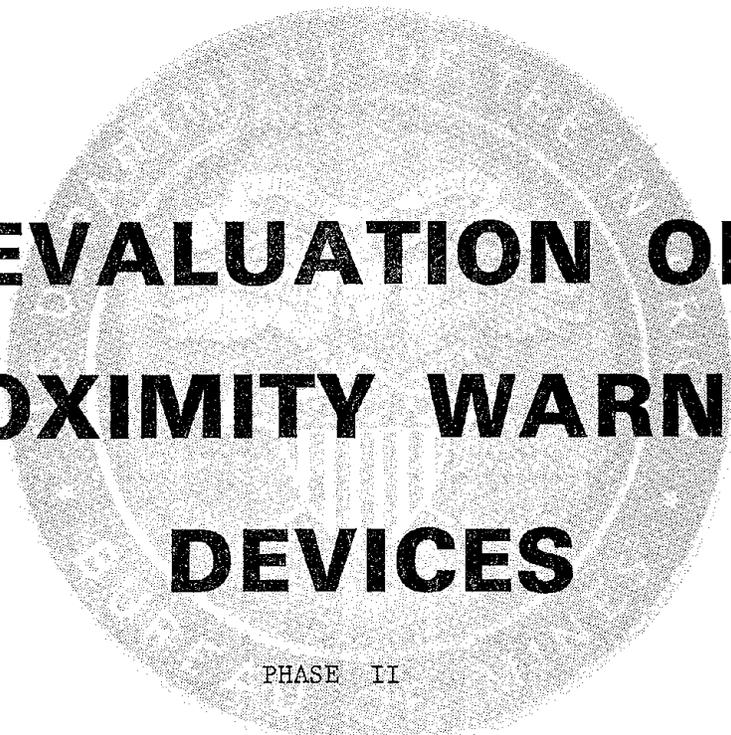


A minerals research contract report
February 1981



**EVALUATION OF
PROXIMITY WARNING
DEVICES**

PHASE II

Bureau of Mines Open File Report 112-81

Contract J0188082
Southwest Research Institute

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of the interior Department's Bureau of Mines or of the U. S. Government.

REPORT DOCUMENTATION PAGE	1. REPORT NO. BuMines OFR 112-81	2.	3. Recipient's Accession No.								
4. Title and Subtitle Evaluation of Proximity Warning Devices. Phase II		5. Report Date February 13, 1981									
7. Author(s) T. C. Green, J. P. Cater, and J. H. Nixon		6. 8. Performing Organization Rept. No.									
9. Performing Organization Name and Address Southwest Research Institute Electromagnetics Division 6220 Culebra Road San Antonio, TX 78284		10. Project/Task/Work Unit No. 11. Contract(C) or Grant(G) No. (C) J0188082 (G)									
12. Sponsoring Organization Name and Address Office of the Director--Minerals Health and Safety Technology Bureau of Mines U.S. Department of the Interior Washington, DC 20241		13. Type of Report & Period Covered Contract research, 9/29/78--12/30/80									
15. Supplementary Notes Supplements BuMines OFR 22-80 (PB 80-144413). Approved by the Director, Bureau of Mines, for placement on open file, July 2, 1981.											
16. Abstract (Limit: 200 words) A two-phase program evaluated commercial proximity warning devices and then served to design and develop an automatic electrostatic field strength measurement device with improved performance. The phase I program consisted of test and evaluation of three commercial proximity warning devices, all of which operate on the principle of electrostatic field intensity measurement for determining proximity to high-voltage powerlines. Performance testing of these devices utilized full-scale cranes and powerline systems and a scale-model facility. Under the phase II program, a microprocessor-based data acquisition system was designed and developed to collect and measure field strength at distributed points around the crane boom. This unit measures the field strength about a crane boom using 17 distributed sensors. Keyboard control is provided for the equipment operator. Measured field strength values are displayed on a line printer and recorded on magnetic tape. Laboratory testing of this unit demonstrated performance characteristics and field strength measurement accuracy within the design goals.											
17. Document Analysis a. Descriptors <table border="0" style="width: 100%;"> <tr> <td style="width: 50%;">Mining</td> <td style="width: 50%;">Improved performance</td> </tr> <tr> <td>Proximity warning devices</td> <td>Full-scale cranes</td> </tr> <tr> <td>Automatic electrostatic field strength</td> <td>Microprocessor-based data acquisition</td> </tr> <tr> <td>Measurement devices</td> <td>Keyboard control</td> </tr> </table> b. Identifiers/Open-Ended Terms c. COSATI Field/Group 08I				Mining	Improved performance	Proximity warning devices	Full-scale cranes	Automatic electrostatic field strength	Microprocessor-based data acquisition	Measurement devices	Keyboard control
Mining	Improved performance										
Proximity warning devices	Full-scale cranes										
Automatic electrostatic field strength	Microprocessor-based data acquisition										
Measurement devices	Keyboard control										
18. Availability Statement Unlimited release by NTIS.		19. Security Class (This Report) Unclassified	21. No. of Pages 40								
		20. Security Class (This Page) Unclassified	22. Price								

FOREWORD

This report was prepared by Southwest Research Institute, Electromagnetics Division, 6220 Culebra Road, San Antonio, TX 78284, under USBM Contract No. J0188082. The contract was administered under the technical direction of Pittsburgh Mining and Safety Research Center with Roger L. King acting as Technical Project Officer. Doyne W. Teets was the contract administrator for the Bureau of Mines. This Phase II completion report is a summary of the work over the period 29 September 1978 to 31 December 1980. No concepts or technology set forth in this report is considered a subject invention as defined in the contract under which the work was performed. This report was submitted by the authors on 13 February 1981.

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I. INTRODUCTION

The Phase II completion report provided herein describes the work performed under U. S. Bureau of Mines Contract J0188082, "Evaluation of Proximity Warning Devices," conducted by Southwest Research Institute over the period 29 September 1978 through 31 December 1980. The program was conducted in two phases with Phase I consisting of testing and evaluation of commercially available proximity warning devices and Phase II consisting of the design and development of a microprocessor-based electrostatic field strength measurement instrument group for crane boom applications.

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.

A complete description of the work accomplished under Phase I, including the test and evaluation of the proximity warning devices and conclusions and recommendations for device improvement are found in the Phase I interim report dated 22 February 1980. The results of the Phase I work are, therefore, not specifically included in this final report.

The evaluation of the proximity warning devices in the Phase I program, however, did show that in addition to design deficiencies, which varied from device to device, the reliability of all the proximity warning devices was severely limited by the physical principle (i.e., electrostatic field sensing) on which these devices were operated. Categories of physical phenomena observed to produce undesirable performance in the commercially available proximity warning devices included field distortion from multi-power line circuits, polarization effects, boom shielding of the sensors, and sensitivity variations with boom orientation and extension.

The objective of the Phase II program was to develop a microprocessor-based data acquisition system to collect and measure field strengths at distributed points around the crane boom. The developed equipment group (referred to as the Distributed Sensor AC Electrometer) is designed

to accurately measure the distributed field strength about a crane boom with minimum error. Specific sources of measurement error determined in the Phase I program which this system is designed to minimize include:

- (1) Polarization effects.
- (2) Sensor shielding by the crane boom.
- (3) Sensitivity variation with boom orientation.
- (4) Sensitivity variation with boom extensions.
- (5) Sensitivity variation with sensor position on boom.

The system input is derived from 17 distributed sensors around the crane boom as well as keyboard entry for header information. The output of this system is corresponding field strength values on both a line printer and on an integral magnetic tape unit. The Distributed Sensor AC Electrometer developed under the Phase II program can be used to map the electrostatic field distribution around high voltage power line circuits of various configurations and for various crane boom parameters. The use of multiple sensors allows a complete mapping of the electrostatic field distribution along the crane boom as well as measurement of the field polarization. The developed measurement device, therefore, should be a valuable instrument to the Bureau of Mines for measuring and characterizing electrostatic field distributions about various power line circuit configurations. This data should be of significant benefit to the commercial proximity warning device manufacturers in optimizing system design configuration and improving reliability.

II. EXECUTIVE SUMMARY

A. Background

The results of the Phase I program revealed that the electrostatic field distribution around overhead power lines vary significantly with power line circuit configuration. In addition, the field distribution is distorted by the presence of the crane boom to the extent that theoretical predictions of the electrostatic field distribution (in the presence of a crane boom) are qualitative at best and cannot be used for quantitative predictions of absolute field strength values in practical scenarios. The objective of the Phase II program was to design and develop a microprocessor-based electrostatic field strength measurement instrument group which could accurately and efficiently measure the field distribution in the vicinity of overhead power lines and record the data on magnetic tape for post-processing analysis. In addition, the developed equipment group (referred to as the Distributed Sensor AC Electrometer) is designed to measure the electrostatic field distortions along the complete length of a typical crane boom eliminating many of the sources of field strength measurement errors typically found in commercial proximity warning devices. The field strength data obtained from a comprehensive set of measurements using the AC electrometer should be a significant aid in the design of commercial proximity warning devices. The design objectives for the Distributed Sensor AC Electrometer developed under the Phase II program are listed below.

1. Minimize Electric Field Measurement Errors

The Distributed Sensor AC Electrometer is designed to accurately measure the distributed field strength about a crane boom with minimum error. Sources of the measurement error which this system must minimize include:

- (1) Polarization effects.
- (2) Sensor Shielding by the crane boom.
- (3) Effects of sensitivity variation with boom orientation.
- (4) Effects of sensitivity variation with boom extension.
- (5) Measurements over full boom length.

All of the above sources of error can generally be overcome by the placement of multiple point sensors distributed around the boom and along the length of the boom. Figure 1 illustrates the concept of multiple sensor placement along the crane boom. The output of each sensor must be separately monitored and recorded to totally map the field distribution along the crane boom.

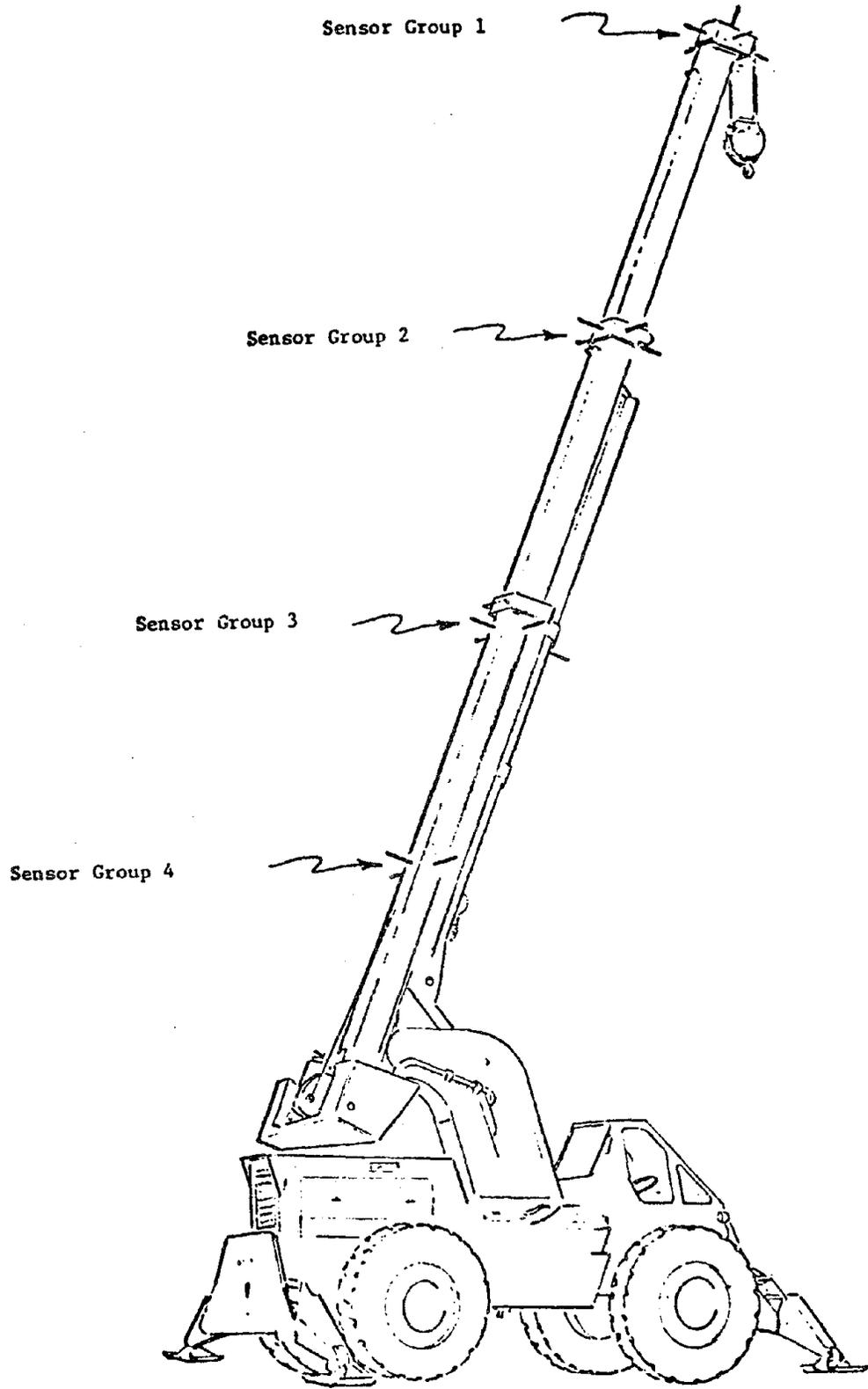


FIGURE 1. MULTIPLE SENSOR CONFIGURATION

2. Distributed Processing

One of the design objectives for the Distributed Sensor AC Electrometer is to use a distributed processor system which allows rapid and accurate measurement of the field strength from the multiple sensors. Under the distributed processing philosophy, microprocessors are utilized in both a master control unit and at discrete locations along the crane boom to monitor and record the field strength voltage from the multiple sensors. Use of the microprocessor in the master control unit provides a powerful capability for processing the measured field strength data, including such features as self-calibration, averaging, storage, display, printing, and operator inputs to the measurement process. This concept also provides high reliability operation since each sensor can perform internal self-tests and can monitor the data line for transmission or reception errors.

B. Measurement Equipment Group Description

The Distributed Sensor AC Electrometer equipment group developed under the Phase II program consists of the master processor, four remote processors and 17 electric field probes. The complete equipment group is shown in Figure 2. During normal operation, the master processor (shown in Figure 3) queries each of the four remote processors which in turn sample data from up to five electric field probes (20 total). This data is transmitted via serial data line to the master processor where it is analyzed, printed, and recorded. Unique features of the display and recording system include the internal real time clock and user defined header data. With each data set taken, the time (minute, hour, day, month, and year) and a ten-digit header entered by the operator is printed on the paper record and recorded on magnetic tape. This allows data archiving as well as provides for post-analysis of the field strength data. Other features of the system include a calibration mode, averaging of successive measurement data, and a self-check function for all the distributed sensors.

The complete equipment group has been operationally integrated and laboratory testing completed. All sensors have been monitored satisfactorily by the remote processors and data transferred to the master processor. Calibrated field strength data was recorded for laboratory conditions.

A follow-on program has been proposed to the U. S. Bureau of Mines to install the Distributed Sensor AC Electrometer on commercial crane booms and perform an extensive series of measurements for various power line configurations and crane boom orientations.* These tests will be conducted both at SwRI and U. S. Bureau of Mines test facilities.

*SwRI proposal 16-2994A dated 18 November 1980.

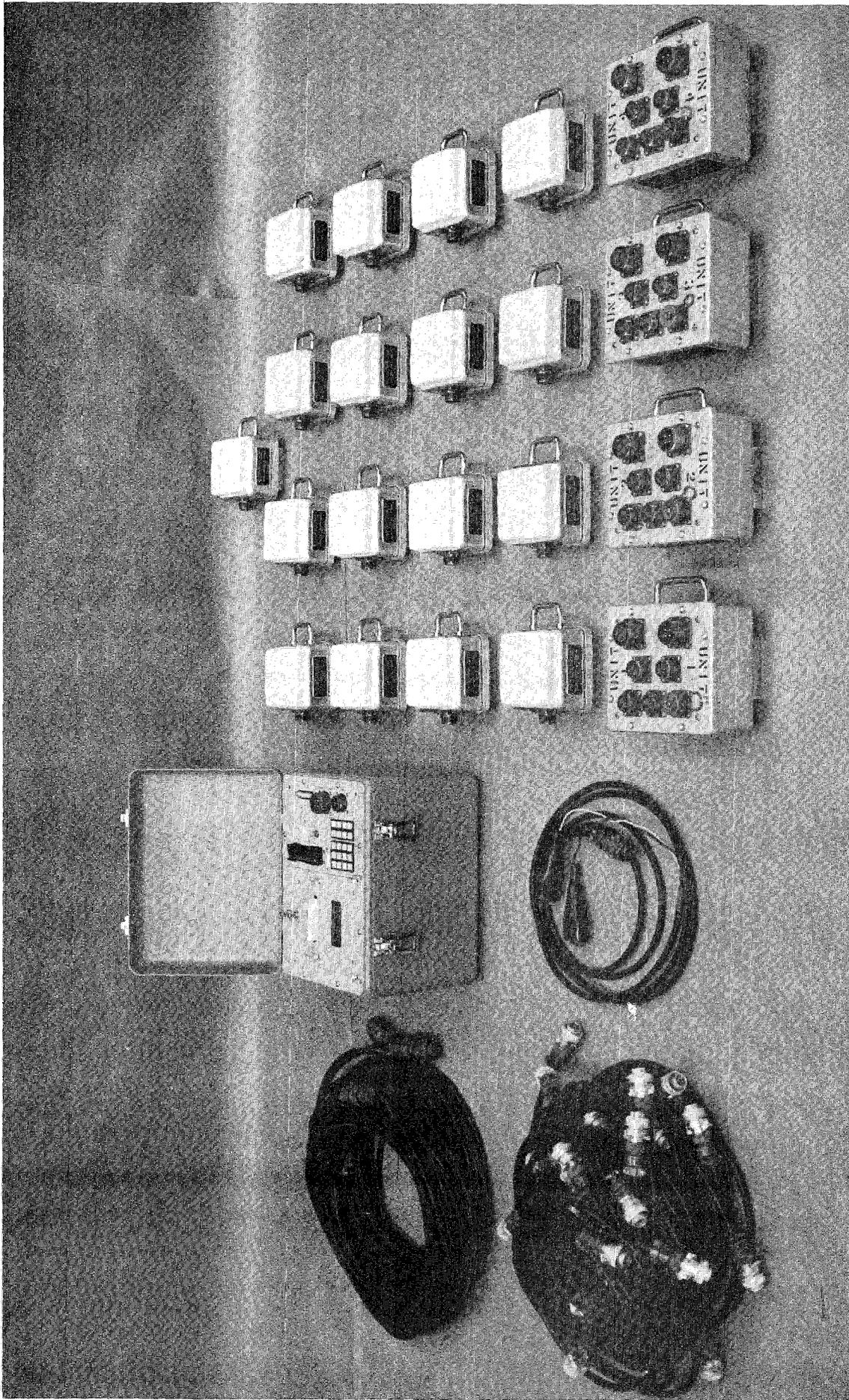


FIGURE 2. DISTRIBUTED SENSOR AC ELECTROMETER EQUIPMENT GROUP

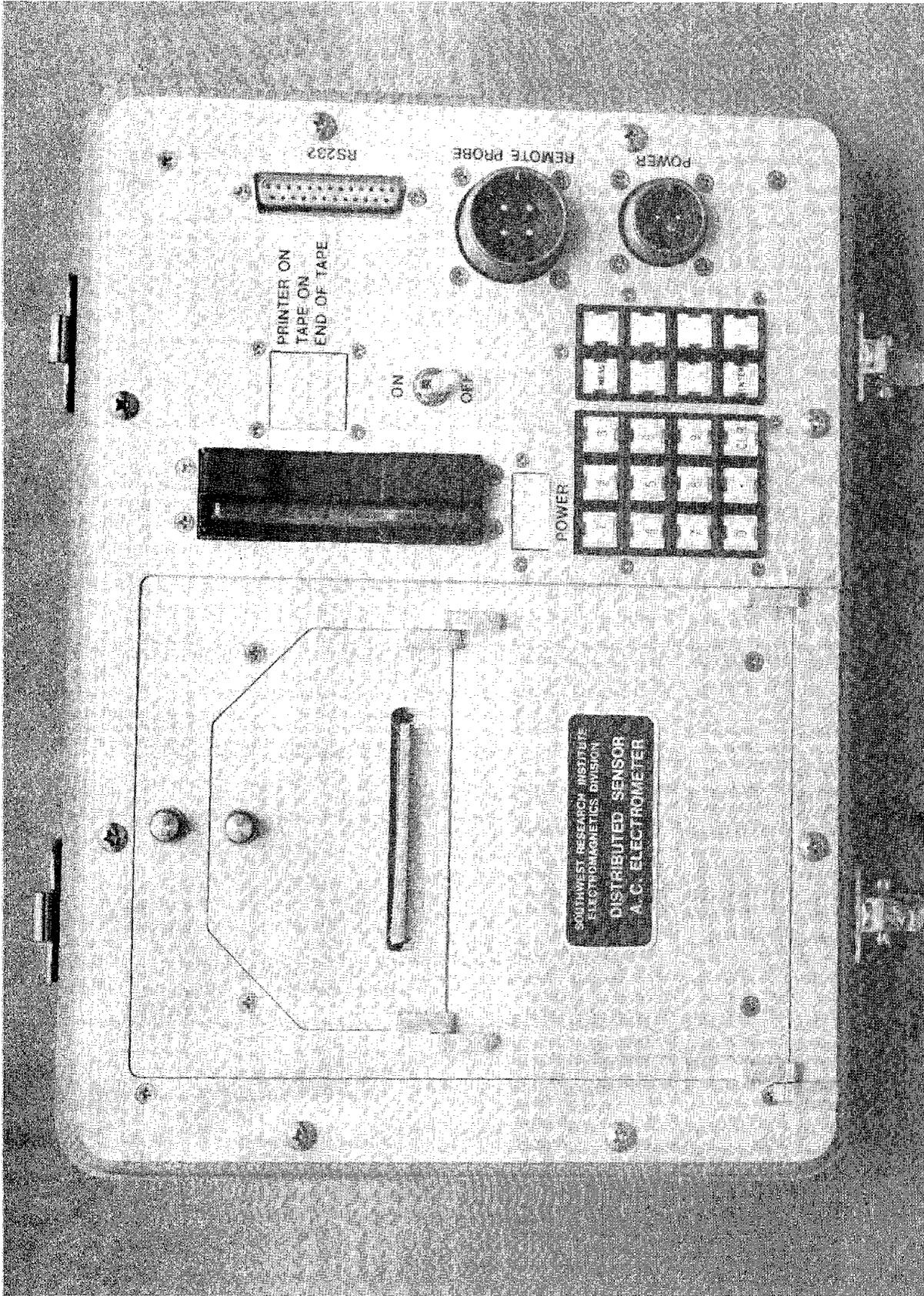


FIGURE 3. MASTER PROCESSOR

III. TECHNICAL DISCUSSION

A. Specific Approach to AC Field Measurements

The basic measurement approach used in the Distributed Sensor AC Electrometer is high impedance AC field metrology. In fact, the method of AC pickup is similar to that used in commercially available crane-mounted power line proximity alarm systems. Several differences exist, however, which make the SwRI system quite unique. The primary difference is the capability of actual quantized measurement rather than a threshold alarm capability and the configuration and number of sensors.

The development of a system with a capability for quantized field measurements around the boom of a crane presents numerous problems, if the field is to be measured accurately. Since the field will vary somewhat proportionately to the distance from a power line, the problem arises as to where to actually measure the existing field during the power line approach. A measurement at any specific point on the boom of the crane will give the value of the exact AC field at that point; however, the field strength at other places on the boom may be greater or less than the measured value, thus causing some uncertainty in the measurement for an alarm field value, depending on the approach configuration. The uncertainty is due both to the varying distance to the source and to the shadowing effect of the boom.

The solution to the point measurement problem was solved in the SwRI distributed sensor system by providing the capability for up to 17 simultaneous AC field measurements around the crane boom, thus providing a field contour description of the ambient 60 Hz field during power line approach. Use of multiple sensors deployed on all sides and over the length of the crane boom also provides accurate measurements on fields of arbitrary polarization.

The logistics of taking such a large group of measurements would normally be rather complex and tedious for the instrumentation operator. The SwRI system, however, is provided with a multi-processor control architecture to establish the concurrence of measurements in time, and the sequential distribution of the measured data to a master control center, all under computer control. In effect, the operator is working with a total of up to 17 individual field sensor systems, but the system appears (to the operator) as a single control panel, AC field strength instrument.

Another significant feature of this system is the use of a capacitive electric field sensor for each of the remote field probes. Since the reception of 60 Hz electrostatic fields is very inefficient with dipole or monopole-type antennas (the antenna length being much shorter

than a small fraction of the wave length), a capacitive plate sensor shown in Figure 4 was utilized at each remote probe to provide a reliable and efficient voltage transfer device and to produce a low profile sensor at each point on the crane boom. The use of a high impedance input amplifier at each remote probe location also allows the use of a rather small (3 inch square) capacitive plate field sensor. This ensures that the sensor effective size will not interfere with the AC fields being measured.

A design consideration which arises when making quantitative field measurements around crane booms is the need for a wide dynamic range system. This is due to the large range of field strength values anticipated for the various power line configurations under test (e.g., 110 Vac to 100 kV). The wide dynamic range is provided in each remote probe by a compression amplifier having a transfer response curve approximating the function $V_{out} = \sqrt{V_{in}/A}$.

B. Electronic System Design Concepts

All of the electronic assemblies developed in Phase II utilize state-of-the-art circuit design and components to provide tremendous system flexibility and simple operation. The instrumentation is, in effect, a five-computer network configured as shown in Figure 5. The master computer, which also contains the operator control panel, normally resides in the cab of the crane on which the measurements are to be taken. Each of the remote task computers in turn has the capability for connection of up to five remote field probes, and is programmed to acquire data from these probes upon command from the master computer.

One of the significant design features in this system is the distribution system of commands and remote data along the boom of the crane. In order to provide the minimum in wiring harnesses and system cabling, the data transfer technique along the boom is serial multiplexed with each computer talking over a single one-way party line. This design feature allows a boom cable having only four wires to be used to connect the entire system together. The signals on each of these wires are: (1) ground, (2) +12 Volts, (3) RS232 up boom data, and (4) RS232 down boom data. In addition to providing a simplified cabling arrangement, the serial data transfer system provides for later expansion to more than four remote computers.

The capability also exists to delete remote processors when needed. This will allow instrumentation of very small cranes where the full array of remote field probes is not needed. The deletion of remotes requires no operator interaction other than the simple disconnection of the unnecessary probes and remote processors.

It should be pointed out that while the computer network in Figure 5 looks rather complex for operator control, the software in the master computer is written so that the operator need only control the

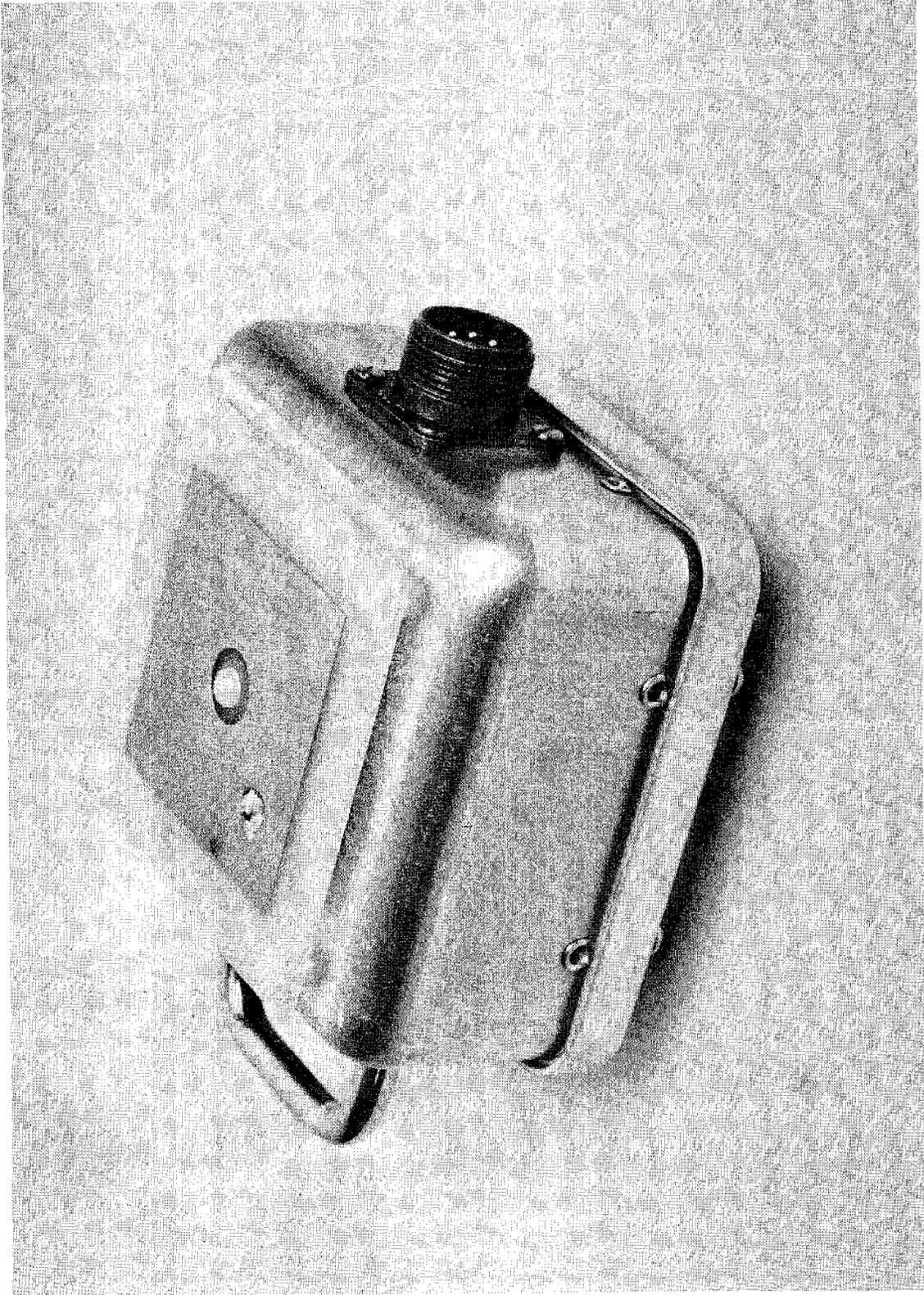


FIGURE 4. CAPACITIVE PLATE SENSOR

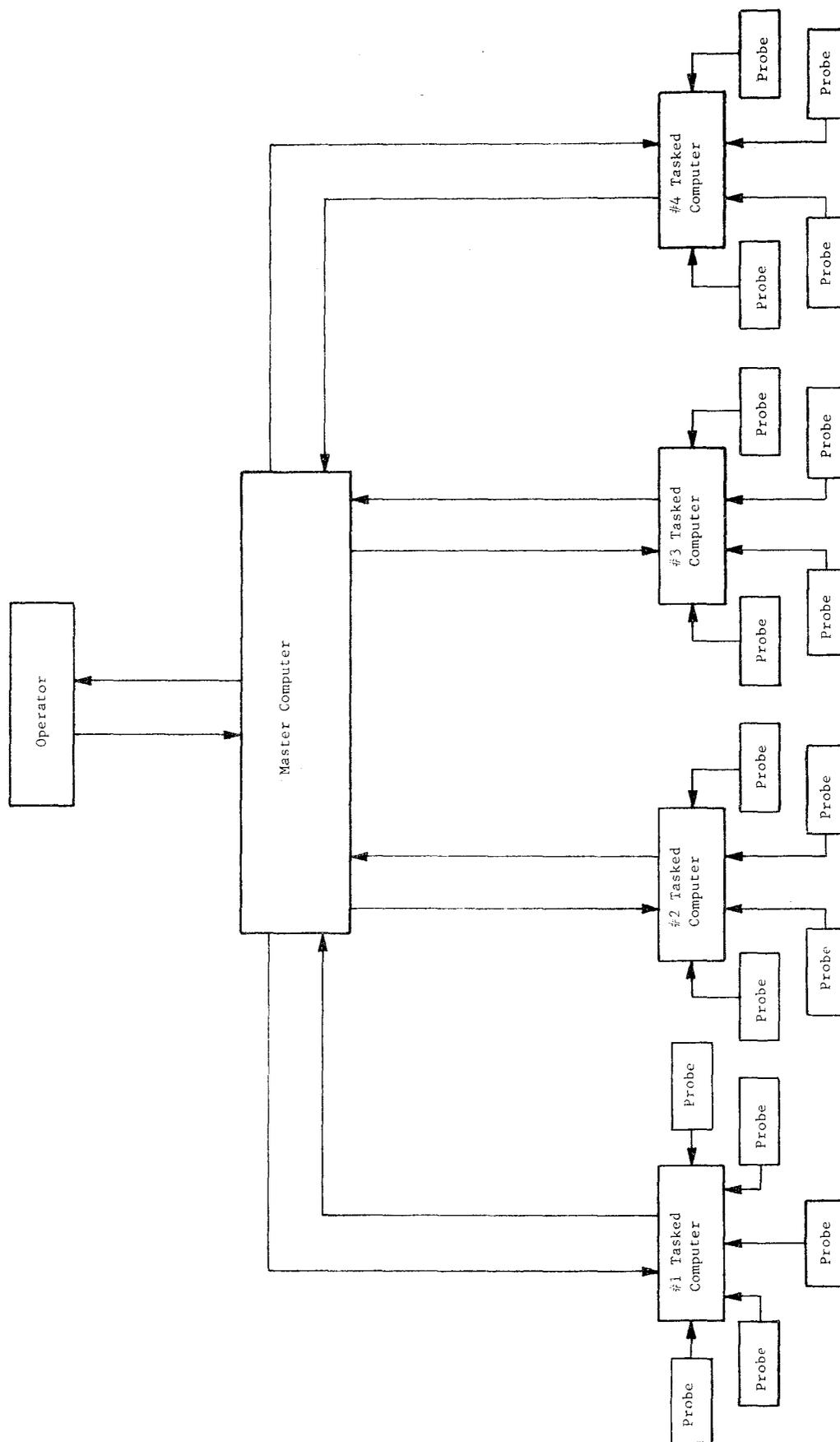


FIGURE 5. BLOCK DIAGRAM--AC ELECTROMETER

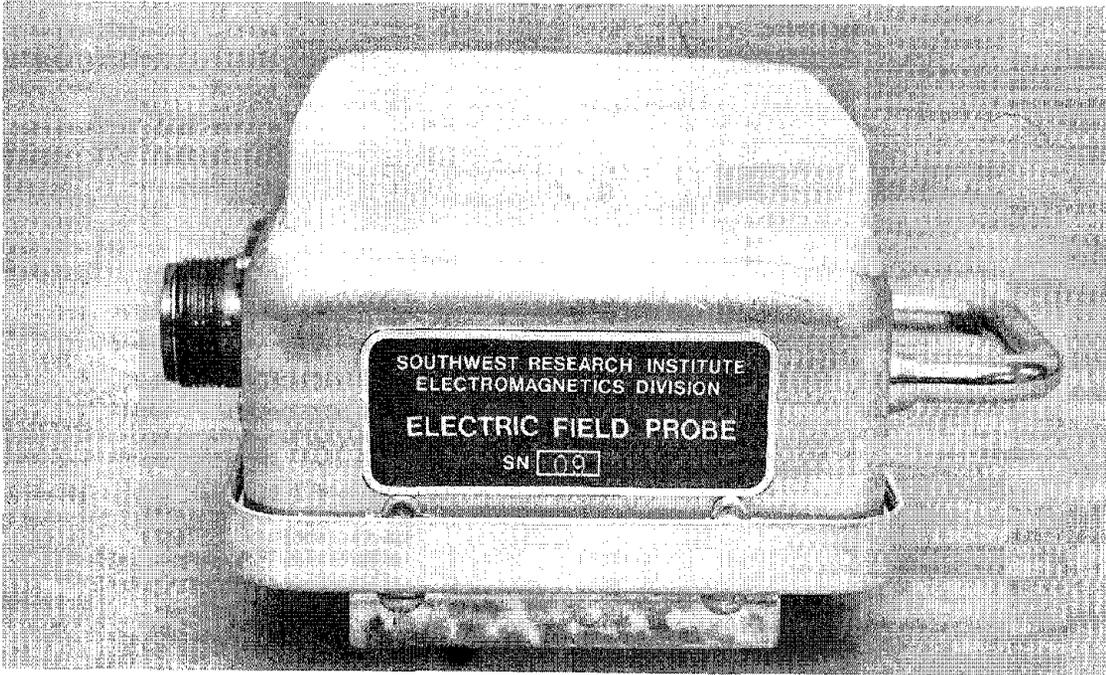
single master computer through the operator control panel. All testing of the remote computers and associated data collection from each of the remote probes is controlled automatically by serial data commands transferred along the boom of the crane under measurement.

During normal operation, when the operator desires to initiate data acquisition, the master computer queries each of the four remote task computers which in turn samples data from each of its four electric field probes. After the simultaneous data acquisition has occurred, the master computer begins to sequentially query each task computer for the resultant measured field data. This data is transmitted down the crane boom in a processor sequential manner via the serial data line to the master control unit (master computer) where it is processed and scaled according to calibration data, then printed, and finally recorded on the internal magnetic tape system. A feature added to the printer and recording system for increased data file management capabilities is the master computer internal real time clock and operator defined numeric header. With each data set taken, i.e., each time data acquisition is commanded, the time (hours, minutes, seconds, days, month, and year) and a ten-digit header, entered by the operator, is printed by the internal printer mechanism for a paper record and recorded on the magnetic tape system for later file identification. The combined file identification system is the equivalent of named and dated data files for later processing, analysis, and archiving of data. A complete measurement set for 17 probes, including automatic internal self checks requires nominally 5 seconds.

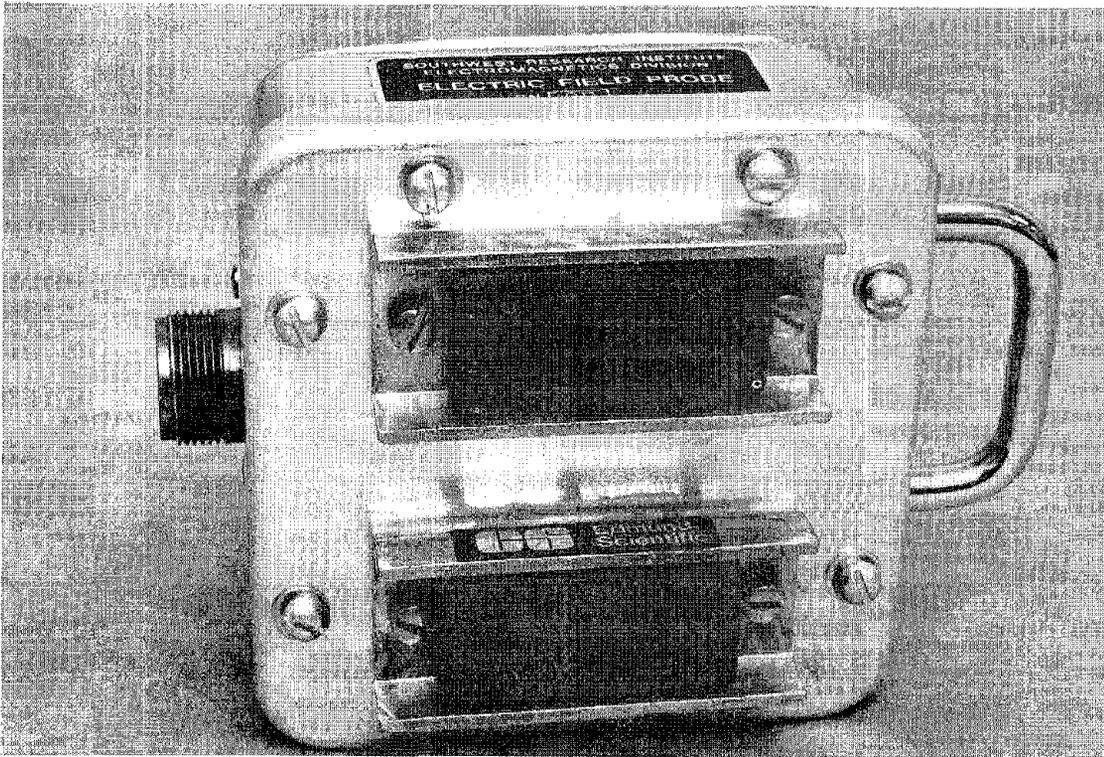
C. Electronic System Implementation

1. Remote AC Field Probe

The electric field probe shown in Figure 6a and 6b consists of five separate electronic sections as shown in the block diagram in Figure 7. The signal received by the capacitive sensor probe is buffered by the high impedance input, source follower amplifier, Q1, with positive AC feed back to increase the effective AC input impedance to 30 megohms. The buffered signal is then filtered by a three-pole passive 60 Hz filter to remove extraneous high frequency signals and input noise. The buffered filtered signal is amplified and compressed by the compression amplifier (U2). The characteristic transfer function of this amplifier is $V_{out} = (V_n/A)^{1/B}$ where B is nominally 2. The effect of the exponent on the transfer function is to increase the dynamic range of the entire probe, thus allowing measurements of widely varying fields from 100 Vac to many kilovolts AC. The output of the AC compression amplifier is converted to an AC proportional direct current level by the RMS converter (U3). The AC proportional rectified signal is then transferred through a short length of cable to the remote processor (task computer) for digitization and subsequent transferral of the measured field data to the master computer.



a. Field Probe



b. Magnetic Attachment Bracket

FIGURE 6. ELECTRIC FIELD PROBE

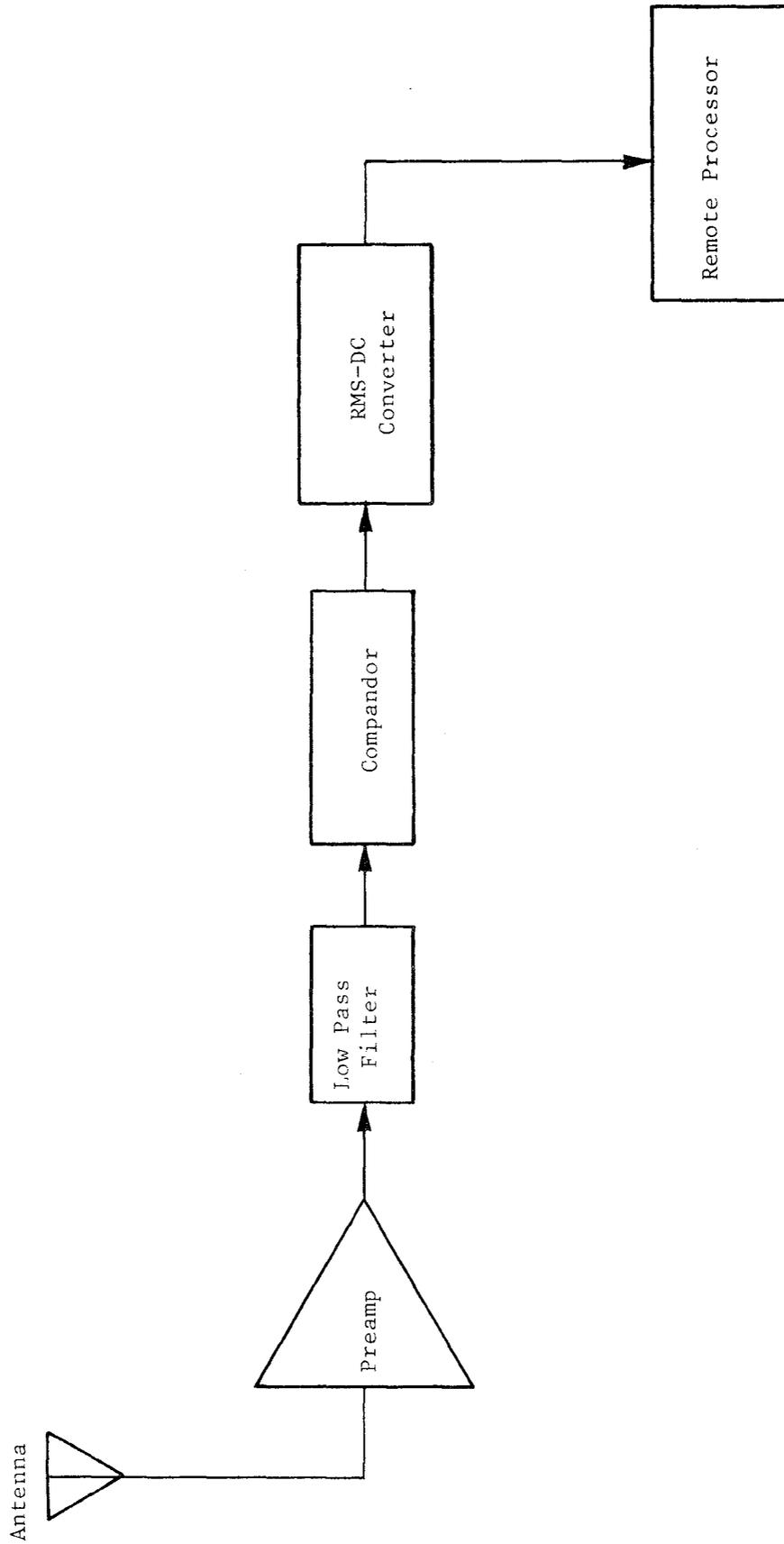


FIGURE 7. BLOCK DIAGRAM--ELECTRIC FIELD PROBE

The typical transfer characteristic of a remote analog probe is plotted in Figure 8. The characteristics of all the 17 remote probes supplied with the distributed AC sensor electrometer are within 5% of the measured curve.

2. Remote Processor

The remote processor (task computer) shown in Figure 9a and 9b functions as a data management and interface unit between the individual remote electric field probes and the master computer. The task of each remote processor (given by the master computer) is to digitize the electric field potential values from up to five electric field probes and transmit the corresponding digital data, along with the operational status of each probe, to the master computer. This function is accomplished in each of the remote task computers by a 6500/1 single chip microcomputer. The software, which is identical in each remote processor computer, checks the serial "up boom" data line between it and the master computer for the receipt of its particular task address. When it determines that its specific address has been transmitted along the "up boom" data line, it sequences through the five electric remote field probe connectors, checking for the presence of probes, testing connected probes for proper operation by injecting a calibrated amplitude 60 Hz test signal into each probe, and comparing the resultant output of each probe with a preset threshold tolerance. If a probe is not connected or the probe malfunctions due to a component failure, the probe output signal which is proportional to the AC calibration signal will fall outside these threshold boundaries. In this instance, a fault condition will be serially transmitted to the master computer on the "down boom" data line at the request of the master computer.

If the integrity checks are positive (the probes are connected and the calibration output falls within the required threshold band), the remote processor then digitizes the electric field value measured at each probe and, upon command from the master computer, transfers the data in binary form along the "down boom" line. A flow chart of the described operation is described in Section D.

3. Master Processor

The master computer processor functions as the system controller and instrument input/output device to the operator. It is responsible for (1) sequentially accessing the four remote processors in data collection, (2) commanding simultaneous data acquisition and calibration, (3) determining calibration constants and scaling factors for the measured electric fields, (4) printing the resultant data on the internal impact printer, and (5) storing the measured data on the internal magnetic tape recording system. The master computer for the distributed sensor AC electrometer is shown in Figure 10. The operator

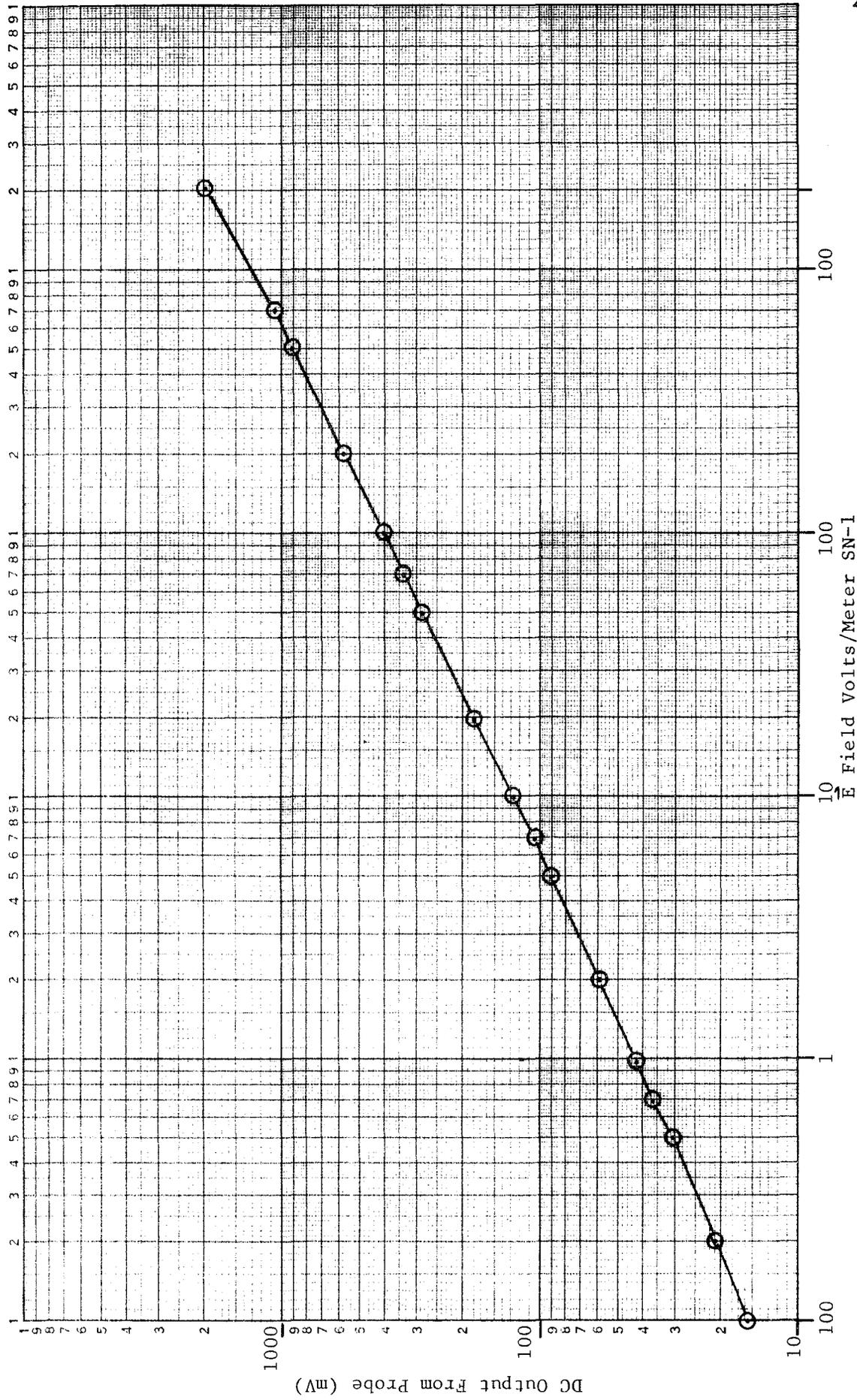
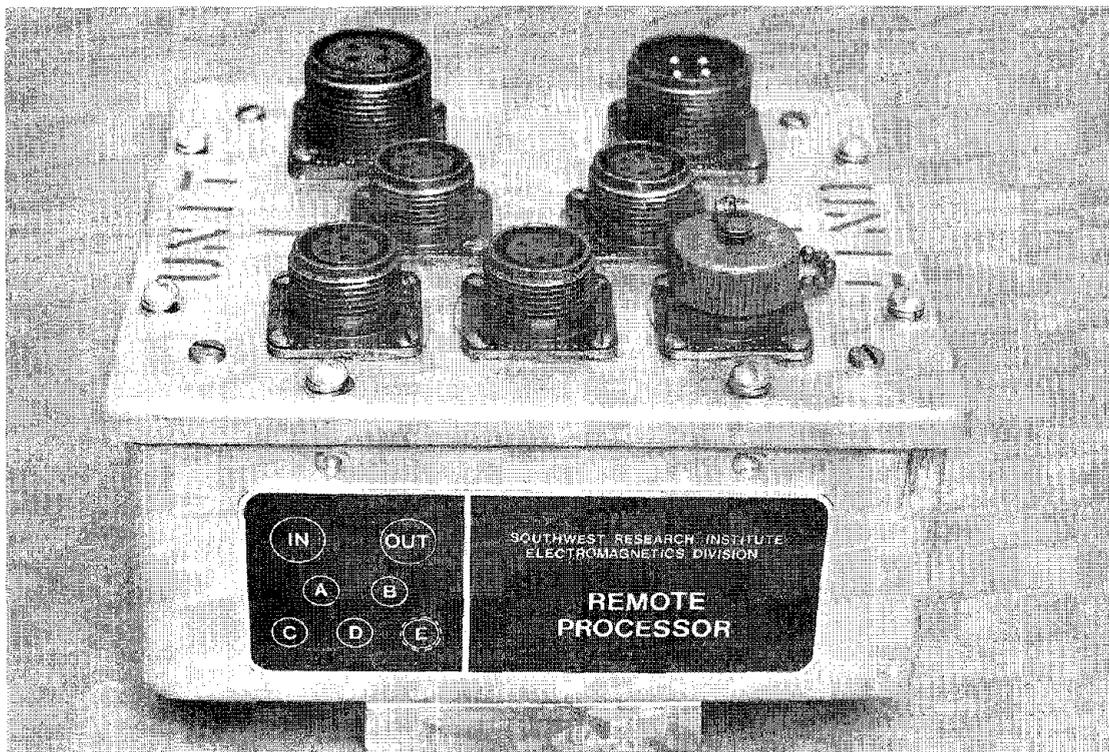
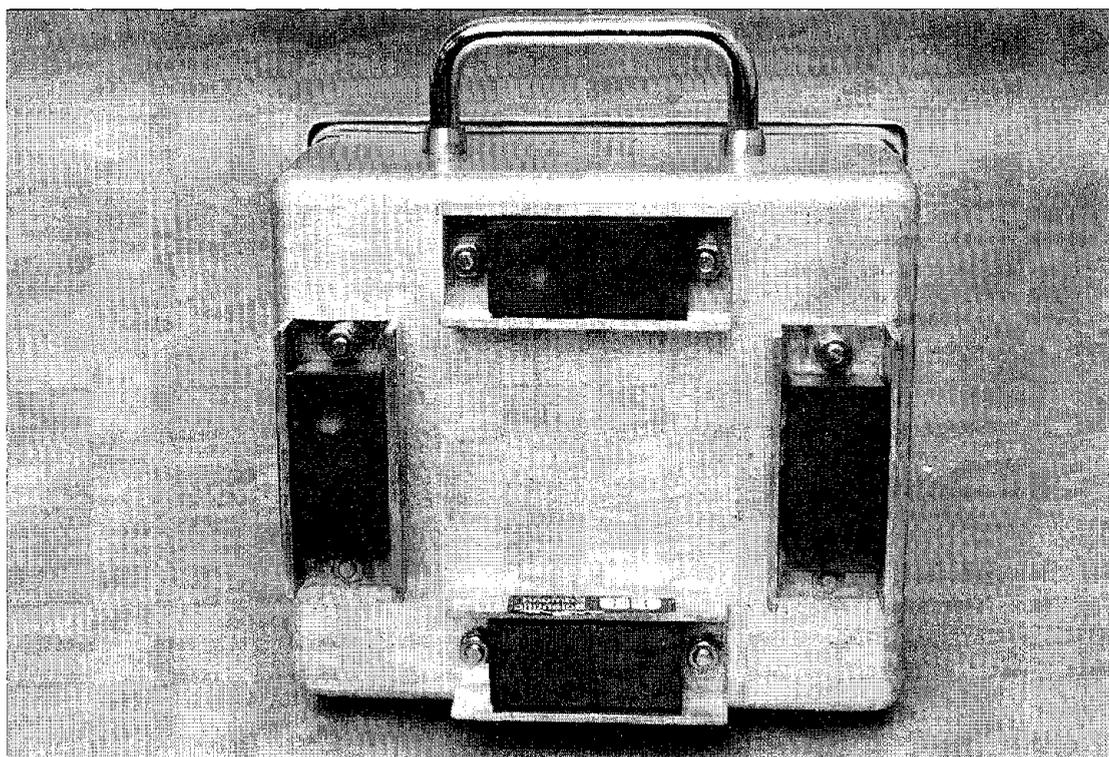


FIGURE 8. FIELD PROBE TRANSFER CHARACTERISTICS



a. Processor Package and Connectors



b. Magnetic Attachment Bracket

FIGURE 9. REMOTE PROCESSOR

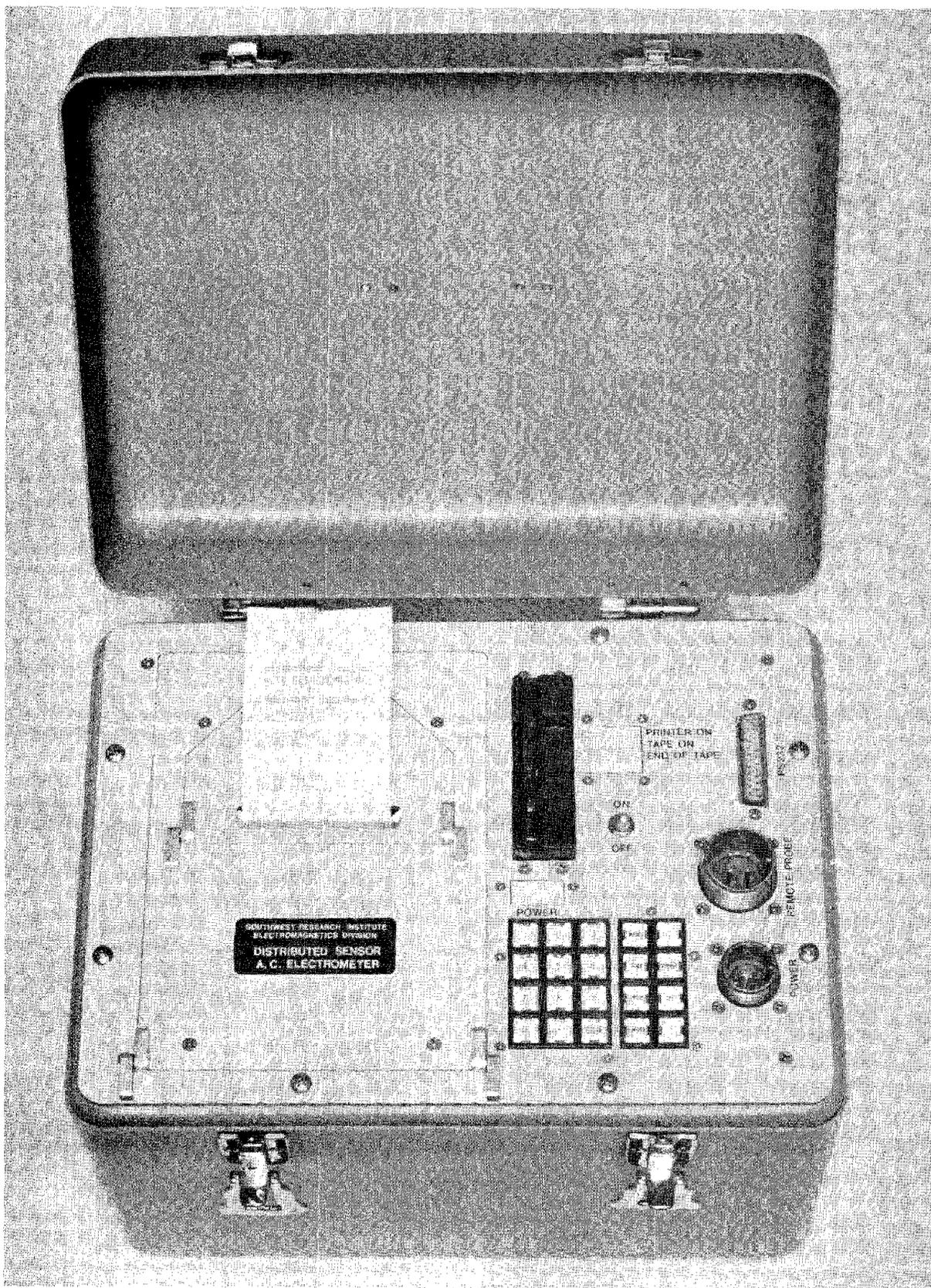


FIGURE 10. MASTER PROCESSOR AND CARRYING CASE

controls, printer, and magnetic tape recorder can be seen on the front panel along with annunciator lamps to signal system operation. Figure 11a and 11b show the master processor chassis removed from its portable container. All circuitry and electromechanical components are readily accessible for maintenance and component removal and replacement.

One of the significant advances of this instrumentation over existing field sensors is the capability for the master computer to be calibrated for a particular crane or crane boom configuration. The electric field calibration is accomplished by entering the calibration mode via the front panel keyboard and then applying a known calibrated field to each field probe.

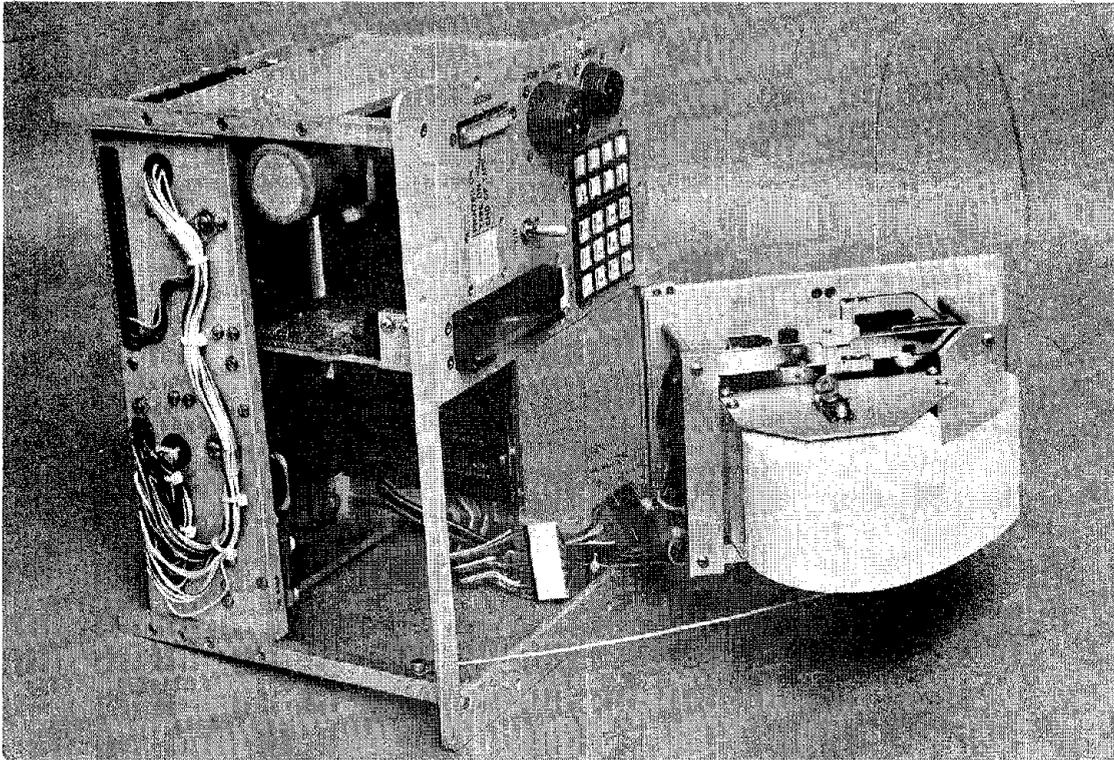
Initial system calibration was accomplished by measuring the characteristic transfer function for each probe, fitting a power equation to the transfer curve and then using the derived equation coefficients as the calibration constants. The constants for each probe are stored in system read only memory (ROM) and are used to normalize data during data acquisition.

The application of the known calibration field to each probe can be accomplished in the field by the use of the capacitive plate test fixture developed at SwRI for the remote probe system. The capacitive plate field generator shown in Figure 12 consists of two aluminum plates each measuring 24 inches by 24 inches spaced .1 meter apart. The grounded plate is cut out so that each remote probe may be placed within the capacitive plate system with a known distance configuration. Although this field calibration method may be somewhat awkward on larger cranes, it does allow the operator to verify all operating parameters and confirm calibration factors for critical field measurements.

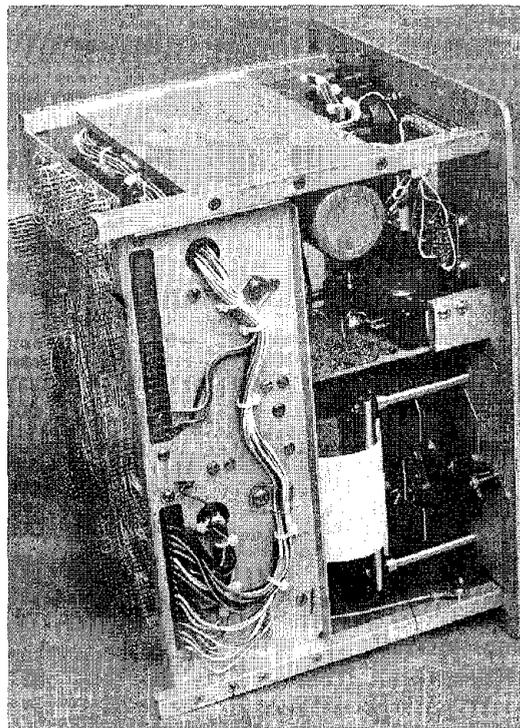
Each initial calibration curve fit to the recorded data points was computed on an HP65 calculator using the power curve fitting program supplied in the statistical program library. The calculated equation coefficients were then converted to 32-bit floating point format and stored in non-volatile memory in the master processor. Software was developed to use these coefficients in conjunction with the AM9511 math processor to convert the averaged digitized electric field probe outputs to the electric field strength in volts per meter.

A sample graph showing the typical transfer function of all probes is included in Figure 8. The straightness of the responses on log-log paper demonstrates the power response characterization capabilities. Typical variability from unit to unit is $\pm 5\%$.

After each probe has been calibrated with the known calibration field, the master computer acquires the probe calibration constants, stores them, and uses the calibration factors for data scaling



a. Front and Side View



b. Bottom and Rear Panel View

FIGURE 11. MASTER PROCESSOR

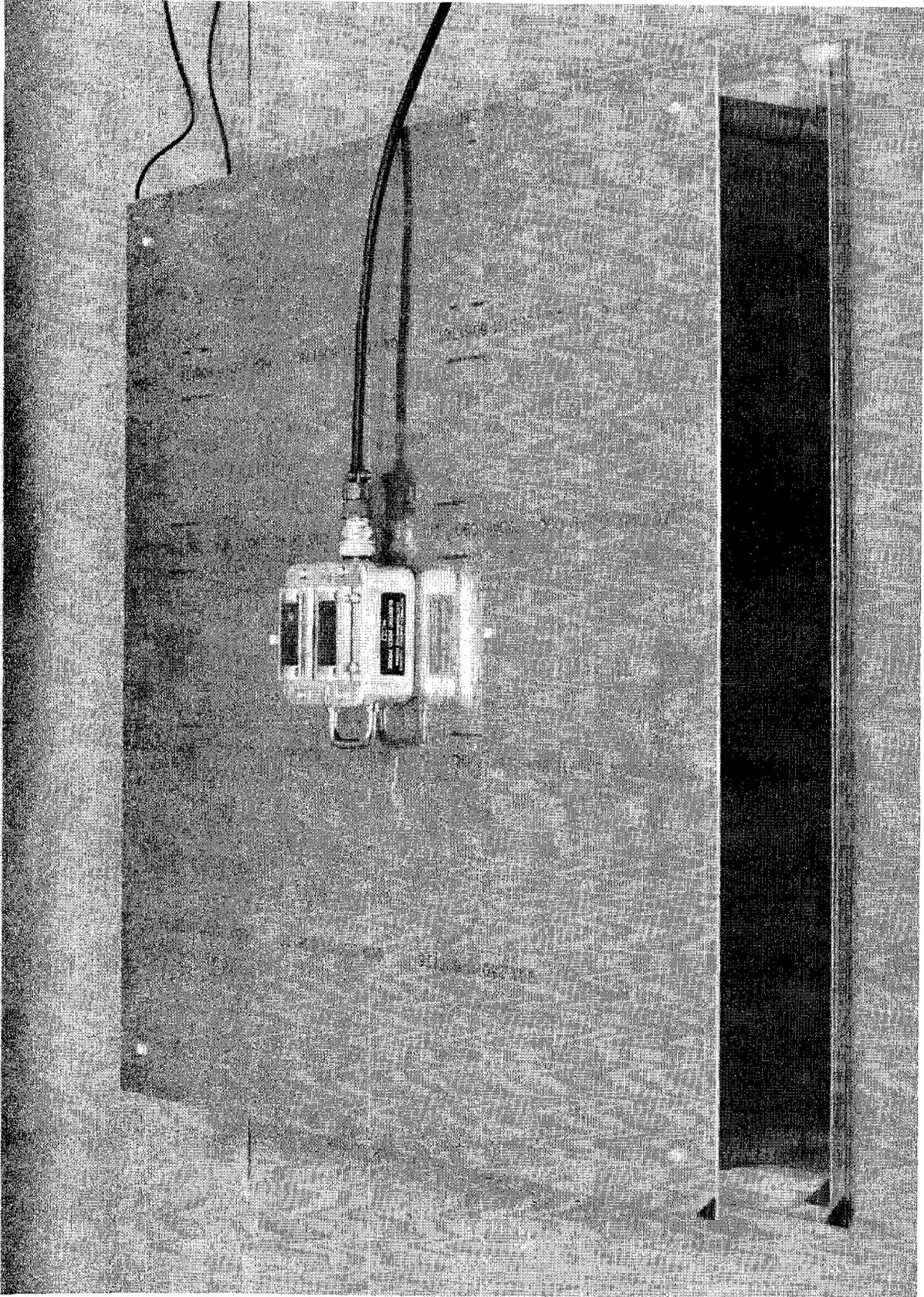


FIGURE 12. FIELD PROBE CALIBRATION FIXTURE

during actual field measurements. In this way, the system can be assured of accurate data collection given varying environmental conditions such as temperature, humidity, etc.*

4. System Cabling Techniques

The cabling for the entire system shown in the lower left corner of Figure 2 is relatively simple, considering the complexity of the system configuration. Each remote field probe is connected to a remote processor (task computer) by a six-foot length of five-conductor cable. One added conductor is supplied in this cable group to allow the remote computer to query for probe presence during the measurement process. In this manner, the remote computer can determine if a probe is connected and malfunctioning or simply not connected to the connector. This feature allows the system to be used with a variable number of probes connected, providing a versatile data acquisition capability.

The longer set of four cables, three at 25 feet in length and the fourth at 35 feet in length, is used to interconnect the remote processors and the master computer control unit. This durable four-conductor cable extends from the cab of the crane under measurement to the tip of the boom being measured. Connection is by weather-proof, military standard screw-on type connectors.

D. Software Design and Implementation

1. Software Design Concepts

The software utilized in the Distributed Sensor AC Electrometer is written in 6502 assembly language code. The main function of this software is data collection, data conversion, data recording, and output.

There are basically two software packages which run independently of each other. The first of these is utilized in the remote processors and is primarily responsible for data collection/conversion and testing remote field probes status and integrity. The second software package is utilized in the master processor. It is responsible for communication and command of the remote processors, data reduction and conversion, and hard copy and recording of data on cassette tape. To aid in the data reduction and conversion process, an AMD 9511 arithmetic processor has been incorporated. This hardware device solves fixed and floating point arithmetic and a variety of floating point transcendental operations.

*The probes can be calibrated in the laboratory "on the crane" using the calibration test fixture. Obviously it is preferable to calibrate one time in the laboratory and to not have to field calibrate. One of the initial tasks in a follow-on program will be to determine the need for field calibration.

The software in both processing units is written following a modular software design concept. The modular concept is the development of functional subroutines, each assigned a particular task. These subroutines are linked together in a main line program which accomplishes the desired function. This type of design leads to easy modification of existing software operation and allows future addition of new features.

2. Flow Chart of Operation

During data acquisition, two independent, but interactive, software programs are running in the distributed sensor system. The master computer contains a system controller-type software which tasks and queries each remote computer for measured field data, then sequentially prints and records the reported data from each remote processor. The flow chart of the master computer operation is given in Figure 13.

The primary operating mode of the master processor is in the keyboard query loop where the master computer awaits operator commands. From this point in the program, the operator can command data acquisition, header or time print out, or header or time information entry. If data acquisition is commanded, the master computer signals over the "up boom" data line for all remote processors to perform self-test and acquire field data. After a delay of nominally 5 seconds, for awaiting the acquisition of self-test data from all probes, the master computer begins to sequentially query the remote processors for individual field strength data from each remote probe. As the data is acquired, the master computer stores the information for operator print out and serial data storage on the internal magnetic tape. Following the completion of data collection, the master processor returns to the keyboard query loop awaiting for their operator instructions.

If the operator command is HEADER PRINTOUT for header confirmation, the master computer simply prints the information stored temporarily for the current data collection file which is an identification number supplied by the operator. TIME PRINTOUT does the same for the time of day and calendar information supplied from the internal time-of-day clock.

If the operator commands HEADER INFORMATION set, then the master computer requests a ten-digit header ID number from the operator for use in field data identification. The header is stored temporarily for use on subsequent data sets collected along with the updated time and calendar information.

The second software system in operation during data acquisition functions at each remote processor (task computer). The primary operation loop for the remote processors is the "serial wait loop" for

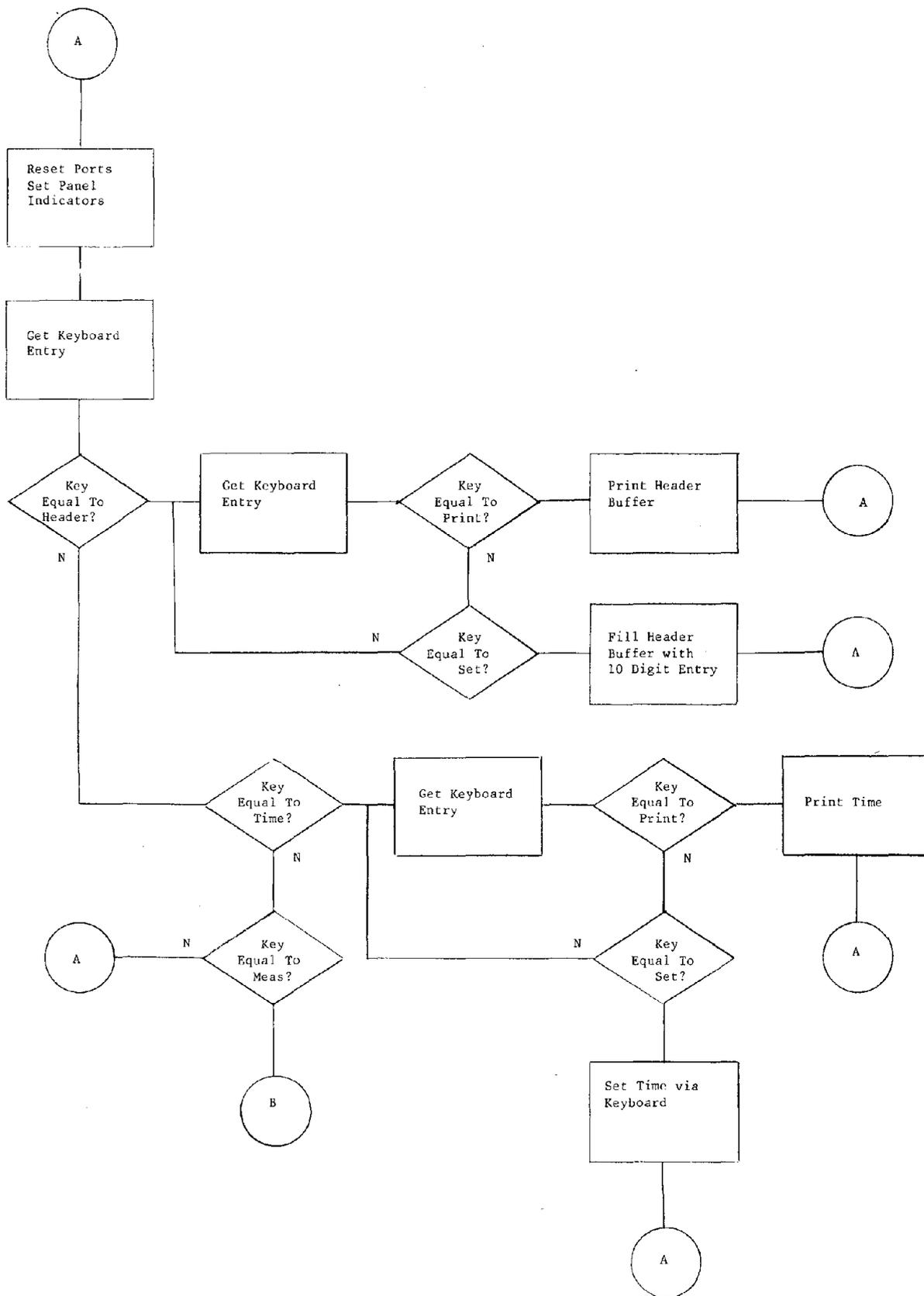


FIGURE 13. MASTER PROCESSOR SOFTWARE FLOW DIAGRAM

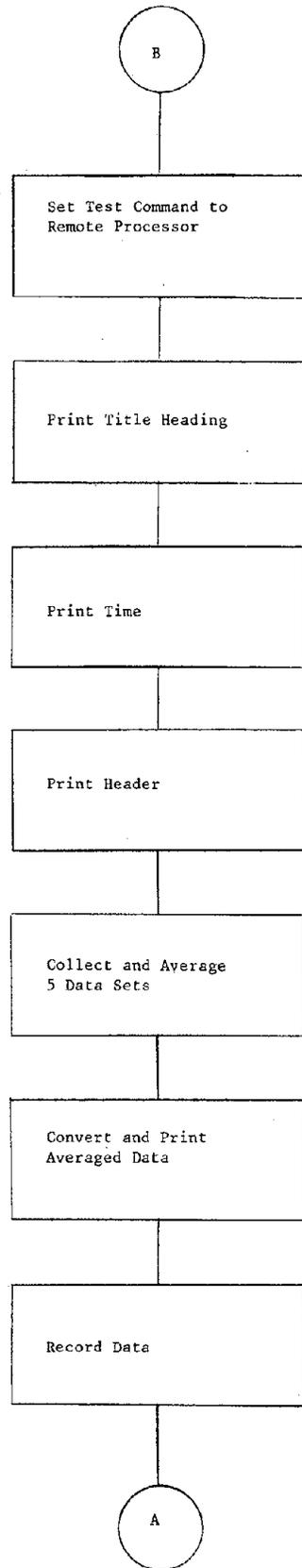


FIGURE 13. MASTER PROCESSOR SOFTWARE FLOW DIAGRAM (CONT)

"up boom" data. The remote processor continuously polls the "up boom" data line awaiting a command for either data acquisition or acquired field data transmission. The flow chart in Figure 14 illustrates the particular wait loop along with the remainder of the tasking software. Three sequential commands to the remote software processor are generated by the master computer when the operator depresses the MEAS key.

Any of three commands can be expected to activate any individual remote processor unit. The "test" command forces all remote processors into a self-test mode with the calibration signal applied to the input of each remote probe amplifier. The data is taken in turn from each remote probe, then averaged and compared with a threshold value to determine correct operation and calibration for each probe. If any probe is found to be out of tolerance in amplification, a malfunction bit is set for later transmission to the master computer.

A second command recognized by all remote processors is the "data acquisition" command. This command forces each processor to begin sequencing through the connected remote probes and digitizing the field values for 16 individual successive measurements. The 16 measurements are then averaged for each remote probe and stored in temporary buffer awaiting the processor "transmit data" command from the master computer.

The third command encountered by the remote processors on the "up boom" line is the "transmit data" command for each individual remote processor. This command has an associated address corresponding to the individual remote processor, so that the "down boom" line is not simultaneously acquired by more than one remote processor. If a valid address is found for the data transmit command, then after a short delay, the addressed remote processor begins serially transmitting the digitized data to the master computer. Each data set transmitted to the master computer contains not only binary field strength data but status data concerning the connection and calibration of each of the connected remote field probes.

E. System Operating Procedures

1. System Installation

Installation of the Distributed Sensor AC Electrometer has been simplified by the incorporation of magnetic bases on each of the remote processor units and remote field probe units. Depending on the length of the boom to be measured and the particular orientation of field measurements desired, the processors and probes may be placed in an orderly equidistant fashion along the crane boom as shown in Figure 1. The system should be cabled with the 25-foot sections between each of the remote processors and the 35-foot section from the lowest remote processor to the cab of the crane which contains the master computer control unit.

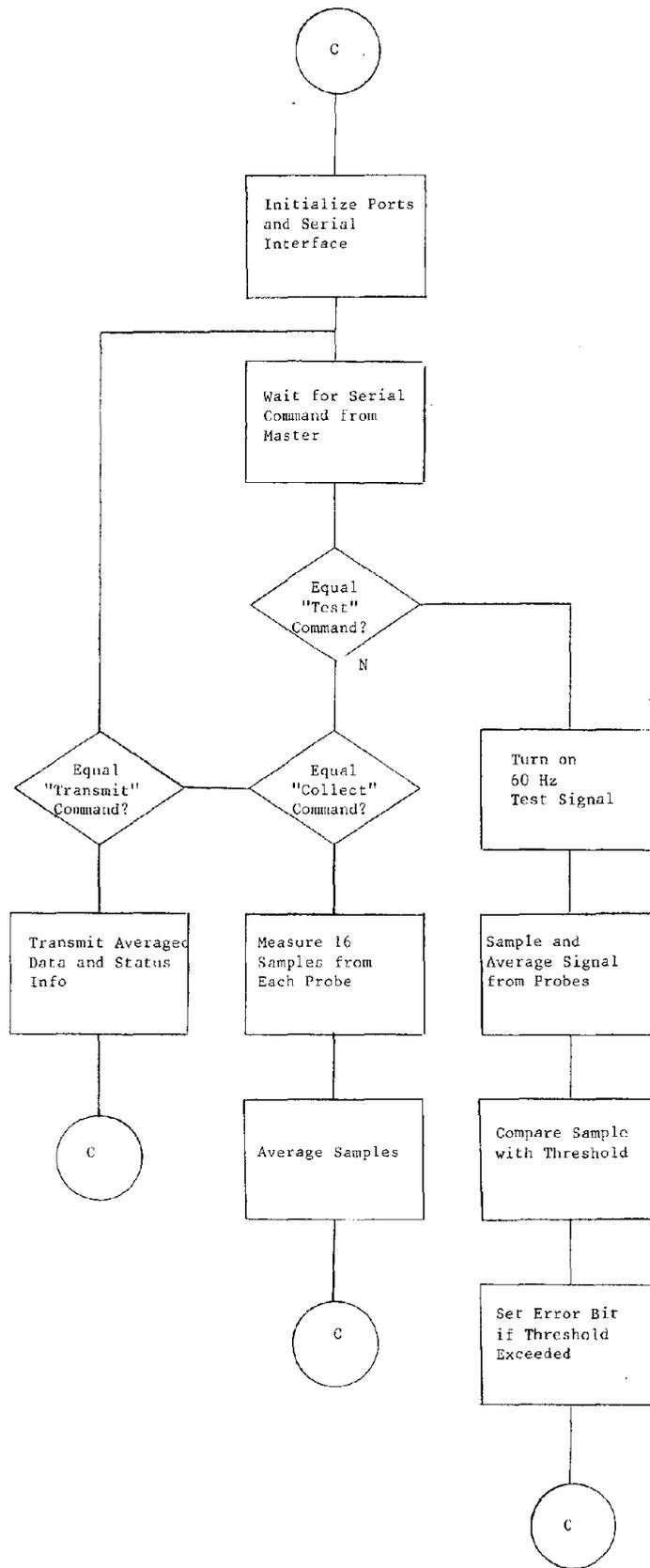


FIGURE 14. REMOTE PROCESSOR SOFTWARE FLOW DIAGRAM

A power cable supplied with the master control unit should be connected to the power receptacle on the control panel at one end and clamped to a 12 volt or equivalent dc battery source at the opposite end of the cable.

WARNING: Connection of the master control unit to any battery or supply voltage which may exceed 14 volts could lead to possible damage of the master control unit and associated remote processors and field probes.

As with standard wiring practices for a power connection, the red clamp should be connected to the positive battery terminal and the black power clamp should be connected to ground or the negative 12 volt battery terminal.

2. Data Acquisition Techniques

After all installation connections are properly made and the power cable is attached to a 12 volt source, the system will, on POWER ON initiation, begin its reset sequence by printing out the heading identification label, followed by the stored header, and time of day and day clock information. Before the actual beginning of the first data set, the operator should verify that the header is correct for the current data set and, if not, should change or update the header as discussed in Section E.3.

After the header has been verified, the operator should position the boom of the crane into the proper position with respect to the power line and depress the MEAS pushbutton on the right two-column keyboard of the operator control panel. The system will then print ELECTRIC FIELD MEASUREMENTS, the header and time of day, and then pause for approximately five seconds while the various remote probes are being calibrated, self-tested, and finally commanded to acquire data. At the end of this time, the printer will begin printing the measured field values for the various probes along with their identification numbers, ranging from 1 A, B, C, or D to 4 A, B, C, or D.

If a probe is not connected to an associated remote processor, then that identification number will not be printed on the data listing. If that probe is connected and malfunctioning, however, by erratic gain or out-of-tolerance operation, then the system will print malfunction beside the probe ID number and will not supply measured field value for that probe.

3. Printout Instructions and Interpretation

In addition to the capability of measurements, the system has several other command keys which allow the operator to set predetermined variables within the measurement system. The TIME PRINT mode prints the time of day and calendar upon operator command, while the DECIMAL POINT key "." provides a single line feed each time it is depressed. The HEADER PRINT command provides for visual confirmation of the internal header.

If the operator depresses TIME and SET in that sequence, the system will respond with:

```
ENTER TIME THIS ORDER  
HR,MIN,DAY,MO,YR
```

At this point the operator should enter the requested data with leading zeros included. For example, the entry sequence:

```
1604 25 1281
```

will preset the internal calendar clock to a time of 4:04 P.M. and a date of 25 December 1981. As the final digit is entered for the year, the system will respond to the operator by typing PRESS ENTER TO SET. As the ENTER key is pressed, the system will record this time, display it, and begin operation from that point. Note that the clock is a 24-hour clock and should be set accordingly. Internal battery backup of the calendar ensures infrequent time setting.

To set a new header with current information, the operator should depress the HEADER key followed by the SET key. The system will then pause awaiting a ten-digit maximum ID number from the operator to be entered via the keyboard. After the 10th key is depressed (or if the ID number is shorter, the ENTER key is depressed) the system will respond by typing the currently updated header information. After these data changes, the system is ready for field strength measurement.

V. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. Phase I

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.

2. Phase II

The Distributed Sensor AC Electrometer designed and developed by SwRI under the Phase II program provides a state-of-the-art automatic data logging device for the measurement of the electrostatic field environment in the presence of high voltage power lines. The incorporation of multiple sensors allows complete mapping of electrostatic field

characteristics in the presence of a crane boom and eliminates field measurement errors due to such factors as polarization, sensor shielding by the crane boom, and sensitivity variations as a function of boom orientation and extension. The distributed processing concept incorporated into the AC electrometer provides maximum accuracy and minimum response time for the field strength measurements. Unique features of the system such as automatic self-checks of the field probes and data conversion circuits and the capability for magnetic tape storage of all measured data enhance the usefulness and reliability of the developed equipment group.

Laboratory tests of the Distributed Sensor AC Electrometer using a electrostatic field calibration fixture has demonstrated the design goal dynamic range and measurement accuracy. Dynamic range is in excess of 60 dB with typical field strength measurement accuracy of nominally 5%.

B. Recommendations

1. Phase I

a. Recommended Design Objectives for Improved Performance

(1) 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.

(2) 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.

(3) 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.

(4) 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.

(5) 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.

b. 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.

2. Phase II

It is recommended that the Distributed Sensor AC Electrometer be used for extensive data logging of electrostatic field strengths for a significant sampling of high voltage power line configurations and voltage level parameters. These tests could be accomplished both in controlled environments such as the SwRI radiolocation field laboratories and in practical environments such as the San Antonio local utility and/or Bureau of Mines test facilities. The field strength data recorded on magnetic tape should be reduced by off-line computer processing and compared to theoretical data predicted for each measurement condition.

Results of the above recommended program would provide the Bureau of Mines with a large empirical data base of electrostatic field strength distribution about a variety of high voltage power line configurations. This data in conjunction with theoretical prediction techniques could be used to map other power line configurations not included in this measurement program. Ultimately, the complete data set (both measured and theoretical data) can be used to provide design guidance for commercial manufacturers of crane-mounted proximity warning devices.