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MEASUREMENTS OF INDUCED VOLTAGES AND CURRENTS IN A DISTRIBUTION POWER LINE AND ASSOCIATED ATMOSPHERIC PARAMETERS

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ABSTRACT

The frequency and intensity of thunderstorms around the Kennedy Space Center (KSC) has affected scheduled launch, landing, and other ground operations for many years. In order to protect against and provide safe working facilities, KSC has performed and hosted several studies on lightning phenomena. For the reasons mentioned above, KSC has established the Atmospheric Science Field Laboratory (ASFL). At these facilities KSC launches wire-towing rockets into thunderstorms to trigger natural lightning to the launch site.

A program named "Rocket Triggered Lightning Program" (RTLP) is being conducted at the ASFL. This report calls for two of the experiments conducted this summer 1988 Rocket Triggered Lightning Program. One experiment was to suspend an electric field mill over the launching area from a balloon about 500 meters hight to measure the space charges over the launching area. The other was to connect a wave form recorder to a nearby distribution power line to record currents and voltages wave forms induced by natural and triggered lightning.

ACKNOWLEDGEMENTS

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Very special thanks are due to my NASA colleagues for their patience and warm hospitality. In particular to Mr. William Jafferis, my principle contact, whose daily interaction of ideas and research helped to achieve the goals pursued. Also to Rocco Sanicandro, Jim Stahman, Mike Brooks, Launa Maier, and Nidhi Okonski for their assistance in the development of this project.

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INTRODUCTION

The frequency and intensity of thunderstorms around the Kennedy Space Center (KSC) has been a serious problem for many years. This affects scheduled launch, landing, and other ground operations. Also, there is at KSC a great amount of sensitive equipment (electrical, mechanical, communications, computer networks, fuel storage, transfer facilities, towers, etc.) that are vulnerable to the hazard of lightning. In addition, the employees working on towers and other outdoors areas are also exposed to lightning and bad weather conditions.

In order to protect against and provide safe working facilities, KSC has performed and hosted several studies on lightning phenomena and also has provided a lightning detection system. However, the frequency of Space Shuttle launches, a Space Station Program, and other ground operations, requires a better understanding of lightning phenomena and its potential hazards in order to maintain safety, protect the equipment, and maintain cost effective scheduling.

In addition to this, there are strong indications that lightning strikes to airplanes and missiles in flight are nearly always triggered by the rapid penetration of an airborne conductor into a region of high ambient electrostatic field. By "triggered" is mean that the discharge would not have occurred at the same time and place in the absence of the aircraft.

Aircraft-triggered lightning represents a significant hazard to aviation and to rocket launch operations. Atlas/Centaur 67, carrying a U.S. Navy communication satellite, was struck and destroyed about one minute after launch from Kennedy Space Center on March 26, 1987, for a total cost to the Navy of $161M, to cite only one example. The severity of this hazard is expected to increase as modern aircraft designs take more advantage of poorly conducting composite structural materials, micro-electronics, and fly-by-wire technology.

Triggered strikes are not confined to cumulonimbus clouds. They can occur in other types of precipitating and non-precipitating clouds which may not otherwise be producing lightning. There is, therefore, a strong operational need to understand and avoid the conditions under which strikes can occur.

For the reasons mentioned above, KSC has established the Atmospheric Science Field Laboratory (ASFL), (See figure 1). At these facilities KSC launches rockets (some wire-towing, some not) into thunderstorms to trigger natural lightning to the launch site. In this way, time and corrected measurements of large and complex natural events can be made in a controlled open field laboratory.

A program named "Rocket Triggered Lightning Program" (RTLP) is being conducted at the ASFL. This report calls for one of the experiments conducted this summer 1988 Rocket Triggered Lightning Program.

The experiment of this summer 1988 at the Atmospheric Science Field Laboratory (ASFL) consisted of triggering lightnings from both an over ground and over water launching pads (See figure 2). Rockets of about one meter long were launched. Some of them carrying a spool of wire of about 700 meters long (See figure 3). One end of the wire was attached to ground, while the other was carried by the rocket near a charge cell. If conditions were favorable, a lightning was developed.

For this experiment, a tethered balloon was placed over the launching area approximately at 500 meters height (See figure 4). A Lightning Strike Object (LSO) was suspended from the balloon. The LSO had inside all sorts of instrumentation to study the effects of a lightning strike in space in the absence of ground.

Also, an Electric Field Mill (EFM) was suspended from the balloon about 100 feet from it to measure the space charge above the triggering site. At same time, there were several EFM in the triggering area. There was one over the caboose (control room), other over the water (in the lagoon), other near the Atmospheric Science Field Laboratory building, and many others over the KSC and Cape Canaveral area.

In addition to electric field measurements, wind velocity and direction and amount of precipitation were recorded to correlate all this data to the triggered lightning phenomena.

Nearby the triggering site, there was a distribution power line (See figure 5). This line was not energized. The end sides of this line were terminated with resistors equal to the characteristic impedance of it to avoid reflections. A wave form recorder was connected to the top phase of the line in order to record induced voltages and currents at the line due to natural or triggered lightnings. Also induced voltages and currents were recorded using a resistor voltage divider, a Pearson coil, digital oscilloscope, waveform recorder, and digital computer.

DESCRIPTION OF WORK

ELECTRIC FIELD MILL CALIBRATION

The first phase of this experiment was to set up the Electric Field Mills to be operative. The EFM network was used to monitor charge cells over the triggering site. (see description of an EFM in appendix 1).

Each EFM was required to be cleaned and calibrated. To clean the EFM it was disconnected from its power supply and both the stator and rotor blades were thoroughly cleaned with a piece of cloth and solvent, if required. To calibrate an EFM it was required a high voltage power supply; a conducting, 30 cm diameter, round, flat, reinforced plate; and a digital voltmeter (See figure 6). The conducting plate was placed 30 cms above the ground surfaces and voltages of +1,000 and -1,000 were applied to the plate. The output of the EFM was monitored and adjusted to obtain a reading of 2.5 volts. The mill output voltage was converted to electric fields in volts per meter (V/m) by multiplying by 1500. The 2.5 volts reading was equivalent as having an electric field of 3750 V/m. Also, magnets were aligned to make the pick-up coil signal to coincide with the peak of the sinusoidal output voltage of the non inverted stator plate segments.

All EFM were connected to a multi channel strip chart recorder to obtain a visual reading of the electric field over the launching area. The multi channel strip chart was also calibrated.

ELECTRIC FIELD MILL SYSTEM CALIBRATION

The Electric Field Mill System as a whole system needs to be calibrated also in order to obtain correct electric field measurements. Calibration is accomplished by placing either a conducting plate of enough diameter or a long horizontal conductor over each Field Mill, one at a time. A variable DC high voltage power supply is connected to the conductor or plate. The distance from the conductor or plate to ground is recorded. The output voltage of the Filed Mill is recorded for different values of DC voltage applied. It is expected a linear relation between the applied voltage and the E.F.M. output.

Launa Maiers from NASA/Computer System Corporation came with the idea of doing system calibration using a cage as shown in figure 7. This cage is one meter long in all directions (one cubic meter) with a conducting screen in the top. It also has seven copper conductors at equal spacing and interconnected with two 15 megohms resistors in series. (See figure 7). The top screen is also connected to the top most conductor through two 15 megohms resistors in series. The lower conductor is connected to ground through two 15 megohms resistors in series.

To perform the calibration, the cage is positioned as shown in figure 8 and the DC high voltage power supply is connected between the top screen and ground. The conductors and resistors will make the voltage gradient to vanish uniformly from maximum at the top screen to zero at ground level. In this way, there will be no side effect from objects near the Electric Field Mill.

The method was used on an E.F.M. near the A.S.F.L. building (See figure 9). A variable power supply was connected between the top screen and ground. A digital voltmeter was connected to the output of the Field Mill, and other between the conductor near to ground and ground. This last voltmeter was suppose to be reading 1/8 of the electric field value. A high voltage probe was used to measure the voltage at the top screen (electric field value). The experiment was performed three times. Results are tabulated in Tables 1, 2, and 3.

Results were arranged on graph form (graphs 1 to 9). The relation between field values and field mill output seems to be quite linear. However, the intercept (output value at field equal to zero) is not zero. Also, the relation between tap voltage and output voltage is not linear. Electric field value is not the tap voltage multiplied by 8 as expected.

During the experiment it was observed that when a person walked near the set up, about 5 feet or less, the output voltage from the Electric Field Mill decreased. However, the voltage at the top screen seemed to be constant.

DISTRIBUTION POWER LINE

After the EFM network was working properly, the set up for the distribution power line near the launching pad (see figure 5) was done. Line terminators, Pearson coil, and a voltage divider were devised for current and voltage measurements.

Six 500 ohms high voltage resistors were used as line terminators, one for each phase and at each end of the line (see figure 5). These terminators prevents for current and voltage surges from bouncing from terminal to terminal at the power line. Surge bouncing changes substantially the voltage and current wave form.

For voltage measurements, a voltage divider consisting of one 5.5 Kohms high voltage, five 1.1 Kohms medium voltage, and one 3 ohms low voltage resistor were used (see figure 10).

The resistors were ordered to Lightning Technology Inc. Due to the special application, they had to be manufactured and a 13 weeks delay was anticipated. Meanwhile, low voltage resistors were put together to obtain the required values. Resistors and Pearson coil were installed as shown in figure 5. The wave form recorders and the line terminators were connected to the distribution power line.

Outputs from the voltage divider and from the Pearson coil were connected to optical transmitters as shown in figure 11. Fiber optics connected the transmitter to the receivers at the caboose. The receivers are inputs to digital oscilloscopes. The digitized signals are input to a wave form recorder. Finally, voltage and current signals are stored in a computer.

STORM DETECTOR

The Electric Field Mill located over the caboose is connected to what is called a Storm Detector. This equipment was set up by The Centre D'Estudes Nucleares De Grenoble (CENG) in summer 1987. It displays, in digital form, the electric field readings over the launching area. Also, it display in a paper strip in numerical form, the actual time (hour, minutes, and seconds) when the electric field changes + or - 1 Kv/m or more and the new electric field value. It displays values of + or - 1 to 9 corresponding to field values + or - over 2 to 10 Kv/m respectively.

An analysis of the data obtained from the Storm Detector was done using Multiplan. Results are shown in Appendix II. From the analysis it was obtained the amount of time in seconds that the electric fields were over + 0r - 2 to 10 Kv/m during a 24 hour period.

When there is a sudden change in the electric field, the Storm Detector prints an *ORAGE* alarm. It means that a lightning was detected. For purpose of assigning an electric field value to the amount of time that the *ORAGE* alarm was in effect, the field value previous to the alarm was used. It is observed that if the continuous field value changes during the alarm period, it is interrupted and the new field value is printed. So the criteria used to assign the field value is completely logical.

By connecting a strip chart to the same Electric Field Mill where the Storm Detector is taking data, it was detected that every time the Storm Detector printed an *ORAGE* alarm a sudden spike was recorded at the strip chart. However, those spikes seemed to be produced by a source other than the field. It seems to be noise produced by other equipment at the caboose. Spikes are approximately of the same magnitude and equal time space, perhaps produced by the air conditioning equipment.

ELECTRONIQUE E.F.M.

The electric field mill over the caboose was furnished and installed by the French people from C.E.N.G. in summer 1987. This E.F.M. was in continuous operation from that day up to this day without any kind of maintenance. In order to check if the instrument was working properly, a recently calibrated E.F.M. was obtained from Pan Am and installed near the caboose. Both field mills were connected to a dual channel strip recorder and electric field data was recorded for several days, including several thunderstorms.

The results of this experiment can be summarized as follows. The electric fields readings of both instruments were almost identical. The Electronique field mill readings were a little more higher due to the higher location (this mill was over the caboose about 13 feet over ground level). The response of both field mills to changes in the electric field were similar.

Another E.F.M. of the type used at KSC was installed near the ASFL building on summer 1987. It was kept running without been connected to any record system up to June of this year. It was retired of operation for repair (replacement of the ball bearings, low pass filter, grounding brush, and operational amplifiers card). It was required to refurbish it completely.

It seems that the Electronique electric field mills requires less maintenance that the ones used now by KSC.

DATA ACQUISITION SYSTEM

A data acquisition system will be used to record data obtained from 1988 Rocket Triggered Lightning Program. Data will be recording according to the following table.

	range
1. one E.F.M. over the caboose	+/- 2 volts
2. one E.F.M. in land	+/- 2 volts
3. one E.F.M. in water	+/- 10 volts
4. one airbone E.F.M. at the balloon	+/- 5 volts
(two components)	+/- 5 volts
5. wind speed	10 volts
6. wind direction	11 volts
7. rain gauge	9 volts
8. timing	2 volts

When the 1988 RTLP finishes at the end of the summer, all data gathered with this system and that obtained from the H.P. system will be transferred to floppy disks and sent to the University of Puerto Rico for further analysis. Correlation of data and characterization of lightnings could be done.

Since the School of Engineering of the University of Puerto Rico prepared a proposal to the National Science Foundation to devise a Lightning Locating System and an Electric Field Mill System, the analysis of data as obtained from this year experiment could be the starting point to sustain that proposal.

No mater what happens with the proposal to NSF, the University of Puerto Rico will start collecting weather data. As part of the Technology Transfer Program from NASA to the University of Puerto Rico, it might be possible to take borrowed some electric field mills, rain buckets, and the data acquisition system to initiate the atmospheric research in Puerto Rico. Since the ASFL is active only from July to September, that equipment is not used for almost ten month.

CONCLUSIONS

The equipment to collect data for the 1988 Rocket Triggered Lightning Program was set up. Data collection will begin at the first weeks of August and will be extended up to the end of September.

So, up to the date of this report, August 5, no data is available to be included on it. Data will be sent at the end of the RTLP to the University of Puerto Rico. All this data will be analyzed and a report will be prepared. The report will be sent to Mr. William Jafferis to NASA/Kennedy Space Center to compare our findings with those from other researchers. A copy of this report will also be sent to Dr. Loren D. Anderson to the University of Central Florida to be included as an appendix to this report.

APPENDIX I

ELECTRIC FIELD MILL

A. Principle of Operation

The earth is considered a conductor and, therefore, static electric fields will be perpendicular to the earth's surface. If a metal plate is suspended above the earth and connected to the earth by a conductor and a resistor as shown in figure 12, any overhead negative (or positive) field will cause plus (or minus) charge to move into the plate until the field bellow it is zero.

If another metal plate is suspended over this plate and also connected to earth by a conductive wire, plus (or minus) charges will flow into it until the field below it is zero. This will release the charge on the lower plate and this charge will flow back to the earth as illustrated in figure 13. If this upper plate were to continuously cover and uncover the lower plate, charges would continuously flow back and forth though the resistor. This current flowing though the resistor can be measured as the resulting voltage across the resistor. The magnitude of this voltage would be proportional to the magnitude of the overhead field. This principle affords a method of constructing an electric strength meter. This is the principle upon which the Electric Field Mills measure electric fields.

In figure 14, it is shown the shape of the upper plate as seen from the top. It looks like a Dutch windmill and, maybe that is the reason they are called field mills. These top plates or rotor rotates at 1800 R.P.M. The bottom plate or stator, is made up of eight pie shape segments (see figure 15). Every other segment is connected electrically and each four segments are grounded through a separate resistor to ground (See figure 16). At certain position, the rotor will exactly cover four stator segments leaving four segments fully exposed to overhead electric fields. For the four segments covered, charge will flow out through their resistor and for the four exposed segments, charge flows into the plates through their resistor. Each rotation the rotor exposes or covers a stator segment plate four times. Therefore, a stationary overhead electric field will produce a 120 cycle per second alternating voltage across both resistors. In order for the differential amplifier to know the polarity of the overhead field or voltage phase, a sensor must know the position of the rotor, or when a set of four blades, or the other, are being covered. This is accomplished by small magnets attached to the rotor shaft and a pick-up coil that senses the magnetic field generated (see figure 18).

Since the induced currents in the resistors are proportional to the overhead field, the field mills have to be calibrated in order to make a quantitative measurement of the field. The constant of proportionality is partially dependent on the "form factor" of the field mill. Ambient fields are altered or distorted when metallic conductors are placed into their field region. Metallic conductor will enhance electric fields (see figure 17), in their general area and in particular, at sharp points or edges of the conductor where induced charges collect.

To calibrate the electric field mill, a known uniform electric field must be available. This can be accomplished by placing a flat metallic plate over the mill and charging it to a known voltage value (See figure 18). Assuming a parallel plate capacitor between the calibration plate and the earth, the electric field can be calculated and from this the scale factor for the mill can be calculated.

After the current through the resistors has been detected and rectified, it is smoothed out by means of a low pass filter. Field changes having a rise time in excess of 0.1 second are filtered out. Changes faster than this occur during lightning discharges.

APPENDIX II

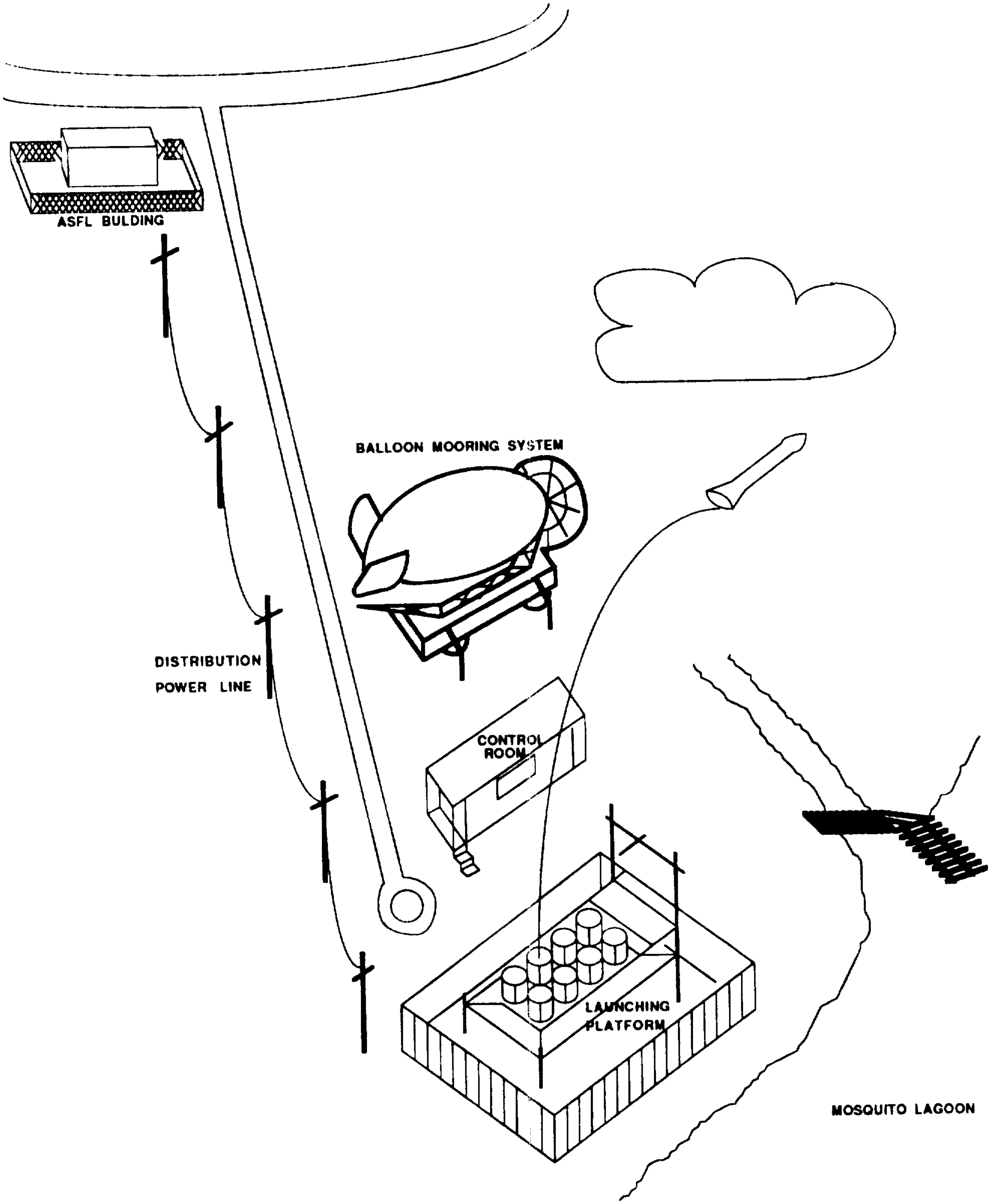
STORM DETECTOR

At the top of the caboose there is installed an Electric Field Mill. This field mill is connected to what is called a Storm Detector. This detector prints the time of the day when the electric field changes +/- 1 KV or more and the electric field value. It also prints *ORAGE* when the field changes abruptly. The print will be:

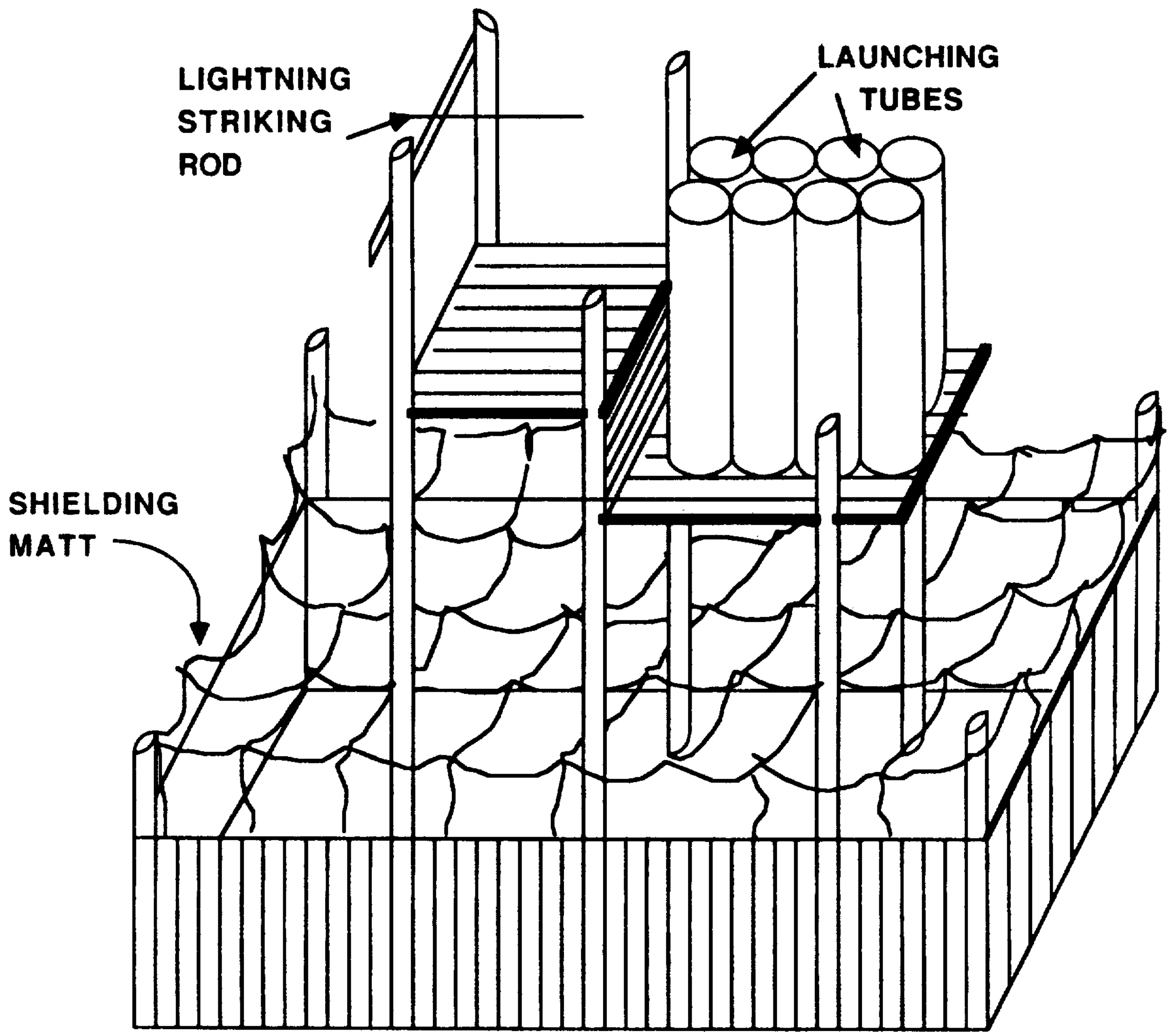
print	field value is greater than
--	--
--	--
5	6 KV
4	5 KV
3	4 KV
2	3 KV
1	2 KV
	field value is less than
-1	-2 KV
-2	-3 KV
-3	-4 KV
-4	-5 KV
-5	-6 KV
--	--
--	--
--	--
ORAGE	sudden change

One day of data from this Storm Detector is summarized on tables 4 to 11. On these tables, data was analyzed and is presented as the total amount of time that the field value exceeds certain field value during a storm. On graph 10 it is shown the time distribution of electric field during the storm.

FIGURES

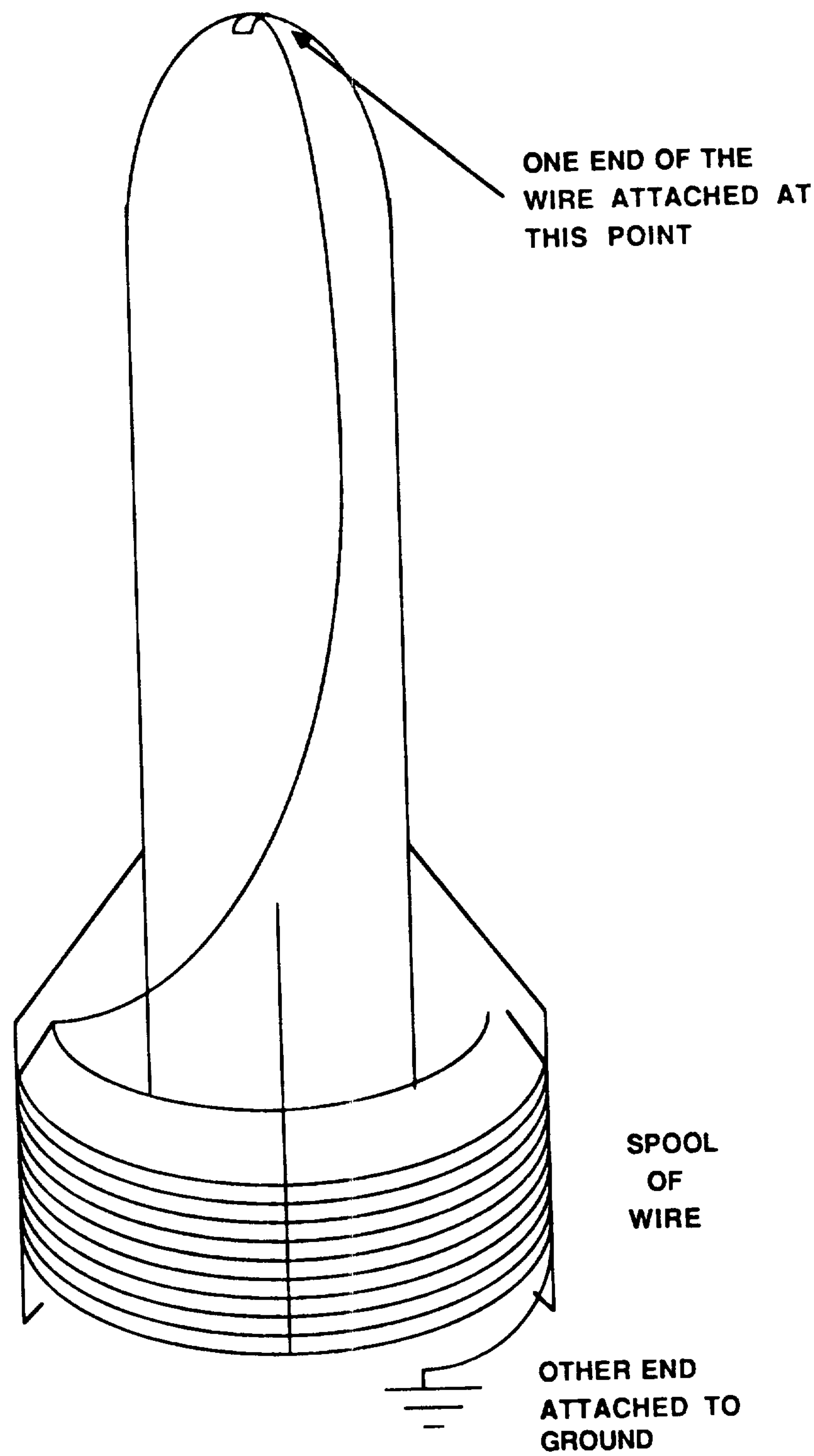


ATMOSPHERIC SCIENCE FIELD LABORATORY
FIGURE 1



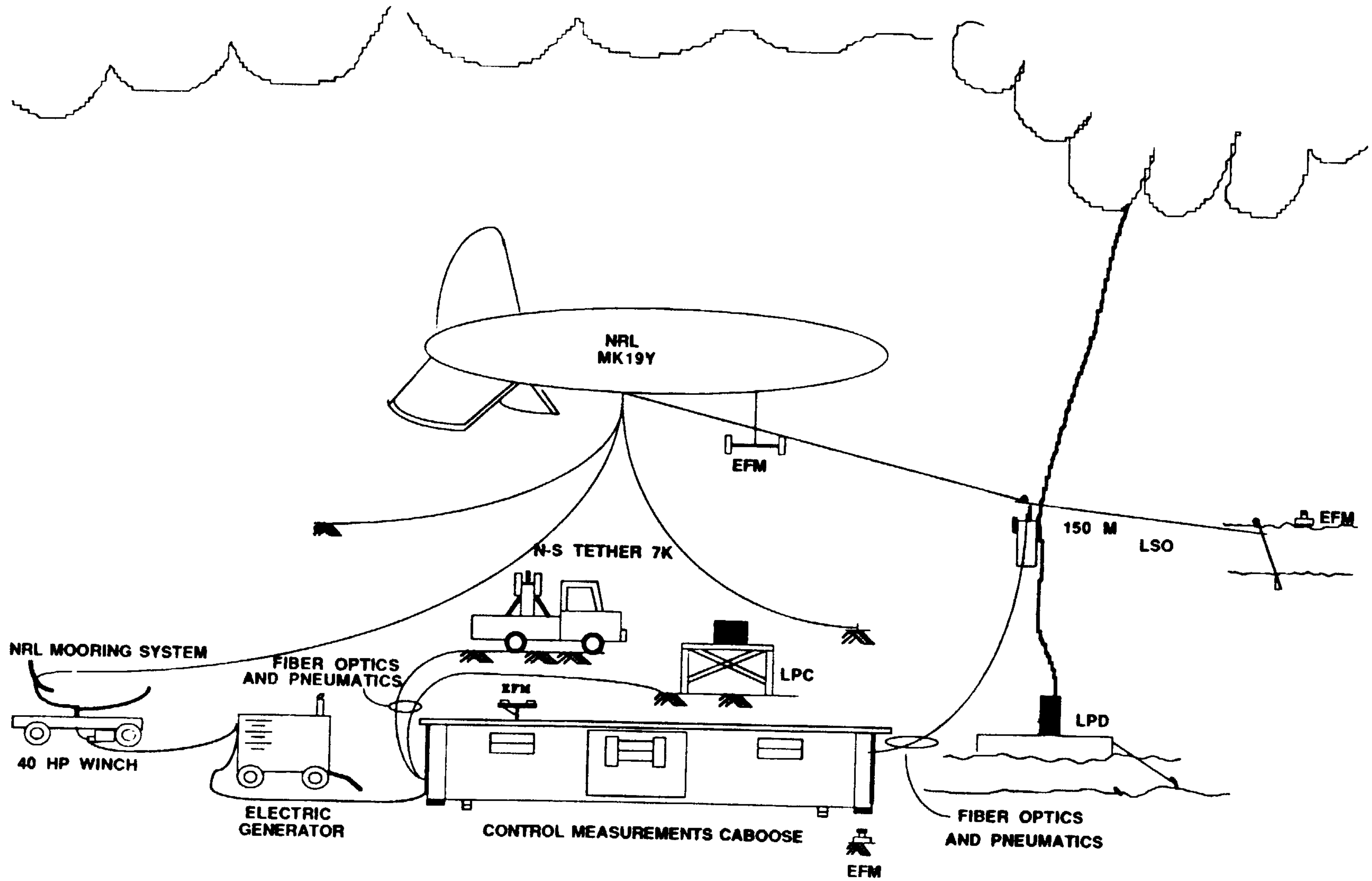
ROCKET TRIGGERED LIGHTNING SITE

FIGURE 2



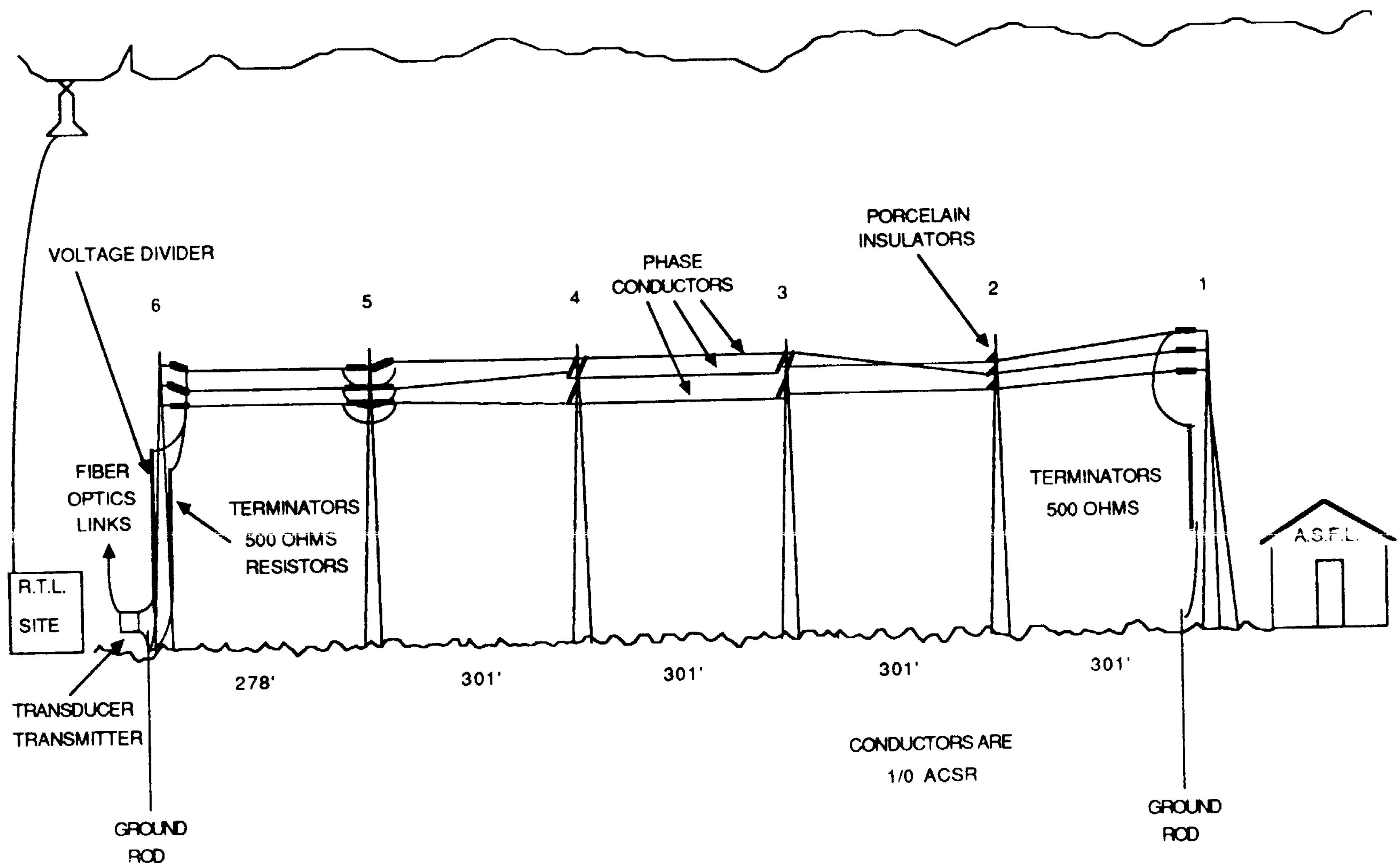
ROCKET WITH SPOOL OF WIRE

FIGURE 3



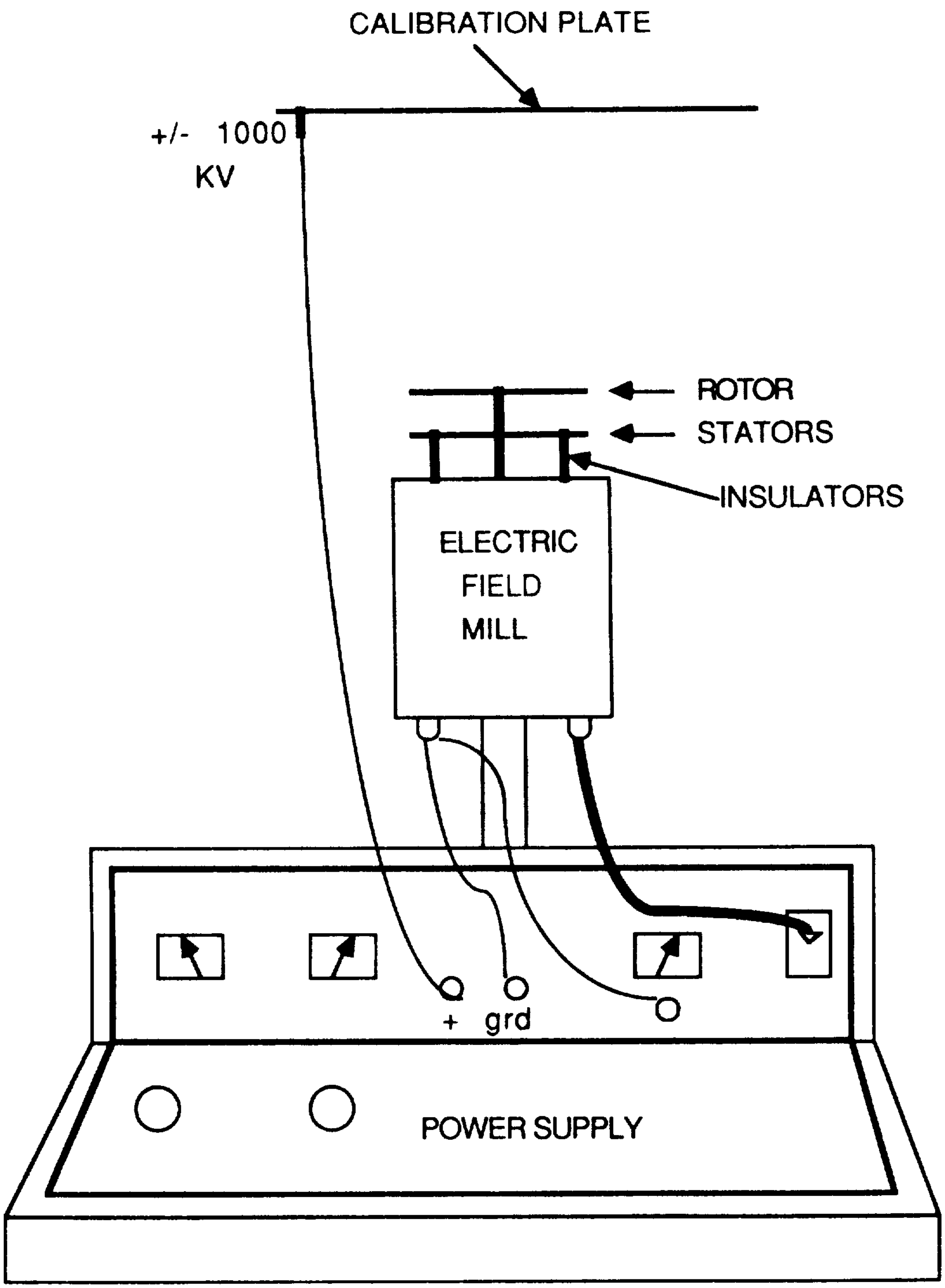
KSC / NRL AFWAL / ONERA - CENG

FIGURE 4



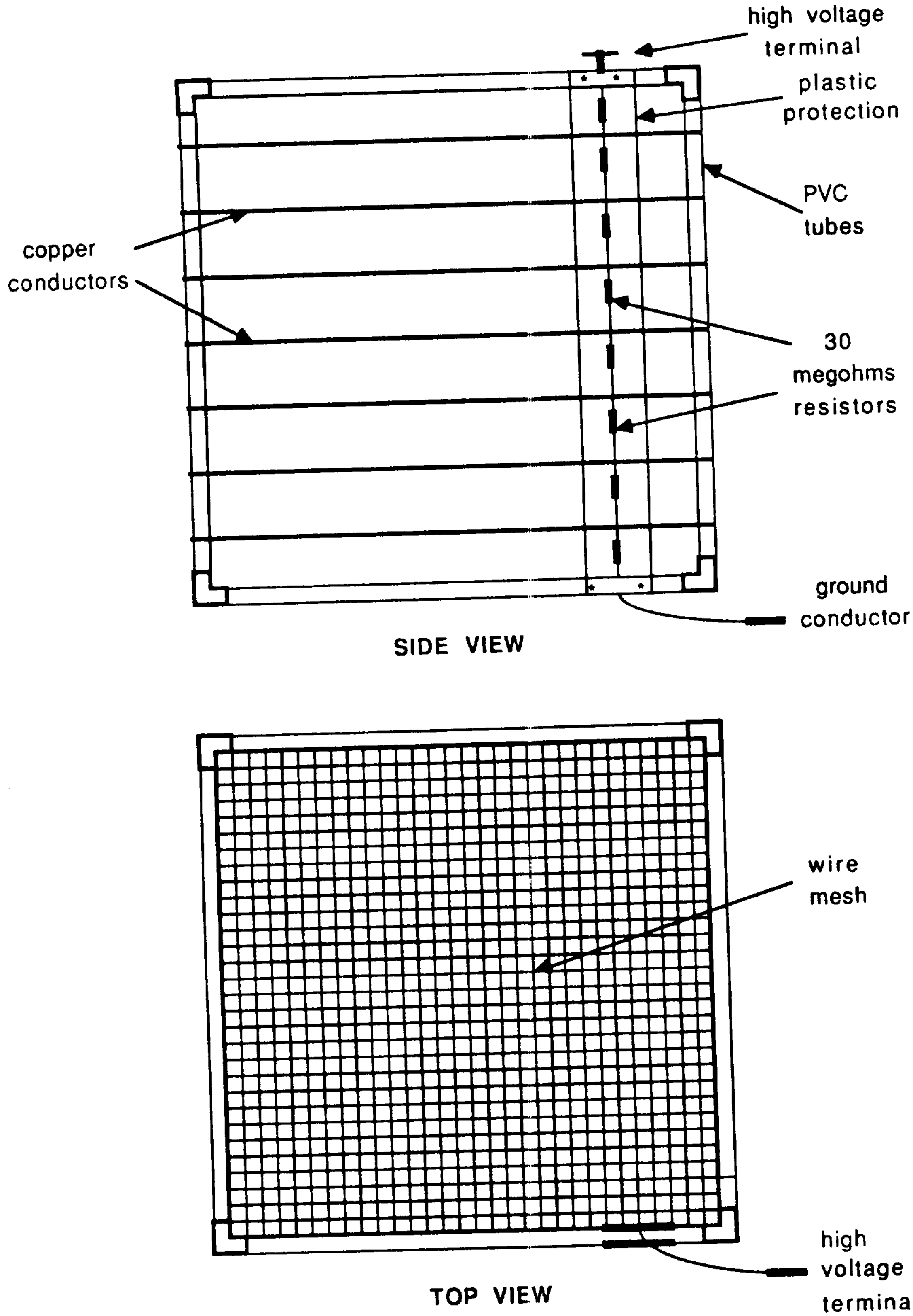
DISTRIBUTION POWER LINE CONFIGURATION
(NOT TO SCALE)

FIGURE 5



ELECTRIC FIELD MILL CALIBRATION

FIGURE 6

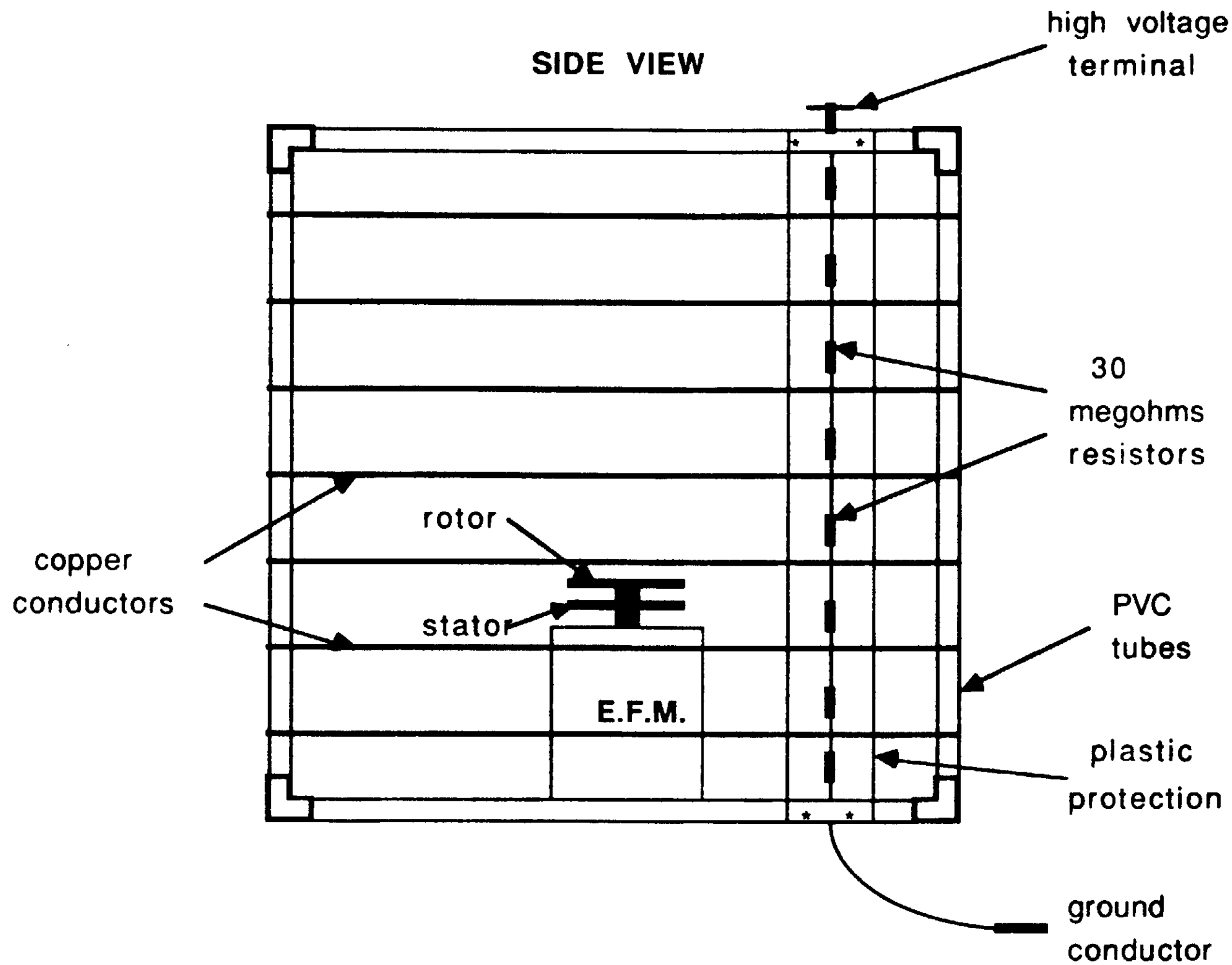


E.F.M. CALIBRATION CAGE

FIGURE 7

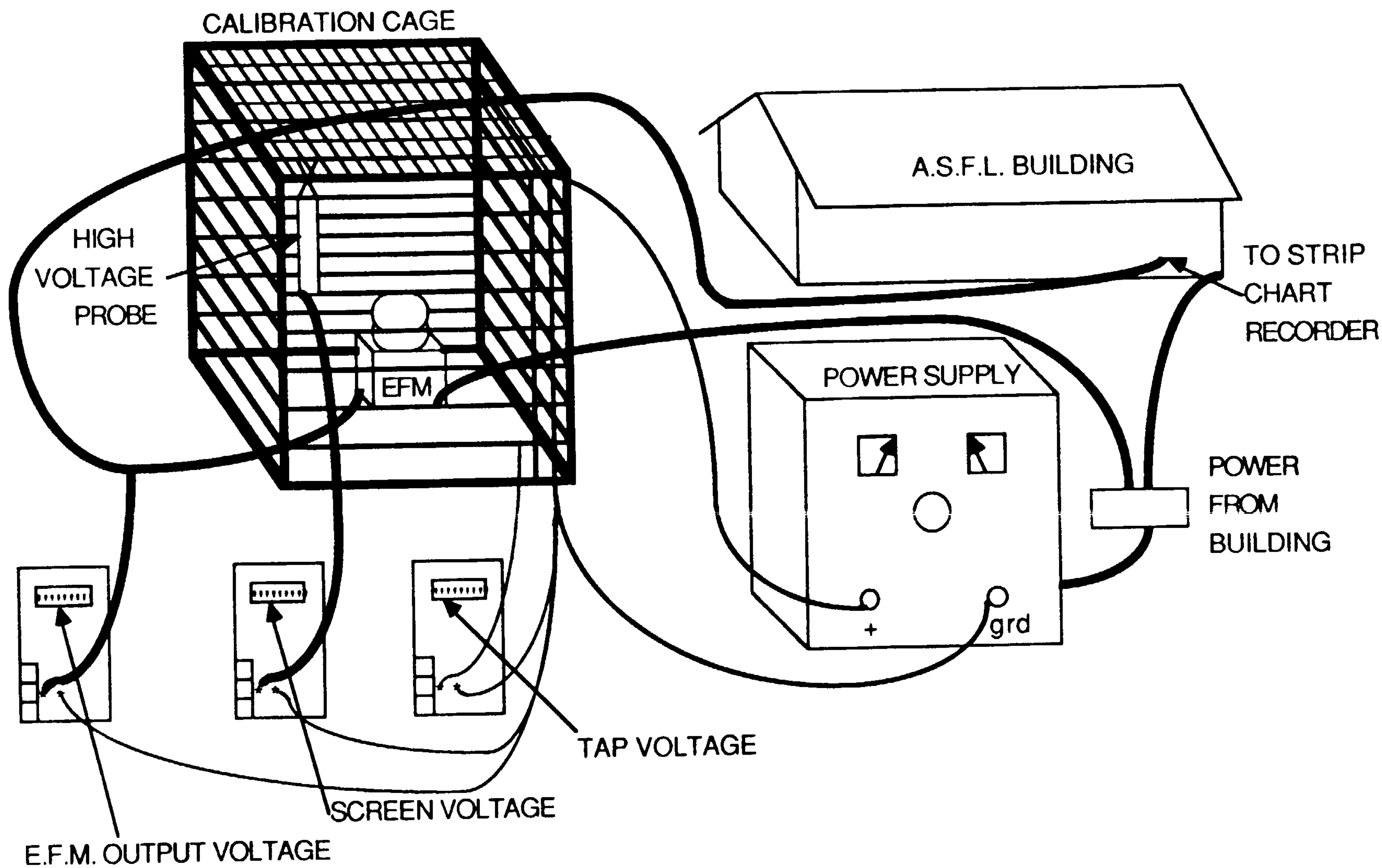
C.4

SIDE VIEW



POSITION OF THE E.F.M.
IN THE CALIBRATION CAGE

FIGURE 8



CALIBRATION SITE
FIGURE 9

TERMINATORS AND VOLTAGE DIVIDER

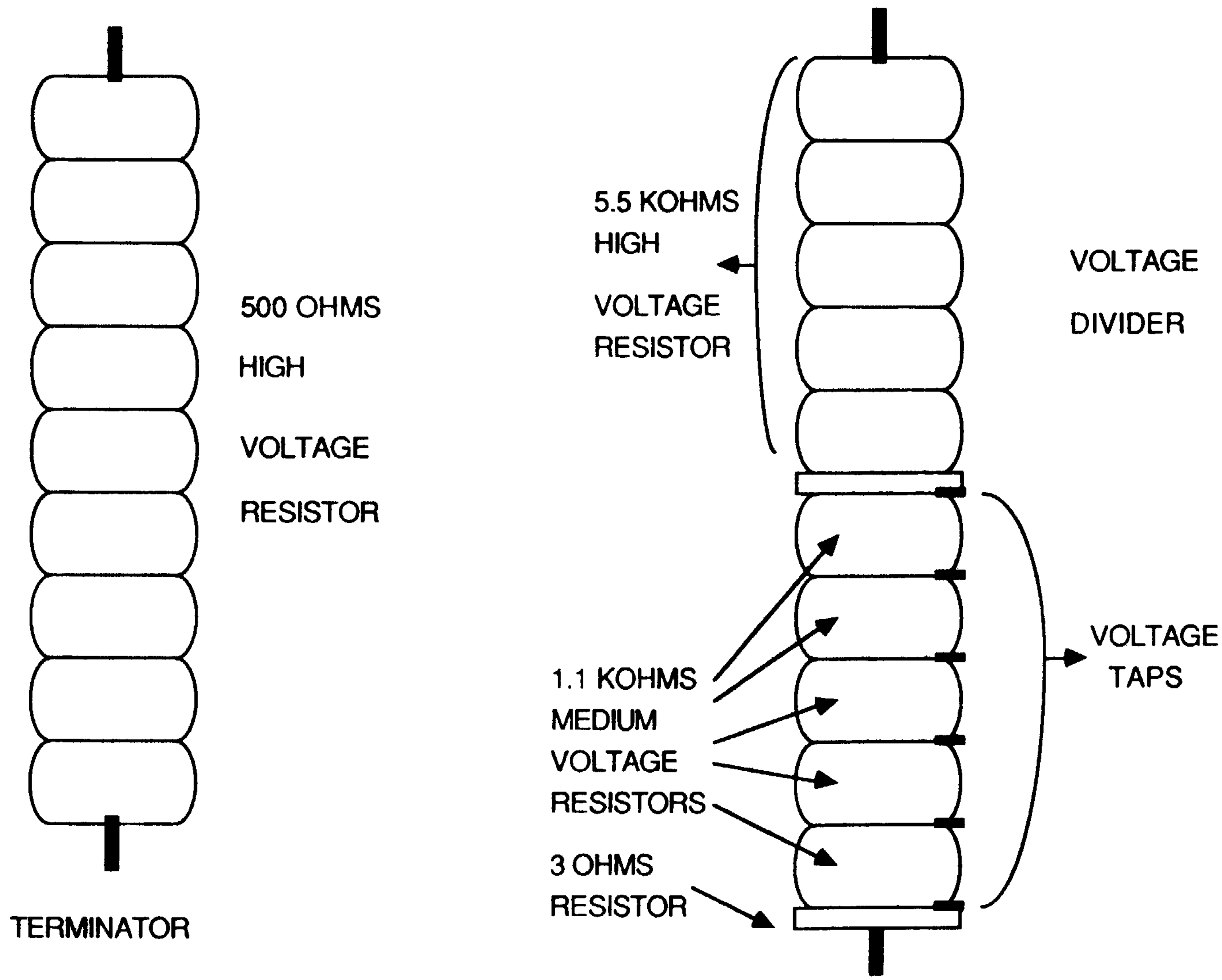
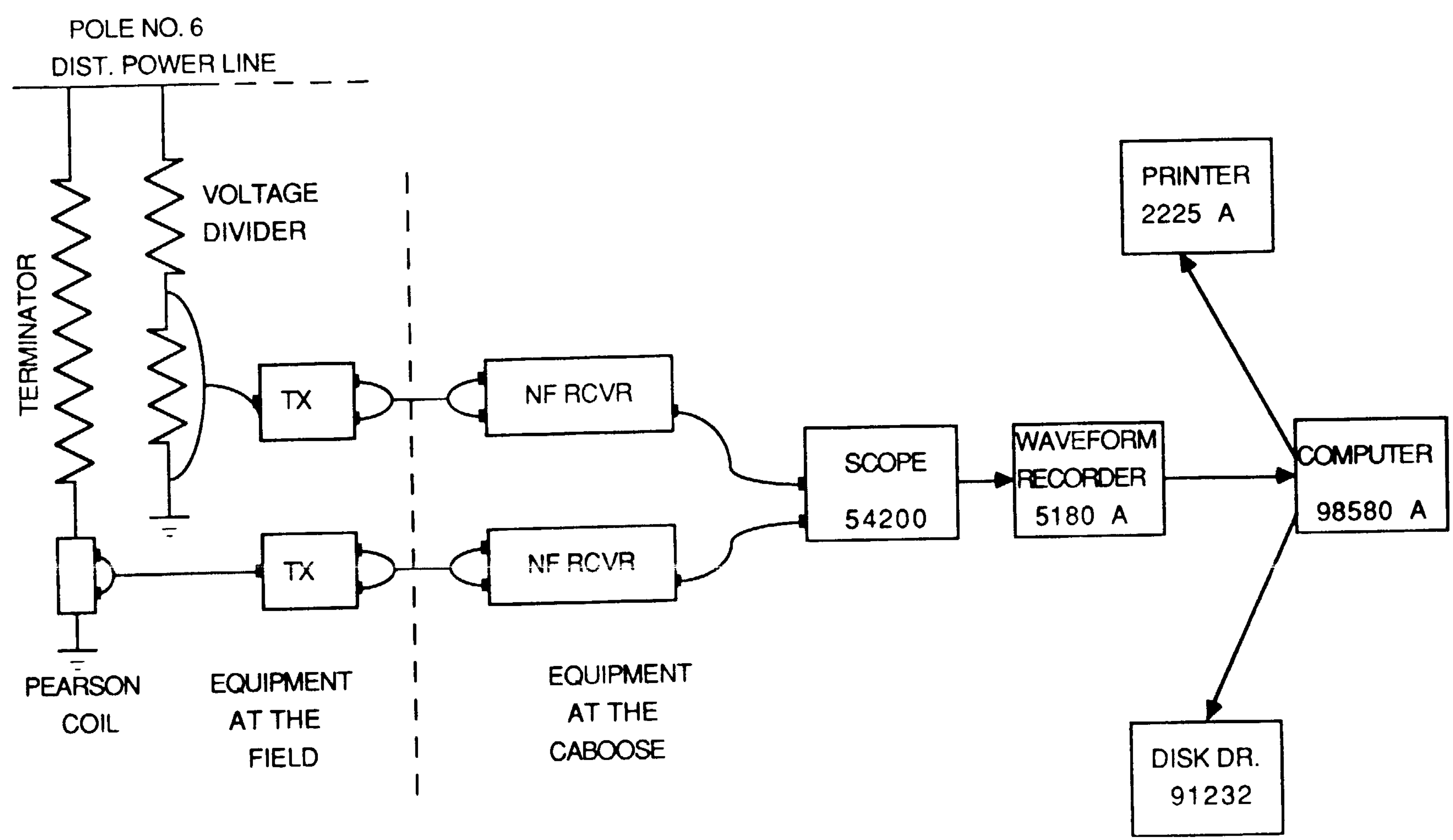


FIGURE 10



INSTRUMENTATION USED TO MEASURE INDUCED VOLTAGES AND CURRENTS AT THE DISTRIBUTION POWER LINE

FIGURE 11

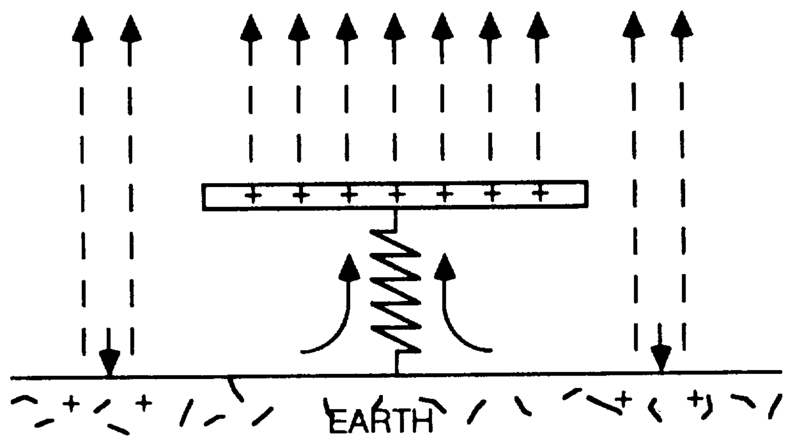


FIGURE 12

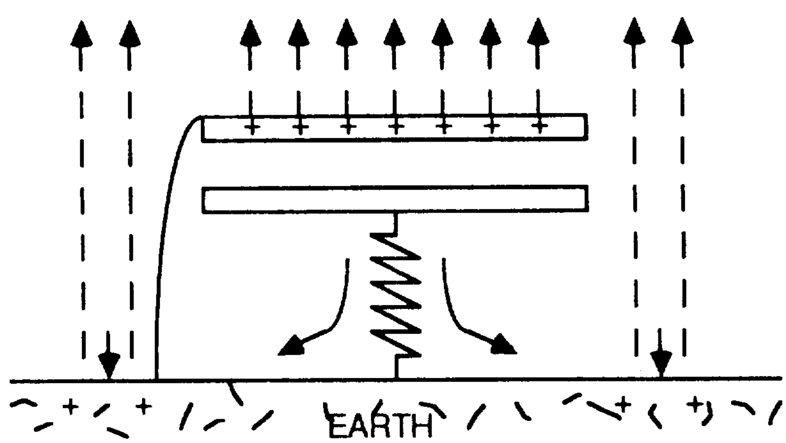


FIGURE 13

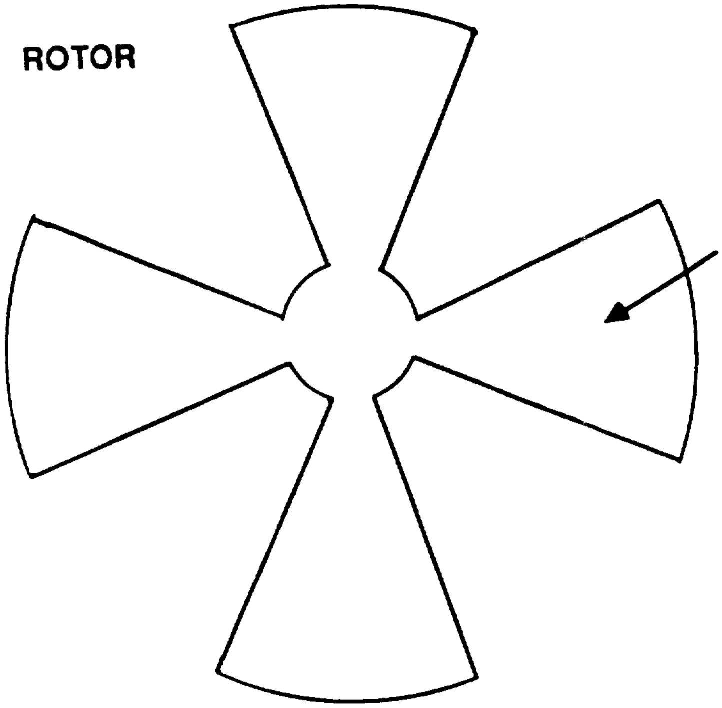


FIGURE 14

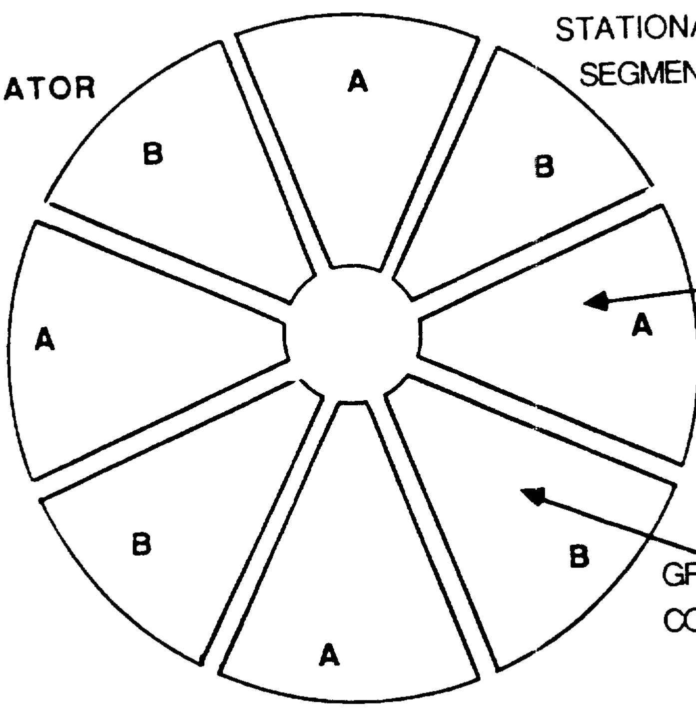


FIGURE 15

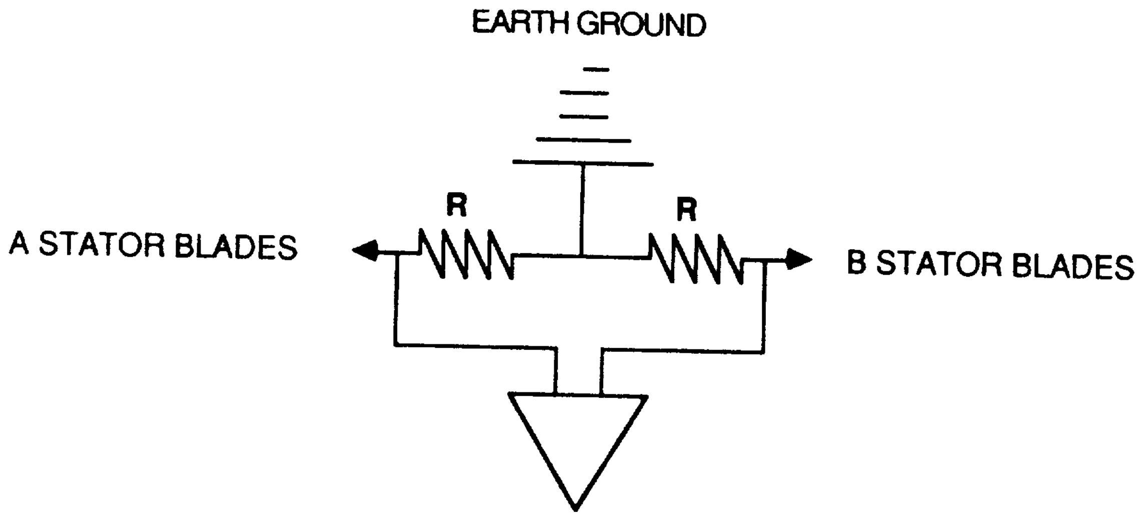


FIGURE 16

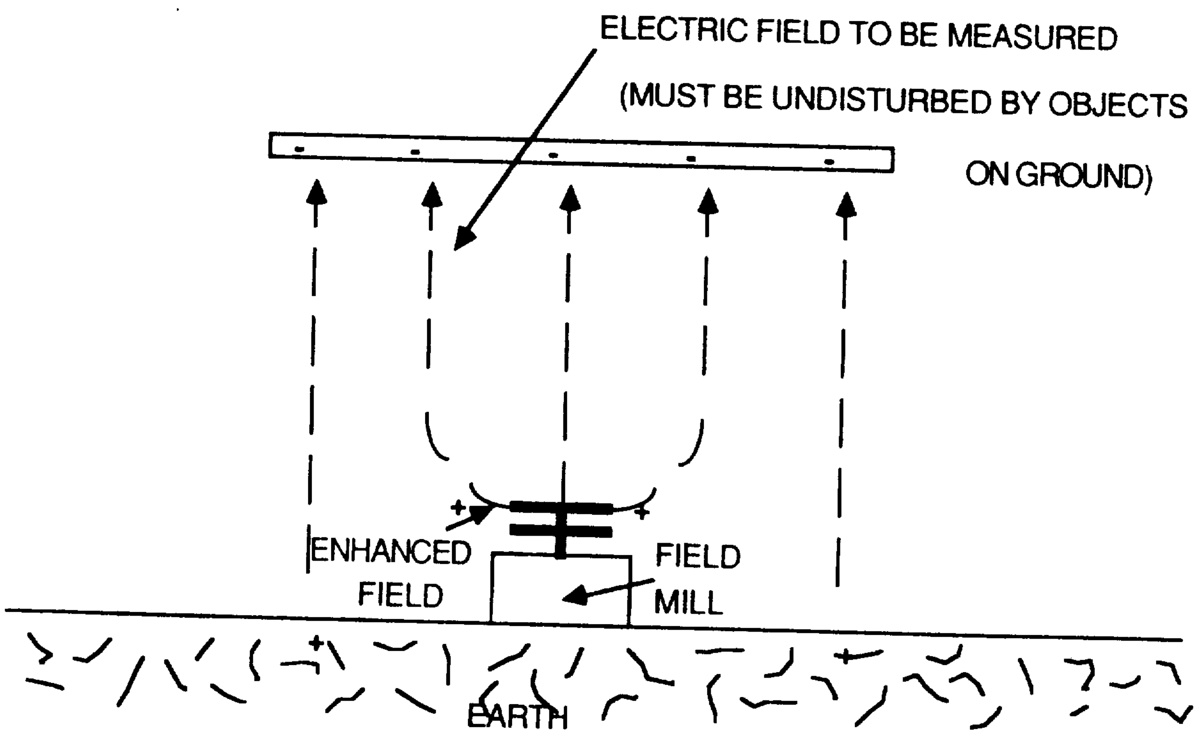
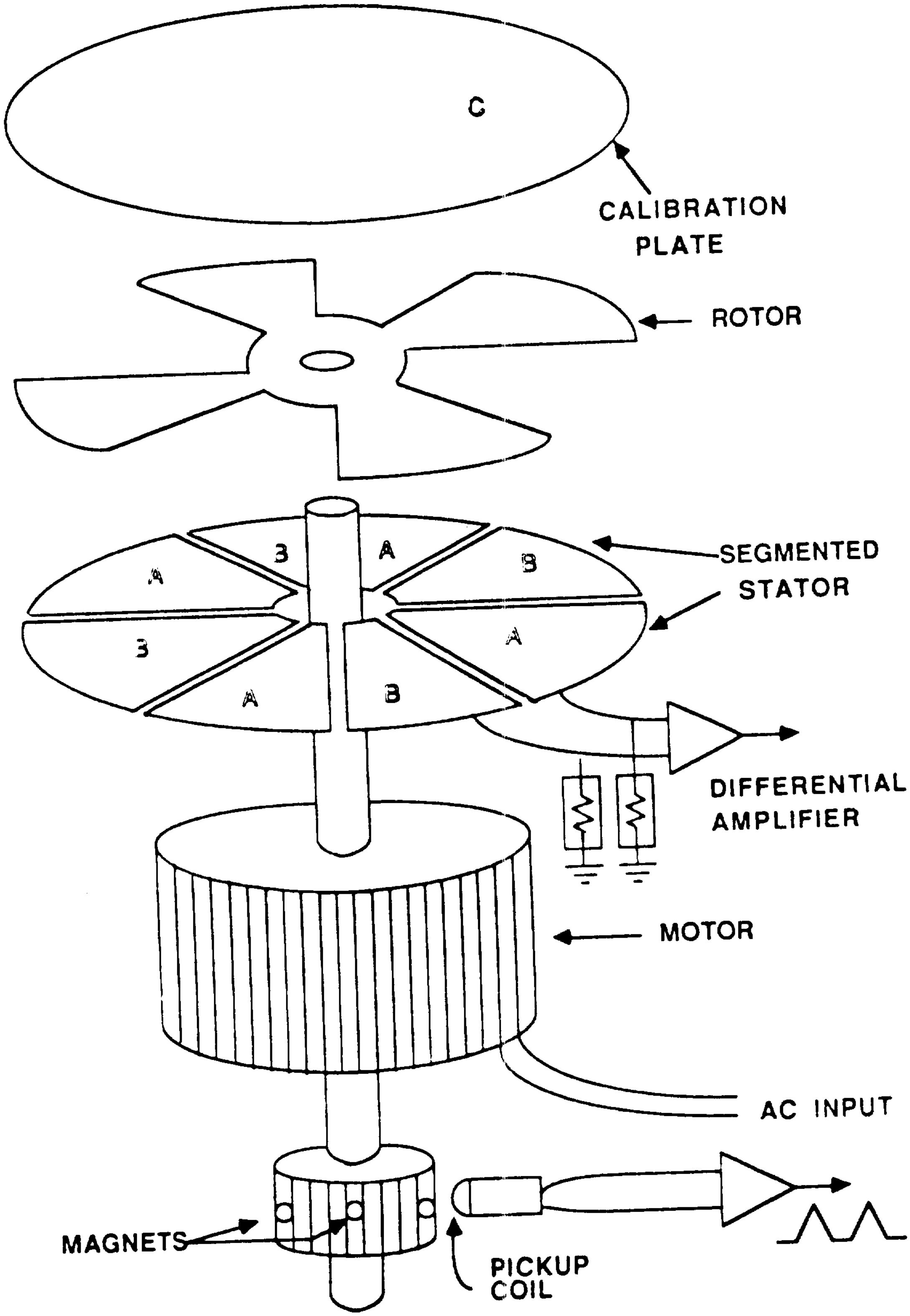


FIGURE 17



ELECTRIC FIELD MILL MECHANICAL PARTS

FIGURE 18

TABLES

	A	B	C	D	E
1		ELECTRIC FIELD MILL CALIBRATION			
2					
3	PLATE VOLT.	MEASURED	OUTPUT	CALC. OUTP.	ERROR
4	KV	VOLTAGE	VOLTAGE	VOLTAGE	VOLTAGE
5					
6	0.0	0.00	0.000		0.000
7	4.0				
8	5.0	41.00	2.212	2.357	-0.145
9	6.0	48.00	2.732	2.802	-0.070
10	7.0	55.00	3.282	3.248	0.034
11	8.0	61.00	3.748	3.694	0.055
12	9.0	67.00	4.240	4.139	0.101
13	10.0	72.00	4.604	4.585	0.019
14	11.0	77.00	5.053	5.030	0.023
15	12.0	81.00	5.449	5.476	-0.027
16	13.0	87.00	6.016	5.922	0.095
17	14.0	91.00	6.400	6.367	0.033
18	15.0	95.00	6.825	6.813	0.012
19	16.0	98.00	7.155	7.258	-0.103
20	17.0	104.00	7.746	7.704	0.042
21	18.0	107.00	8.101	8.150	-0.048
22	19.0	112.00	8.636	8.595	0.041
23	20.0	115.00	9.032	9.041	-0.009
24	21.0	118.00	9.467	9.486	-0.019
25	22.0	122.00	9.898	9.932	-0.034
26	23.0	126.00	10.389	10.378	0.012
27	24.0	129.00	10.800	10.823	-0.023
28					
29					
30			FIRST TRIAL		

TABLE 1

	A	B	C	D	E
1		ELECTRIC FIELD MILL CALIBRATION			
2					
3	PLATE VOLT.	MEASURED	OUTPUT	CALC. OUTP.	ERROR
4	KV	VOLTAGE	VOLTAGE	VOLTAGE	VOLTAGE
5					
6	0.0	0.00	0.000		
7	4.3	41.00	2.278	2.217	0.061
8	5.0	44.00	2.493	2.532	-0.039
9	6.0	51.00	3.002	2.983	0.019
10	7.0	56.00	3.410	3.433	-0.023
11	8.0	61.00	3.847	3.883	-0.036
12	9.0	66.00	4.264	4.333	-0.069
13	10.0	73.00	4.823	4.783	0.040
14	11.0	78.00	5.273	5.234	0.039
15	12.0	83.00	5.772	5.684	0.088
16	13.0	86.00	6.109	6.134	-0.025
17	14.0	91.00	6.544	6.584	-0.040
18	15.0	95.00	6.985	7.034	-0.049
19	16.0	99.00	7.363	7.485	-0.122
20	17.0	105.00	7.985	7.935	0.050
21	18.0	109.00	8.400	8.385	0.015
22	19.0	112.00	8.900	8.835	0.065
23	20.0	115.00	9.320	9.285	0.035
24	21.0	117.00	9.770	9.736	0.034
25	22.0	121.00	10.200	10.186	0.014
26	23.0	125.00	10.660	10.636	0.024
27	24.0	128.00	10.990	11.086	-0.096
28	25.0	132.00	10.990	11.536	-0.546
29					
30					
31			SECOND TRIAL		

TABLE 2

	A	B	C	D	E
1		ELECTRIC FIELD MILL CALIBRATION			
2					
3	PLATE VOLT.	MEASURED	OUTPUT	CALC. OUTP.	ERROR
4	KV	VOLTAGE	VOLTAGE	VOLTAGE	VOLTAGE
5					
6	0.0	0.00	0.000		
7	4.8	39.60	2.384	2.257	0.127
8	5.0	40.40	2.428	2.350	0.078
9	6.0	45.50	2.795	2.818	-0.023
10	7.0	51.50	3.254	3.286	-0.032
11	8.0	58.30	3.801	3.754	0.048
12	9.0	63.40	4.236	4.221	0.015
13	10.0	67.90	4.632	4.689	-0.057
14	11.0	73.30	5.123	5.157	-0.034
15	12.0	78.10	5.566	5.625	-0.059
16	13.0	84.40	6.183	6.093	0.091
17	14.0	89.60	6.693	6.560	0.133
18	15.0	92.20	6.962	7.028	-0.066
19	16.0	96.10	7.378	7.496	-0.118
20	17.0	100.60	7.860	7.964	-0.104
21	18.0	105.40	8.380	8.432	-0.052
22	19.0	110.20	8.960	8.899	0.061
23	20.0	114.60	9.460	9.367	0.093
24	21.0	117.40	9.789	9.835	-0.046
25	22.0	121.60	10.297	10.303	-0.006
26	23.0	126.00	10.837	10.771	0.067
27	23.9	127.10	10.987	11.192	-0.205
28					
29					
30			THIRD TRIAL		

TABLE 3

	A	B	C	D	E	F	G	H	I
1								EFM at caboose 01/07/1988-01	
2	HH	MM	SS	Value	sec	orage	num		
3	17	1	0	99					
4	17	3	9	-1	69	0	0	Total of seconds electric field was	
5	17	3	13	96	65	65	6	greater than 6 Kv	0
6	17	4	18	-1	26	0	0		
7	17	4	34	92	10	10	2	greater than 5 Kv	0
8	17	4	44	-1	40	0	0		
9	17	5	1	92	23	23	2	greater than 4 Kv	0
10	17	5	24	-2	20	0	0		
11	17	5	28	92	16	16	2	greater than 3 Kv	0
12	17	5	44	-1	30	0	0		
13	17	5	55	92	19	19	2	greater than 2 Kv	0
14	17	6	14	-1	23	0	0		
15	17	6	21	92	16	16	2	greater than 1 Kv	0
16	17	6	37	-2	45	0	0		
17	17	6	48	94	34	34	4	greater than 0 Kv	0
18	17	7	22	-2	22	0	0		
19	17	7	43	91	1	1	1	greater than -1 Kv	867
20	17	7	44	-1	6	0	0		
21	17	7	45	91	5	5	1	greater than -2 Kv	551
22	17	7	50	-1	12	0	0		
23	17	8	2	-2	22	0	0	greater than -3 Kv	235
24	17	8	10	92	14	14	2		
25	17	8	24	-1	30	0	0	greater than -4 Kv	34
26	17	8	37	92	17	17	2		
27	17	8	54	-1	9	0	0	greater than -5 Kv	6
28	17	9	3	-2	15	0	0		
29	17	9	4	92	14	14	2	greater than -6 Kv	0
30	17	9	18	-2	26	0	0		
31	17	9	31	92	13	13	2		
32	17	9	44	-1	15	0	0	Total of seconds of orages	301
33	17	9	58	91	1	1	1		
34	17	9	59	-1	5	0	0	Number of orages	42
35	17	10	0	91	4	4	1		
36	17	10	4	-2	10	0	0		
37	17	10	14	-3	15	0	0		
38	17	10	25	92	4	4	2		
39	17	10	29	-3	13	0	0		
40	17	10	42	-4	6	0	0		
41	17	10	48	-1	29	0	0		
42	17	10	52	92	25	25	2		
43	17	11	17	-1	12	0	0		
44	17	11	26	92	3	3	2		
45	17	11	29	-2	41	0	0		
46	17	11	53	92	17	17	2		
47	17	12	10	-1	10	0	0		
48	17	12	20	92		0	2		
49									
50									
51					852	**TABLE 4**			
52									

	A	B	C	D	E	F	G	H	I
1								EFM at caboose 01/07/1988-02	
2	HH	MM	SS	Value	sec	orage	num		
3	17	12	20	92					
4	17	12	40	-1	18	0	0	Total of seconds electric field was	
5	17	12	58	91	0	0	1	greater than 6 Kv	0
6	17	12	58	-1	0	0	0		
7	17	12	58	1	41	0	0	greater than 5 Kv	0
8	17	12	59	93	40	40	3		
9	17	13	39	1	37	0	0	greater than 4 Kv	0
10	17	13	51	92	25	25	2		
11	17	14	16	-1	11	0	0	greater than 3 Kv	0
12	17	14	18	92	9	9	2	-	
13	17	14	27	-2	9	0	0	greater than 2 Kv	78
14	17	14	36	-1	47	0	0		
15	17	14	45	92	38	38	2	greater than 1 Kv	78
16	17	15	23	-1	271	0	0		
17	17	15	40	106	254	254	16	greater than 0 Kv	78
18	17	19	54	-1	16	0	0		
19	17	19	57	92	13	13	2	greater than -1 Kv	2143
20	17	20	10	-1	231	0	0		
21	17	20	25	104	216	216	14	greater than -2 Kv	1218
22	17	24	1	-2	46	0	0		
23	17	24	8	94	39	39	4	greater than -3 Kv	293
24	17	24	47	-1	41	0	0		
25	17	25	9	92	19	19	2	greater than -4 Kv	90
26	17	25	28	-2	135	0	0		
27	17	25	36	94	127	127	4	greater than -5 Kv	46
28	17	26	31	94	72	72	4		
29	17	27	43	-4	37	0	0	greater than -6 Kv	4
30	17	27	59	92	21	21	2		
31	17	28	20	-1	75	0	0		
32	17	28	27	96	68	68	6	Total of seconds of orages	1217
33	17	29	35	-3	44	0	0		
34	17	29	48	93	31	31	3	Number of orages	89
35	17	30	19	-4	5	0	0		
36	17	30	20	91	4	4	1		
37	17	30	24	-5	4	0	0		
38	17	30	28	-6	46	0	0		
39	17	30	46	93	28	28	3		
40	17	31	14	-1	88	0	0		
41	17	31	16	97	86	86	7		
42	17	32	42	-6	3	0	0		
43	17	32	45	-7	33	0	0		
44	17	33	15	91	3	3	1		
45	17	33	18	-1	127	0	0		
46	17	33	21	99	124	124	9		
47	17	35	25	-2	13	0	0		
48	17	35	38	91		0	1		
49									
50									
51					2595				
52									

TABLE 5

	A	B	C	D	E	F	G	H	I
1								EFM at caboose 01/07/1988-02	
2	HH	MM	SS	Value	sec	orage	num		
3	17	35	38	91					
4	17	35	41	-1	17	0	0	Total of seconds electric field was	
5	17	35	42	91	16	16	1	greater than 6 Kv	0
6	17	35	58	-1	4	0	0		
7	17	36	2	-2	5	0	0	greater than 5 Kv	0
8	17	36	7	-3	11	0	0		
9	17	36	8	92	10	10	2	greater than 4 Kv	0
10	17	36	18	-1	10	0	0		
11	17	36	28	-2	5	0	0	greater than 3 Kv	0
12	17	36	33	-1	50	0	0		
13	17	36	35	94	48	48	4	greater than 2 Kv	38
14	17	37	23	-1	10	0	0		
15	17	37	33	-3	26	0	0	greater than 1 Kv	38
16	17	37	41	92	18	18	2		
17	17	37	59	-1	0	0	0	greater than 0 Kv	38
18	17	37	59	1	38	0	0		
19	17	38	8	94	29	29	4	greater than -1 Kv	684
20	17	38	37	-1	80	0	0		
21	17	39	1	96	56	56	6	greater than -2 Kv	432
22	17	39	57	-2	4	0	0		
23	17	40	1	-3	14	0	0	greater than -3 Kv	180
24	17	40	15	-1	18	0	0		
25	17	40	22	92	11	11	2	greater than -4 Kv	157
26	17	40	33	-3	27	0	0		
27	17	40	49	92	11	11	2	greater than -5 Kv	16
28	17	41	0	-1	16	0	0		
29	17	41	16	91	0	0	1	greater than -6 Kv	0
30	17	41	16	-1	6	0	0		
31	17	41	17	91	5	5	1		
32	17	41	22	-2	4	0	0	Total of seconds of orages	247
33	17	41	26	-1	28	0	0		
34	17	41	43	92	11	11	2	Number of orages	35
35	17	41	54	-3	17	0	0		
36	17	42	10	91	1	1	1		
37	17	42	11	-3	4	0	0		
38	17	42	11	91	4	4	1		
39	17	42	15	-3	11	0	0		
40	17	42	26	-4	10	0	0		
41	17	42	36	-1	7	0	0		
42	17	42	37	92	6	6	2		
43	17	42	43	-1	6	0	0		
44	17	42	49	-2	5	0	0		
45	17	42	54	-3	31	0	0		
46	17	43	4	92	21	21	2		
47	17	43	25	-4	6	0	0		
48	17	43	31	92		0	2		
49									
50									
51					717		**TABLE 6**		
52									

	A	B	C	D	E	F	G	H	I
1								EFM at caboose 01/07/1988-02	
2	HH	MM	SS	Value	sec	orage	num		
3								Total of seconds electric field was	
4	17	43	31	92	5	5	2	greater than 6 Kv	0
5	17	43	36	-5	23	0	0		
6	17	43	58	91	1	1	1	greater than 5 Kv	0
7	17	43	59	-1	19	0	0		
8	17	44	6	91	12	12	1	greater than 4 Kv	36
9	17	44	18	-1	16	0	0		
10	17	44	32	92	2	2	2	greater than 3 Kv	234
11	17	44	34	-2	5	0	0		
12	17	44	39	-3	9	0	0	greater than 2 Kv	421
13	17	44	48	-4	9	0	0		
14	17	44	57	-1	13	0	0	greater than 1 Kv	421
15	17	44	59	92	11	11	2		
16	17	45	10	1	26	0	0	greater than 0 Kv	421
17	17	45	32	92	4	4	2		
18	17	45	36	-1	41	0	0	greater than -1 Kv	299
19	17	45	39	92	38	38	2		
20	17	46	17	-1	8	0	0	greater than -2 Kv	178
21	17	46	25	-2	11	0	0		
22	17	46	33	91	3	3	1	greater than -3 Kv	57
23	17	46	36	-1	24	0	0		
24	17	46	49	91	11	11	1	greater than -4 Kv	41
25	17	47	0	1	72	0	0		
26	17	47	15	96	57	57	6	greater than -5 Kv	32
27	17	48	12	2	74	0	0		
28	17	49	23	92	3	3	2	greater than -6 Kv	23
29	17	49	26	2	22	0	0		
30	17	49	48	1	8	0	0		
31	17	49	50	92	6	6	2	Total of seconds of orages	255
32	17	49	56	2	34	0	0		
33	17	50	17	92	13	13	2	Number of orages	40
34	17	50	30	2	25	0	0		
35	17	50	44	92	11	11	2		
36	17	50	55	3	36	0	0		
37	17	51	16	92	15	15	2		
38	17	51	31	2	23	0	0		
39	17	51	43	92	11	11	2		
40	17	51	54	2	11	0	0		
41	17	52	5	1	34	0	0		
42	17	52	12	92	27	27	2		
43	17	52	39	1	11	0	0		
44	17	52	42	92	8	8	2		
45	17	52	50	1	36	0	0		
46	17	53	9	92	17	17	2		
47	17	53	26	2	9	0	0		
48	17	53	35	92		0	2		
49									
50					854	TABLE 7			
51									
52									

	A	B	C	D	E	F	G	H	I
1								EFM at caboose 01/07/1988-02	
2	HH	MM	SS	Value	sec	orage	num		
3									
4	17	53	35	92	2	2	2	Total of seconds electric field was	
5	17	53	37	2	41	0	0	greater than 6 Kv	0
6	17	54	2	92	16	16	2		
7	17	54	18	1	28	0	0	greater than 5 Kv	0
8	17	54	29	92	17	17	2		
9	17	54	46	2	16	0	0	greater than 4 Kv	279
10	17	54	56	92	6	6	2		
11	17	55	2	1	12	0	0	greater than 3 Kv	493
12	17	55	14	2	16	0	0		
13	17	55	23	92	7	7	2	greater than 2 Kv	947
14	17	55	30	1	257	0	0		
15	17	55	50	96	237	237	6	greater than 1 Kv	947
16	17	59	47	-2	17	0	0		
17	18	0	4	-1	1980	0	0	greater than 0 Kv	947
18	18	0	9	150	1975	1975	60		
19	18	33	4	-1	37	0	0	greater than -1 Kv	4454
20	18	33	19	92	22	22	2		
21	18	33	41	-2	12	0	0	greater than -2 Kv	2321
22	18	33	46	92	7	7	2		
23	18	33	53	-2	36	0	0	greater than -3 Kv	188
24	18	34	13	92	16	16	2		
25	18	34	29	-2	75	0	0	greater than -4 Kv	0
26	18	34	40	96	64	64	6		
27	18	35	44	-2	48	0	0	greater than -5 Kv	0
28	18	36	1	94	31	31	4		
29	18	36	32	-1	116	0	0	greater than -6 Kv	0
30	18	36	55	98	93	93	8		
31	18	38	28	2	19	0	0		
32	18	38	47	3	150	0	0	Total of seconds of orages	2931
33	18	38	51	102	146	146	12		
34	18	41	17	3	129	0	0	Number of orages	142
35	18	41	34	100	112	112	10		
36	18	43	26	2	52	0	0		
37	18	43	48	94	30	30	4		
38	18	44	18	1	85	0	0		
39	18	44	42	96	61	61	6		
40	18	45	43	1	39	0	0		
41	18	46	4	92	18	18	2		
42	18	46	22	1	8	0	0		
43	18	46	30	8	97	0	0		
44	18	48	7	1	25	0	0		
45	18	48	18	92	14	14	2		
46	18	48	32	2	70	0	0		
47	18	48	45	96	57	57	6		
48	18	49	42	2		0	0		
49									
50									
51					6296	TABLE 8			
52									

	A	B	C	D	E	F	G	H	I
1								EFM at caboose 01/07/1988-02	
2	HH	MM	SS	Value	sec	orage	num		
3									
4	18	49	42	2	14	0	0	Total of seconds electric field was	
5	18	49	56	1	35	0	0	greater than 6 Kv	0
6	18	50	5	92	26	26	2		
7	18	50	31	-1	8	0	0	greater than 5 Kv	282
8	18	50	39	-2	8	0	0		
9	18	50	46	92	1	1	2	greater than 4 Kv	401
10	18	50	47	-3	15	0	0		
11	18	51	2	-4	17	0	0	greater than 3 Kv	578
12	18	51	12	92	7	7	2		
13	18	51	19	-4	51	0	0	greater than 2 Kv	881
14	18	51	39	94	31	31	4		
15	18	52	10	-5	44	0	0	greater than 1 Kv	881
16	18	52	34	92	20	20	2		
17	18	52	54	-5	60	0	0	greater than 0 Kv	881
18	18	53	1	94	53	53	4		
19	18	53	54	-4	17	0	0	greater than -1 Kv	861
20	18	53	55	92	16	16	2		
21	18	54	11	-3	206	0	0	greater than -2 Kv	732
22	18	54	22	106	195	195	16		
23	18	57	37	-2	185	0	0	greater than -3 Kv	603
24	18	57	58	104	164	164	14		
25	19	0	42	-1	121	0	0	greater than -4 Kv	410
26	19	1	7	95	96	96	5		
27	19	2	43	1	22	0	0	greater than -5 Kv	189
28	19	2	44	91	21	21	1		
29	19	3	5	2	29	0	0	greater than -6 Kv	104
30	19	3	10	92	24	24	2		
31	19	3	34	3	69	0	0		
32	19	3	37	96	66	66	6	Total of seconds of orages	1315
33	19	4	43	4	195	0	0		
34	19	4	58	104	180	180	14	Number of orages	108
35	19	7	58	4	87	0	0		
36	19	8	7	96	78	78	6		
37	19	9	25	3	50	0	0		
38	19	9	28	94	47	47	4		
39	19	10	15	2	37	0	0		
40	19	10	23	94	29	29	4		
41	19	10	52	1	212	0	0		
42	19	11	16	98	188	188	8		
43	19	14	24	1	34	0	0		
44	19	14	47	92	11	11	2		
45	19	14	58	2	78	0	0		
46	19	15	14	96	62	62	6		
47	19	16	16	2	19	0	0		
48	19	16	35	92		0	2		
49									
50						TABLE 9			
51					2928				
52									

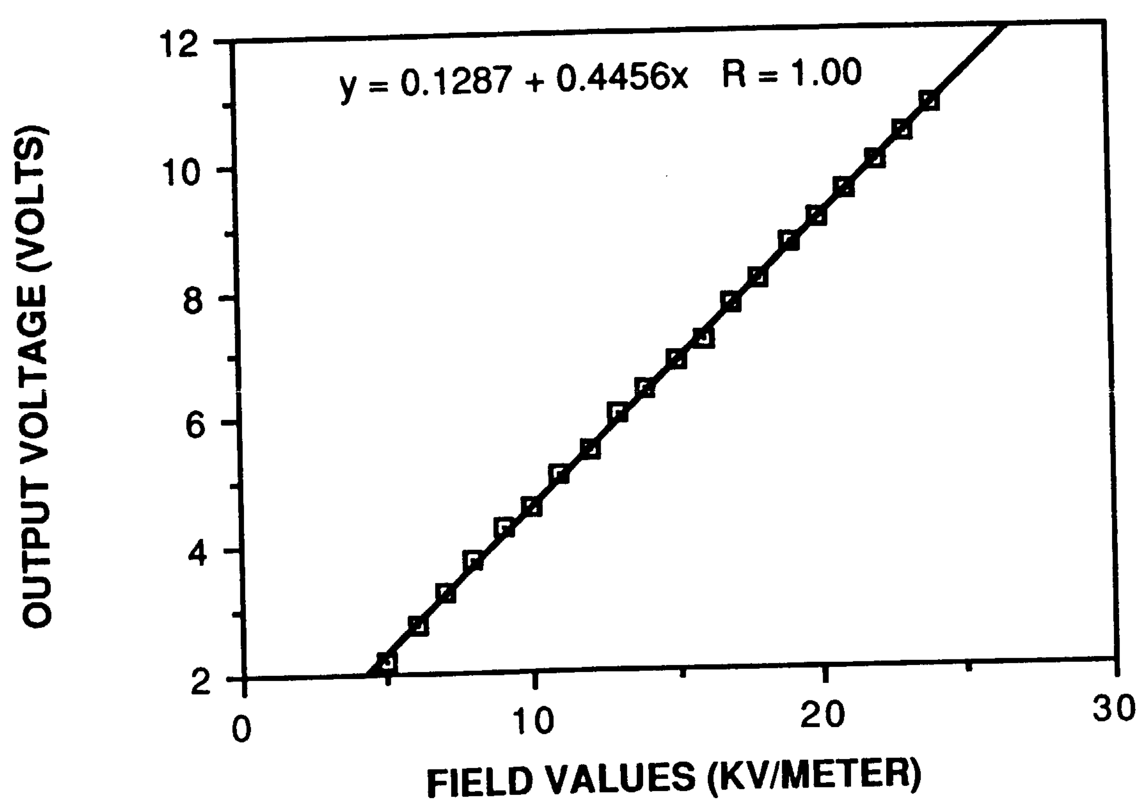
	A	B	C	D	E	F	G	H	I
1								EFM at caboose 01/07/1988-02	
2	HH	MM	SS	Value	sec	orage	num		
3									
4	19	16	35	92	26	26	2	Total of seconds electric field was	
5	19	17	1	1	4579	0	0	greater than 6 Kv	0
6	19	17	2	140	4578	4578	50		
7	19	41	18	140	3122	3122	50	greater than 5 Kv	0
8	20	1	14	112	1926	1926	22		
9	20	33	20	1	30	0	0	greater than 4 Kv	0
10	20	33	20	94	30	30	4		
11	20	33	50	1	211	0	0	greater than 3 Kv	0
12	20	34	14	96	187	187	6		
13	20	37	21	-1	116	0	0	greater than 2 Kv	4820
14	20	37	22	100	115	115	10		
15	20	39	17	-1	20	0	0	greater than 1 Kv	4820
16	20	39	37	95		0	5		
17						0	0	greater than 0 Kv	4820
18						0	0		
19						0	0	greater than -1 Kv	272
20						0	0		
21						0	0	greater than -2 Kv	136
22						0	0		
23						0	0	greater than -3 Kv	0
24						0	0		
25						0	0	greater than -4 Kv	0
26						0	0		
27						0	0	greater than -5 Kv	0
28						0	0		
29						0	0	greater than -6 Kv	0
30						0	0		
31						0	0		
32						0	0	Total of seconds of orages	9984
33						0	0		
34						0	0	Number of orages	149
35						0	0		
36						0	0		
37						0	0		
38						0	0		
39						0	0		
40						0	0		
41						0	0		
42						0	0		
43						0	0		
44						0	0		
45						0	0		
46						0	0		
47						0	0		
48						0	0		
49									
50									
51					14940	TABLE 10			
52									

	A	B	C	D	E	F	G	H	I	J	K
1	EFM at caboose 01/07/1988-SUM			VALUES FROM TABLES...							
2											
3		1	2	3	4	5	6	7	HH	MM	SS
4	Total of seconds electric field was										
5	greater than 6 Kv	0	0	0	0	0	0	0	00	00	00
6											
7	greater than 5 Kv	0	0	0	0	0	282	0	00	04	42
8											
9	greater than 4 Kv	0	0	0	36	279	401	0	00	11	56
10											
11	greater than 3 Kv	0	0	0	234	493	578	0	00	21	45
12											
13	greater than 2 Kv	0	78	38	421	947	881	4820	01	59	45
14											
15	greater than 1 Kv	0	78	38	421	947	881	4820	01	59	45
16											
17	greater than 0 Kv	0	78	38	421	947	881	4820	01	59	45
18											
19	greater than -1 Kv	867	2143	684	299	4454	861	272	02	39	40
20											
21	greater than -2 Kv	551	1218	432	178	2321	732	136	01	32	48
22											
23	greater than -3 Kv	235	293	180	57	188	603	0	00	25	56
24											
25	greater than -4 Kv	34	90	157	41	0	410	0	00	12	12
26											
27	greater than -5 Kv	6	46	16	32	0	189	0	00	04	49
28											
29	greater than -6 Kv	0	4	0	23	0	104	0	00	02	11
30											
31											
32	Total of seconds of orages	301	1217	247	255	2931	1315	9984	04	30	50
33											
34	Number of orages	42	89	35	40	142	108	149			

TABLE 11

GRAPHS

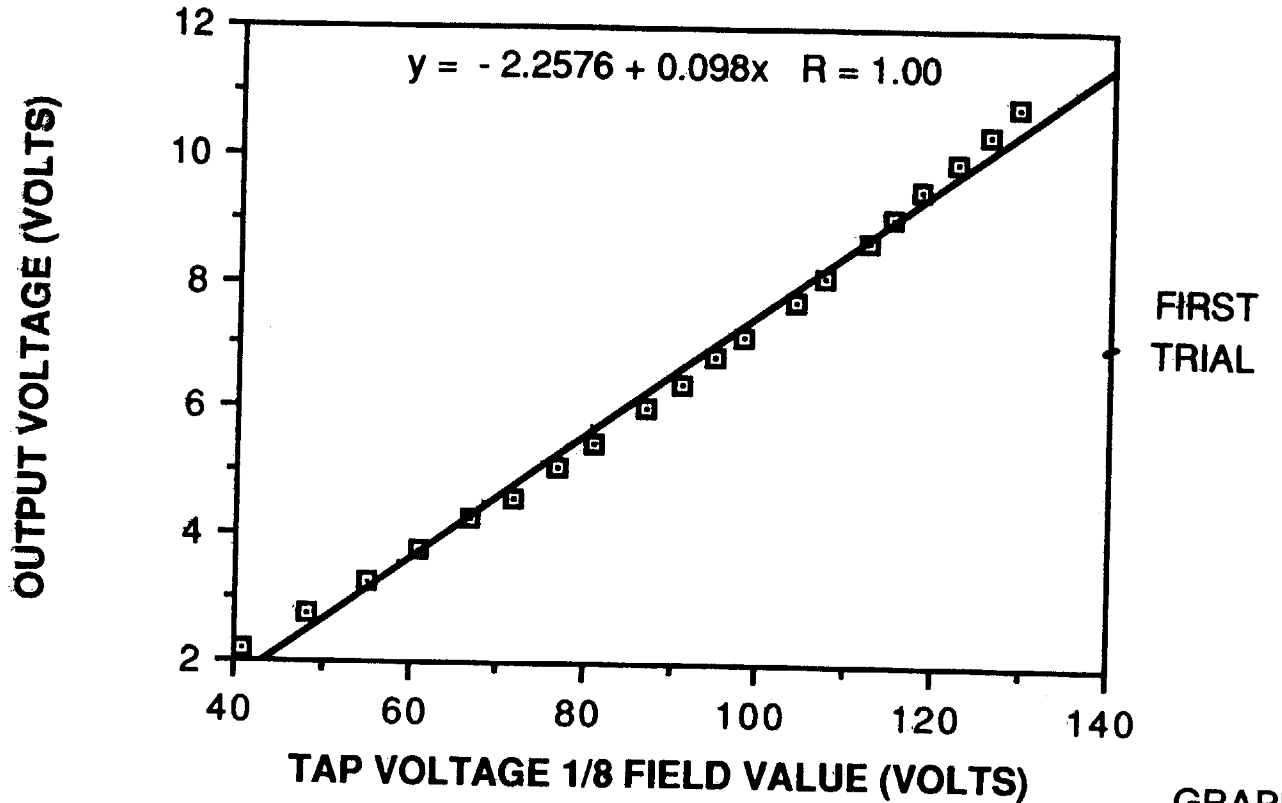
ELECTRIC FIELD MILL CALIBRATION



FIRST
TRIAL

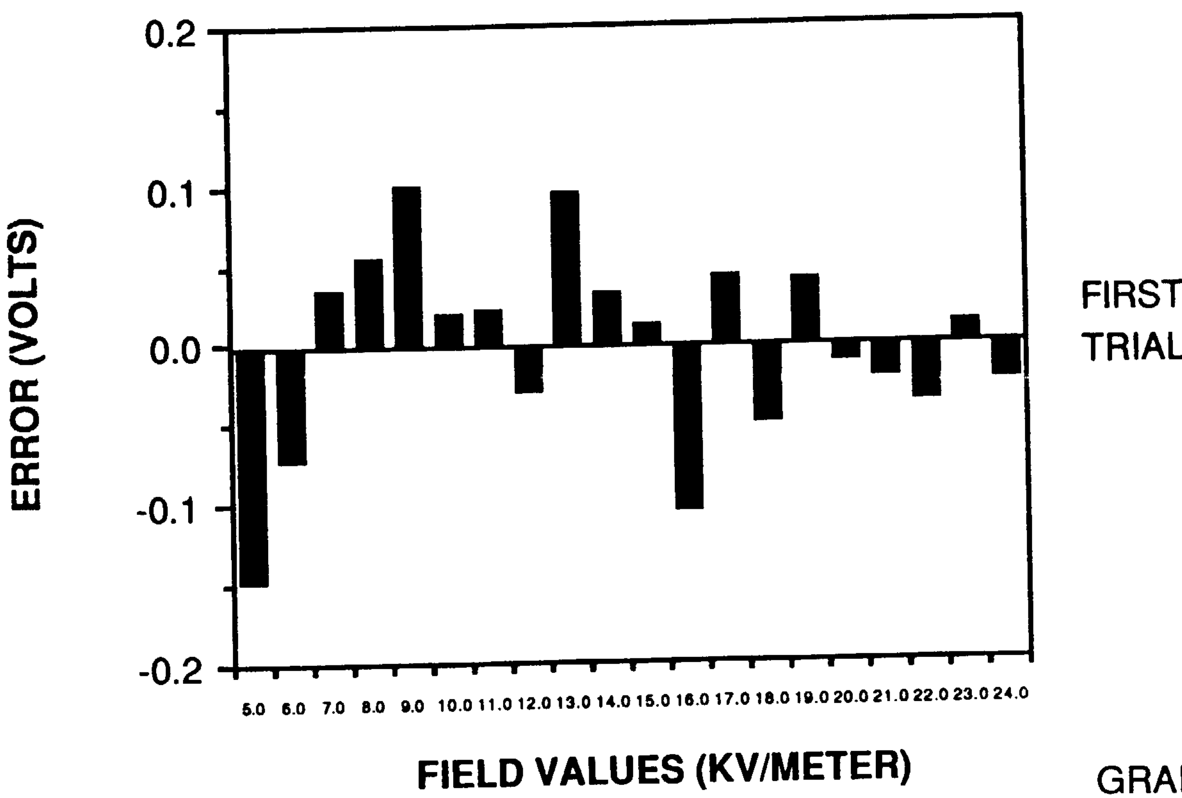
GRAPH # 1

ELECTRIC FIELD MILL CALIBRATION

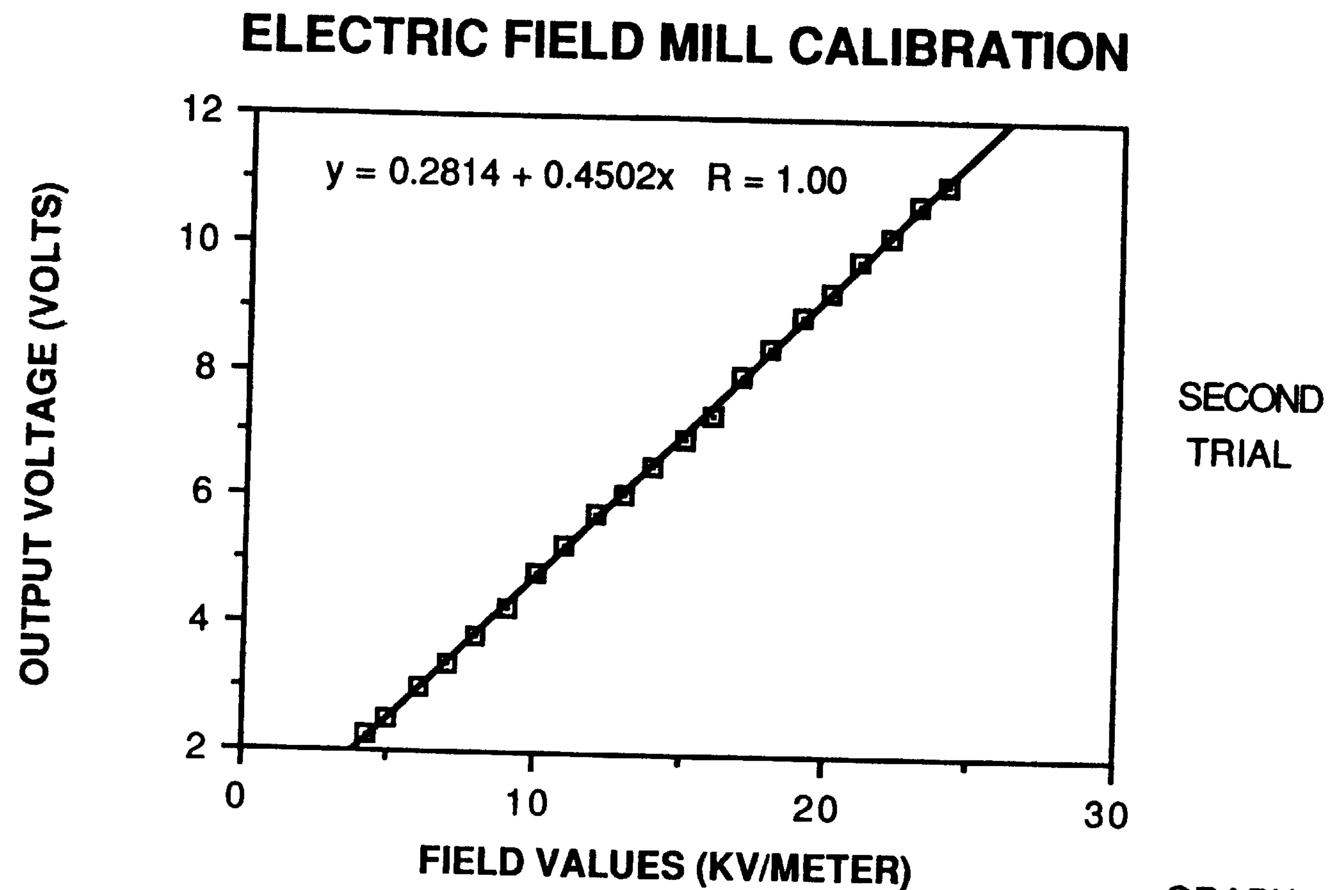


GRAPH # 2

ELECTRIC FIELD MILL CALIBRATION ERROR

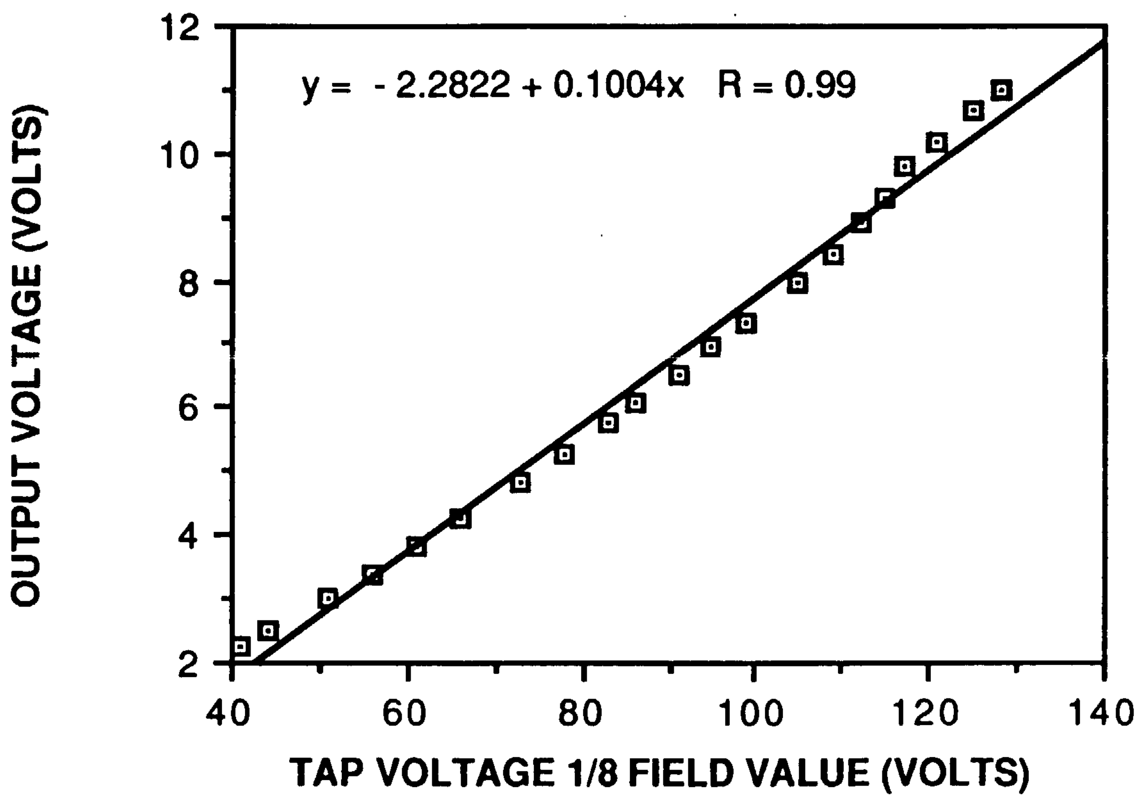


GRAPH #3


ELECTRIC FIELD MILL CALIBRATION
y = 0.2814 + 0.4502x   R = 1.00
12
10
8
6
4
2
0
10
20
30
OUTPUT VOLTAGE (VOLTS)
FIELD VALUES (KV/METER)
SECOND
TRIAL

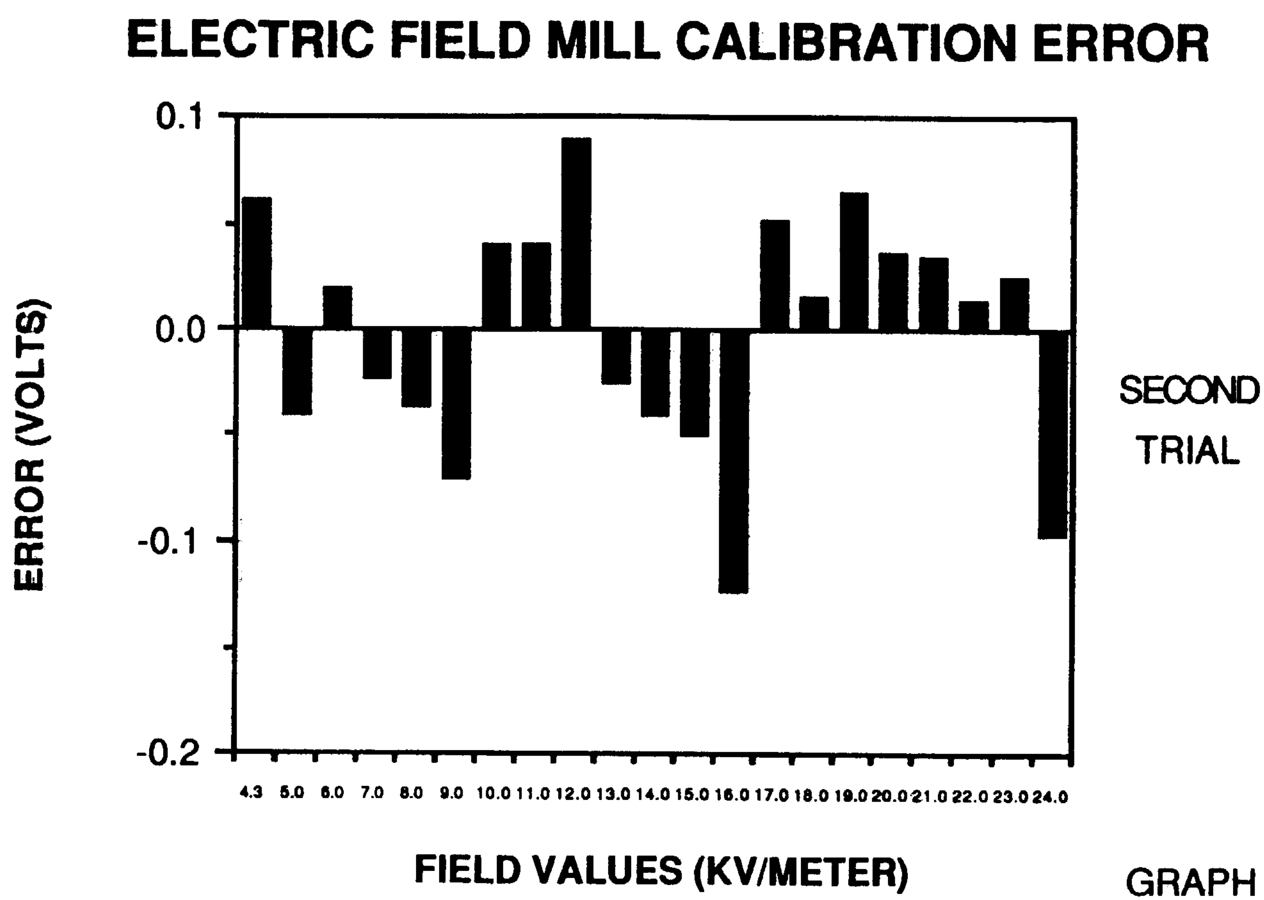
GRAPH # 4

ELECTRIC FIELD MILL CALIBRATION



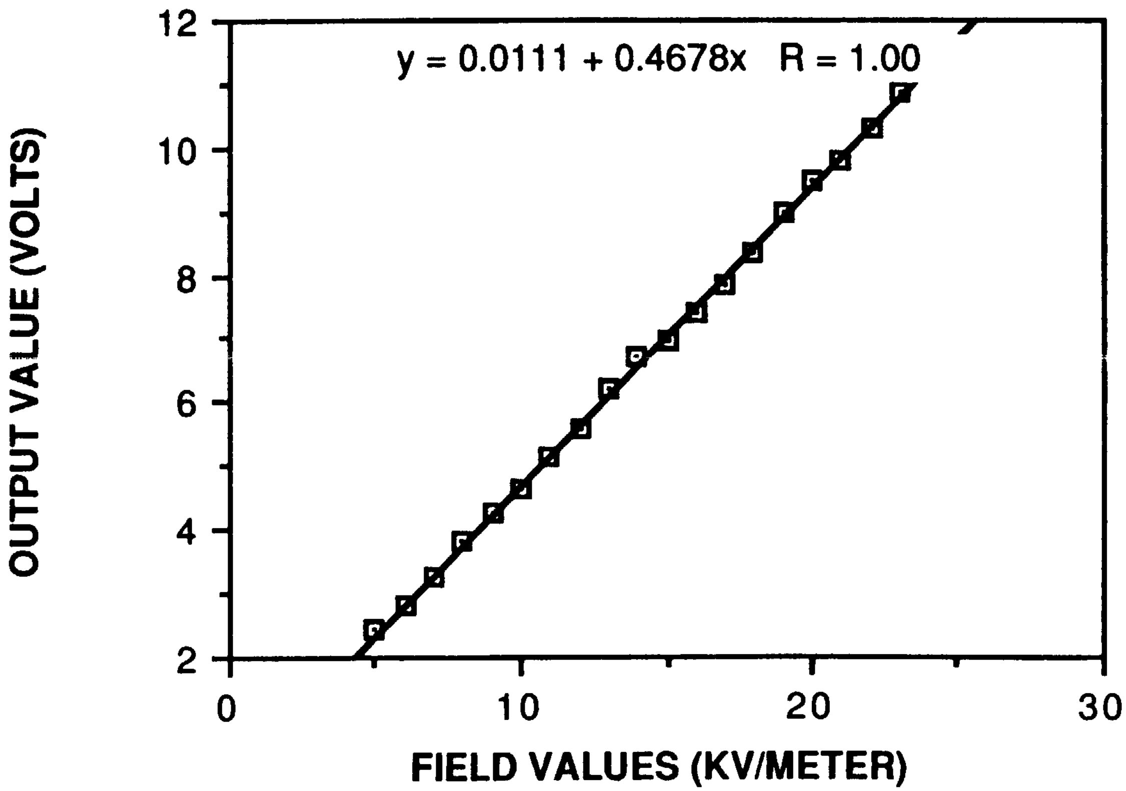
SECOND TRIAL

GRAPH # 5


ELECTRIC FIELD MILL CALIBRATION ERROR
ERROR (VOLTS)
0.1
0.0
-0.1
-0.2
4.3 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0 21.0 22.0 23.0 24.0
FIELD VALUES (KV/METER)
SECOND
TRIAL

GRAPH # 6

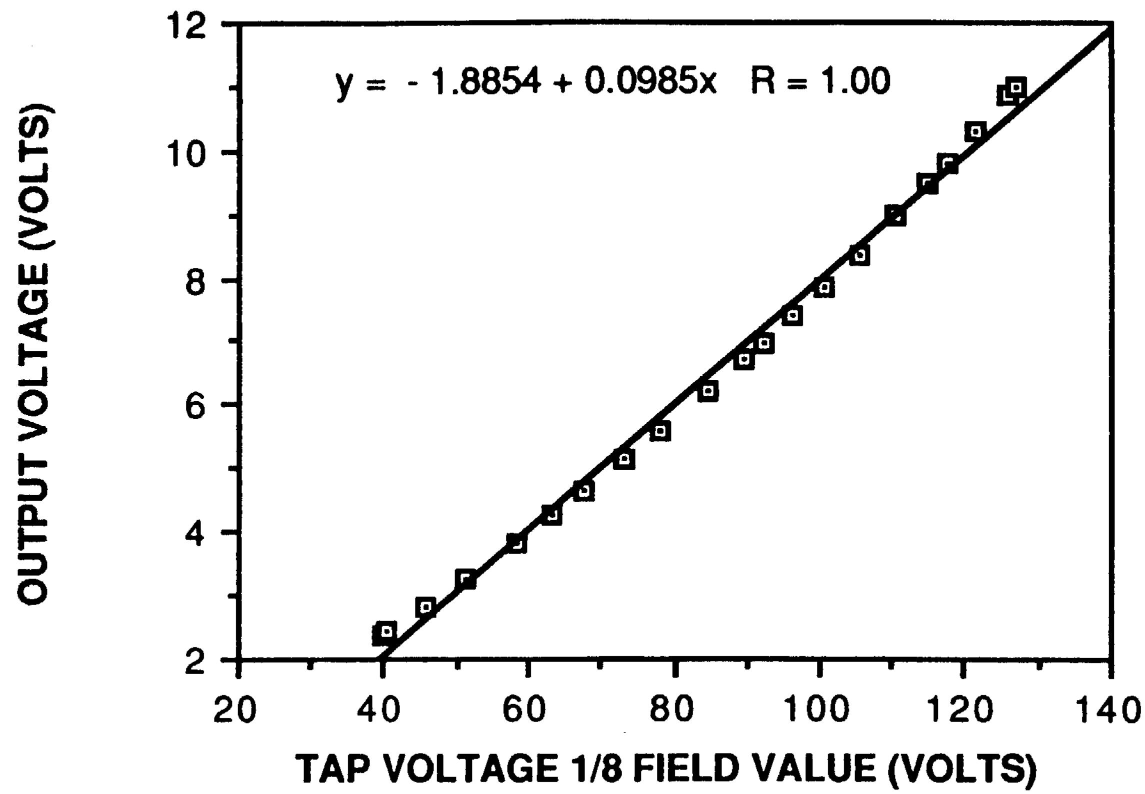
ELECTRIC FIELD MILL CALIBRATION



THIRD TRIAL

GRAPH # 7

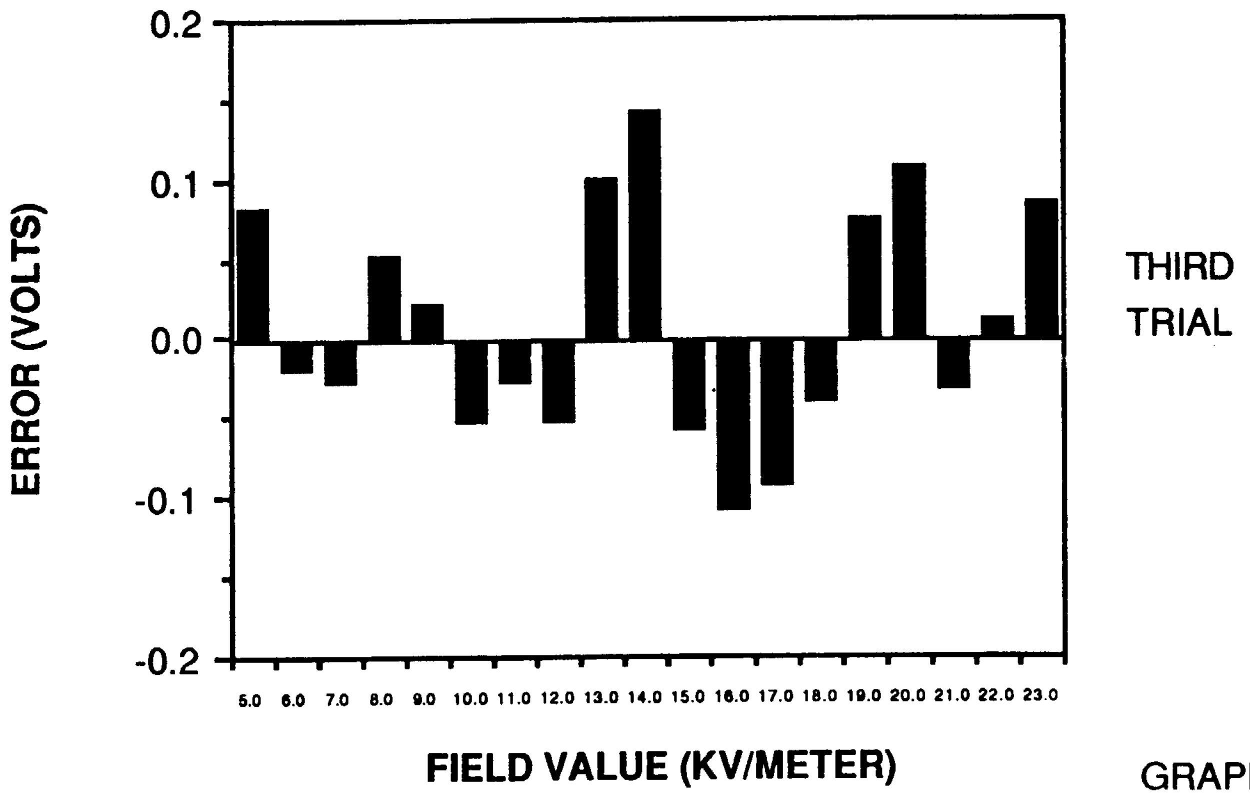
ELECTRIC FIELD MILL CALIBRATION



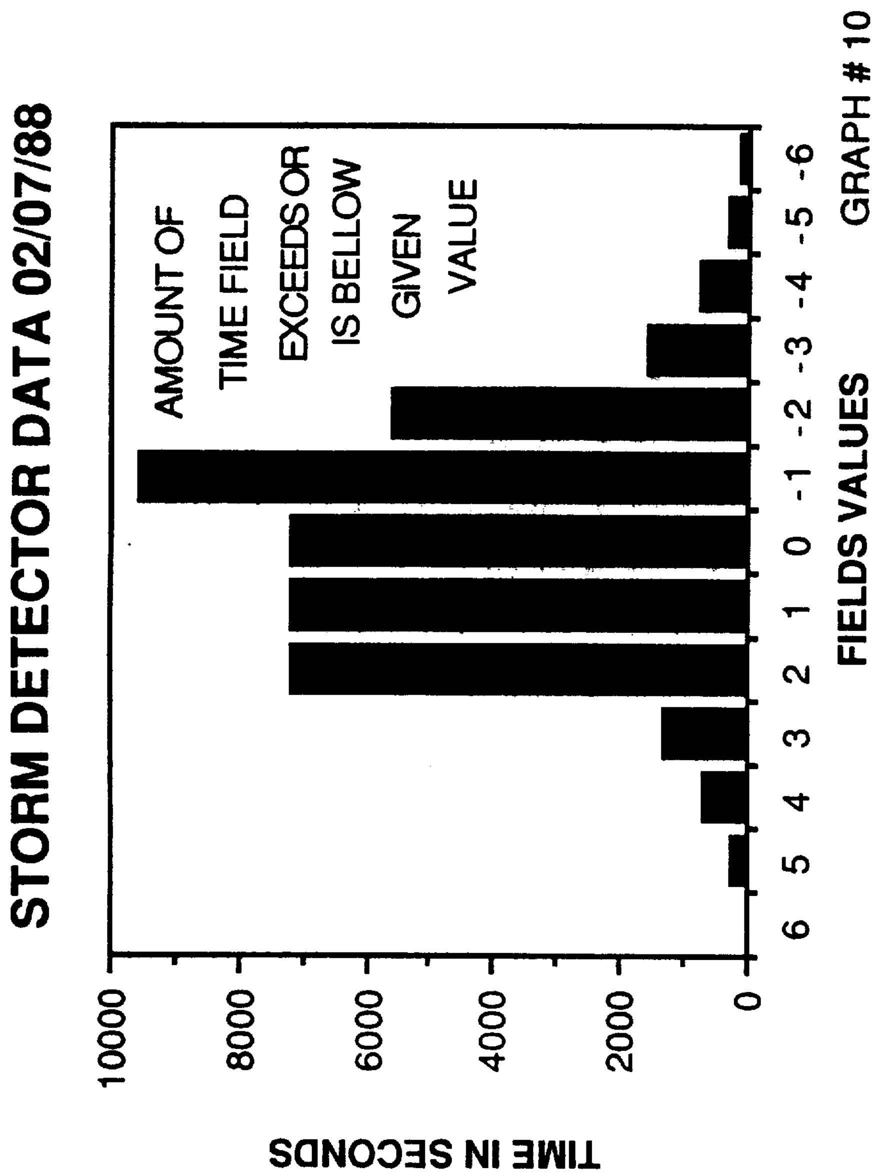
THIRD
TRIAL

GRAPH # 8

ELECTRIC FIELD MILL CALIBRATION ERROR



GRAPH # 9


STORM DETECTOR DATA 02/07/88
AMOUNT OF
TIME FIELD
EXCEEDS OR
IS BELLOW
GIVEN
VALUE
TIME IN SECONDS
10000
8000
6000
4000
2000
0
6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6
FIELDS VALUES
GRAPH # 10