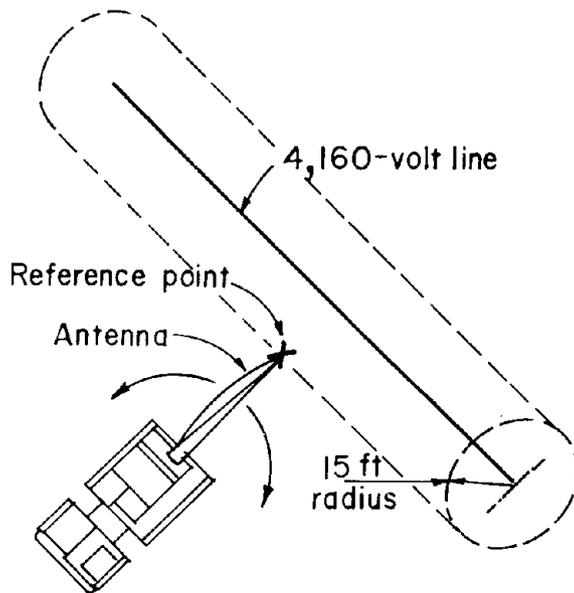
#### MESA

|                  |                                     |
|------------------|-------------------------------------|
| John Greenhalgh  | Coal Mine Health and Safety         |
| Roy Jones        | Coal Mine Health and Safety         |
| Fred Williams    | Coal Mine Health and Safety         |
| Richard Reynolds | Pittsburgh Technical Support Center |

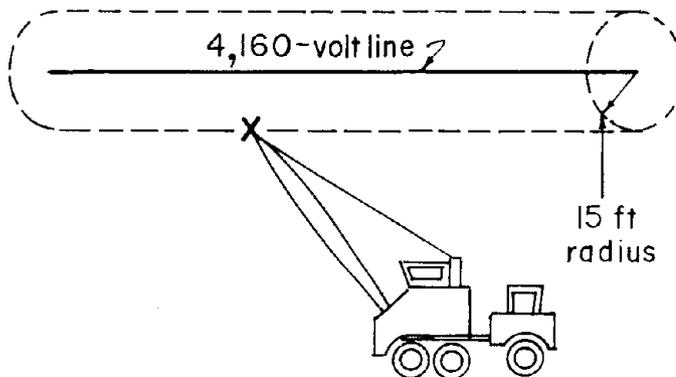
The following tests were conducted to determine the sensitivity of the device under simulated working conditions (see appendix I).

#### Radial Swing Test

After the initial installation of the "Sigalarm," the crane was positioned approximately 50 feet away from a 4,160 volt distribution line, which was about 25 feet above the ground. The sensitivity was set to detect the high voltage line when the boom was at a reference point approximately 15 feet from the line. The boom was then swung clockwise and counterclockwise from the reference position (see figure 1, Radial Swing Test).



RADIAL SWING TEST  
(Boom below but not under line)  
FIGURE 1. - Radial swing test.



VERTICAL LIFTING TEST  
(Boom under line)  
FIGURE 2. - Vertical lifting test.

This test was performed to determine the ability of the warning device to repeat its signal within a reasonable distance from the reference point. It was found that while swinging the boom from either direction toward the reference point, the device would produce a warning when within 1 foot of the reference point.

#### Vertical Lifting Test

With the boom of the crane at the same reference point as in the radial test, the boom was lowered and raised vertically. In this test the alarm produced a warning within 1 foot of the reference point. (See figure 2, Vertical Lifting Test.)

In this test, it was noted that, although the antenna for the detection circuit was along the crane boom, the boom did not appreciably shield the antenna from the electrostatic field of the energized lines during the test.

#### Boom Extension Test

The crane on which the "Sigalarm" was installed had an extendable boom (see appendix II). As the boom was extended the antenna became longer and changed the sensitivity setting of the device. Therefore, a test was designed to detect the effect of setting the sensitivity with the boom extended and then operating the crane with the boom contracted. For this test the boom was extended in a parallel position to a 66 kv line which was approximately 120 feet away, as shown in figure 3.

At this point, the sensitivity of the device was set so that a warning was barely detectable. Next the boom was contracted and swung toward the lines until a warning was again detectable as in figure 4.

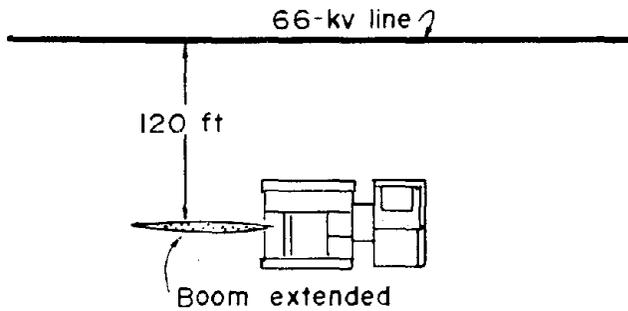


FIGURE 3. - Boom extension test, extended.

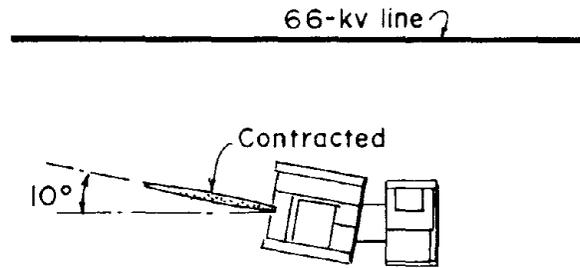


FIGURE 4. - Boom extension test, contracted.

The results of this type of test can be very illusive depending on the percentage of change in antenna length as the boom is extended and contracted. In the test described, the boom was moved through a 10° arc toward the lines before a warning was given. This situation has the inherent good feature that the boom is always shorter when the sensitivity is reduced. However, the operator should be cautioned to always reset the sensitivity when the boom length is changed.

Multiple Lines Test

It is not unusual to find several powerlines on the property where a crane may be working. Therefore, for this test the crane was positioned between two powerlines which were approximately 150 feet apart, as shown in figure 5.

In this situation, it was found that the device could not practically be adjusted to detect the 110 v line. This was because the electric field of the 66 kv was much larger than the field of the 110 v line at the chosen position in the crane work area. Because of this, extra caution should be exercised in using the devices between two powerlines.

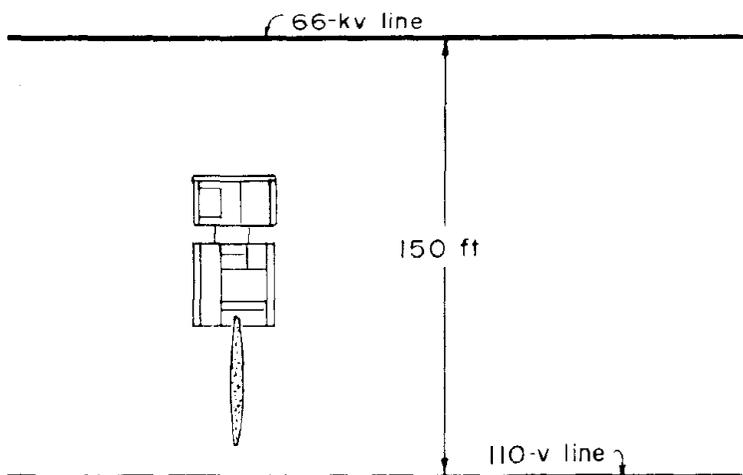


FIGURE 5. - Multiple lines test.

OBSERVATIONS

The following observations were made during installation and field tests:

1. By placing the antenna along the boom and spacing it approximately 8 inches above the boom structure, there is no appreciable shielding of the antenna by the boom.

2. The device gave consistent results during the test. It produced a

warning within 1 foot of the set point regardless of the direction of boom movement as was demonstrated in the vertical and radial tests.

3. The device did hold up under vibration and varying weather conditions to which it was submitted.

4. It was accepted favorably by the two crane operators at the mine.

5. The operator of a crane with an extendable boom should be aware that the device is less sensitive when the boom is not extended.

6. When the crane is operated between two powerlines, that are transmitting at different voltage levels, it is possible that the device could be keying on the higher voltage line when the more immediate hazard is the lower voltage line.

#### CONCLUSIONS

When this particular device is used on an extendable boom the crane operator must adjust its sensitivity and be very familiar with its limitations before he begins to rely on it for warnings. In no case should the device be used to indicate when the boom is actually in a dangerous position, that is, 1 foot from a 66 kv line. The device should be used to warn the operator when the boom of the crane penetrates the safe limits as set forth in the Title 30, Code of Federal Regulations, Section 77.907-2 (see appendix III).

The following are some desirable design changes which would improve the device's operation:

1. The device should be energized automatically when the crane is readied for operation.

2. The device should automatically set itself for maximum sensitivity when it is energized. This would necessitate the operator adjusting it for proper operation and prevent him from forgetting to make the adjustment.

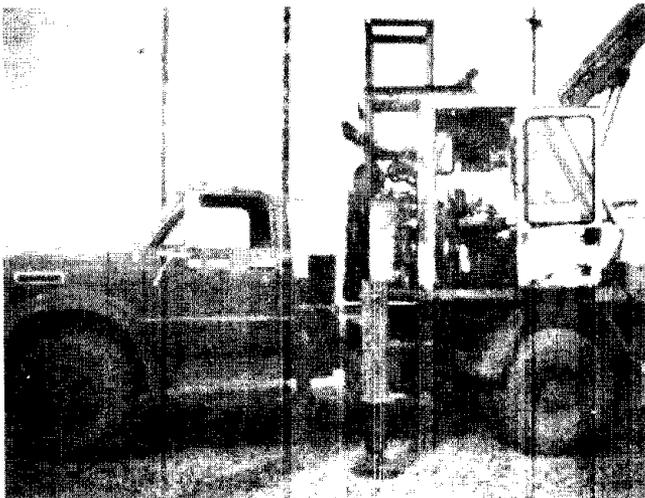
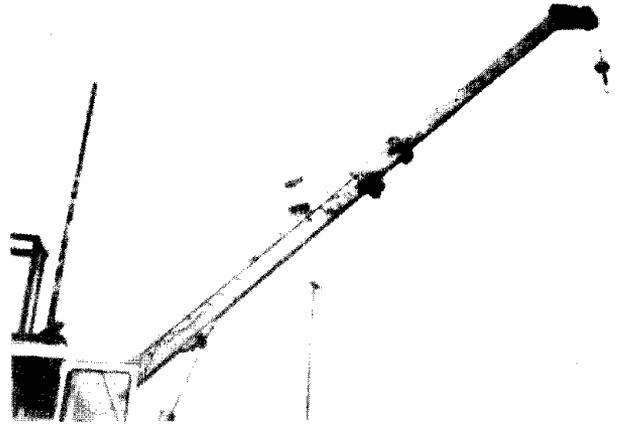
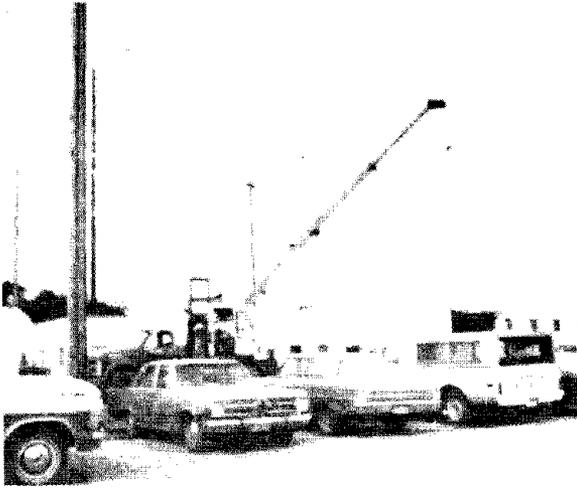
Field tests for a period of 6 months demonstrated that the device is rugged enough for mine use and that it does, indeed, operate with very good reliability. If installed on equipment with masts and booms, it will alert the operators of such equipment to the hazards of overhead lines and has the potential to prevent contact electrocutions and save lives in the future.

It also has the capability of automatically stopping a machine function such as boom swing, boom elevate, and boom extend if the operator fails to heed the audible warning.

APPENDIX I

| Test                       | Powerline voltage | Distance to powerline from reference point | Number of trials |
|----------------------------|-------------------|--------------------------------------------|------------------|
| Radial swing test.....     | 4,160 v           | 15 feet                                    | 4                |
| Vertical lifting test..... | 4,160             | 15 feet                                    | 4                |
| Boom extension test.....   | 66 kv             | 120 feet                                   | 3                |
| Multiple lines test.....   | 66 kv             | 145 feet                                   | 4                |
|                            | 110 v             | 10 feet                                    | 4                |

APPENDIX II



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## APPENDIX III

## 77.807-2 Booms and masts; minimum distance from high-voltage lines.

The booms and masts of equipment operated on the surface of any coal mine shall not be operated within 10 feet of an energized overhead powerline. Where the voltage of overhead powerlines is 69,000 volts, or more, the minimum distance from the boom or mast shall be as follows:

| <u>Nominal powerline voltage (in 1,000 volts)</u> | <u>Minimum distance<br/>(feet)</u> |
|---------------------------------------------------|------------------------------------|
| 69-114.....                                       | 12                                 |
| 115-229.....                                      | 15                                 |
| 230-344.....                                      | 20                                 |
| 345-499.....                                      | 25                                 |
| 500 or more.....                                  | 35                                 |

## APPENDIX B

FORTRAN LISTING OF COMPUTER PROGRAM COMPONENT

```

C      PROGRAM COMPONENT COMPUTES LOCII OF CONSTANT ELECTRIC FIELD
C      STRENGTH COMPONENTS
C      IN SPECIFIED DIRECTIONS.  BASED ON EQUATION 2 PHASE I REPORT
REAL K ;EQUIVALENT AMPLITUDE OF RELATIVE ELECTRIC FIELD
      ;STRENGTH COMPONENT
ACCEPT 'R(IN)',RIN ;WIRE RADIUS(IN)
RFT = RIN/12. ;WIRE RADIUS(FT)
ACCEPT 'D',D ;1/2 WIRE SEPARATION(FT)
A = SQRT(D**2 - RFT**2)
ACCEPT 'K',K ;K MUST BE DETERMINED BY TRIAL AND ERROR TO
      ;INSURE THAT THE LOCUS
C      PASSES THROUGH A POINT 10 FT TO THE LEFT(I.E. XR=-10) OF THE
C      NEAREST WIRE.
ACCEPT 'ELEVATION ANGLE', ELEV
WRITE(12,900)RIN,D,K,ELEV ;DOCUMENT INPUT PARAMETERS ON
      ;OUTPUT LISTING
900  FORMAT(1X,F6.3,F7.1,F7.0,F7.0)
      THETA = ELEV/57.29578
      COSTH = COS(THETA)
      SINTH = SIN(THETA)
      DO 20 XR = -20,0,1 ;ITERATE XR(THE X COORDINATE RELATIVE
      ;TO NEAR WIRE) FROM -20 FT TO 0 FT
      X = XR - D ;X COORDINATE RELATIVE TO TRANSMISSION LINE CENTER
      Y = -20.01 ;INITIALIZE Y FOR REFERENCE CALCULATION
      B = ((X-A)**2 + Y**2)*((X+A)**2 + Y**2) ;DENOMINATOR OF EQ(2)
      ;IN PHASE(I) REPORT
      CX = K*(X**2 - A**2 - Y**2) ;NUMERATOR FOR X COMPONENT
      CY = K*X*Y ;NUMERATOR FOR Y COMPONENT
      EL = B - CX*COSTH - CY*SINTH ;INITIAL "LAST" VALUE OF QUANTITY
      ;WHICH MUST BE ZERO ON CONTOUR
C
      DO 10 Y = -20,20,.01 ;SWEEP Y FROM 20 FT BELOW WIRES TO 20 FT
      ;ABOVE WIRES
      B = ((X-A)**2 + Y**2)*((X+A)**2 + Y**2)
      CX = K*(X**2 - A**2 - Y**2)
      CY = K*X*Y
      E = B - CX*COSTH - CY*SINTH ;CURRENT VALUE OF QUANTITY WHICH
      ;MUST BE ZERO ON CONTOUR
      IF(EL*E.LT.0.)WRITE(12,9) XR,Y ;THE RESULTING OUTPUT COORDINATE
      ;IS WITHIN 0.01 FT OF THE CONTOUR
9      FORMAT(1X,2F7.3)
      EL = E ;THE CURRENT VALUE E WILL BE USED AS THE LAST VALUE "EL"
      ;IN THE NEXT ITERATION
10     CONTINUE
20     CONTINUE
      END
)

```

## APPENDIX C

FORTRAN LISTING OF COMPUTER PROGRAM MULTI

```

C      PROGRAM MULTI COMPUTES EFIELD COMPONENTS FOR MULTI-CIRCUIT,
C      MULTI-PHASE POWER LINE SYSTEM.  CIRCUITS MUST BE PARALLEL.
      COMPLEX P,EX,EY,V,Q
      EQUIVALENCE (Q,V)

      DIMENSION XW(12),YW(12),RW(12),KV(12),V(12),Q(12),P(78),EXV(14)
      DIMENSION EYV(14),DEG(12)
      REAL KV
C      ENTER THE LINE DESCRIPTION
      ACCEPT "NUMBER OF CONDUCTORS: ",N
      DO 10 I=1,N
      TYPE "CONDUCTOR :",I
      ACCEPT "WIRE DIAMETER ",D
      RW(I)=(D/2)*2.54/100
      ACCEPT "COORDINATES (X,Y) IN FEET ",XFT,YFT
      ACCEPT "VOLTAGE AND PHASE (KV,DEG) ",KV(I),DEG(I)
      XW(I)=XFT*.3048 ;CONVERT COORDINATES FROM FEET TO METERS
      YW(I)=YFT*.3048 ;CONVERT COORDINATES FROM FEET TO METERS
      VOLTS=KV(I)*1000 ;CONVERT FROM KILOVOLTS TO VOLTS
      CALL CONV(VOLTS,DEG(I),V(I))
10     CONTINUE
C
      CALL MATRIX(XW,YW,RW,N,P) ;CALCULATE THE ELEMENTS OF THE
C      P MATRIX AND STORE IN A SINGLE DIMENSION REPRESENTATION OF
C      DIMENSION MATRIX
      CALL SQROT(P,V,0,1,N) ;RECIPROCATATE THE MATRIX EQUATION V=PQ
      ;TO SOLVE FOR THE INDIVIDUAL LINE
      ;CHARGES PER UNIT LENGTH
C
      WRITE HEADER FOR PRINTOUT
      WRITE(12,20)
20     FORMAT(2X,"LINE DESCRIPTION">//8X,"X",8X,"Y",8X,"KV",8X,"PHASE",
1      8X,"RADIUS"/)
      DO 50 I=1,N
      WRITE(12,45) XW(I)/.3048,YW(I)/.3048,KV(I),DEG(I),RW(I)/.0254
45     FORMAT(1X,2(4X,F6.2),2(4X,I4),10X,F5.3)
50     CONTINUE
C      ENTER THE HORIZONTAL AND VERTICAL LIMITS BETWEEN WHICH
C      ELECTROSTATIC FIELDS ARE TO BE CALCULATED.
      ACCEPT "HORIZONTAL LIMITS (LEFT,RIGHT) ",XLF,XRF
      ACCEPT "VERTICAL LIMITS (UPPER,LOWER)",YUF,YLF
      SX = (XRF-XLF)/13 ;X INCREMENT
      SY = (YUF-YUF)/13 ;Y INCREMENT
C
      TYPE "X INCREMENT:",SX
      TYPE "Y INCREMENT:",SY
      TYPE "LEFT LIMIT : ",XLF
      TYPE "RIGHT LIMIT : ",XRF
      TYPE "UPPER LIMIT : ",YUF
      TYPE "LOWER LIMIT : ",YLF
C
C      WRITE HEADER
      WRITE(12,9)(T,T=XLF,XRF,SX)
9      FORMAT (//T50,"EH(V/M)"/T52,"EV(V/M)"/
1      2X," X",14(F5.1,1H',3X)/
2      " Y")
C
C

```

```
C
C   ITERATE THE OBSERVATION COORDINATES(X,Y) AND CALCULATE TOTAL E-FIELD.
DO 200 YFT = YUF,YLF,SY ;INCREMENT Y

Y = 0.3048*YFT ;CONVERT TO METERS
I = 0
DO 100 XFT = XLF,XRF,SX ;INCREMENT X

I = I+1
X = 0.3048*XFT ;CONVERT TO METERS.
CALL EFIELD(Q,XW,YW,N,X,Y,EX,EY) ;CALCULATE E-FIELD
EXV(I) = CABS(EX)
EYV(I) = CABS(EY)
100 CONTINUE
C
C
WRITE(12,900)EXV,EYV,YFT
900 FORMAT(1H0,14(1X,18)/2X,14(1X,18)/1X,F5.1,1H')
C
200 CONTINUE
STOP
END

)
```

```
      SUBROUTINE CONV(V,PH,VO)
C
C      SUBROUTINE TO CONVERT VOLTAGE AMP AND PHASE TO
C      VOLTAGE PHASOR
C
C      INPUTS :
C      V - VOLTAGE AMPLITUDE
C      PH - PHASE IN DEGREES
C
C      OUTPUTS -
C      VO - VOLTAGE PHASOR
C
C      COMPLEX J,VO
C
C      PHR = PH / 57.29577951
C      J = CMPLX(0.,1.)
C
C      VO = V * CEXP(J * PHR)
C
C      RETURN
C      END
)
```

```

C      SUBROUTINE MATRIX CALCULATES THE ELEMENTS OF THE P MATRIX AND
C      STORES THE ELEMENTS IN AN EQUIVALENT REPRESENTATION OF A TWO
C      DIMENSIONAL MATRIX
      SUBROUTINE MATRIX(XW,YW,RW,N,P)
      COMPLEX P(78)          ;SINGLE DIMENSION VERSION OF P MATRIX
      DIMENSION XW(1),YW(1) ; (X,Y) COORDINATES OF EACH WIRE
      DIMENSION RW(1) ;RADIUS OF EACH WIRE
      DATA EPS0,PI/8.854E-12,3.14159265/
      IF(N.GT.12)STOP N.GT.12 ;PREVENT ARRAY OVERFLOW

      DO 100 I = 1,N
      DO 100 J = I,N
      RNIJ = SQRT((XW(I) - XW(J))**2 + (YW(I) - YW(J))**2) ;DISTANCE
C      BETWEEN I 'TH AND J 'TH WIRE
      RDIJ = SQRT((XW(I) - XW(J))**2 + (YW(I) + YW(J))**2) ;DISTANCE
C      BETWEEN I 'TH AND J 'TH IMAGE
      IF(RNIJ.EQ.0.)RNIJ = RW(I) ;SELF TERM
      PIJ = ALOG(RNIJ/RDIJ)/(2.*PI*EPS0) ; I,J ELEMENT OF MATRIX
C      EQUATION V=PQ
      K = (I-1)*N - (I*I - I)/2 + J
      P(K) = PIJ ;STORE IN 1-D MATRIX
100    CONTINUE
      RETURN
      END
)

```

```

C   SUBROUTINE SQROT   THIS SUBROUTINE CONSIDERS THE MATRIX EQUATION
C   ZI=V WHICH REPRESENTS A SYSTEM OF SIMULTANEOUS LINEAR EQUATIONS.
C   THE SQUARE MATRIX Z IS ASSUMED SYMMETRIC.  SUBROUTINE SQROT WAS
C   DEVELOPED BY PROFESSOR J. H. RICHMOND OF OHIO STATE UNIVERSITY AS
C   PART OF CONTRACT NGL-008-138 FOR NASA.
      SUBROUTINE SQROT(C,S,IWR,I12,NEQ)
      COMPLEX C(1),S(1),SS
2     FORMAT(1X,1I5,1F10.3,1F15.7,1F10.0,2F15.6)
3     FORMAT(1H0)
      N=NEQ
      IF(I12.EQ.2)GO TO 20
      C(1)=CSQRT(C(1))
      DO 4 K=2,N
4     C(K)=C(K)/C(1)
      DO 10 I=2,N
      IMO=I-1
      IPO=I+1
      ID=(I-1)*N-(I*I-I)/2
      II=ID+I
      DO 5 L=1,IMO
      LI=(L-1)*N-(L*L-L)/2+I
5     C(II)=C(II)-C(LI)*C(LI)
      C(II)=CSQRT(C(II))
      IF(IPO.GT.N)GO TO 10
      DO 8 J=IPO,N
      IJ=ID+J
      DO 6 M=1,IMO
      MD=(M-1)*N-(M*M-M)/2
      MI=MD+I
      MJ=MD+J
6     C(IJ)=C(IJ)-C(MJ)*C(MI)
8     C(IJ)=C(IJ)/C(II)
10    CONTINUE
20    S(1)=S(1)/C(1)
      DO 30 I=2,N
      IMO=I-1
      DO 25 L=1,IMO
      LI=(L-1)*N-(L*L-L)/2+I
25    S(I)=S(I)-C(LI)*S(L)
      II=(I-1)*N-(I*I-I)/2+I
30    S(I)=S(I)/C(II)
      NN=((N+1)*N)/2
      S(N)=S(N)/C(NN)
      NNO=N-1
      DO 40 I=1,NNO
      K=N-I
      KPO=K+1
      KD=(K-1)*N-(K*K-K)/2
      DO 35 L=KPO,N
      KL=KD+L
35    S(K)=S(K)-C(KL)*S(L)
      KK=KD+K
40    S(K)=S(K)/C(KK)
      IF(IWR.LE.0) GO TO 100
      CNOR=.0
      DO 50 I=1,N
      SA=CABS(S(I))
50    IF(SA.GT.CNOR)CNOR=SA
      IF(CNOR.LE.0.)CNOR=1.
      DO 60 I=1,N

```

```
SS=S(I)
SA=CABS(SS)
SNOR=SA/CNDR
PH=.0
IF(SA.GT.0.)PH=57.29578*ATAN2(AIMAG(SS),REAL(SS))
SSR=REAL(SS)
SSI=AIMAG(SS)
60 WRITE(6,2)I,SNOR,SA,PH,SSR,SSI
WRITE(6,3)
100 RETURN
END
```

)

```

C      SUBROUTINE EFIELD CALCULATES TOTAL PHASOR ELECTRIC FIELD COMPONENTS
C      AT (X,Y) RESULTING FROM N LINE CHARGES LOCATED AT (XW,YW) AND HAVING
C      Q(I) COLUMBS PER UNIT LENGTH
      SUBROUTINE EFIELD(Q,XW,YW,N,X,Y,EX,EY)
      COMPLEX EX,EY ;X Y COMPONENTS OF ELECTRIC FIELD VECTOR
      COMPLEX Q ;PHASOR CHARGE PER UNIT LENGTH
      DIMENSION Q(1),XW(1),YW(1)
      DATA EPS0,PI/8.854E-12,3.14159265/

      EX = 0
      EY = 0
      DO 100 I = 1,N
      DENA = (X-XW(I))**2 + (Y-YW(I))**2 ;SQUARE OF DISTANCE TO ACTUAL LINE
      DENI = (X-XW(I))**2 + (Y+YW(I))**2 ;SQUARE OF DISTANCE TO IMAGE LINE
      EX = EX + Q(I)*((X-XW(I))/DENA - (X-XW(I))/DENI) ;ADD CONTRIBUTION
C      OF I 'TH ACTUAL AND IMAGE LINES TO X COMPONENT OF ELECTRIC FIELD VECTOR
      EY = EY + Q(I)*((Y-YW(I))/DENA - (Y+YW(I))/DENI) ;ADD CONTRIBUTION
C      OF J 'TH ACTUAL AND IMAGE LINES TO Y COMPONENT OF ELECTRIC FIELD VECTOR
100 CONTINUE
      EX = EX/(2.*PI*EPS0) ;MKS UNITS CORRECTION
      EY = EY/(2.*PI*EPS0)
      RETURN
      END

```

)

APPENDIX D

ENVIRONMENTAL TEST DETAILS

## ENVIRONMENTAL TEST DETAILS

Pretest performance and test chamber operations checks were conducted prior to commencing with actual tests. These checks were conducted to establish a working standard to be used for comparisons throughout the remaining environmental testing. These tests (and/or checks) were performed at ambient conditions with the standards established as shown in Table D-1.

The response of the devices was tested during various stages of the environmental tests by injecting a test signal directly into the probe input port of each device. As shown in Figure D-1, the injection signal was a 60 Hz signal, amplitude modulated by a triangular wave. For each device, the peak amplitude of the injection signal was adjusted to be about twice the alarm threshold signal for ambient conditions. This form of injection signal provided a quick indication of device sensitivity fluctuations, since the total on-time of the alarm signal would increase for increased device sensitivity. The parameters labeled "unit on/time" in the following tables provide a measure of the sensitivity variation, and vary from zero to nine seconds. A value of zero on-time indicates that the device sensitivity has decreased to the extent that even the peak injection signal produces no response. A value of nine seconds on-time indicates that the device sensitivity has increased to the extent that the minimum resolvable amplitude of injection signal produces alarms.

### 1.0 Low Temperature Tests

The low temperature test was conducted on all systems simultaneously in a Model TR4D-100240 test chamber (Mfgr: Tenney Engineering, Inc.). The low temperature test limits were set at  $-60^{\circ}\text{F}$  for two hours and  $-30^{\circ}\text{F}$  for two hours. Each system was operated at  $-30^{\circ}\text{F}$  and test data recorded. The systems and chamber were allowed to return to ambient and test data again recorded. The equipment was visually inspected for deterioration and corrosion. The results are tabulated in Table D-2.

The no response of the Electro-Alarm system was attributed to a seizure of the dynamotor assembly.

### 2.0 High Temperature Test

The high temperature test was conducted on all systems simultaneously in the above mentioned test chamber. The test chamber was programmed to provide  $120^{\circ}\text{F}$  for three hours, elevate to  $160^{\circ}\text{F}$  for four hours, and finally lower to  $120^{\circ}\text{F}$  for one hour. Test data was sampled at the end of the one hour  $120^{\circ}\text{F}$  cycle. The systems and test chamber were allowed to cool to  $80^{\circ}\text{F}$  ambient and test data again recorded. The high temperature tests were repeated until three full cycles were completed. The results are tabulated in Table D-3.

TABLE D-1  
EQUIPMENT STANDARDS

| <u>Unit</u>    | <u>Unit On/Time<br/>(Seconds)</u> | <u>Total Cycle Time<br/>(Seconds)</u> |
|----------------|-----------------------------------|---------------------------------------|
| SR Instruments | 4                                 | 9                                     |
| Electro-Alarm  | 4                                 | 9                                     |
| Sigalarm       | 4                                 | 9                                     |

Strip chart recorder set at 2 mm/second.

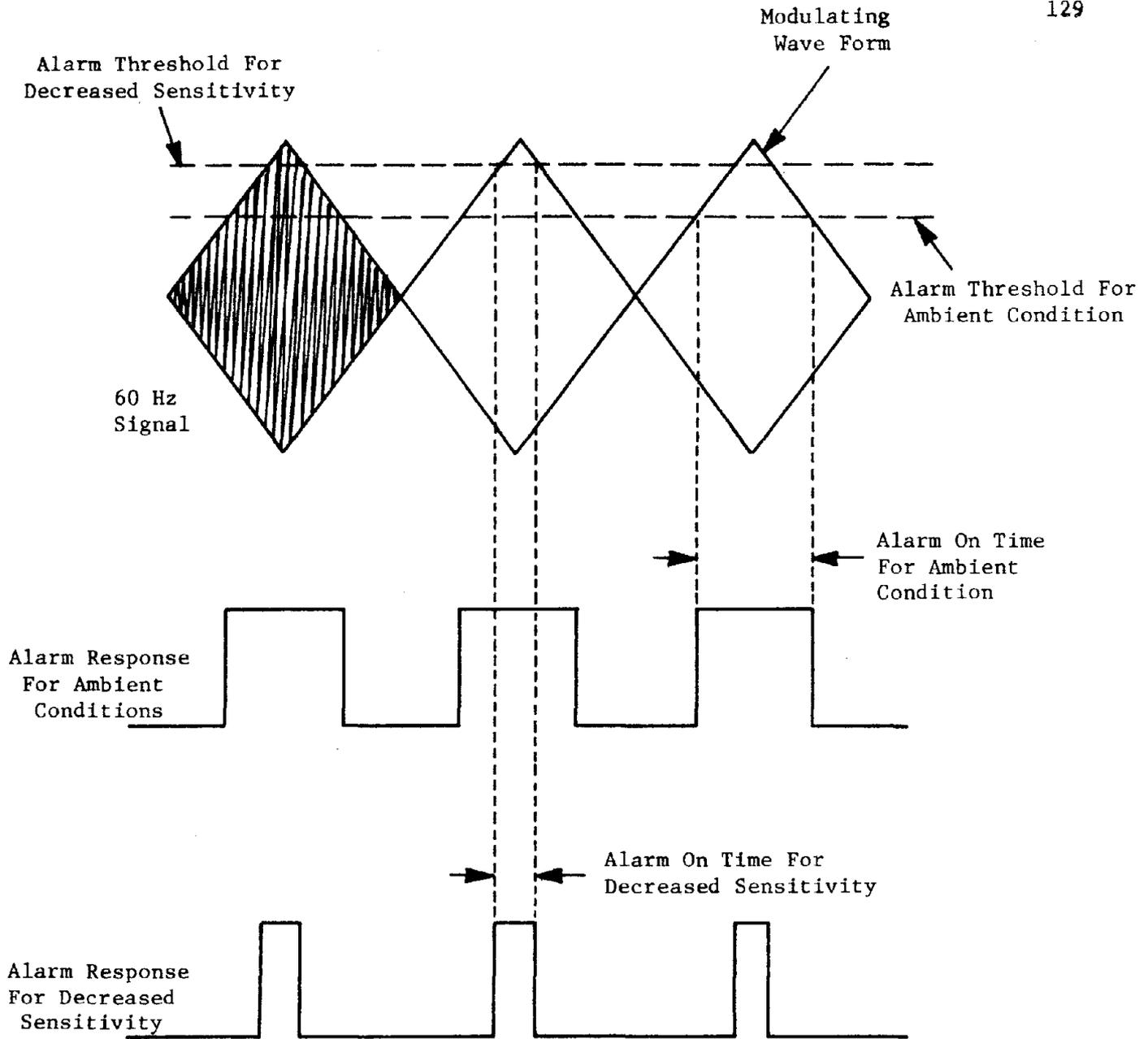


FIGURE D-1

INJECTION SIGNAL DURING ENVIRONMENTAL TESTS

TABLE D-2  
LOW TEMPERATURE

| <u>Unit</u>    | <u>Unit On/Time<br/>(Seconds)</u> | <u>Total Cycle Time<br/>(Seconds)</u> |
|----------------|-----------------------------------|---------------------------------------|
| SR Instruments |                                   |                                       |
| Pretest Cal    | 2                                 | 9                                     |
| -30°F          | 8                                 | 9                                     |
| 80°F Ambient   | 3                                 | 9                                     |
| Electro-Alarm  |                                   |                                       |
| Pretest Cal    | 4                                 | 9                                     |
| -30°F          | No response                       | -                                     |
| 80°F Ambient   | No response                       | -                                     |
| Sigalarm       |                                   |                                       |
| Pretest Cal    | 3                                 | 9                                     |
| -30°F          | 7.5                               | 9                                     |
| 80°F Ambient   | 3                                 | 9                                     |

Strip chart recorder set at 2 mm/second.

All systems showed absence of any deterioration or corrosion.

TABLE D-3  
HIGH TEMPERATURE

| <u>Unit</u>     | <u>Unit On/Time<br/>(Seconds)</u> | <u>Total Cycle Time<br/>(Seconds)</u> |
|-----------------|-----------------------------------|---------------------------------------|
| SR Instruments  |                                   |                                       |
| Pretest Cal     | 4                                 | 9                                     |
| 120°F 1st Cycle | No response                       | -                                     |
| 80°F Ambient    | 3                                 | 9                                     |
| 120°F 2nd Cycle | No response                       | -                                     |
| 80°F 3rd Cycle  | 2                                 | 9                                     |
| 120°F 3rd Cycle | No response                       | -                                     |
| Test Concluded  | *                                 | -                                     |
| Electro-Alarm   |                                   |                                       |
| Pretest Cal     | 5                                 | 9                                     |
| 120°F 1st Cycle | 4                                 | 9                                     |
| 80°F Ambient    | 4                                 | 9                                     |
| 120°F 2nd Cycle | 4                                 | 9                                     |
| 80°F Ambient    | 3.5                               | 9                                     |
| 120°F 3rd Cycle | 4                                 | 9                                     |
| Test Concluded  | -                                 | -                                     |
| Sigalarm        |                                   |                                       |
| Pretest Cal     | 3.5                               | 9                                     |
| 120°F 1st Cycle | 3.5                               | 9                                     |
| 80°F Ambient    | 3                                 | 9                                     |
| 120°F 2nd Cycle | 3.5                               | 9                                     |
| 80°F Ambient    | 3                                 | 9                                     |
| 120°F 3rd Cycle | 3.5                               | 9                                     |
| Test Concluded  | -                                 | -                                     |

Strip chart recorder set a 2 mm/second.

\*Third ambient cycle terminated for the following:

SR Instruments stops responding to the injection signal at approximately 85°F at 2 seconds On/Time with cycle time remaining at 9 seconds. SR Instruments unit begins to return on cool down to ambient at approximately 80°F at 1 second On/Time with cycle time of 9 seconds.

### 3.0 Humidity Test

The humidity tests were conducted on all equipment simultaneously in the above mentioned test chamber over five continuous 24-hour cycles. The test chamber was programmed for 95% relative humidity, cycling from 150°F within two hours and continuing on 150°F for additional 16 hours to a decrease in temperature to 80°F within 7 hours and maintaining 80°F for four hours more. Test data was taken at the end of each prolonged 16-hour 150°F segment. The results are tabulated in Table D-4.

### 4.0 Humidity Test Post Inspection

The test items were inspected at the conclusion of the humidity test and the following corrosion noted:

#### (1) SR Instruments

- (a) Corrosion on the on-off switch lever (external).
- (b) Corrosion on mounting nuts (external).
- (c) Corrosion on terminal block screws (external).
- (d) Corrosion on cover fasteners (external).
- (e) Minor corrosion on electrical terminal (internal).

#### (2) Electro-Alarm

- (a) Corrosion on high/low switch handle (external).
- (b) Corrosion on light bezel (external).
- (c) Corrosion on surface of main enclosure and sensor box (external).
- (d) Corrosion on interconnect cable plugs (external).
- (e) No corrosion found on internal inspection.

#### (3) Sigalarm

- (a) Corrosion on the on-off switch lever (external).
- (b) Corrosion test switch mounting nut (external).
- (c) Corrosion on terminal block screws (external).
- (d) No corrosion found on internal inspection.

All corrosion observed did not adversely alter the performance of any system or subsystem thereof.

### 5.0 Vibration Test

The vibration test consisted of dynamically vibrating all systems in the X, Y, and Z axis. The test was controlled at a constant displacement from 7 to 200 Hz. A constant acceleration of 1.5 g was maintained.

There were no failures noted during the vibration test and all systems responded when placed in an operational mode.

TABLE D-4

## HUMIDITY

| <u>Unit</u>           | <u>Unit On/Time<br/>(Seconds)</u> | <u>Total Cycle Time<br/>(Seconds)</u> |
|-----------------------|-----------------------------------|---------------------------------------|
| <u>SR Instruments</u> |                                   |                                       |
| Pretest cal           | 4                                 | 9                                     |
| Cycle 1               | No response                       | -                                     |
| Cycle 2*              | No response                       | -                                     |
| Cycle 3               | No response                       | -                                     |
| Cycle 4               | No response                       | -                                     |
| Cycle 5               | No response                       | -                                     |
| 80°F Ambient          | 3                                 | 10                                    |
| <u>Electro-Alarm</u>  |                                   |                                       |
| Pretest Cal           | 5                                 | 9                                     |
| Cycle 1               | 5                                 | 9                                     |
| Cycle 2               | 4                                 | 9                                     |
| Cycle 3               | 4                                 | 9                                     |
| Cycle 4               | 4                                 | 9                                     |
| Cycle 5               | 4                                 | 9                                     |
| 80°F Ambient          | 5                                 | 10                                    |
| <u>Sigalarm</u>       |                                   |                                       |
| Pretest Cal           | 3                                 | 9                                     |
| Cycle 1               | 3                                 | 9                                     |
| Cycle 2               | 3                                 | 9                                     |
| Cycle 3               | 3                                 | 9                                     |
| Cycle 4               | 3                                 | 9                                     |
| Cycle 5               | 3                                 | 9                                     |
| 80°F Ambient          | 4                                 | 10                                    |

Strip chart recorder set at 2 mm/second.

\*Special test conducted on SR Instruments:

|              |             |            |       |
|--------------|-------------|------------|-------|
| 80°F On Time | 3 Sec       | Cycle Time | 9 Sec |
| 85°F         | 2 Sec       |            | 9 Sec |
| 90°F         | 1 Sec       |            | 9 Sec |
| 93°F         | No response |            |       |

## 6.0 Dripproof Test

Dripproof test was conducted on all systems using spray nozzle device and garden hose. The water pressure at the nozzle device was approximately 35 psig. Each system was subjected to a water spray for a five minute duration simulating a moderate rain storm.

The dripproof test results are as follows:

### (1) SR Instruments

- (a) Water collected in Sonalert device (horn).
- (b) Moisture present internally on the printed wiring assembly.
- (c) Interconnect cable plugs showed evidence of slight wetting.

### (2) Electro-Alarm

- (a) Sensor device enclosure showed evidence of water leakage. Gaskets were in place at the time of test.

### (3) Sigalarm

- (a) No evidence of moisture internally.

All systems responded when placed in operational mode.

## 7.0 Shock Test

Each system was subjected to a drop from a height of 48" onto a two-inch thick plywood pallet backed by a concrete floor. All major surfaces were tested and the damage listed below:

### (1) SR Instruments

- (a) Four sheet metal screws came out of the back panel.
- (b) Mount bracket warping upon impact.

### (2) Electro-Alarm

- (a) Standoff sleeves on back panel assembly (internal) deformed on impact.
- (b) Two sealed relays came loose from the receptacle causing pins to bend and center guide to break.
- (c) Vacuum tube 12V6 broken.
- (d) Dynamotor came loose from shock mounts. Probable cause for major damage internally.
- (e) Two unidentified relays sheared from their receptacles.
- (f) Sensitivity knob and pot broken.
- (g) Lamps and lenses broke on impact.
- (h) Enclosure bent and warped.

(3) Sigalarm

- (a) Terminal strip broken.
- (b) Damage to enclosure (corner dent).
- (c) Printed wiring cable torn with an open in wiring.

All systems were subjected to an operational check after being dropped. Results are as follows:

(1) SR Instruments

- (a) System was energized and the units responded with the appropriate audio and visual functions.

(2) Electro-Alarm

- (a) Damage was so extensive that this unit was deemed inoperable.
- (b) After major repairs, the unit was energized but some electronic components still failed to respond properly.

(3) Sigalarm

- (a) System was energized and the units responded with the appropriate audio and visual functions. Test circuitry was inoperable.