DC + Low Freq Power Rel. Sypt Measurements

AN EVALUATION OF INSTRUMENTATION USED TO MEASURE AC POWER SYSTEM MAGNETIC FIELDS

A Report of the IEEE Magnetic Fields Task Force* of the AC Fields Working Group of the Corona and Field Effects Subcommittee of the Transmission and Distribution Committee

ABSTRACT

A workshop was organized by the AC Fields Working Group for the purpose of evaluating instrumentation designed for measuring power system magnetic fields. The instruments tested varied from simple single axis survey meters to microcontroller based instruments designed for long term data collection and analysis. The working group designed a series of tests which were used to evaluate each instrument. These included calibration and harmonic response tests, tests of susceptibility to high 60 Hz electric fields and electromagnetic interference and the measurement of fields typical of transmission line, appliance, substation and office/shop environments. Results for each of these tests are presented and discussed. With some minor exceptions, the performance of all instruments was satisfactory.

I. INTRODUCTION

The magnetic field environment associated with the transmission, distribution and utilization of electrical energy has been of considerable interest during the last several years. The interest has been heightened by research which suggests an association between magnetic fields and biological effects [1, 2].

The area of responsibility for the Working Group on AC Fields is the "*Treatment of empirical and analytical aspects of electromagnetic fields from AC transmission and distribution facilities including associated effects, measurement techniques and instrumentation.*" Thus, studies related to the characterization of AC magnetic fields fall within the scope of activity for this working group. The subject of magnetic field calculation has been addressed in a recent working group paper [3]. Since that paper was written, the working group has also become interested in the performance of instruments used to measure AC power system magnetic fields. Because of this interest, the working group decided that a document summarizing the theory of magnetic field measurement should be written and that a workshop be held where existing magnetic field instrumentation would be evaluated. Further, the workshop should be organized similar to one on electric fields held several years ago [4]. The measurement theory document with examples of measurement results is now available as a working group paper [5]. This paper is a summary of the workshop accomplishments.

The workshop was held at the Bonneville Power Administration Laboratory in Vancouver, Washington, in May 1989. The workshop organizing committee prepared a tentative agenda for the workshop which was discussed and revised by the working group. Next, a list of all known instruments was prepared. The manufacturers of these instruments were informed about the workshop agenda and invited to participate. The experiments to be performed were designed by working group members and constructed by BPA personnel. Several working group members arrived one day early to verify that all experiments were set up properly.

The paper will be organized as follows. First, a list of the instruments and their characteristics are given. Second, the tests that were conducted are reviewed. Third, test results will be summarized and finally there is a discussion of the results and some conclusions.

II. PARTICIPANTS

Those who participated in the workshop were: D. Baron (Holaday Ind.), K. Bell (PG&E), D. Bracken (T. D. Bracken Inc.), J. Cartwright (R. W. Beck), V. Chartier (BPA), J. Deadman (McGill University), D. Deno (EFM Co.), T. Dovan (State Electricity Commission of Victoria, Australia), J. Hatfield (Hatfield and Dawson), K. Jaffa (Utah Power and Light), P. Jutras (IREQ), J. Lee (Taiwan Power Co.), E. Leeper (Monitor Ind.), M. Misakian (NIST), R. Olsen (Washington State University), L. Prabin (Sydkraft AB), W. Rankin (Holaday Ind.), R. St. Marseille (Positron), S. Sebo (Ohio State University), D. Sesia (Positron), M. Stenson (HVTRC), J. Stewart (PTI), L. Tetzner (Holaday Ind.), T. Vinh (AEP), B. Wiberg (Sydkraft AB), P. Wong (Powertech Labs. Inc.).

III. REVIEW OF FIELD MEASUREMENT INSTRUMENTS

This section provides a summary of the physical and electrical characteristics of the power frequency magnetic field measurement instruments which are listed in Table I. More than half of these are commercial devices while the others are scientific instruments which were developed for research purposes.

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The nature of the instruments being reviewed here varies from a simple sensor for point-in-time measurements to a microcontroller based device for a complex characterization of human exposure to electric and magnetic fields. A variety of different filtering arrangements are used by the various meters including no filtering, integrators and bandpass filters. Specifications provided by the manufacturers for the instruments evaluated during this workshop are given in Table II.

Depending on the design, the instruments can generally be classified into three groups: field survey instruments, data recorders and personal exposure meters.

Field Survey Instruments: These devices are designed basically as hand held instruments for single point-in-time measurements. Some of the instruments are capable of measuring both electric and magnetic fields.

For magnetic field measurements, the field survey instruments (except for meter A) use separate air-core coil probes which are held and oriented by the operator for sensing the magnetic field in a desired direction. The sensing coil diameter varied considerably in the assorted instruments from 4 cm to 17 cm. Most of the instruments provide a form of digital readout.

Data Recorders: These instruments are designed as data acquisition units that can be used for characterization of electric and/or magnetic fields either over time or distance in specific locations such as rooms in a house, different areas in a work place, or along a lateral profile under a transmission line. The instruments can be operated unattended during the period of data collection.

To further characterize the magnetic field, three-axis coils are used for sensing the three orthogonal magnetic components. In all instruments tested at the workshop, the resultant magnetic field value is the vector sum (i.e., the square root of the sum of the squares) of the rms values of the components. It should be noted that in general, vectorially summing the rms values of the three orthogonal components will not yield the maximum value of the magnetic field (i.e., the rms value of the magnetic field along the semi-major axis of the field ellipse) because of phase differences between the spatial components. [5, 6] However, an upper limit to the maximum field value is provided by this summation. The maximum error made in using this upper limit is approximately 40% in the case for circular polarization. The error is zero for linearly polarized fields. It is also interesting to note that the rms value of the total magnetic field is equal to the vector sum of the rms values of the spatial components [6].

Data samples obtained at a fixed pre-programmed rate are stored in the recorder memory for later retrieval and analysis by a host computer. Sampling can also be triggered at constant distance intervals using a distance measuring wheel.

Personal Exposure Meters: These instruments are designed for characterization of human exposure to electric and magnetic fields arising from occupational or residential environments.

The instrument's size is critical as they are continuously worn by a person during the measurement period. Except for one instrument which stored the cumulative average level in an electrolytic cell, the design of the exposure meters in terms of field sensors, data collection and storage is similar to that of the data recorders discussed above.

The instruments are microprocessor or microcontroller based with miniaturized sensors and circuitry for minimal device size. Depending on the data sampling rate, the exposure meter memory can store (record) data for periods ranging from 24 hours to seven days. Because of this capability, exposure meters have sometimes been used in the same fashion as data recorders [5].

TABLE I: MAGNETIC FIELD INSTRUMENTS INCLUDED IN TESTS

LABEL	MANUFACTURER/ DEVELOPER	MODEL +	FUNCTION*
A**++	Electric Field Measurements Co., West Stockbridge, MA	116 PLUS	S
B**	Electric Field Measurements Co.	120	S
C**	Holaday Industries Eden Prairie, MN	HI-3600-02	S
D**	Integrity Electronics & Research, Buffalo, NY	IER-109	S
E**	Monitor Industries Boulder, CO	42B-1	S
F**	Sydkraft (Malmö, Sweden)	88-05	S
G	Electric Power Research Institute (EPRI)	STAR/ VANA	(S) R E
H	Inst. de Recherche Hydro Quebec (IREQ) (Electric and Magnetic Field Recording Instrument)	N/A	R
I**	Sydkraft (3 dimensional magnetic flux denisty meter)	N/A	R
J	EPRI	EMDEX	(S)(R)E
K**	Electric Field Measurements Co.	EMDEX-C	(S)R(E)
L	IREQ (Dosimeter)	N/A	(R) E
M**	Positron Industries (Electromagnetic Dosimeter) Montreal, Quebec	378108	(R) E
N	EPRI	AMEX	E

* S = survey meter; R = recorder/datalogger; E = exposure meter. Parentheses indicate meter not tested in that category.

\+ N/A = not available: because instrument under development or is a prototype, no model designation has been given.

** Commercially available.

++ Used with a Fluke 27 multimeter.

IV. SUMMARY OF TESTS PERFORMED

A. Calibration Test-Linearity

The 28 turn 2m by 2m shielded loop shown in Fig. 1 was located 1m above the floor in the BPA High Voltage Laboratory to calibrate the instruments from ambient level to 1G. The loop size exceeds the dimensions recommended in the IEEE Standard 644-1987 [7] and is larger than what is normally needed. The larger loop size was used because of the uncertainty of the dimensions of the meters that would be brought to the workshop and also because of the uncertainty of the coil locations in the exposure instruments. This large loop insured a large uniform field volume near its center. The turns were stacked vertically to reduce the inductance of the loop. Fortunately, the vertical magnetic field in the high voltage laboratory was very low; about 0.02 mG. The sensitivity of each instrument could essentially be determined in this very low ambient field, or at least it was possible to determine which instruments could make magnetic field measurements down to 0.2 mG. This loop was driven by a signal generator which could be tuned to 60 Hz or any low order harmonic.

Table II : SUMMARY OF MAGNETIC FIELD INSTRUMENT SPECIFICATIONS*

INSTRUMENT DESIGNATION	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Function: Survey (S); Recorder (R); Exposure Meter (E)	S	S	S	S	S	S	(S)RE	R	R	(S)(R)E	(S)R(E)	(R)E	(R)E	E
Range: Maximum full scale, mg	**	30000	25000	20000	2500	20000	510	1000	200	25500	25500	500	2000	125
Number of scales:	**	12	AUTO	4	5	5	2	2	AUTO	4 AUTO	4 AUTO	16 BINS	16 BINS	1
Autoranging (AUTO)														
Output: Analog (A) Digital (D)	D	A	D	D	A	D,A	D	D	D	D	D	D	D	***
Sensor: Number of axes	1	1	1	1	1	1	3	3	3	3	3	3	3	1
Number of turns	N/S	2000	N/S	N/S	N/S	6000	6000	2000	6000	6000	N/S	N/S	N/S	6000
Core	Ferrite	Air	Air	Air	Air	Air	iron	air	air	iron	iron&air	air	air	iron
Diameter, cm	4	10	17	5	17	10	N/S	7	10	1	2	1x4	2x2.5x2.5	
Frequency response category: Integrated (I); Linear (L) Narrow Band (N); Broad Band (B)	**	I,L		N	I,L	N	N	I,N	N	B	B	N	N	L
Bandwidth (Hz)	**	35-600	30-1000	60	40-1000	60	60	40-1000	60	60	40-400	50/60	50/60	
Detector: True rms (RMS); average sensing rms (AVG)	**	AVG	RMS	N/S	RMS	AVG	RMS	RMS	AVG	AVG	AVG	PEAK	RMS	AVG
Size, cm	4x4x5	24x14x5	42x9x3	8x10x18	5x8x20	12x8x22	14x8x6	28x16 (Dia)	60x40x2	15x12x5	15x12x4	2x4x14	2x8x15	3x5x1
Mass, g	100	500	850	425	825	900	450	2200	11000	453	624	250	275	35

* Specifications contained in this table were supplied by the manufacturers. The accuracy of this information was not verified at the workshop.

** Depends on the multimeter used with the probe.

N/S Not specified.

N/A Not applicable.

*** Time-integrated field read by external unit.

One of the problems that was not anticipated was the effect of the grounding mat in the high voltage laboratory on the magnetic field at the center of the loop since the loop was only 1m above the floor. Calculations and tests determined that the image currents created by the ground mat reduced the field at the center of the calibration loops. The ground mat, a mesh made of #8 copper wire, is buried in the concrete floor. The mesh is square with each side having a dimension of about 6-inches. The experiments which were conducted to determine the effect of this ground mat on the generated magnetic field will be discussed later in this paper.

In addition to the 2m by 2m loop described above, a single turn loop of the same side dimensions was constructed and driven by a high current power supply. This loop was intended to be used for testing instruments at magnetic field levels in excess of 1 G. Unfortunately, there was not enough time to characterize this loop. As a result, the data taken were not within the desired accuracy and are not reported here.

During the linearity tests, the calibration loop was used to check the 60 Hz calibration of each instrument at levels from .02 mG to 1 G.

B. Effect of Calibration Loop Size

Three loops of different dimensions were used to determine the effect of size on the calibration of instruments with sensors of different size. Each instrument's calibration was checked successively in the 2m by 2m loop described above, in a 1m by 1m, 28-turn loop and finally a 0.3m by 0.4m commercial calibration loop available from Electric Field Measurement Company.

C. Frequency Response

The response of each meter to low order harmonics was identified in the 2m by 2m loop. The purpose of this test was to characterize the frequency response of each meter.

D. 60-Hz Electric Field Test

Each instrument was subjected to various levels of 60 Hz electric fields to determine the effect of a relatively strong electric field on the magnetic field instruments. This field was created by energizing a piece of 5 cm diameter aluminum pipe from the 1 MV cascade generators in the high voltage laboratory [8]. The instruments were placed on a wooden table approximately 10 meters underneath the pipe. The ambient magnetic field (approximately .05 mG vertical) was measured while the electric field at the surface of the table was increased from 0 to 15 kV/m in 2.5 kV/m intervals. The single axis meters were oriented to measure the vertical magnetic field.

E. EMI Test

The problem of magnetic field instrument sensitivity to EMI was known before the workshop. Some instruments, if not properly shielded, had been affected by strong VHF fields such as TV broadcast signals. To simulate these fields, each instrument was subjected to a horizontally polarized, approximately 1 V/m (120 dBμV/m), frequency modulated 110 MHz field. This field was generated by a biconical antenna connected to a VHF signal generator. The field at the location of the magnetic field instruments was measured with another calibrated biconical antenna. Each instrument was used to measure the ambient magnetic field (vertical in the case for single axis instruments) while the VHF field was switched on and off.

F. Transmission Line Lateral Profile Test

Each of the field survey instruments was simultaneously used to measure the magnetic field along a lateral profile underneath two parallel single circuit 230-kV lines, coming out of the Ross Substation. Each of the six instruments was placed on a wooden table and the table was moved from one station to the next. The meters were read simultaneously. Vertical and horizontal fields were separately measured on successive traverses of the lateral profile. A sketch of these lines and the

measurement points are shown in Fig. 2.

G. Appliance Test

Since appliance magnetic field measurements are often of interest, a test was performed using three different appliances; a heat gun, a space heater and an electric drill. The heat gun produced fields from both the heating element and a motor. The space heater had no motor so that all of the fields were produced by the heating element. The field from the drill was due to its motor. This is an important distinction because electric motors often produce a magnetic field which contains significant harmonic levels.

Six field survey meters were used which had probes that were manually oriented to obtain the peak magnetic field by three different people. Each person used each instrument in turn to measure the fields from each of the three appliances at two specific distances (0.3m and 1m) from each appliance. A seventh instrument (Instrument J) was used at the same locations. This instrument could measure the magnetic field along three orthogonal axes and calculate the resultant magnetic field. As mentioned earlier, this represents an upper limit on the maximum value of the field. Instrument J was operated by a fourth person and was useful for making comparisons since the probe did not have to be manually oriented to find the maximum field.

The purpose of this test was to compare readings obtained in a non-uniform field using different instruments and operators.

H. Ross Substation Walkthrough (High field)

The data recording instruments and exposure instruments were compared on a walkthrough in the BPA Ross substation. This substation has both 115- and 230-kV switchyards. One of the tasks of a BPA substation operator is daily inspection. The operator has an inspection route that is normally followed. This route was marked with white stones before the workshop. This ensured that the route could be reliably repeated. The total time to traverse the route was about 17 minutes (1020 seconds). Similar walkthroughs have been used in past investigations of EMF instruments [9, 10].

I. Office/Shop Walkthrough (Low field)

The data recording instruments and exposure instruments were also compared in a lower magnetic field environment by performing a walkthrough in the BPA Ampere building which is located east of the Ross substation. This building is somewhat typical of offices with lights, computers, etc.; however, it also has machine shops, instrumentation repair and calibration shops, electrical shops, etc. The walkthrough included indoor and outdoor walks, sitting at a computer for one minute and operating a bench grinder for one minute. The total time of the lower field walkthrough was approximately 10 minutes.

V. TEST RESULTS

A. Calibration Test-Linearity

Each instrument tested at the workshop was originally calibrated by the manufacturer in its own laboratory. The instruments were tested as received.

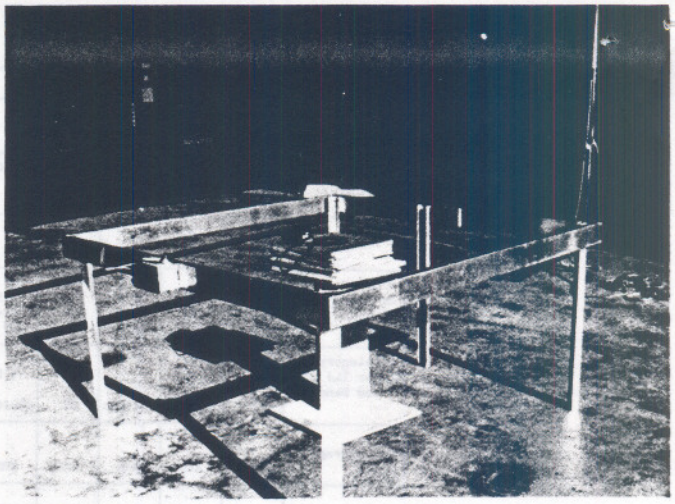

Fig. 1
The 2m by 2m Calibration Loop

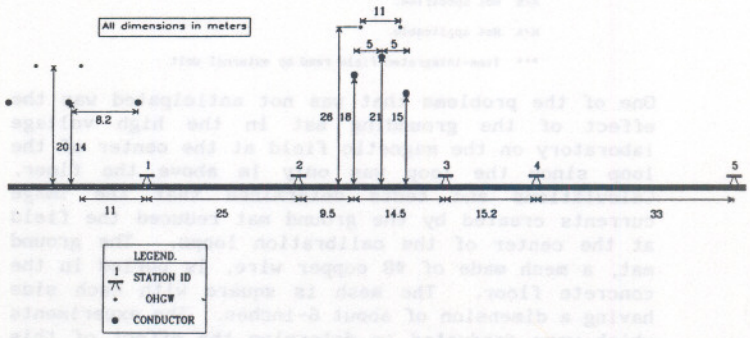

Fig. 2
Location of Measurement Points for 230 kV Transmission Line Lateral Profile Test

At the workshop, calibrations of the magnetic field instruments were checked for field values ranging from near 0.2 mG to 1 G at 60 Hz. The calibration apparatus consisted of the 2m by 2m loop of wire described in Section IV and its associated signal generator. The magnitude of the image field perturbation was determined by BPA staff, following the workshop, by measuring the magnetic field at the center of the loop as a function of loop height above the floor surface with constant energizing current in the loop. The field value was observed to increase up to a height of about 4.5 m and from these results, it was inferred that image field perturbation amounted to -3.8% at the 1m height during the workshop tests.

Figure 3 shows results of the calibration checks for the various magnetic field meters. The "actual" field values in Figure 3 represent calculated fields at the center of the square loop using the formula $B = \sqrt{2}\mu_0 IN/\pi a$ tesla (1 tesla = 10^4 gauss) where μ_0 is the magnetic permeability of air, I is the current, N is the number of turns, and 2a is the side dimension of the square loop. The calculated ("actual") fields have been corrected for the perturbation due to the image field noted above. The current I was measured with a 0.1 ohm shunt-voltmeter combination, which had been calibrated in the BPA standards laboratory. The uncertainty in the calculation for the applied

magnetic field is estimated to be less than ±1% and consists primarily of uncertainties in the values of the current I and side dimension of the loop. No adjustments were made in the calculated fields for the approximately 0.015 mG ambient field along the axis of the loop because its phase relative to the applied field was unknown. Ignoring the ambient field will influence the results shown in Figure 3(a-b), but its impact for higher field values should be negligible. Also ignored is a small effect due to the vertical stacking of the 28 turns of wire (a reduction of about -0.1% in the magnetic field at the center of the loop).

Experience during the workshop indicated that the error in repeatability of measurements for an individual instrument by different observers is less than 2% for instruments with digital displays and less than 5% for instruments with analog displays. The latter uncertainty is probably due in part to the effects of parallax.

The data in Figure 3 show that most of the field instrument readings are too low for flux densities above about 2 mG. The difference between the applied and measured values was largest for the lowest applied fields (the maximum difference was -66% for meter A). The difference decreased for larger applied fields where the maximum difference was about -8% for meters B and F near 1 G. The tendency for the measurements to be too low may indicate that, in some instances, the calibration loop or coil used to calibrate the field instrument was too small for the probe. A formula for calculating the magnetic field from a square loop of wire of many turns is available in several references [5, 7, 11]. This formula can be used to calculate the field non-uniformity over the dimensions of the magnetic field probe and thus allows one to determine the appropriate size loop. Measurement results which demonstrate the effects of using a loop that is too small, for a given magnetic field probe, are discussed in Section V-B.

Two multi-axis field instruments (Instruments L and M) that record the values of the magnetic field in "bins", or magnetic field intervals, were also examined in the 2m by 2m calibration loop. Spot checks of their performance were made for field values ranging from about 0.2 mG to near 1 G and the resulting data are shown in Table III. Both instruments recorded most of the field values in the appropriate bins. However, two exceptions were observed for each device as indicated with asterisks in Table III. A careful examination of the bin edges could not be performed because of the limited time and these results are not definitive.

B. Effect of Calibration Loop Size

The effect of calibration loop size on the calibration of different measuring instruments is shown in Table IV. The percent of deviation of the measured field from the actual field is given in Table IV for successive measurements at 100 mG and 1G in the three loops. Two significant results of this comparison are:

A calibration loop must not be too small with respect to the sensing coil of the instrument. For example, Instrument C has

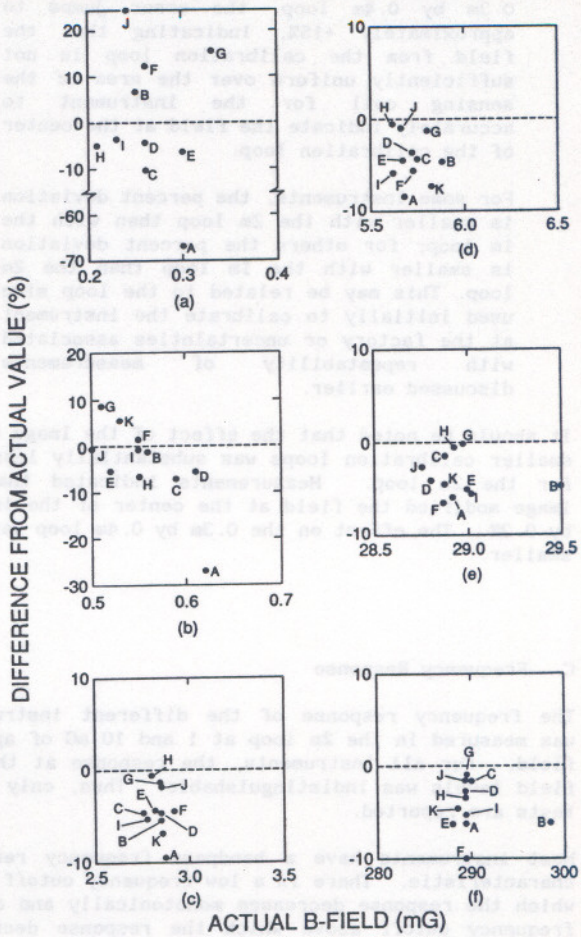

Fig. 3
Results of the Calibration Checks on all Instruments

Table III. Applied Magnetic Field Values and Bin Intervals (* indicates measurements which fall into an incorrect bin)

Instrument	Applied B-Field (mG)	Bin Interval (mG)
L	0.28	0.24- 0.49
	* 0.53	0.24- 0.49
	* 2.76	1.00- 2.00
	5.50	3.90- 7.80
	28.70	15.60-31.30
	58.08	31.30-62.50
	299.30	250.0-500.0
	578.80	>550.0
M	0.24	0.24- 0.49
	* 0.53	0.24- 0.49
	2.86	2.00- 3.90
	5.73	3.90- 7.80
	29.03	15.60-31.30
	56.40	31.30-62.50
	289.71	250.0-500.0
	*578.58	250.0-500.0
	963.24	500.0-1000.0

a large sensing coil compared to the other instruments. It shows good accuracy when calibrated in a 1 or 2 meter square loop, either of which is large compared to the sensing coil. When calibrated in the 0.3m by 0.4m loop, the error jumps to approximately +15%, indicating that the field from the calibration loop is not sufficiently uniform over the area of the sensing coil for the instrument to accurately indicate the field at the center of the calibration loop.

For some instruments, the percent deviation is smaller with the 2m loop than with the 1m loop; for others the percent deviation is smaller with the 1m loop than the 2m loop. This may be related to the loop size used initially to calibrate the instrument at the factory or uncertainties associated with repeatability of measurements discussed earlier.

It should be noted that the effect of the image on the smaller calibration loops was substantially less than for the 2m loop. Measurements indicated that the image modified the field at the center of the 1m loop by 0.3%. The effect on the 0.3m by 0.4m loop was even smaller.

C. Frequency Response

The frequency response of the different instruments was measured in the 2m loop at 1 and 10 mG of applied field. For all instruments, the response at the two field levels was indistinguishable. Thus, only 10 mG tests are reported.

Most instruments have a bandpass frequency response characteristic. There is a low frequency cutoff below which the response decreases monotonically and a high frequency cutoff above which the response decreases monotonically. The purpose of the low frequency cutoff is to prevent erroneous readings due to movements of the sensor coil in the earth's relatively large but steady magnetic field. The upper cutoff frequency occurs either because an imperfect sensor core material is used or because a high frequency filter is built into the instrument.

During these tests, the low frequency cutoff was not measured because 60 Hz was the lowest frequency used. The only information given here about this cutoff is the data provided by the manufacturers in Table II. The upper cutoff frequency for each instrument may not have been found since 540 Hz was the highest frequency used. Again, information on this cutoff is given in Table II.

The instruments can be divided into three general categories with respect to frequency response between the two cutoffs. Some instruments have switchable filters and thus may appear in more than one category. The categories are:

1. Linear response -

These instruments have neither a narrowband filter nor an integrator. Ideally, they exhibit a linear response with frequency because the output of the sensor loop is proportional to the derivative of the magnetic field normal to the sensor. Instrument A has this response while instruments B and E can be configured to have this response.

Table IV
CALIBRATION LOOP COMPARISON
Percent Error at Two Field Levels for Each Loop

Meter	Nominal Field	Loop: 2 Meter	1 Meter	.3x.4 Meter
A	100 m	-2.80	-3.57	-1.56
	1 G	-2.61	-3.83	-1.05
B	100 mG	-3.04	-5.07	+1.19
	1 G	-2.81	-4.64	+5.42
C	100 mG	+2.91	+2.62	15.14
	1 G	---	+1.57	14.68
D	100 mG	+0.49	+0.62	+3.59
	1 G	+1.66	-0.62	+3.01
E	100 mG	+0.12	-5.07	+9.79
	1 G	-2.30	-3.10	+9.44
F	100 mG	-4.08	-4.07	+2.04
	1 G	-6.46	-6.12	+0.59
G	100 mG	+3.78	+1.15	+0.67
		+7.45	+6.16	+6.62
		+3.94	+2.78	+4.69
	1 G	---	---	---
H	100 mG	-1.90	---	---
		-2.79	---	---
		-2.63	---	---
	1 G	---	---	---
I	100 mG	-3.25	-3.07	+4.21
	1 G	-3.33	-3.28	+4.91
J	100 mG	+0.94	-3.07	+2.23
		-2.17	-0.08	-0.13
		+1.02	-0.08	+1.05
	1 G	+1.87	+0.87	+3.80
		-1.25	-2.13	-0.23
		+1.84	-0.13	+1.79
K	100 mG	-4.19	-7.07	-0.87
		-5.23	-6.07	-3.99
		-5.27	-6.07	-4.97
	1 G	-4.38	-7.13	-2.61
		-4.33	-5.13	-3.43
		-4.35	-5.13	-1.42
N	100 mG	+4.37	+8.22	+15.57
	1 G	---	---	---

Notes:
1) --- means did not participate or unable to read 1 G
2) Where 3 values are given, they are for X,Y,Z axes (respectively)
3) The output of Instrument N is a 1 minute average at 100 mG

2. Integrated ("flat") response -

In these instruments, the output of the sensor loop is passed through an integrator circuit to produce an output which is proportional to the magnetic field. Ideally then, the response should be independent of frequency. Instruments C, H and K are designed to have this response while Instruments B and E can be configured to have this response.

3. Narrowband response -

In these instruments there is a filter with a narrowband centered on the frequency of interest. In most cases the center frequency is selectable 50/60 Hz but in some cases it is switchable to allow measurement of harmonic frequency content. Instruments D, G, J, L and M have narrowband 50 and/or 60 Hz filters while instrument F has switchable 60 and 180 Hz filters.

Examples of the different types of frequency response are shown in Figure 4: the linear response (Instrument A), the integrated ("flat") response (Instrument B with integrator) and the narrowband response (Instrument D). The performance of the remainder of the instruments is summarized in Table V. Several observations can be made about these data.

Instruments A, B (without integrator) and E (without integrator) can be characterized to have linear responses. The response of each tends to droop with respect to an ideal linear response at higher frequencies. This effect is more pronounced with meter A, possibly due to the frequency response of the ferrite core.

Instruments B (with integrator), C, E (with integrator), H, J and K can be characterized as having "flat" frequency response. Of these instruments, only B, E and H are close to the ideally flat response. The response of the others tend to decrease at higher harmonic frequencies.

Instruments D, F, G and I have "narrowband" frequency responses. Each (except F with its 180 Hz filter switched on) has a center frequency of 60 Hz. Instruments F and I have the narrowest response.

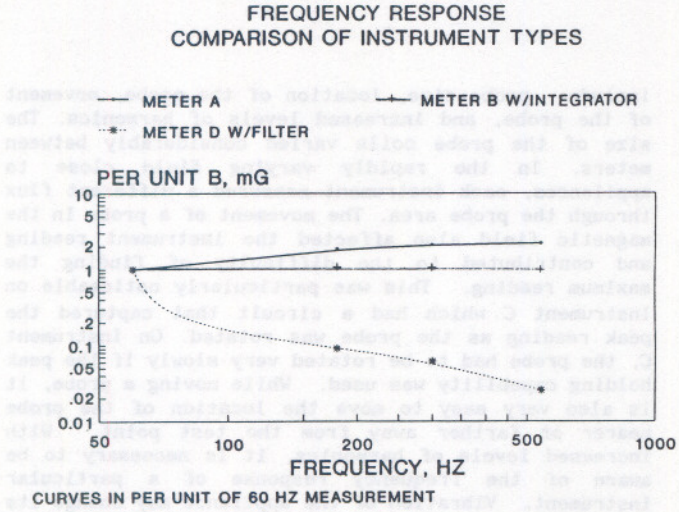

Figure 4
Comparison of Instrument Types for Frequency Response
(A - "linear response," B - "flat response,"
D - "narrowband response")

Meter	Category	Response @60Hz	@180Hz	Per unit(10mG) @300Hz	@540Hz
A	linear	.945	1.775	1.985	2.084
B	linear	.928	2.988	4.696	7.427
B	flat	.938	1.014	.989	1.033
C	flat	.982	.853	.652	.372
D	narrowband	.981	.088	.060	.025
E	linear	.994	2.747	4.591	8.105
E	flat	1.030	.988	.975	.955
F (60Hz)	narrowband	.949	.009	.000	.001
F (180Hz)	narrowband	.121	.987	.044	.006
G	narrowband	1.037	.096	.057	.033
H	flat	.982	.937	.945	.955
I	narrowband	.954	.016	.009	.010
J	flat	.999	.983	.769	.475
K	flat	.928	.761	.507	.265

Table V
Per Unit Instrument Response to 10 mG
Applied Field at Several Frequencies

D. 60 Hz Electric Field Test

The instruments which showed a discernible change in magnetic field reading as the electric field was raised were B (0.23 mG at 15 kV/m), C (2.3 mG at 15 kV/m), D (0.2 mG at 15 kV/m), F (0.2 mG at 15 kV/m), and L (0.49-1.0 mG bin at 15 kV/m). In this group, the only instrument which was appreciably affected by the electric field was C. The 0.2 mG errors noted on the other survey meters were not thought to be serious and the increase in reading for L was also not serious. It should be noted that Instruments M, J and K were not affected by the electric field but also read a larger ambient magnetic field than the others. This is because the noise floor of these instruments appears to be larger than for the single axis instruments.

Because of the result noted above, further testing on Instrument C was conducted several weeks after the workshop. Three instruments were used: the original meter, an instrument of design identical to the original meter in order to determine if the effect seen was design related or peculiar to the particular instrument tested and an instrument modified by the manufacturer to minimize the effect of high electric fields on magnetic field readings.

All three model C instruments were exposed simultaneously to a high 60 Hz electric field at various levels and a magnetic field at several known levels. The performance of the original instrument was comparable to the second identical instrument. The original instrument could be used to accurately measure 0.1 mG fields if the electric field was less than 5 kV/m and 1 mG fields if the electric field was less than 10 kV/m. Fields 10 mG and larger could be accurately measured up to 15 kV/m. The modified instrument supplied by the manufacturer performed well at all electric field levels. The modification has been incorporated into the design of all instruments sold by this manufacturer and older units may be retrofitted with the modification upon request.

E. Electromagnetic Interference Tests

Only two instruments, D and L were affected by the presence of EMI. Instrument L was affected only when the ribbon cable between the instrument and the readout unit was used. When this cable was removed, the instrument performed well in the EMI environment. Instrument D, however, was significantly affected by

EMI. In order to remove the effect it was necessary to reduce the EMI field by 30 dB below the 1 V/m test field.

F. Transmission Line Lateral Profile Measurements

Table VI contains the results of the simultaneous vertical magnetic field measurements at the five stations. All of the instruments measured within 7.5% of the average reading at each station. During these measurements Instrument E was operated in the linear mode. In this state, the magnetically induced probe voltage is linearly related to frequency so that the magnetic field measurement of harmonics would be multiplied by the harmonic number. The rest of the instruments had either integrators or some other filtering in them to reduce the higher induction effects of harmonics.

The horizontal magnetic field measurements are shown in Table VII. All of the instruments measured within 7.4% of the average reading except at Station 5 where the field level was low.

At Station 5, Instrument E indicated significantly higher horizontal fields than the other instruments. One can postulate that the harmonic levels at this location were larger at this lower field level. As a consequence, the horizontal field measurements at Station 5 were made with instrument E in the "flat" mode (i.e. with the integrator connected).

The measurement differences for the profile test are probably due to a combination of some of the following factors; instrument accuracy and calibration, instrument filtering differences, reading errors, slight differences in probe alignment and the presence of harmonics. When making comparative measurements, it is very important to check the impact of these various factors. For instance, if harmonics are significant, the filtering circuits should be investigated. Given the presence of these sources of error, it is concluded that there was fairly good agreement between the six instruments that were used.

G. Appliance Measurements

The results of the measurements near appliances are shown in Tables VIII and IX. In Table VIII, the measured fields are grouped according to the operator. The readings for each instrument are grouped together in Table IX. Thus the repeatability of magnetic field measurements taken by the three instrument operators is shown in Table VIII while the repeatability of the field values as measured by the six instruments is shown in Table IX.

These data in Tables VIII and IX indicate that appliance measurements near appliances are extremely difficult to make with a probe that is manually oriented to obtain the maximum magnetic field. There is considerable variability in the measurements due to the difficulty in locating the maximum field with a single axis probe. The ratio of the highest to the lowest reading varied from 1.4 to 4.1 at 0.3m and from 1.1 to 16 at 1.0m. In most cases the ratio ranged from 1.1 to 3. The measurements at 1.0 m (where the magnetic field is more uniform) generally have less variability than those at 0.3m. However, this was not always the case as the largest ratio of high/low readings occurred at 1.0m.

In addition to the problem of locating the maximum field, there are several other complicating factors when making measurements near appliances. These include: probe size, location of the probe, movement of the probe, and increased levels of harmonics. The size of the probe coils varied considerably between meters. In the rapidly varying field close to appliances, each instrument measured a different flux through the probe area. The movement of a probe in the magnetic field also affected the instrument reading and contributed to the difficulty of finding the maximum reading. This was particularly noticeable on Instrument C which had a circuit that captured the peak reading as the probe was rotated. On Instrument C, the probe had to be rotated very slowly if the peak holding capability was used. While moving a probe, it is also very easy to move the location of the probe nearer or farther away from the test point. With increased levels of harmonics, it is necessary to be aware of the frequency response of a particular instrument. Vibration of the appliance may change its location with respect to the probe. Ambient magnetic fields may also affect the appliance measurements. During these tests, the ambient field increased dramatically at one time due to the operation of a large test transformer. The appliance measurements had to be postponed until the transformer was turned off.

For these reasons, appliance measurements are not very repeatable between instruments and operators. The variability is much greater than when making measurements of a transmission line profile.

TABLE VI

SIMULTANEOUS VERTICAL MAGNETIC FIELD MEASUREMENTS-mG

METER	STN 1	STN 2	STN 3	STN 4	STN 5
A	4.3	4.3	4.5	3.5	.8
B	4.3	4.5	4.6	3.2	.80
C	4.46	4.65	4.72	3.53	.870
D	4.24	4.87	4.63	3.62	.867
E*	4.45	4.7	4.75	3.6	.84
F	4.1	4.4	4.4	3.3	.81
AVERAGE	4.31	4.57	4.60	3.46	.831
MAX. DEV.	4.9%	6.6%	4.3%	7.5%	4.7%

* Meter E was in the linear mode.

TABLE VII

SIMULTANEOUS HORIZONTAL MAGNETIC FIELD MEASUREMENTS-mG

METER	STN 1	STN 2	STN 3	STN 4	STN 5
A	10.1	7.5	9.9	3.3	.40
B	9.3	7.4	9.5	3.3	.45
C	10.13	7.72	10.10	3.48	.339
D	10.58	7.65	9.94	3.38	.308
E*	10.0	6.85	9.95	3.4	.35
F	9.4	7.3	9.3	3.2	.31
AVERAGE	9.92	7.40	9.78	3.34	.360
MAX. DEV.	6.7%	7.4%	4.9%	4.2%	25%

* Meter E was in the linear mode except for Station 5 when it was in the flat mode.

TABLE VIII

MEASUREMENTS OF MAGNETIC FIELDS FROM THREE ELECTRICAL APPLIANCES DATA ARRANGED BY OPERATOR (mG)

OP. NO.	MTR	HEAT GUN @0.3m	HEAT GUN @1.0m	HEATER @0.3m	HEATER @1.0m	DRILL @0.3m	DRILL @1.0m
1	A	13.7	0.0	70.2	2.1	48.2	1.3
1	B	23.5	0.15	45	2.0	21	1.15
1	C	12.8	0.55	53.7	1.7	26.1	1.02
1	D	14.01	0.21	65	2.36	34	0.97
1	E	12.5	0.2	50	2.0	23.5	1.1
1	F	13	0.2	64	2.5	12.4	1.7
1	MAX/MIN RATIO	1.9	>3.7	1.4	1.5	3.9	1.8
2	A	12.4	0.0	60.2	1.9	48	1.5
2	B	12	0.05	55	2.0	39	1.4
2	C	20.8	0.81	39.6	2.0	41.2	1.3
2	D	20.7	0.17	67	2.05	47.5	1.33
2	E	18	0.17	48	2.05	55	1.25
2	F	15	0.16	87	2.1	56	1.23
2	MAX/MIN RATIO	1.7	>16.2	2.2	1.1	1.4	1.2
3	A	3.7	0.0	56.6	1.7	45	1.5
3	B	6.2	0.21	42.0	2.2	22	1.1
3	C	6.66	0.08	71.9	1.9	50.5	1.06
3	D	1.84	0.171	21.2	2.01	12.3	0.64
3	E	5.1	0.14	52	1.8	15	1.1
3	F	2.1	0.27	48	1.59	32	0.87
	MAX/MIN RATIO	3.6	>3.4	3.4	1.4	4.1	2.3
4	J	8.0	0.5	62	1.4	29	1.3

TABLE IX

MAX/MIN RATIOS OF MAGNETIC FIELD MEASUREMENTS BY 3 DIFFERENT OPERATORS FROM THREE ELECTRICAL APPLIANCES DATA ARRANGED BY INSTRUMENT TYPE (mG)

METER NO.	HEAT GUN @0.3m	HEAT GUN @1.0m	HEATER @0.3m	HEATER @1.0m	DRILL @0.3m	DRILL @1.0m
A	3.7	undef.	1.24	1.23	1.07	1.15
B	3.8	4.2	1.31	1.1	1.86	1.27
C	3.12	>1.47	1.82	1.14	1.93	1.27
D	11.25	1.23	3.19	1.17	3.86	2.08
E	3.53	1.43	1.08	1.14	3.67	1.08
F	7.14	1.69	1.81	1.57	4.52	1.95

H. Results of Ross Substation and Office Walkthrough Tests

For this series of tests, the data recorder and exposure instruments (Instruments G, J, K, M and N on Table I) were used. Measurements were also made with Instrument L. Unfortunately, an apparent malfunction during operation or data retrieval precluded analysis of the data from this instrument. Some of the relevant characteristics of these instruments are shown in Table X.

TABLE X

OPERATING CHARACTERISTICS OF MAGNETIC FIELD DATA RECORDERS AND EXPOSURE METERS DURING TESTS

Instrument	Measurement Rate	Sensor Location
G(Star)	1/second	Hip (belt)
G(Vana)	1/foot	0.75m height on wheel
J	1/(5 seconds)	Hip (belt)
K	1/meter	0.5m height on wheel
L	1/(5 seconds)	Hip (belt)
M	1/(5 seconds)	Hip (belt)
N	Continuous Integration	Wrist

The results of measurements along the high-field substation walkthrough are summarized in Tables XI and XII. The results for instruments that sampled at a constant time interval (exposure instruments) are given in Table XI while the results for constant distance intervals (data recorders) are given in Table XII. The summary measures for exposure instruments that are shown in Table XI indicate that Instruments G, J and M agreed closely with respect to the mean, median, percentiles, minimum and maximum fields. This consistency was observed for different instruments and for different individuals with the same instrument. The agreement over all the statistical measures gives added confidence to the consistency of results. Because the distributions of field measurements are highly skewed, it is not advisable to rely on one indicator, say the mean, for comparison. These results indicate that at least in high-field environments where the fields are above several milligauss, consistent exposure measurements were obtained with the different instruments.

The mean levels derived from the time-integrated field recorded by Instrument N, worn on the wrist, during the high-field walkthrough were consistent over the three trials. These levels (≈50 mG) were slightly higher than the mean levels determined from the data recording instruments (≈46 mG). This slight difference is likely due to the single axis response of Instrument N and the conversion factor of 2 used to account for the random and variable orientation of the unit with the magnetic field when worn on the wrist. One other consideration in using Instrument N in a high field area is that its amplitude response rolls off for fields above 125 mG. This does not appear to be a factor in this case but might be in other high field situations.

The results shown in Table XII indicate that both distance-triggered meters agreed as they were wheeled along approximately the same path in the substation. The differences between the two meters is within the variation expected due to slightly different paths, different sampling intervals and different heights (.75 m for Instrument G (VANA) and 0.5 m for

Instrument K). Comparing Tables XI and XII indicates that the results for sampling at equal distance intervals along the route are essentially the same as the results measured at equal time intervals by the exposure meters.

The results of the three walkthroughs of the low-field office environment are shown in Tables XIII and XIV for equal time interval and equal distance interval sampling, respectively. In this case the results for an exposure instrument or data recorder are consistent from trial to trial with different individuals.

However, in comparing different instruments, the summary measures for Instrument M tend to be higher by about a factor of 2 than those for Instruments G and J. For the higher fields along this office walkthrough this discrepancy between instruments might be accounted for by the different positions on the body where the various instruments were worn. For example, Instrument M might have been closer to the bench grinder than Instruments G and J. However, the discrepancy at the minimum and 25 percentile fields remains unexplained: The low field areas are probably fairly uniform and body position should not make a difference. Since Instrument M has a narrow bandpass, it should not respond to harmonics that might be present. In fact, given the frequency responses of the various instruments, one would expect Instrument M to give the lowest reading, not the highest, when harmonics are present.

The number of trials and time available were insufficient to allow a resolution of the differences between the instruments noted above. Clearly, additional work is required to resolve the apparent differences. However, these results do indicate that care must be taken to understand the uncertainties and difficulties of making measurements in low-field office (and residential) environments. Similarly, caution must be exercised in interpreting results and attributing accuracies to exposure measurements in low field environments.

The mean fields for the low-field environment derived from the time-integrated field of Instrument N are similar to the mean fields measured by the exposure instruments. However, the variability of the wrist-watch style single-axis device is apparent for the three cases given in Table XIII although Case 2 and Case 3 agree well with Case 2 and Case 3 of Instrument M. The different arm motions of the subjects and different positions relative to the local sources are likely responsible for the different results. As with the comparisons between the various exposure meters, additional work is needed to reach conclusions regarding the uncertainties in the use of this type of instrument in low fields.

The results shown in Table XIII indicate that the two distance-triggered data recorders agreed for measurements along the low field walkthrough to the extent expected given slightly different paths and heights. In addition, the results shown in Table XIV can also be favorably compared with the results from Instruments G and J in Table XIII. However, the personal exposure measurements tend to be higher than those taken with the data recorders. This is probably because the wearers could move closer to sources along the route than the wheel-mounted devices could.

Based on the limited measurements with and comparisons between exposure meters performed during the workshop, we conclude that additional investigation of the performance and uncertainties of the use of these devices is warranted. This is especially true if comparisons are made between absolute measurements made with these devices. The performance of the instruments in low fields (<10 mG) is of particular concern since this is the range within which most exposures fall.

TABLE XI
MAGNETIC FIELD EXPOSURE MEASUREMENTS IN mG DURING WALK THROUGH HIGH FIELD AREA IN SUBSTATION
(Data taken at constant time intervals)

MTR	Trial	No Samp.	Total Time	Mean	StDev	Min	25%	50%	75%	Max
G	Hi#1	816	816	46.2	52.5	3.20	12.1	26.5	56.5	284
(STAR)										
J	Hi#1	153	765	46.0	49.5	3.96	12.6	26.3	58.6	258
	Hi#2	161	805	47.1	52.1	3.62	12.8	27.9	59.6	287
	Hi#3	164	820	45.4	50.7	3.71	12.0	23.9	58.1	251
M	Hi#1	154	770	45.3	48.6	3.67	16.8	26.5	53.6	282
	Hi#2	161	805	45.2	53.3	3.67	12.2	26.0	53.6	270
N	Hi#1	1	750	49.5						
	Hi#2	1	802	51.5						
	Hi#3	1	801	50.5						

TABLE XII
MAGNETIC FIELD MEASUREMENTS IN mG ALONG ROUTE OF WALK THROUGH HIGH-FIELD AREA IN IN SUBSTATION (Data taken at constant distance intervals)

MTR	Trial	No Samp.	Total Dist. (ft)	Mean	StDev	Min	25%	50%	75%	Max
G	Hi#1	2425	2425	49.3	56.5	4.5	12.4	27.7	59.4	331
(VANA)	Hi#2	2629	2629	49.3	56.4	4.5	12.3	28.2	62.0	331
K	Hi#1	794*	2604	43.2	46.3	3.7	11.0	23.1	58.3	251

*The manufacturer indicated an intermittent malfunction may have caused some measurements to be omitted.

TABLE XIII
MAGNETIC FIELD EXPOSURE MEASUREMENTS IN mG DURING WALK THROUGH LOW-FIELD AREA IN OFFICE/SHOP
(Data taken at constant distance intervals)

MTR	Trial	No Samples	Total Time(s)	Mean	StDev	Min	25%	50%	75%	Max
G	Lo#1	724	724	2.1	2.5	.1	.6	1.4	2.3	14.6
(STAR)	Lo#2	765	765	1.7	1.4	.1	.8	1.4	2.0	7.8
J	Lo#1	133	665	2.7	3.0	.6	.9	1.7	2.5	16.9
	Lo#2	125	625	2.7	3.0	.6	1.0	1.8	2.5	11.8
	Lo#3	131	655	2.6	3.5	.6	1.0	1.8	2.8	22.2
M	Lo#1	127	635	4.1	3.8	1.5	2.2	3.1	3.8	17.6
	Lo#2	124	620	4.2	4.6	1.5	2.2	3.4	4.2	47.0
	Lo#3	130	650	3.3	2.6	1.5	2.2	3.4	3.7	28.0
N	Lo#1	1	635	10.6						
	Lo#2	1	620	4.0						
	Lo#3	1	650	3.5						

TABLE XIV
MAGNETIC FIELD MEASUREMENTS IN mG ALONG ROUTE OF WALK THROUGH LOW-FIELD AREA IN OFFICE/SHOP
(Data taken at constant distance intervals)

MTR	Distance Trial	n	Feet	Mean	StDev	Min	25%	50%	75%	Max
G	Lo#1	1834	1833	1.8	2.6	.1	.7	1.2	2.1	36.3
(VANA)	Lo#2	1872	1871	1.6	1.3	.1	.8	1.3	2.0	9.6
K	Lo#1	1117*	1832	1.9	1.3	.2	.9	1.6	2.2	12.2

* The manufacturer indicated an intermittent malfunction may have caused some measurements to be omitted.

VI. CONCLUSIONS

1. The calibration of all instruments was generally satisfactory: all instruments read systematically low and within 10% of the applied field at field levels greater than 1 mG. The majority were within 5% but instruments A, B, E, F, I and K were out of or only marginally within the 5% calibration limit set in IEEE Standard 644-1987 [7]. Below 1 mG, the spread of the readings was considerably larger: as much as 30%. Only instruments B, D, E, H and I were consistently within 10% at field levels down to .2 mG.

2. For accurate calibration, square loops with side dimensions of at least 1 meter are suggested. For indoor calibrations, the presence of grounding mats and their effect on the calibration process should be considered.

3. There was considerable variation in the frequency response of the various instruments. The frequency response can influence the performance of instruments in environments where harmonics are present.

4. With appropriate design, magnetic field measuring instruments can be made immune to 60 Hz electric fields and to VHF electromagnetic interference.

5. All field survey instruments (A-F) were found to agree within +/- 7.5% of the mean measured field when compared along a lateral profile under two power lines except at one station with low field level and high harmonic content.

6. Because of nonuniformity and harmonic content of the fields near appliances, consistent measurements are difficult. The measurements are dependent on both the instrument and the operator. Normal variations in the ratio between high and low readings ranged from 1.1 to 3. However, ratios as high as 16 were found between instruments (same operator) and 11 between operators (same instrument).

7. Exposure measurements made with different data recording instruments in a high field environment were in agreement. However, in a low field environment, there were significant differences between instruments. These discrepancies could not be resolved within the limited scope of this workshop.

8. The output of an instrument with a three axis sensor coil is the vector sum of the rms values of the individual vector components. This represents an upper limit on the maximum field (i.e., the rms value of the magnetic field along the semi-major axis of the field ellipse).

9. Additional investigation of the performance of magnetic field exposure measuring devices is warranted.

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