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Calibration Check of Bonneville Power Administration 60-Hz Electric Field Exposure Monitor and Measurement of Its Surface Field Enhancement for Various Uniform and Nonuniform Operating Configurations

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Electronics and Electrical Engineering
Electrosystems Division
Gaithersburg, Maryland 20899

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Abstract

This report presents the results of tests requested by the Bonneville Power Administration (BPA) on a 60-Hz Electric Field Exposure Monitor (EFEM) developed by their Instrumentation and Standards Branch. The unit is designed to be worn on the body, such as in a shirt pocket or attached to the clothing. The calibration of two sample units is examined, information on surface field enhancement (which results from the EFEM sensors' elevated position relative to the surface of the body) is presented, the effect of material covering the sensor is specified, and the applicability of calibration and operational information obtained in uniform fields to nonuniform fields is investigated.

Keywords: calibration accuracy; Electric Field Exposure Monitor (EFEM); enhancement; flush mounted; nonuniform field; parallel plates; sensor; surface field enhancement; uniform field.

SUMMARY

This report presents the results of tests requested by the Bonneville Power Administration (BPA) on a 60-Hz Electric Field Exposure Monitor (EFEM) developed by their Instrumentation and Standards Branch. The unit is designed to be worn on the body, such as in a shirt pocket or attached to the clothing. The calibration of two sample units is examined, information on surface field enhancement (which results from the EFEM sensors' elevated position relative to the surface of the body) is presented, the effect of material covering the sensor is specified, and the applicability of calibration and operational information obtained in uniform fields to nonuniform fields is investigated.

The uniform field calibration is found, with the exception of one point for each sample unit, to be within 4% of the design value for one unit and within 5% for the other unit. Surface field enhancement in a uniform field varies from approximately 54% with the EFEM case in contact with a grounded surface down to approximately 31% with the case separated 2 to 4 cm from the surface by a material with low (<2) dielectric constant. The comparable figures for two different nonuniform field configurations are 51% to 52% enhancement with the EFEM case in contact with the surface, down to 10% at an EFEM sensor distance of 6 cm from the surface. Enhancement caused by cotton and/or wool cloth over the sensor is relatively independent of field type and averages between 1.5% and 2.5% for one layer and between 4% and 5% for two layers.

The report shows that, with the exception of enhancement caused by cloth over the EFEM sensor, surface field enhancement information determined in a uniform field cannot be applied to a nonuniform field without some modification. The nonuniform field information was obtained using a rectangular tower between parallel plates. Although it might be argued that such data could be extrapolated to estimate enhancement for an EFEM placed on a human, the human form is not the same as that of the tower. Further testing employing a more realistic geometry would be necessary to provide rigorous information.

1. INTRODUCTION

For a number of years, there has been concern over the possible biological effects from long-term exposure to electric fields arising from the transmission of electric power across the country via high voltage transmission lines. Of concern has been the level of exposure received both by workers in the field and by people living near the transmission lines. A great deal of research has been and is being done on the subject, but to date results are inconclusive and sometimes contradictory. One failing of studies involving human subjects up to the present has been the lack of instrumentation to obtain accurate electric field exposure data. This may be due in part to the lack of agreement concerning the manner in which the electric field interacts with the body (which necessarily affects the method by which exposure is measured). In any event, various electric field monitors have recently been developed in response to this need, and one of them, the 60-Hz Electric Field Exposure Monitor (EFEM) from the Bonneville Power Administration (BPA) Instrumentation and Standards Branch is the subject of this report. Its calibration is checked and a determination made as to the applicability of the calibration performed under uniform field conditions for subsequent use in nonuniform field conditions.

The BPA Electric Field Exposure Monitor is in the shape of a small rectangular box, approximately 7 cm x 5.7 cm x 1.6 cm, and designed to be worn on the body, such as in a shirt pocket or attached to the clothing in some fashion. The box consists of a steel case with a copper foil sensing plate attached to, but insulated from, one of the large sides to form a small parallel plate arrangement. Every four seconds, analog circuitry detects the average current induced between the plates by the electric field and places a "count" in one of eight memory locations or "bins", according to the magnitude of the induced current. The induced current's relationship to the electric field is determined by calibration and the memory locations can be adjusted to store counts for different field strength intervals. At the end of a measurement period (which can be as long as nine hours), the EFEM is inserted into a separate instrument for readout of the number of counts stored in each bin [1,2].

Because of the field enhancement resulting from the sensors' elevated position relative to the surface of the body, the electric field strength indicated by the EFEM is higher than the actual field strength at the surface of the body where the EFEM is placed. This effect will vary with mounting position, distance from the body, material between the EFEM and the body (if any), and material covering the EFEM (if any).

This report examines the uniform field calibration of two sample units, determines the "surface field enhancement" for various EFEM configurations, and provides information on how valid the uniform field calibration is for measurements made under nonuniform field conditions.

2. BACKGROUND: SELECTION OF ELECTRIC FIELD MEASUREMENT METHOD, THE EFEM, AND SURFACE FIELD ENHANCEMENT

The selection of the measurement method to best indicate electric field magnitude in biological effect studies depends upon how the electric field interacts with the biological systems. At the present time, the mechanisms for the biological effects that have been reported in the literature are not well known. There has been speculation by biologists that two possible mechanisms may be (1) surface interactions (i.e., surface field mechanism), and

(2) interactions at cell membranes (which might be related to internal currents induced by the field) inside the body. The EFEM makes measurements that are more closely related to the first mechanism. But again, there is more than one measurement approach that could be used to characterize the electric field. For example, the unperturbed electric field to which the biological system (person) is exposed, i.e., the field which existed prior to the entrance of the person, could be measured, or the electric field at the surface of the person could be measured. Although the EFEM indication is much closer to the second example, it measures neither one directly and its indication must be mathematically adjusted to arrive at the desired information.

Previous studies [1,3,4] have determined factors (enhancement factor, activity factor, etc.) by which the EFEM reading can be multiplied to arrive at an approximate value for the unperturbed electric field at the EFEM location. The numerical values of the factors depend on such variables as where on the body the EFEM is attached, the activity being engaged in during measurement, the body impedance to ground, etc. This report, in addition to checking the calibration accuracy of two sample EFEM units, determines a surface field enhancement factor, i.e., the amount that the EFEM reading exceeds the actual surface field at the location of the EFEM, and examines the variation of this factor with uniformity of the field, the location of the EFEM on the body, the distance from and the angle formed with the body surface, the materials (if any) between it and the body surface, the materials covering the sensor, etc. The EFEM reading will almost always be higher than the true body surface field because its sensor is located above the body surface.

3. TEST PROCEDURE AND APPARATUS

3.1 Calibration Check

The eight memory locations or bins of the two EFEMS sent to NBS for evaluation have been designed by BPA to register electric field levels as indicated in Table 1. For example, exposure to an electric field of 4 kV/m should cause a count to be placed in bin #2 every four seconds. Determination of the actual bin edges is a relatively lengthy process because, for each edge, the EFEM must be subjected to a range of electric field values which will be certain to contain that bin edge. Since the actual boundary might differ from the value given in the table, the initial tests must cover a relatively wide range of electric field values. Once the general area of the bin edge is determined, further testing can locate the edge value to an acceptable narrow electric field range. The problem is that to locate the boundary, counts must always be obtained from fields that are both higher and lower than the boundary. Narrowing the range too quickly may miss the boundary entirely, thereby requiring additional testing.

Initial calibration of the EFEM by BPA was accomplished in a uniform field generated between two parallel plates (bottom plate grounded) with the EFEM sensor flush with the bottom plate, and the EFEM case electrically connected to the bottom plate. This is also the configuration which NBS used to check the accuracy of the calibration for the two sample EFEM units.

The NBS parallel plates are approximtely 168 cm square and were spaced 40.0 cm apart for all uniform field measurements except those required to determine the boundary between the bins representing the two highest electric field levels. The plate spacing was reduced to 33.15 cm for this latter measurement in order to reduce the voltage required from the supply transformers.

Table 1. BPA Design Electric Field Ranges for EFEM Bins

EFEM sensor flush with surface, EFEM case connected to surface

Bin Number	Bin Range (kV/m)	Median Bin Value (kV/m)
0	0 to 1	0.5
1	1 to 3	2
2	3 to 6	4.5
3	6 to 10	8
4	10 to 15	12.5
5	15 to 21	18
6	21 to 28	24.5
7	28 to 36	32
8[a]	>36 plus total running time	

[a]The number of counts in the overrange bin equals the difference between the reading in bin 8 and the sum of readings in all the other bins (bins 0 to 7).

Previous studies [5] have shown that in the absence of nearby ground planes, the electric field between parallel plates, where the shortest plate dimension is at least twice the plate spacing, d, to be uniform and equal to V/d within 0.4% (where V is the voltage between the plates) for areas on the bottom plate which are at least one plate spacing away from the plate edge. The parallel plate setup at NBS thus provides a relatively large central area with good field uniformity. Since control and measurement instrumentation which is located within 30 to 60 cm of the plate edges at one side is a possible source of nonuniformity, an independent check of electric field over the central area of the bottom plate was made with a flat plate probe. The field was uniform within the above-stated 0.4%.

The electric field between the parallel plates can be calculated as the quantity V/d where V is the voltage between the plates and d is the distance between them, as noted above. The voltage is measured with a mirror-backed analog electrostatic voltmeter with four ranges. Each electrostatic voltmeter range was calibrated against an accurate (less than 0.1% uncertainty) digital voltmeter which measured voltage scaled down by a high voltage divider system, with an uncertainty of less than 0.01%. In spite of this, the combined effects of calibration and scale reading errors produce an electrostatic voltage measurement uncertainty between scale marks of 0.6%. Combined with the ±0.5% uncertainty in determining the distance between the parallel plates and the possible 0.4% variation in electric field at the bottom plate from the theoretical, the overall electric field uncertainty as determined by V/d is approximately ±0.9%. The root-sum-of-squares (RSS) is used to arrive at this overall uncertainty.

To reduce this uncertainty, and at the same time improve the repeatability of measurements, a sensor patch approximately 10 cm square was installed flush with, but insulated from, the surrounding bottom plate at a location 73 cm from each of the two nearest plate edges. The electric field, E, induces a current, i, in the patch according to the relation

$$i = 2\pi f \varepsilon_0 AE \ , \tag{1}$$

where A is the area of the patch, ε_0 is the permittivity of free space (8.8542×10^{-12} $C^2/N{\cdot}m^2$) and f is the frequency (60 Hz). The current is subsequently converted into a voltage by an operational amplifier circuit according to the relation

$$i = BV_0, \tag{2}$$

where V_0 is the operational amplifier output voltage and the value of B is a constant controlled by the circuit feedback resistor. Its value was measured by inserting different levels of current into the amplifier and measuring the corresponding output voltages. Combining equations (1) and (2) gives the relation

$$E = \frac{B}{2\pi f \varepsilon_0 A} V_0 \ , \tag{3}$$

where f and ε_0 are known with negligible uncertainty. The uncertainties in B, A, and V_0 are less than ±0.3, ±0.4, and ±0.08% respectively so that the uncertainty of E obtained by this method is less than ±0.5%.

As mentioned earlier, an independent check of electric field was made with a flat plate probe which could be moved to different areas on the bottom plate. Its dimensions are 8.5 cm square with a central sensor area of 5 cm square surrounded by a 1.75 cm guard band. Its measurement uncertainty is less than ±0.5%. The flat plate probe measures the field in the same manner as the stationary patch but uses a different operational amplifier. The difference between the patch and the flat plate probe readings was less than 0.2%.

The total harmonic distortion of the electric field generated between the plates was checked by means of a spectrum analyzer connected to the operational amplifier output from the 10 cm square patch on the bottom plate. Current induced into the sensor patch is proportional to the derivative of the electric field, causing each harmonic at the operational amplifier output to be multiplied in value by its harmonic number. Corrections to the individual harmonic amplitudes were thus necessary before total harmonic distortion could be computed. The total harmonic distortion is less than 0.6% at electric field values to 25 kV/m and less than 1.0% for values up to 36 kV/m.

For the calibration check, the EFEM was inserted into a holder designed so that the EFEM sensor could be adjusted flush with the bottom plate of the parallel plate apparatus (see fig. 1). The holder also permitted electrical isolation of the EFEM case from the bottom plate, if desired, in order to see what effect this had on the calibration. The holder is located 72 cm and 80 cm from the two nearest plate edges, the opposite edges from which the sensor patch is located. The shortest distance between the sensor patch and EFEM (edge to edge) is approximately 19 cm.

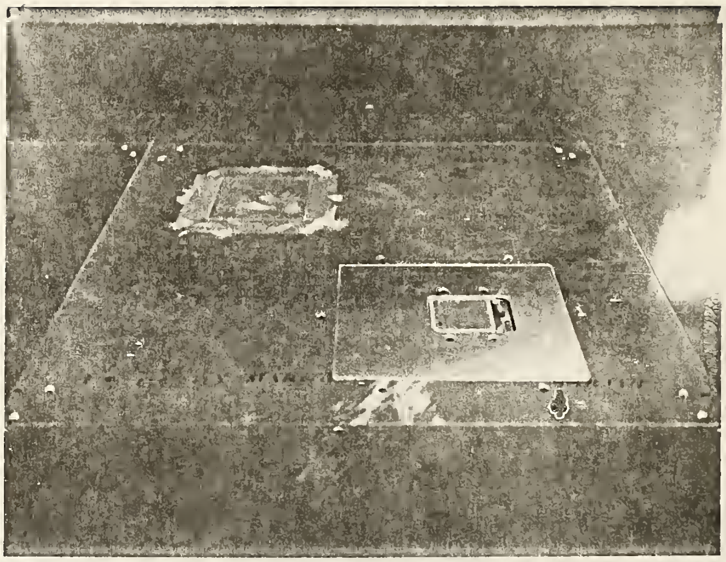

Figure 1. Electric field sensor patch (10 x 10 cm), and EFEM located in holder flush with bottom plate of parallel plate structure.

The EFEM begins registering counts in its various memory locations as soon as it is removed from the charger/reader unit. The procedure followed for each measurement was to start a timer as soon as the EFEM was removed (thereby keeping track of time spent at zero or near zero field), insert it into its holder in the bottom plate, energize the electric field (which had already been adjusted to the next desired value), leave at that value for 60 seconds, and then quickly change it to a somewhat higher value for another 60 seconds, etc. The EFEM would be exposed to a series of perhaps five to seven different electric field values, each for 60 seconds, and hopefully to values which fall on either side of the bin edge being determined. The EFEM was then inserted into the reader and notation made of the time spent in each of the bin ranges. If, for example, a determination of the edge between bins #2 and #3 was underway, the EFEM might first be subjected to fields of 5.7, 5.8, 5.9, 6.0, 6.1, 6.2, and 6.3 kV/m, each for 60 seconds. When placed in the reader at the conclusion of that series of measurements, there would be a certain number of counts in bin #0 corresponding to the time spent in near zero field, and a certain number of counts in each of bins #2 and #3 (assuming 5.7 to 6.3 kV/m encompassed the actual bin edge), which would indicate between which two electric field values the actual bin edge fell, e.g., if approximately 75 counts were in bin #2 and 30 counts were in bin #3, it would indicate that the boundary was between 6.1 and 6.2 kV/m. The EFEM would then be subjected to a series of electric fields between 6.1 and 6.2 kV/m to further narrow the range and finally determine the boundary to a precision of ±0.2% or better.

3.2 Real Time EFEM (OLEFEM)

Measurements designed to determine the effect of different configurations and locations on the EFEM indication would be very time consuming, as the foregoing description of the EFEM calibration check procedure indicates. For this reason, the BPA provided a modified EFEM in which the electric field information is converted to light pulses and transmitted by fiber optics to a separate receiver which converts the information to a frequency that can be measured by an ordinary counter in real time. This modified unit is referred to in this report as the optic link electric field exposure monitor or OLEFEM.

The OLEFEM was also calibrated in the parallel plate structure and a relationship derived from which the electric field value could be calculated from the frequency readout with an imprecision of less than ±0.3%.

The OLEFEM is nearly the same size as the regular EFEM. The nonconducting optic cable is connected at the center of one of the short edges of the device. Measurements were made to determine if the optic cable had any effect on the electric field by placing the cable in various locations near and on top of the electric field sensor plate. No effects were discernable.

3.3 Surface Field Enhancement

After calibration in the ground plane, the OLEFEM was placed on top of the bottom plate, in the same location, and its indication recorded for two or three of the same electric field values that were used in the initial calibration. The increase in OLEFEM indication when located as a "bump" on the ground plane, rather than being flush with the surface at the same location, is a measure of the surface field enhancement. This procedure was repeated with the OLEFEM separated from the bottom plate by various thicknesses of foam, which has a dielectric constant similar to that of air, and for one or two layers of cotton and/or wool cloth. From this data a graph of surface field enhancement vs. distance from the ground plane is derived.

Determination of the electric field was made with the sensor patch before the OLEFEM was placed in position because its presence as a bump has a small (<0.5%) but measurable effect on the electric field indication from the sensor patch. This is because the EFEM projection above the bottom plate tends to distort the uniform field.

3.4 Application of Uniform Field Data to Nonuniform Field Conditions

In use, the EFEM will almost always be measuring nonuniform electric fields. Even if the field over a certain volume is relatively uniform, the entrance of a person into that volume causes the field at the surface of the person to be nonuniform. For this reason, the applicability of calibrations and surface field enhancement factors obtained under uniform field conditions (the only easily reproducible way to obtain such data) to various nonuniform field conditions must be examined.

To obtain nonuniform field information, a metal tower approximately 30.5 cm high, and 33.3 cm by 18.5 cm on its sides, was constructed with provision for flush mounting of an electric field sensor patch either on top or on either of the larger sides, and for mounting of the OLEFEM either flush or as a bump, again either on top or on one of the larger sides. The parallel plate spacing was increased to approximately 60 cm and the tower placed in the center between the plates. To prevent corona, the edges of the tower were rounded by means of wood quarter rounds set flush with the sides and top and painted with conductive paint (see figs. 2 and 3).

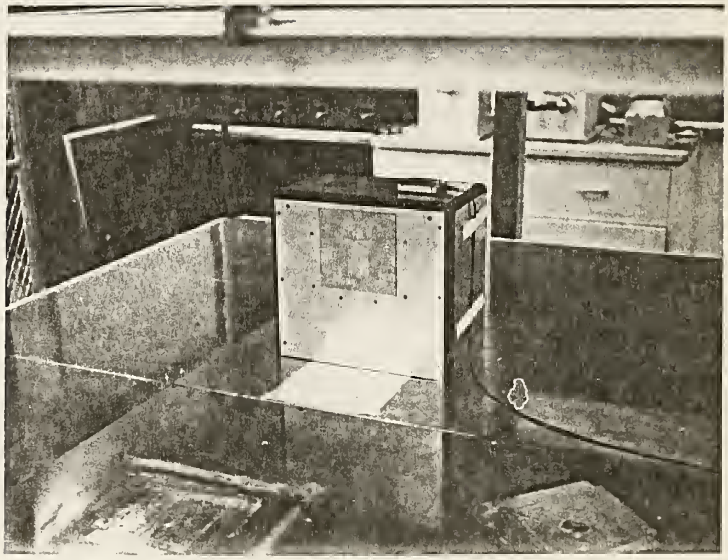

Figure 2. Metal tower used to produce nonuniform fields between the parallel plates. The OLEFEM is mounted as a "bump" on the top surface.

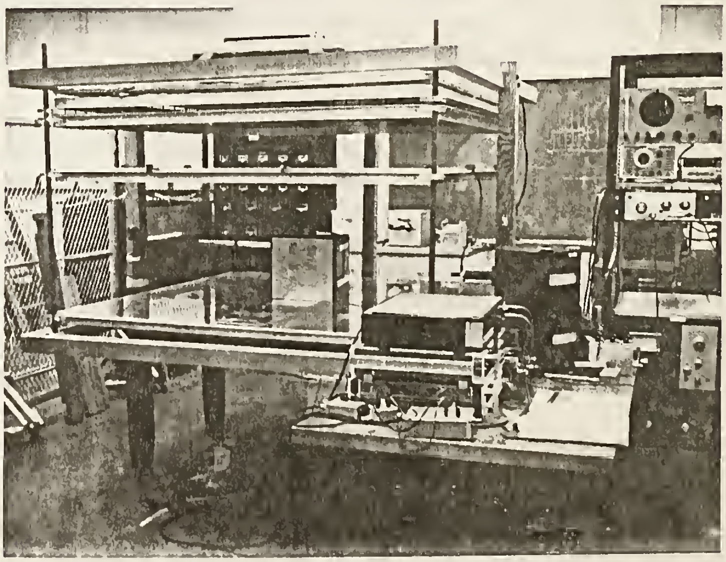

Figure 3. Parallel plate arrangement with plates spaced at approximately 60 cm and the metal tower installed for nonuniform measurements.

To compare the OLEFEM indication with the field at the surface of the tower, an electric field sensor patch the same size as either the OLEFEM or EFEM sensor was fabricated and placed in the same relative position on the tower as the OLEFEM. Thus if measurements were being made on the top of the tower, the sensor patch was located flush with the top surface with its center approximately 9.5 cm from one end and equidistant between the sides, while the OLEFEM was located with the center of its sensor approximately 9.5 cm from the other end and again centered between the sides. This arrangement can be observed in figure 2. The same arrangement was used for measurements on the sides of the tower; i.e., the electric field sensor was mounted flush on one of the larger sides with its center approximately 9.5 cm down from the top edge and centered between the short sides, while the OLEFEM was mounted on the opposite side in the same relative position. To confirm that the positions were exposed to equal electric fields, readings were taken with the sensor patch mounted in each of the two comparable positions. The results agreed within experimental error.

To obtain some indication of the degree of nonuniformity across the OLEFEM sensor, the tower electric field sensor patch was constructed from four separate smaller patches whose total area adds up to that of the OLEFEM sensor. The dimensions of each small patch are the same as the full sensor in one direction, but only one fourth of the full sensor in the other direction. The small patch outputs can be measured separately, combined in pairs or all combined to give a total patch reading. The tower was also designed so that the long dimension of the patch sections could be placed in either direction, i.e., parallel to either the short or long dimension of the tower top plate when mounted on top, or either horizontal or vertical when mounted on the side.

Before use on the tower, the four-section sensor patch was checked in the uniform field parallel plate structure using the large 10 x 10 cm patch as a reference (see fig. 4). An electric field would be set using eq (3) with V_o being the operational amplifier output for an input from the 10 x 10 cm patch. When using the same operational amplifier circuit (thereby keeping B the same) and same electric field, each small sensor patch would be connected to the operational amplifier in turn, and the resulting V_{o1}, V_{o2}, V_{o3}, and V_{o4} recorded. In addition, operational amplifier output readings were taken with sensor sections #1 and #2 combined, with sections #3 and #4 combined, and with all four combined. This was done for five different electric fields between 3.0 and 36 kV/m. The results were compared with the V_o calculated for each configuration based on a rearrangement of eq (3)

$$V_o = \frac{2\pi f \varepsilon_o AE}{B} , \tag{4}$$

where E, B, f, and ε_o are all known and A was determined by measuring the total sensor area and dividing by four. The value used for A would of course depend on the number of sensor sections combined to achieve the reading.

The measured V_{oall} (all four sensor sections combined) agreed with the calculated V_{oall} to within ±0.3%. Because of slight variations in size among the four sensor sections, the measured V_o for three of the sections when checked individually differed from the calculated V_o by an amount exceeding the above ±0.3%. It averaged 0.0% for section #1, +0.4% for section #2, +0.6% for section #3, and -1.2% for section #4, and remained fairly consistent at each electric field calibration point, thus providing a reliable correction factor for the reading from each section. (None was needed for section #1.)

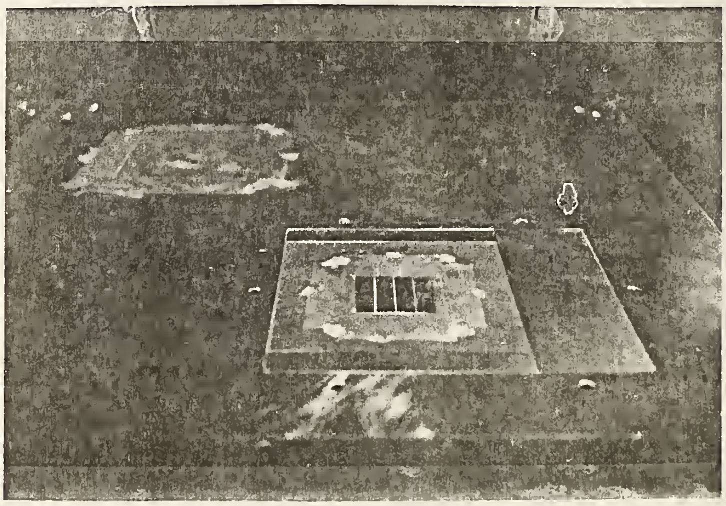

Figure 4. Four section sensor to be used on tower is mounted in bottom plate of parallel plate structure for calibration.

A holder was designed for the OLEFEM, similar to that used for the EFEMs in the parallel plate structure, so that the OLEFEM could be adjusted flush with the surface of the tower, either on top or on the side. For measurements with the OLEFEM sitting as a bump on the surface, a plain flat metal plate was substituted for the holder. Metal conductive tape on the back (inside the tower) was used to hold the four section sensor and OLEFEM mounting plate or plain metal plates, as the case may be, in place on the sides of the tower.

Measurements were also made in which the OLEFEM was separated from the tower surface by the same thickness of foam material or cloth as used in the uniform field measurements. Double stick tape was required to accomplish the desired configurations on the side of the tower and on occasion additional tape was necessary across the top of the OLEFEM to the tower sides. The effect of this tape on the measurements was checked by measuring the same setup on the tower top, both with and without tape. Some types of tape did produce a measurable difference but a type was found which produced no discernable effect, and this is the type used for all of the reported measurements.

To avoid effects from the OLEFEM, measurements of the electric field at the surface of the tower were in all cases made with the four section sensor patch before the OLEFEM was placed on or in the tower. In place of the OLEFEM and/or its holder was a plain metal plate level with the tower surface. The electric field was then switched off to allow placement of the OLEFEM in its desired position on the tower. The electric field was then switched back on, restoring it to its original value.

4. RESULTS

4.1 EFEM Uniform Field Calibration Check

Table 2 lists the bin edge electric field values, as determined in the NBS uniform field parallel plate structure, for the BPA EFEM units #R-11 and #R-15 mounted flush with the bottom plate. The first column designates the bin edge. The second column lists the design electric field for that bin edge or boundary and the final columns list the actual electric field determined at that boundary for each EFEM, and the percentage difference between the actual and design fields.

Table 2. NBS Determined Electric Field Values at the Boundaries Between EFEM Bins

EFEM sensor flush with surface, EFEM case connected to surface

Bin Edge	Design E-Field (kV/m)	EFEM #R-11 Actual E-Field (kV/m)	Percentage Δ Between Actual and Design	EFEM #R-15 Actual E-Field (kV/m)	Percentage Δ Between Actual and Design
0/1	1.0	0.883 ± 0.3%	-11.7	0.942 ± 0.3%	-5.8
1/2	3.0	2.962 ± 0.4%	- 1.3	3.047 ± 0.2%	1.6
2/3	6.0	6.037 ± 0.2%	0.6	6.20 ± 0.3%	3.3
3/4	10.0	10.187 ± 0.1%	1.9	10.374 ± 0.15%	3.7
4/5	15.0	15.337 ± 0.1%	2.3	15.615 ± 0.15%	4.1
5/6	21.0	21.575 ± 0.1%	2.7	21.805 ± 0.1%	3.8
6/7	28.0	28.925 ± 0.1%	3.3	29.29 ± 0.2%	4.6
7/8	36.0	37.28 ± 0.1%	3.6	37.60 ± 0.1%	4.4

The plus and minus percentage following the actual electric field boundary value is the uncertainty caused by the spacing between applied electric field values during the final series of readings at each boundary (see the discussion under Calibration Check). This percentage could have been reduced further by making another series of measurements, but it was felt that the marginal improvement involved did not justify the extra time required.

The above calibration checks were performed with the EFEM sensor flush with the bottom plate and the EFEM case electrically connected to the grounded bottom plate. Some of the boundaries were also redetermined with the EFEM case separated from the grounded bottom plate by an impedance consisting of a specific resistance value in parallel with the approximately 15 pF capacitance inherent between the EFEM holder and the bottom plate. The boundary electric field determined did not change from the original value by more than 1.0% until the resistor value was increased to about 50 MΩ. Since the impedance of the 15 pF capacitance is approximately 180 MΩ at 60 Hz, this result suggests that the impedance between case and surface must be above approximately 40 MΩ (50 MΩ in parallel with 180 MΩ) before a 1.0% change in EFEM indication occurs.

It should be noted that an increase in value of the electric field at the boundary between EFEM bins is equivalent to a decrease in the resultant EFEM electric field indications, or vice versa. For example, bin #3 of EFEM Unit R-15 had a range of 6.20 to 10.374 kV/m when its calibration was checked with the sensor mounted flush with the bottom plate in a uniform field and with the unit case electrically connected to the plate (the normal method). When the upper boundary was checked again with the case electrically separated from the bottom plate by approximately 100 MΩ, the boundary value had increased to 11.42 kV/m. This means that any electric field between 10.374 and 11.42 kV/m which previously registered in bin #4 would now register in bin #3. The EFEM indications for those fields have thus apparently decreased under the new condition.

In order to obtain information on the surface field enhancement phenomena, some additional tests were made with each EFEM unit mounted as a bump on the bottom plate, directly above its previous flush mounted location. These results are discussed in a following section.

Table 3 lists the calibration results for the OLEFEM mounted with its sensor flush with the grounded bottom plate and its case electrically connected to the plate. Intermediate electric field values of 0.5 kV/m or higher can be calculated by using one of the three linear equations shown below the table or by interpolation between points. Three separate straight line segments are used for improved accuracy. The maximum calculation error when using these equations to determine E from the frequency listed in the table is 0.23%.

Table 3. Electric Field vs Frequency Readout for OLEFEM #R-8

OLEFEM sensor flush with surface, OLEFEM case connected to surface

Point	Electric Field (E) kV/m	Frequency Readout (f) kHz
0	0	0.0462
1	0.5	0.0818
2	1.0	0.142
3	2.0	0.264
4	4.0	0.510
5	9.0	1.124
6	12.0	1.492
7	16.0	1.981
8	20.0	2.471
9	25.0	3.073
10	30.0	3.680
11	36.0	4.441

$E = 8.306\ f - 0.179$ from points #1 through #2

$E = 8.146\ f - 0.155$ from points #2 through #6

$E = 8.237\ f - 0.320$ from points #6 through #11

where E is in kV/m and f is in kHz.

The electric field was set using the 10 x 10 cm sensor patch on the bottom plate. The frequency readout is the midpoint of a range which averaged about 0.2% of the reading, e.g., readings between 3070 and 3076 Hz were obtained at 25.0 kV/m.

4.2 Applicability of Flush OLEFEM Uniform Field Calibration to Flush Nonuniform Field Situations

Before discussing results involving the EFEM mounted on or above a surface, something must be said concerning the applicability of the flush mounted uniform field calibrations to flush mounted nonuniform field conditions. Even though the flush mounting method is not usually possible in a real situation, it serves as a base for later experimental comparisons with situations where the unit is mounted on or above the surface.

Table 4 shows the four-section sensor total electric field indication as calculated from V_0 (operational amplifier output) when the sensor is mounted flush with the tower top or tower side. Next to this is the electric field indication calculated from the OLEFEM frequency readout, using the linear equations of table 3. The OLEFEM was mounted in an equivalent position on the tower with its sensor also flush.

Table 4. Comparison of Sensor Patch and OLEFEM Electric Field Indications When Mounted Flush in Equivalent Nonuniform Fields

	Four Section Sensor Patch		OLEFEM		
Mounting Position	Vo Vrms	Calculated E Vo x 6.28195[a] kV/m	F kHz	Calculated E kV/m	ΔE %
Top of tower	0.6351	3.99	0.5103	4.002	0.3
"	1.9166	12.04	1.500	12.064	0.2
"	4.521	28.401	3.529	28.748	1.2
Side of tower	1.7001	10.68	1.304	10.467	2.0

[a]This number is the calculated value of $B/(2\pi f \varepsilon_0 A)$ from equation (3) in the Test Procedure and Applications section. The area, A, of the four section sensor patch is 5.476 cm^2.

A measure of the field nonuniformity on the top surface of the tower can be obtained by noting the difference in readings between the outermost sections of the four section sensor. When the four-section sensor was aligned so that the long dimension of each section was parallel to the short side of the tower, the difference in field readings was approximately 4%. When mounted on the tower side with the section long dimension horizontal, the difference in reading between the top and bottom sections was approximately 33%.

Examination of table 4 shows that, as expected, the flush mounted calibrations hold for nonuniform field situations up to 33%. Maximum difference between the sensor and OLEFEM indications is 2.0%.

4.3 Surface Field Enhancement - Uniform Field

Raising the EFEM or OLEFEM so that it rests either on the surface or above the surface (as it must in most real situations) causes an increase in the OLEFEM indication or a decrease in the indicated boundary between EFEM bins. The latter, as explained in a previous section, is equivalent to an increase in EFEM indication. The amount of increase is given first for a uniform field situation, and then results from further testing will indicate whether surface field enhancement correction factors derived from the uniform field situation are applicable to nonuniform field situations.

Results are also presented from an investigation of the effect of cotton and/or wool placed over and behind the OLEFEM sensor and the applicability of the measured effects in a uniform field to nonuniform field conditions.

In discussing the following results, the OLEFEM unit is mentioned much more often than either of the EFEM units. However, it must be remembered that the two are approximately equivalent, the only difference being that the EFEM units are a slightly thicker 1.63 cm as opposed to 1.61 cm for the OLEFEM. The OLEFEM is used in most of the testing because of the advantage it has in speed of obtaining data. This was discussed more fully in the section on Test Procedure and Apparatus.

The OLEFEM was placed on the surface of the bottom plate in the parallel plate structure with sensor facing upwards, directly over the spot it occupied when it was calibrated in the flush configuration. Table 5 shows that the increase in indication registered is consistent over a range of electric field values, and that the surface field enhancement factor (the increase in electric field reading when the OLEFEM or EFEM is located as a bump on a surface over the field actually present at that surface) is between 54% and 55%.

Table 5. Surface Field Enhancement Determined for OLEFEM in Uniform field

Surface Electric Field kV/m	OLEFEM Indication Flush kHz	Calculated E kV/m	OLEFEM Indication As Bump kHz	Calculated E_B kV/m	Surface Field Enhancement $[(E_B-E)/E]$%
1.0	0.142	1.0005	0.2075	1.544	54.3
9.0	1.124	9.026	1.724	13.89	53.9
25.0	3.073	24.992	4.736	38.69	54.8

The higher the OLEFEM sensor is raised above the grounded surface while keeping the OLEFEM case electrically connected to the surface, the higher will be the indication. For example, the OLEFEM was raised an additional 1.3 cm above the bottom plate surface by means of a metal spacer for a total sensor height of 2.91 cm, but the case remained connected to ground. Under these conditions, the surface enhancement factor was determined to be 88.6%. This shows that surface field enhancement is a function of the electric field sensor height above the surface.

If the OLEFEM case is separated from the surface, as it will be when carried in a shirt pocket inside of its protective case, the surface field enhancement factor decreases as shown by the solid line in figure 5. An asymptote is eventually reached so that beyond about 5 cm from the surface little further decrease is noted.

As a double check on surface field enhancement, the two EFEMs were each mounted in turn as a bump in the uniform field, and a new determination made for two of the eight bin edge electric field values for each unit. Table 6 shows the results. It should be noted that the bin edge electric field values remain fixed but that the surface electric field required to produce a particular value of electric field at the EFEM sensor will vary depending upon the EFEM sensor location in relation to the surface. In the situation described here, the EFEM is mounted as a bump on the bottom plate surface and hence the surface field is enhanced, i.e., less surface electric field is required to produce a count in a particular EFEM bin than would be required if the EFEM were mounted flush.

Many of the OLEFEM measurements described above were also repeated with a section of cotton cloth, wool cloth, or both placed over the electric field sensor to determine what effect this would have on the indication. In all cases, the indication was increased, i.e., the electric field reading obtained by an EFEM covered by shirt pocket, coat, etc., would need to be decreased an additional small amount to obtain the correct surface field value. A layer of either wool or cotton by itself over the sensor adds between 1.5% and 2.5% to the indication, while a layer of both adds between 4.0% and 5.0%.

Table 6. Surface Field Enhancement Determined for EFEMs in Uniform Field

Bin Edge	EFEM Checked	Boundary E-Field Value Flush (F) kV/m	Boundary E-Field Value As A Bump (B) kV/m	Calculated Surface Field Enhancement [(F-B)/B]%
1/2	R-11	2.962	1.88	57.6
2/3	R-15	6.20	3.938	57.4
5/6	R-11	21.575	13.725	57.2
6/7	R-15	29.29	18.675	56.8

The plastic pouch placed over the OLEFEM increased indications about 1.5%. The pouch plus a layer of wool caused an increase of about 3.5%. The effects appear to be additive.

4.4 Applicability of Surface Field Enhancement Factors Obtained in Uniform Field to Nonuniform Field Situations

Many of the measurements described in the previous section using the OLEFEM under uniform field conditions were also repeated under controlled nonuniform field conditions. The purpose of this is to see if the results of tests performed in a parallel plate uniform field could be used as an indication of what will happen in nonuniform field situations. Much of the data obtained is summarized in figure 5 where percentage surface field enhancement is plotted against the distance which separates the EFEM sensor from the surface upon which a measure of electric field is desired. With the EFEM case in contact with the surface (the sensor therefore being approximately 1.6 cm above the surface), the surface field enhancement is approximately 54% in a uniform field and 51% to 52% for two different nonuniform fields. The dielectric constant of the material normally used to separate the EFEM case from the surface is close to that of air or just slightly larger than one. Cotton and/or wool cloth was used behind the OLEFEM for the very small spacings and the dielectric constants of these materials are approximately 1.8 and 1.3 respectively. A higher dielectric constant for the separating material causes a larger surface field enhancement for an equal spacing.

The solid curve relates surface electric field enhancement to distance above the surface for a uniform electric field. The dashed and dotted curves represent the same information for two different nonuniform field configurations. The data for the dashed curve was taken with the OLEFEM mounted on top of a 30 cm high grounded tower sitting between parallel plates spaced at about 60 cm, while the dotted curve data were taken with the OLEFEM mounted on the side of the same tower near its top.

Two additional measurements of electric field were made with the OLEFEM mounted at a slight angle with respect to the side of the tower with the top of the unit farther away from the tower surface than the bottom. This is a configuration which could easily occur when an EFEM is carried in a shirt pocket. When making an angle of approximately 10° with the tower surface (bottom of the sensor about 2.2 cm away and the top about 3.05 cm away), the surface field enhancement was calculated as 30.5%. When making an angle of approximately 15° (bottom of the sensor about 2.2 cm away and the top about 3.45 cm away), the surface field enhancement was calculated as 27%.

No measurable difference from the uniform field results was observed when the OLEFEM sensor was covered by cotton and/or wool cloth in either of the nonuniform configurations. As before, either cloth alone caused an increase of between 1.5% and 2.5% in the indications that would have been observed without the cloth, and both together caused an increase of between 4.0% and 5.0%. Results with the OLEFEM enclosed in the plastic pouch were also similar to the uniform field measurements, i.e., the pouch caused an increase in reading of about 1.5% by itself and of about 3.5% when combined with a layer of wool.

5. DISCUSSION

The results show that calibration of an EFEM to measure surface electric field when mounted flush in a uniform electric field is also applicable to that EFEM when mounted flush in a nonuniform field. When mounted on or above the surface, the EFEM indication is higher than the actual surface electric field by a surface field enhancement factor. This factor can be determined for specified conditions in a uniform field but, as figure 5 shows, cannot be applied without some modification to a nonuniform field situation.

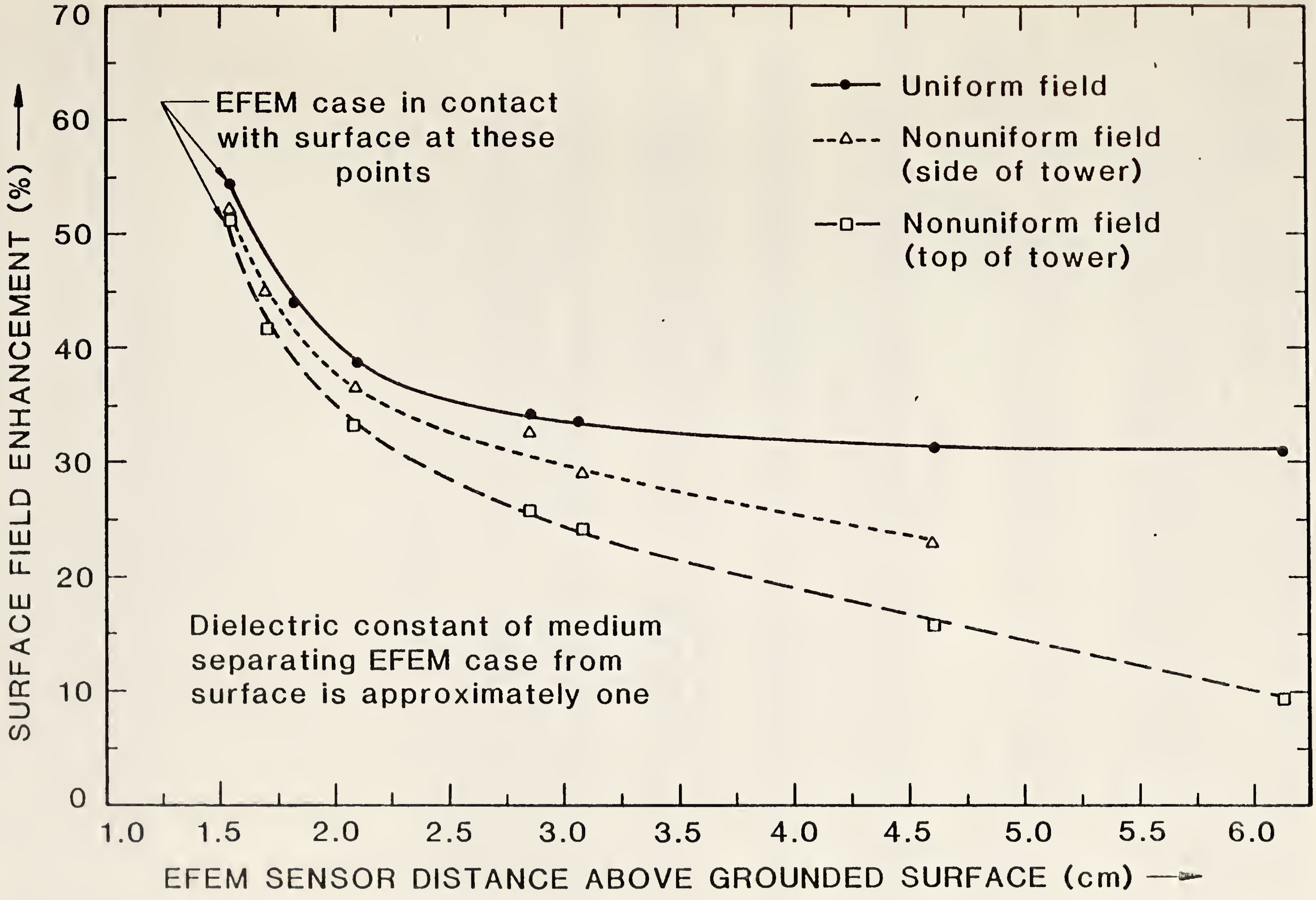

Figure 5. Surface field enhancement as a function of EFEM sensor distance above grounded surface for uniform and nonuniform field configurations.

Figure 5 shows that the surface field enhancement for a given EFEM sensor-to-surface spacing is less for nonuniform fields and least for a top-mounted unit as opposed to a side-mounted unit. Although it might be argued that the information in figure 5 could be extrapolated to estimate enhancement for an EFEM placed on a human, the human form is not the same as that of the rectangular tower used in tests to provide nonuniform field information. Further testing employing a more realistic geometry would be necessary to provide rigorous information.

The enhancement caused by the plastic pouch, cotton cloth, and/or wool cloth over the EFEM sensor is relatively independent of field type and thus the additional enhancement can be estimated depending upon the number of layers of cloth, etc.

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This report presents the results of tests requested by the Bonneville Power Administration (BPA) on a 60-Hz Electric Field Exposure Monitor (EFEM) developed by their Instrumentation and Standards Branch. The unit is designed to be worn on the body, such as in a shirt pocket or attached to the clothing. The calibration of two sample units is examined, information on surface field enhancement (which results from the EFEM sensors' elevated position relative to the surface of the body) is presented, the effect of material covering the sensor is specified, and the applicability of calibration and operational information obtained in uniform fields to nonuniform fields is investigated.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

calibration accuracy; Electric Field Exposure Monitor (EFEM); enhancement; flush mounted; nonuniform field; parallel plates; sensor; surface field enhancement; uniform field

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