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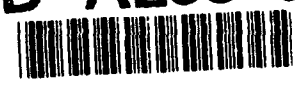

Technical Document 2266
May 1992

VLF/LF Corona Investigation

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A. D. Watt
Electrospace Systems, Inc.

P. M. Hansen
NCCOSC RDT&E Division

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NAVAL COMMAND, CONTROL AND OCEAN SURVEILLANCE CENTER
RDT&E DIVISION
San Diego, California 92152-5000

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ADMINISTRATIVE INFORMATION

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LH

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1.0 INTRODUCTION AND TEST CELL DETAILS

Corona occurs when the electric field surrounding a conductor reaches a critical value such that the surrounding air is ionized to the point where it begins to glow. The voltage at which this visual display starts is called the visual corona inception point. As the voltage is increased, the glow or in some cases flares are seen to increase about the wire. The power required to maintain this discharge is called corona power.

The power lost in corona as the voltage is increased above the inception values is rather well known at power frequencies of 50 to 60 Hertz. At VLF and LF, corona inception occurs at lower electrical field values, but precise relations for predicting onset have not been well known. In addition, it was known that corona power increased with frequency, but the exact amount of corona power to be expected at VLF and LF could not be predicted with certainty.

To determine corona power for given sets of typical conditions, tests were performed at the Forestport, NY, high-voltage test facility during 1985 to determine onset conditions, and in 1989 to measure corona power at VLF and LF. Wire and cable samples were arranged in vertical and horizontal positions for both dry and wet conditions. The vertical test cell is shown in figure 1-1. The high voltage was applied to the cell via a large cylindrical feed line shown in the upper right hand of the figure. The large cylindrical cage surrounding the sample consisted of 1/4-inch hardware cloth supported on a PVC pipe frame. The outer diameter of this coaxial cell is 3.2 meters, and the height is 3.6 meters. The test sample is 1.98 meters long. During the 1985 tests, the shield ring at the upper end of the sample was 0.61 meter in diameter made of aluminum pipe 0.15 meter in diameter. The lower end had a similar ring plus a larger 0.81- by 0.2-meter shield immediately below it. The first value is the overall diameter, and the second is the diameter of the pipe from which it was made. For the 1989 tests, these rings were replaced with single smaller 0.36- by 0.064-meter rings; one at the top and one at the bottom. Figure 1-2 shows a #8 stranded wire well into corona during the 1989 tests.

The horizontal test cell configuration used in the 1989 tests is shown in figure 1-3. This cell was mounted outside with the feed trunk as shown on the left side and an insulating guy on the right to keep the wire sample taunt. The wire is mounted above an aluminum sheet over a larger wire mesh. The sample is 6.1 meters long and 2.4 meters above the ground plane. Both of the test cells need an affective length correction for calculating the corona power per unit length.

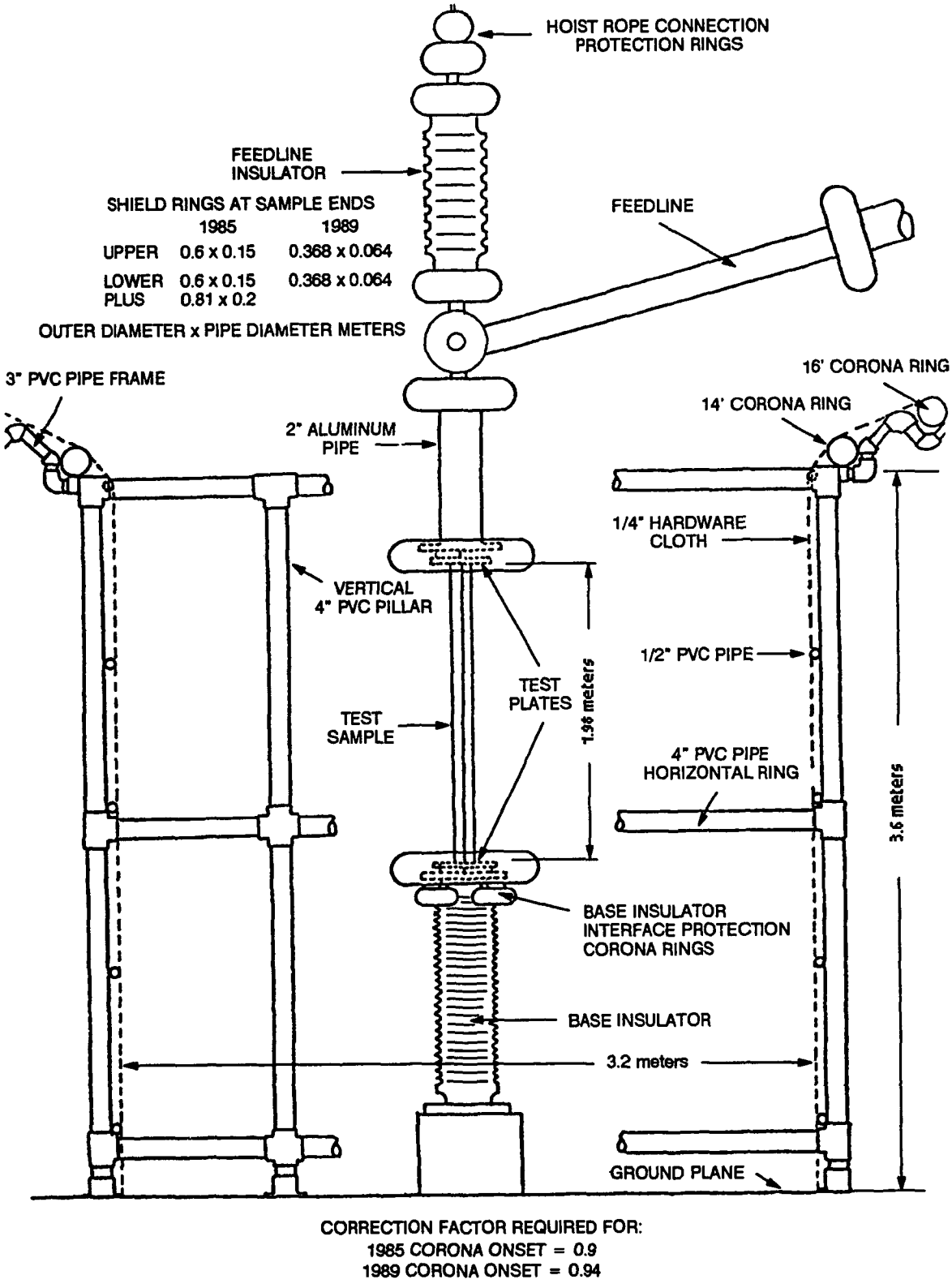

Figure 1-1. Vertical high-voltage corona test cell.

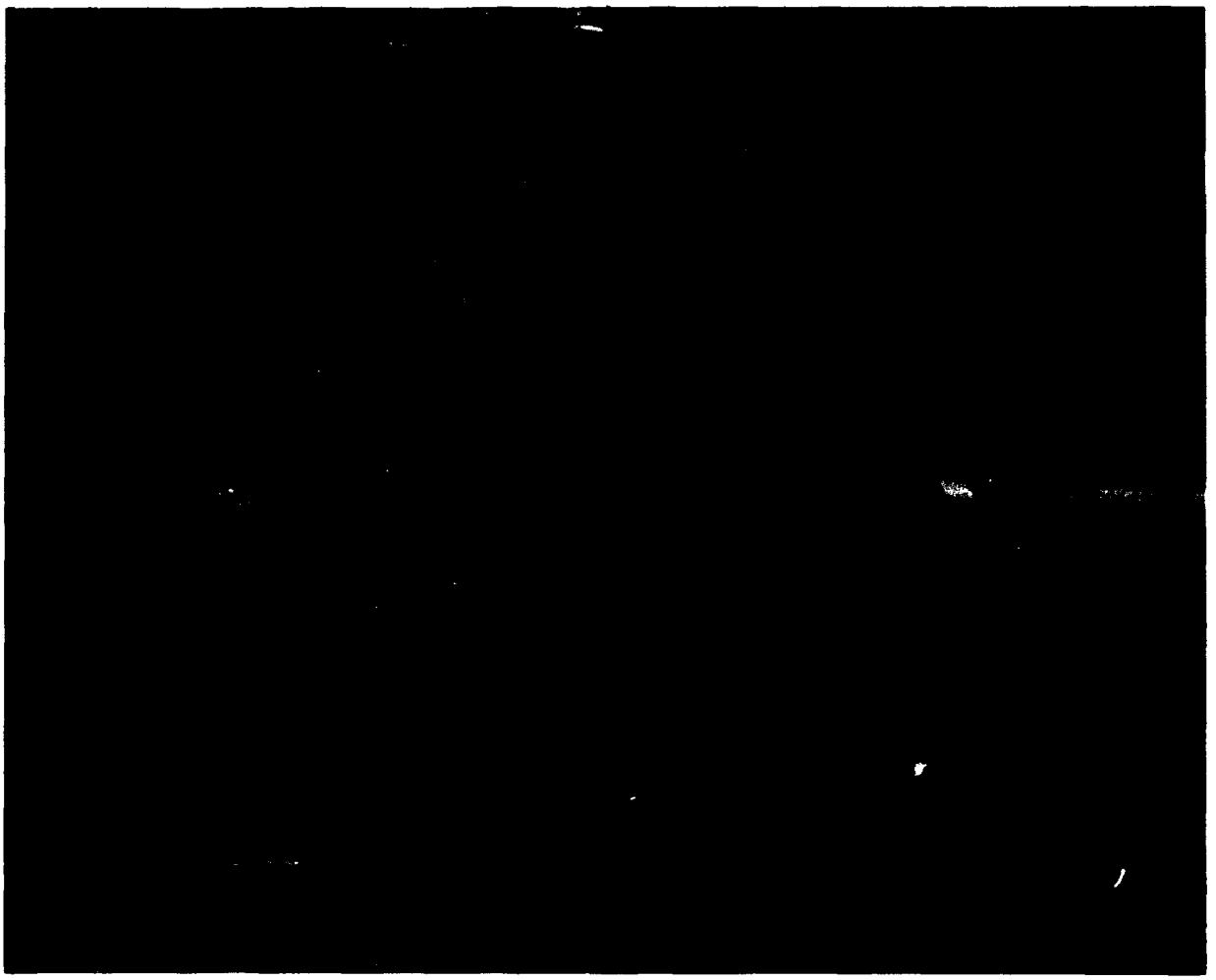

Figure 1-2. Photograph of #8 stranded wire in corona.

The vertical test cell needs an additional correction factor for calculating effective onset gradients because of the short length of the sample and the relatively large corona ring shields at each end. For the 1985 data, the gradient at the center is 0.9 times the calculated value for a long coax. In view of this, the 1985 voltages are multiplied by a 0.9 correction factor. The 1989 configuration requires a correction factor of 0.94. These correction factors were arrived at via three different methods: (1) comparing onset voltages from the vertical cell with those from the horizontal cell for similar conditions, (2) an electrostatic computer simulation, and (3) neon light gradient measurements used in determining the gradients as a function of length along the sample. All three methods yielded similar results.

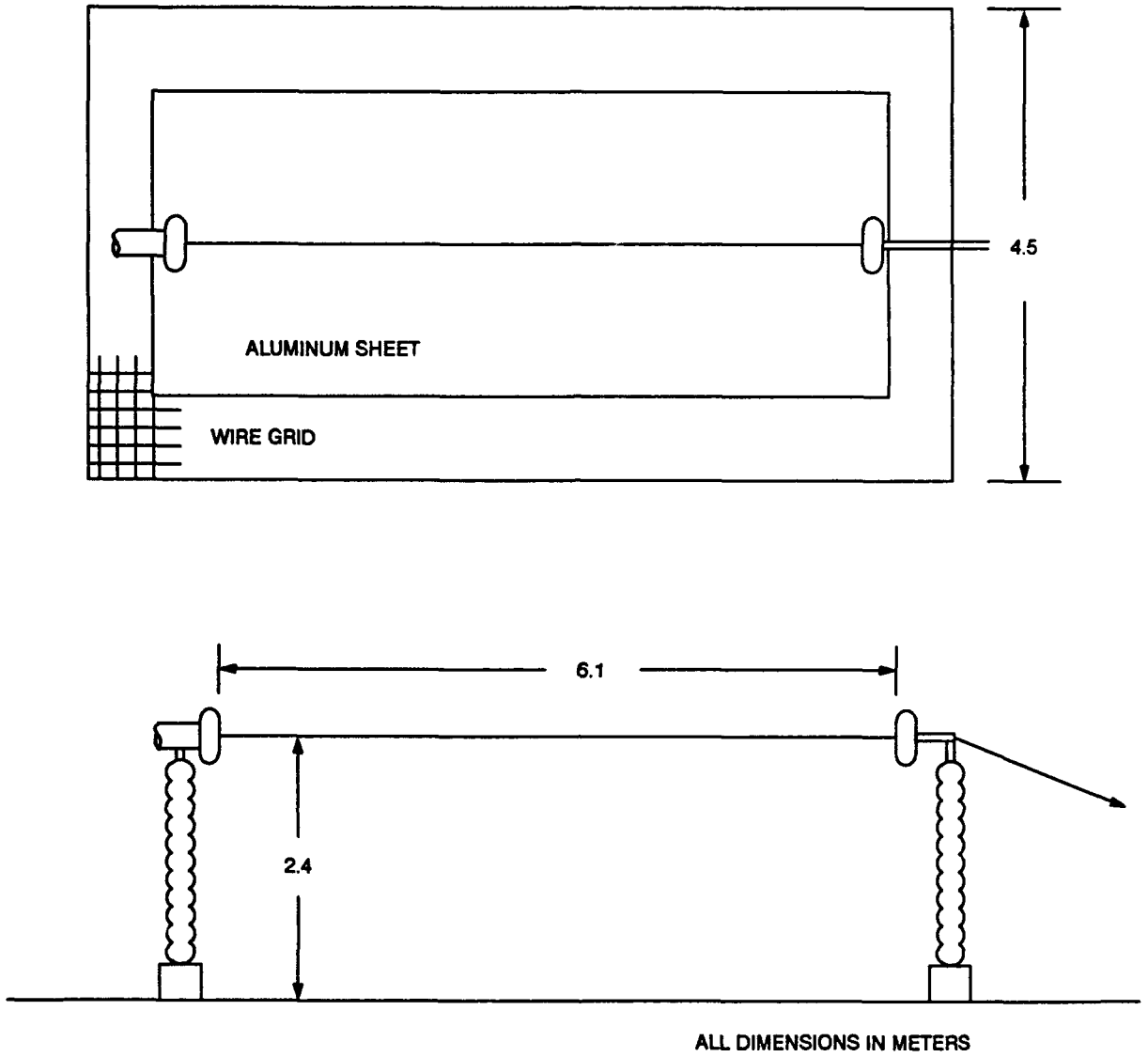

Figure 1-3. Outdoor horizontal high-voltage test cell.

The measurement circuit employed is shown in figure 1-4. The transmission line from the transmitter is connected to a matching transformer that feeds the resonant LC circuit. The voltage, V, out of the transformer is divided by a 100:1 voltage divider and then measured by the first DMM (HP-3468A digital multimeter). The resonant circuit current, I, is obtained with the use of a current transformer. The phase between the voltage and current is measured by a phase meter that feeds the third DMM in the HP-IL loop. The fourth DMM measured the high voltage connected to the sample that has been reduced by a 10,000:1 voltage divider. All the DMM outputs are fed to a HP-71 computer and a printer, to yield realtime printouts of conditions; a disk unit stores all the data on disks.

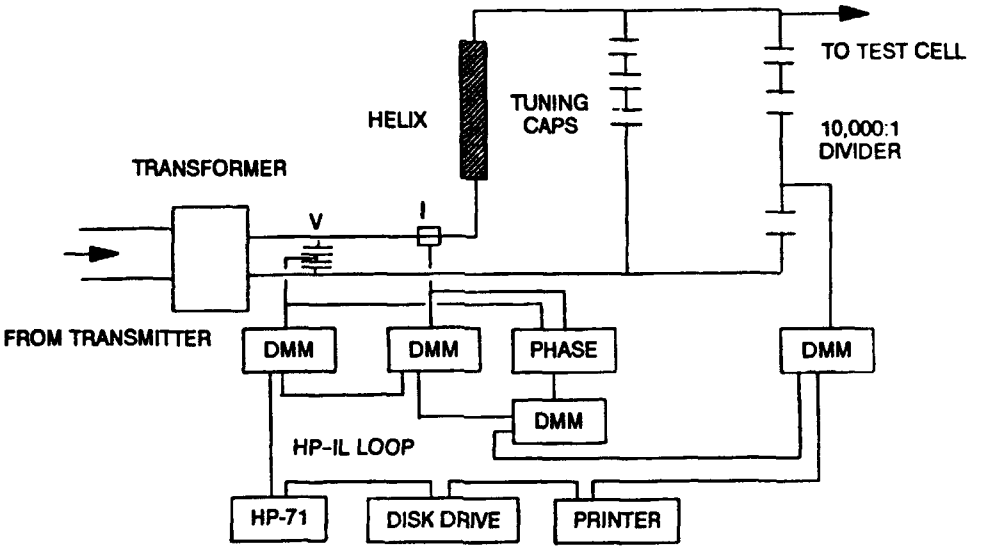

Figure 1-4. Corona power tests instrumentation, Forestport, 1989.

At the voltages involved, the calibration of the high divider required great care since the large divider has a significant capacitance to ground and to the other high-voltage components in the tuning room.

Input power was calculated as E I cos(A) [A = phase difference], which includes all the losses in the tuning helix and capacitors. These losses are determined by measuring the input power over the voltage range with a large diameter pipe in the cell that did not go into corona. Corona power is determined by taking the power observed during the tests with the sample in corona and subtracting the loss power determined during the calibration runs. It is not clear that the loss values of the calibration run remain precisely constant from test to test since at times negative powers appear at the start of a run. In view of this, we have made small changes in the effective loss resistance values at the start of run if it appeared necessary. Analysis of the circuit-only power loss versus voltage show it to increase at a value slightly greater than the square of voltage.

2.0 TEST MATRIX AND TYPICAL DATA FILES

Table 2-1 is representative of the automated data printouts obtained during the tests. The data file number 22 is a run on #8 stranded wire in the vertical test cell, with dry conditions, at 28.4 kHz. The atmospheric temperature, relative humidity, V^2/P, and atmospheric pressure are given along with visually observed corona onset and extinguishing voltages in kV. The high-voltage column gives the voltage across the sample. The power in watts is the total power in the V^2/P column on the right and is representative of the equivalent circuit parallel resistance in ohms. This resistance remains essentially constant at some value until corona is initiated, at which point the value starts to decrease. Although the visual onset is recorded as 35.9 kV, it appears that a small amount of corona started at a voltage of 35.2 kV.

Table 2-2 is a matrix presentation of the sample sizes, conditions, frequency, and data file numbers. The frequencies listed as f0, f1, and f2 are representative of the frequency ranges for each test. The exact frequency employed is given in the original data sheets. Typically, f0 is about 18 kHz, f1 about 27 to 28 kHz, and f2 about 48 to 58 kHz.

A listing by data file number of the conditions of each test is given in tables 2-3 and 2-4. For reference it should be noted that

1 atmosphere = 760 mm of Hg

= 29. 92 inches of Hg

= 1013.25 mbar

= 101.325 kPs, kilo Pascals

The elevation at the test site is 1413 feet (431 meters). The atmospheric density is calculated for each test, and the resulting value in kg/m3 is given in the next to the last column. The last column gives the relative density based on a 15°C reference, i.e., D_{rel} = Dens/1.225. The air density was calculated using the basic program listed in table 2-5.

A listing of some of the results from the 1985 tests is given in table 2-6. It should be noted that for the 1985 vertical tests a correction factor of 0.9 must be used when calculating gradients since the actual onset voltages are higher than would have resulted if the test cell was acting as a long cylinder. The 1989 vertical tests data require a 0.94 correction factor for corona onset gradients.

Table 2-1. Data file #22, vertical, dry, #8 stranded wire.

Temp = 62°F, RH = 74%, atm press = 29.62 in. Hg
Freq = 28.4
Visual onset = 35.9 kV, visual extinguishing = 34.5 kV

Time	Voltage	Current	Phase	Power	High Voltage	V^2/P
11:55:08	1.96E1	8.92E0	1.27E1	1.70E2	2.44E4	3.49E6
11:55:14	1.96E1	8.92E0	1.27E1	1.70E2	2.44E4	3.49E6
11:55:29	2.21E1	1.01E1	1.23E1	2.18E2	2.75E4	3.48E6
11:55:35	2.21E1	1.01E1	1.23E1	2.18E2	2.75E4	3.48E6
11:55:45	2.50E1	1.13E1	1.21E1	2.77E2	3.10E4	3.48E6
11:55:51	2.50E1	1.13E1	1.21E1	2.77E2	3.10E4	3.47E6
11:56:05	2.84E1	1.31E1	1.18E1	3.64E2	3.52E4	3.40E6
11:56:11	2.83E1	1.30E1	1.18E1	3.61E2	3.50E4	3.40E6
11:56:19	2.83E1	1.30E1	1.18E1	3.60E2	3.50E4	3.41E6
11:56:26	2.83E1	1.30E1	1.18E1	3.60E2	3.50E4	3.41E6
11:56:40	3.20E1	1.45E1	1.15E1	4.55E2	3.91E4	3.36E6
11:56:46	3.20E1	1.45E1	1.16E1	4.56E2	3.91E4	3.36E6
11:56:56	3.68E1	1.59E1	8.71E0	5.78E2	4.28E4	3.16E6
11:57:02	3.68E1	1.59E1	8.94E0	5.79E2	4.28E4	3.17E6
11:57:13	4.35E1	1.69E1	2.51E0	7.36E2	4.55E4	2.81E6
11:57:19	4.35E1	1.70E1	2.64E0	7.37E2	4.56E4	2.82E6
11:57:31	5.18E1	1.60E1	-3.69E0	9.31E2	4.84E4	2.52E6
11:57:38	5.18E1	1.80E1	-3.80E0	9.31E2	4.84E4	2.51E6
11:57:49	6.13E1	1.91E1	-9.29E0	1.16E3	5.15E4	2.29E6
11:57:56	6.12E1	1.91E1	-9.27E0	1.16E3	5.14E4	2.29E6
11:58:12	8.87E1	2.23E1	-2.04E1	1.85E3	5.98E4	1.93E6
11:58:18	8.88E1	2.23E1	-2.04E1	1.85E3	5.98E4	1.93E6
11:58:29	1.24E2	2.61E1	-2.87E1	2.84E3	7.00E4	1.72E6
11:58:36	1.24E2	2.61E1	-2.87E1	2.84E3	7.00E4	1.72E6
11:58:51	1.71E2	3.07E1	-3.57E1	4.26E3	3.25E4	1.60E6
11:58:57	1.70E2	3.08E1	-3.56E1	4.27E3	8.27E4	1.60E6
11:59:11	2.29E2	3.57E1	-4.14E1	6.13E3	9.58E4	1.50E6
11:59:17	2.29E2	3.58E1	-4.14E1	6.14E3	9.58E4	1.49E6
11:59:33	3.00E2	3.98E1	-4.58E1	8.33E3	1.07E5	1.37E6
11:59:39	3.00E2	3.98E1	-4.57E1	8.34E3	1.07E5	1.38E6
12:00:00	3.90E2	4.23E1	-4.78E1	1.11E4	1.13E5	1.14E6
12:00:07	3.90E2	4.22E1	-4.78E1	1.11E4	1.13E5	1.15E6
12:02:39	5.22E2	4.44E1	-4.96E1	1.50E4	1.19E5	9.38E5
12:02:45	5.21E2	4.44E1	-4.99E1	1.49E4	1.19E5	9.43E5
12:03:16	6.67E2	4.59E1	-5.25E1	1.86E4	1.23E5	8.10E5
12:03:23	6.67E2	4.59E1	-5.29E1	1.85E4	1.23E5	8.19E5

Table 2-2. Sample sizes, conditions, frequency, and data file numbers for 1989 Forestport data.

Vertical 2-meter-long test samples

Frequency Sample	F0 Dry	F0 Wet	F1 Dry	F1 Wet	F2 Dry	F2 Wet
TC CAL			2, 1		15	
3/8-inch rod dia = 0.952 cm			4,5,6,7,8 19		16	
#8 smooth dia = 0.33 cm			9,10,20		11,12,13, 14	25
#8 strand dia = 0.368 cm			22	27	23	26
#18 smooth dia = 0.145 cm			18		17	
cage 2 #8 strands s = 10 cm			21	28	24	29

Horizontal wire 6.1 meters long, 2.4 meters high

TC CAL	82	103	81	104	80	105
1-inch smooth dia = 2.54 cm	83	98	84	30	85	31
#6 strand cu dia = 0.470 cm	88	100	87	34,35	86	32,33
#8 strand cu dia = 0.368 cm	89	99	90	36	91	37
#10 strand cu dia = 0.234 cm	94	101	93	39	92	38
#18 strand cu dia = 0.145 cm	95	102	96	40	97	41
	F0 = 17.9 kHz		F1 = 27.8 kHz		F2 = 48.7 kHz	

Table 2-3. Forestport data files, 89/09/14 to 89/09/19.

Data File #	Date 09/	Wire	Cond	Freq (kHz)	Temp (°C)	RH (%)	Bar Press (mb)	Air Dens (kg/m3)	Air Dens rel 1.225
2	14	V test ca	dry	29.6					
4,5,6,7	14	V 3/8"	dry	29.6	18.9	73	995	1.181	0.9639
9	14	V #8 sm	dry	29.4	17.2	82	995	1.188	0.9694
11,12,13	14	V #8 sm	dry	57.4	18.9	78	995	1.180	0.9635
15	15	V test ca	dry	57.4	16.7	75	994	1.188	0.9701
16	15	V 3/8"	dry	57.4	18.3	73	995	1.183	0.9657
17	15	V #18 sm	dry	57.5	16.7	72	996	1.192	0.9727
18	15	V #18 sm	dry	29.4	16.7	72	996	1.192	0.9727
21	18	V 2-#8	dry	29.4	16.1	76	1003	1.202	0.9813
22	18	V #8 str	dry	28.4	16.7	74	1003	1.200	0.9795
23	18	V #8 str	dry	57.5	16.1	74	1003	1.203	0.9821
24	18	V 2–#8,10	dry	57.3	16.7	72	994	1.189	0.9710
25	18	V #8 sm	wet	57.4	17.2	74	1004	1.198	0.9783
26	18	V #8 str	wet	57.4	18.3	74	1003	1.193	0.9736
27	18	V #8 str	wet	29.4	18.3	76	1003	1.192	0.9734
28	18	V 2-#8,10	wet	29.4	18.3	74	1003	1.193	0.9736
29	18	V 2-#8,10	wet	57.2	18.3	63	1003	1.194	0.9744
30	19	H 1" al	wet	27.8	16.3	81	1004	1.202	0.9814
31	19	H 1" al	wet	48.4	16.8	81	1004	1.200	0.9795
32	19	H #6 str	wet	48.6	17	82	1003	1.198	0.9777
33	19	H #6 str	wet	48.6	17	83	1003	1.198	0.9776
34	19	H #6 str	wet	27.8	17.3	83	1003	1.196	0.9765
35	19	H #6 str	wet	27.8	17.3	83	1003	1.196	0.9765
36	19	H #8 str	wet	27.8	17.5	84	1002	1.194	0.9747
37	19	H #8 str	wet	48.6	17.5	83	1003	1.195	0.9757
38	19	H #10 str	wet	48.7	17.5	83	1003	1.195	0.9757
39	19	H #10 str	wet	28.8	17.2	83	1002	1.195	0.9759
40	19	H #18 str	wet	27.8	17	84	1002	1.196	0.9766
41	19	H #18 str	wet	48.7	17	84	1002	1.196	0.9766

Table 2-4. Forestport data files, 89/09/21 to 89/09/22.

Data File #	Date 09/	Wire	Cond	Freq (kHz)	Temp °C	RH (%)	Bar Pres (mb)	Air Dens (kg/m3)	Air Dens rel 1.225
2	14	V test ca	dry	29.6					
80	21	H 8" al tu	dry cal	47.6	19	67	1000	1.186	0.9685
81	21	d = 20,3 cm	dry cal	27.6	19	67	1000	1.186	0.9685
82	21	d = 20,3 cm	dry cal	17.8	20.5	64	1001	1.181	0.9643
83	21	H 1" al	dry?	17.8	21.5	65	1001	1.177	0.9605
84	21	H 1" al	dry?	27.8	21.5	65	1001	1.177	0.9605
85	21	H 1" al	dry?	48.4	21.5	66	1000	1.175	0.9595
86	21	H #6 str	dry	48.6	21	66	1000	1.178	0.9613
87	21	H #6 str	dry	27.8	21.5	66	1000	1.175	0.9595
88	21	H #6 str	dry	17.9	21.5	66	1000	1.175	0.9595
89	21	H #8 str	dry	17.9	21	66	1000	1.178	0.9613
90	21	H #8 str	dry	27.8	21.5	67	1000	1.175	0.9594
91	21	H #8 str	dry	48.6	21	68	1000	1.177	0.9611
92	21	H #10 str	dry	48.6	20	78	1000	1.181	0.9639
93	21	H #10 str	dry	27.8	19.5	78	1000	1.183	0.9658
94	21	H #10 str	dry	17.9	19.5	78	1000	1.183	0.9658
95	21	H #16 str	dry	17.9	19	78	1000	1.185	0.9676
96	21	H #16 str	dry	27.8	19	78	1000	1.185	0.9676
97	21	H #16 str	dry	48.7	19	68	1000	1.186	0.9684
98	22	H 1" al s	wet	17.9	22	84	992	1.162	0.9482
99	22	H #8 str	wet	17.9	22	80	991	1.161	0.9476
100	22	H #6 str	wet	17.9	22.5	80	991	1.159	0.9458
101	22	H #10 str	wet	17.9	22.5	80	991	1.159	0.9458
102	22	H #18 str	wet	17.9	21	80	991	1.165	0.9513
103	22	H 8" al c	wet	17.9	23	79	991	1.156	0.9441
104	22	H 8" al c	wet	27.6	23	80	991	1.156	0.9440
105	22	H 8" al c	wet	47.7	21.5	81	991	1.163	0.9494

Table 2-5. Air density calculations, 10/07/91.

DATA FILES 2-6

```
       Table 2-5  ** AIR DENSITY CALCULATIONS ** 10/07/91
START:
CLS 'CONSTANTS  Keenan-Keyes  1977 ASHRAE fundamentals handbook p5.2
        A = 3.2437814#
        B = .00586826#
        C = .0000000117023 79#
        D = .0021878462#

    'INPUTS
        INPUT " ENTER DRY BULB TEMPERATURE, deg C"; TDRY
        INPUT " ENTER RELATIVE HUMIDITY, %"; RH
       ' INPUT " ENTER ATMOSPHERIC PRESSURE, mm "; PAMM
        INPUT "ENTER ATMOSPHERIC PRESSURE, mb "; PAMB
       ' PAAT = PAMM / 760
         PAAT = PAMB / 1013.3

  'CALC WATER VAP PRESSURE
        TKEL = 273.1 + TDRY      'temp deg K
        B1 = 647.27 - TKEL
        E2 = B1 / TKEL * (A + B * B1 + C * B1 * B1 * B1) / (1 + D * B1)
        P2 = 218.167 * 10 ^ (-E2)
        P3 = RH / 100 * P2
        PWVAT = P3          'P water vap pressure atmospheres.
        W = .622 * PWVAT / (PAAT - PWVAT)  'mixing ratio # water/# air
          PWVIN = 29.92 * PWVAT            'water vapor pres, inches Hg

   'CALC DEW POINT TEMP
        A3 = LOG(PWVIN)
        T3 = 79.047 + 30.579 * A3 + 1.8893 * A3 * A3
        T4 = (T3 - 32) * 5 / 9             'T dew pt. deg C

   'CALC AIR DENSITY
        DENS = 1.293 * (273.1 / TKEL) * (PAAT - .378 * PWVAT)
        RDENS = DENS / 1.2257
    GOSUB PRINTER1
     INPUT " MORE, M  OR QUIT, Q"; T$
     IF T$ = "M" OR T$ = "m" THEN GOTO START
     STOP    ' sssssssss SUBS sssssssssssssssssss
PRINTER1:
     CLS
        PRINT "   ***** AIR DENSITY  *****"
        PRINT
        PRINT "   ATMOSPHERIC PRESSURE  = "; PAMB; " mb"
        PRINT "   ATMOSPHERIC PRESSURE  = "; PAAT; " ATM"
        PRINT "   TEMPERATURE, DRY BULB = "; TDRY; " deg, C"
        PRINT "   RELATIVE HUMIDITY     = "; RH; " %"
        PRINT "   AIR DENSITY           = "; DENS; "  kg/m3"
        PRINT "   RELATIVE AIR DENSITY  = "; RDENS
        PRINT "   TEMPERATURE, DEW POINT="; T4
     RETURN
CALCTDEW:
        W3 = W
     FOR T3 = TKEL TO 0 STEP -1
        B1 = 647.27 - T3
        E2 = B1 / T3 * (A + B * B1 + C * B1 * B1 * B1) / (1 + D * B1)
        P2 = 218.167 * 10 ^ (-E2)
        P3 = P2      'rel humidity =100%
        W2 = .622 * P3 / (PAAT - P3)
        IF W2 < W3 THEN RETURN  'T3 is now = to T dew point
      NEXT T3
```

Table 2-6. Corona onset, Forestport, 1985 data.

rms values

D outer = 3.2 m
Vert = 0.9

Freq = 28 kHz
Vertical onset

Wire number	Diameter (cm)	V onset (kV)	V onset cor (kV)	E onset (kV/cm)
Smooth dry				
18	0.106	23.3	20.97	49.38
14	0.167	31.5	28.35	44.92
8	0.33	43.4	39.06	34.42
3/8 inch	0.952	91.6	82.44	29.77
1 1/2 inch	3.795	200	180	21.39
Stranded dry				
16	0.145	27.5	24.75	44.34
12	0.234	34.2	30.78	36.43
8	0.368	40.9	36.81	29.56
6	0.47	45.2	40.68	26.54
0	0.955	84.2	75.78	27.29
Smooth wet				
18	0.106	22.9	20.61	48.53
14	0.167	31.6	28.44	45.06
8	0.33	42	37.8	33.31
3/8 inch	0.952	59.5	53.55	19.34
1 1/2 inch	3.795	107.7	96.93	11.52
Stranded wet				
16	0.145	28	25.2	45.14
12	0.234	36.2	32.58	38.56
8	0.368	38.5	34.65	27.82
6	0.47	43.2	38.88	25.36
0	0.955	60.9	54.81	19.74

3.0 GRADIENT VARIATION VERSUS LENGTH

The corona shields at the ends of the test samples reduce the surface gradient on the sample near these shields. To determine the amount of this reduction, several small neon-bulb gradient sensors were built. Thin copper plates were placed on either side of a plastic square about 1 cm on a side and about 4 mm thick. The plates were attached to the small neon lights, which turn on at about 70 volts.

Table 3-1 shows the results of the neon light calibration tests after correction for small differences in turn-on gradients of the different sensors. Figure 3-1 shows how the gradients are reduced near the shields and also show that the vertical test sample is so short that the center section is about 6 percent below the gradient expected for an infinitely long coax. The horizontal wire, on the other hand, reaches this terminal gradient at about 2 to 5 feet from the ends of the 20-foot horizontal test wire. The lower two curves show the calculated gradients at which the sensors turned on.

The results of these gradient versus length tests are used in arriving at the 6-percent correction factor used in the 1989 vertical tests and also in determining the effective power loss per unit length in later sections.

Table 3-1. Neon light calibration of gradient variations, Forestport, 1989.

lightcal

Vertical Test Cell D outer = 3.2 m d sample = 0.953 cm d_{eff} = 1.303 cm				Horizontal Test Cell h = 2.4 m d sample = 2.54 cm d_{eff} = 2.89 cm			
d frm top (cm)	V onset (kV)	E eff (kV/m)	%	d frm end (ft)	V onset (kV)	E eff (kV/m)	%
20	1.82	50.76	49.79	2	2.74	32.66	77.37
40	1.17	32.74	77.18	4	2.18	25.99	97.25
60	1.03	28.84	87.63	6	2.13	25.39	99.53
80	0.99	27.55	91.71	8	2.12	25.27	100.00
100	0.96	26.89	93.99	10	2.12	25.27	100.00
120	0.96	26.89	93.99	12	2.12	25.27	100.00
140	1.35	37.65	67.12	14	2.16	25.75	98.15
160	1.25	34.92	72.37	16	2.07	24.67	102.42
180	1.48	41.28	61.22	18	2.57	30.63	82.49

Note: Effective diameter, d_{eff} = d sample + 0.35 cm where 0.35 cm = the thickness of the neon light calibration sensor.

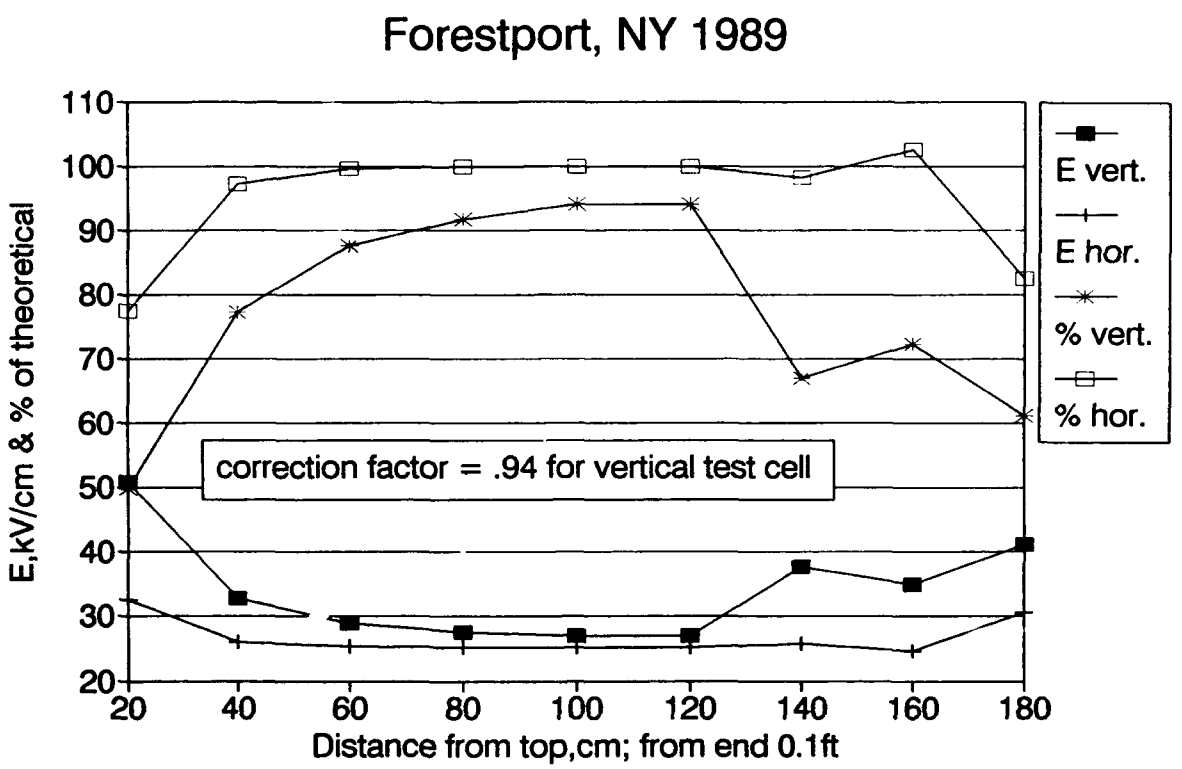

Figure 3-1. Light cell calibration of test cells, Forestport, 1989.

4.0 EFFECTIVE LENGTH CALCULATIONS

The reduction in gradient near the ends of the samples caused the test samples to go into corona near the center and then spread along the wire as the voltage was increased above the corona onset value. The corona power measured needs to be related to a power per unit length of wire such as 1 meter. To do this requires the calculation of the effective length, which will increase as the voltage is raised above the turn-on value. Table 4-1 shows the results of such calculations. The effective length calculations are based on the observed relation that the corona power at least initially increases as the product of the voltage times the difference in voltage above the onset value. The program to calculate the effective length uses the integral of $V \times (V-Vo)$, where V is the effective voltage on the wire as function of length along the wire. Actually it is essentially $G \times (G-Go)$, where G is the gradient at a given point, and Go is the gradient at corona inception. The program assumes zero gradient at the end points.

Table 4-1. Effective length of test cells.

	Horizontal test cell, L = 6.1 meters		Vertical cell, L = 2 meters	
V/Vo	L eff (meters)		L eff (meters)	
1.05	0.334	0.539421	0.362	0.377839
1.11	1.079	1.11331	0.499	0.477232
1.18	1.983	1.632445	0.587	0.570276
1.25	2.498	2.031744	0.656	0.644372
1.33	2.846	2.380992	0.713	0.711461
1.43	3.104	2.702869	0.786	0.775715
1.54	3.3	2.955307	0.855	0.828254
1.67	3.455	3.162576	0.914	0.873308
1.82	3.58	3.322995	0.963	0.909804
2	3.686	3.447391	1.005	0.939445
2.22	3.775	3.541404	1.041	0.962842
2.5	3.853	3.612676	1.072	0.981105
2.86	3.922	3.667894	1.099	0.995057
3.33	3.983	3.71742	1.124	1.006467
4	4.037	3.778535	1.146	1.018775
5	4.086	3.873373	1.165	1.036704
6.67	4.131	4.043713	1.183	1.069822
10	4.171	4.376874	1.199	1.139158

A curve fitting program was used to determined the equations that produced the best fit to the curves in figure 4-1. They have the form:

$$Leff = A + B/X + C/X/X \qquad (4\text{-}1)$$

where X = V/Vo.

For the vertical cell, A = 1.173507
B = 0.141519
C = -1.062714

For the horizontal case, A = 3.466942
B = 4.8356119
C = -8.16248784

These equations, modified slightly to start at a minimum length of 0.5 meter for the vertical cell and 2 meters for the horizontal cell, are used in section 6.0 to calculate power per meter from the observed total corona power.

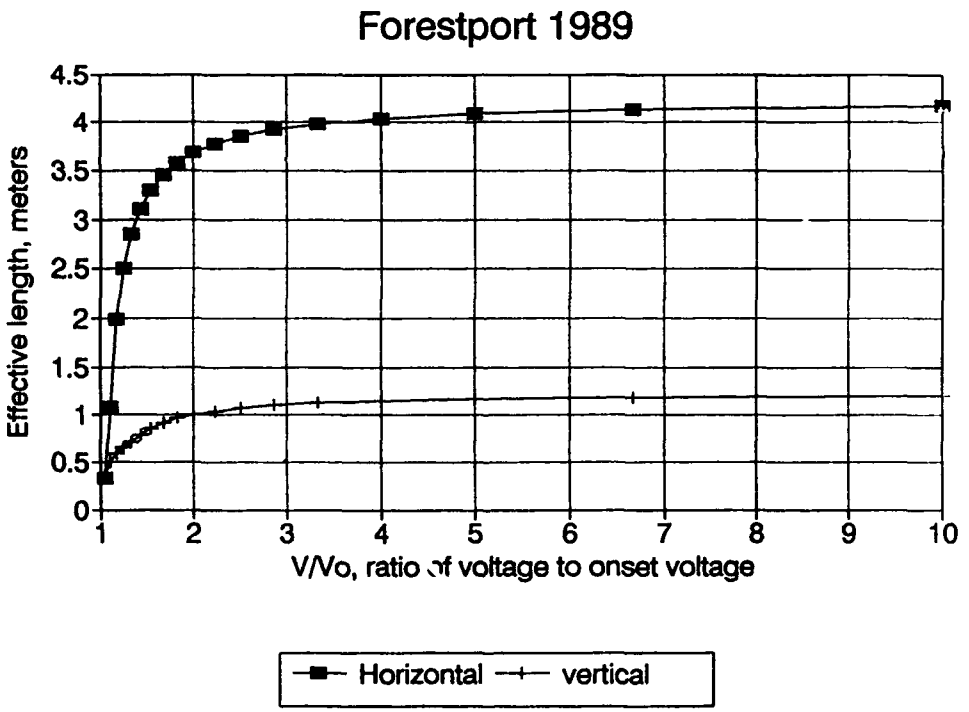

Figure 4-1. Test cell effective lengths, Forestport, 1989.

5.0 CORONA ONSET VOLTAGES AND GRADIENTS

Corona onset voltages were observed during the 1985 and 1989 tests. Table 5-1a summarizes the 1985 onset data using the vertical test cell described in section 1.0. The vertical onset rms voltages recorded are all multiplied by the 0.9 correction factor before the onset gradients are calculated. Table 5-1b shows the same data with an additional correction factor for the air density at the time of the measurements. It is seen that this additional correction is small.

Table 5-1a. Corona onset data rms values, Forestport, 1985 (corrected for air density).

D outer = 3.2 m Ver cor = 0.9		Freq = 28 kHz Vertical onset			Freq = 57 kHz Vertical onset		
Wire Number	Diameter (cm)	V onset (kV)	V onset cor (kV)	E onset (kV/cm)	V onset (kV)	V onset cor (kV)	E onset (kV/cm)
Smooth dry							
18	0.106	23.3	20.97	49.38	22.5	20.25	47.68
14	0.167	31.5	28.35	44.92	30.4	27.36	43.35
8	0.33	43.4	39.06	34.42	43.2	38.88	34.26
3/8 inch	0.952	91.6	82.44	29.77	91.6	82.44	29.77
1 1/2 inch	3.795	200	180	21.39	NA	NA	NA
Stranded dry							
16	0.145	27.5	24.75	44.34	25.8	23.22	41.60
14	0.234	34.2	30.78	36.43	33.3	29.97	35.47
8	0.368	40.9	36.81	29.56	38.7	34.83	27.97
6	0.47	45.2	40.68	26.54	42.1	37.89	24.72
0	0.955	84.2	75.78	27.29	86.5	77.85	28.04
Smooth wet							
18	0.106	22.9	20.61	48.53	22.7	20.43	48.11
14	0.167	31.6	28.44	45.06	29.1	26.19	41.50
8	0.33	42	37.8	33.31	39.9	35.91	31.65
3/8 inch	0.952	59.5	53.55	19.34	59.5	53.55	19.34
1 1/2 inch	3.795	107.7	96.93	11.52	NA	NA	NA
Stranded wet							
16	0.145	28	25.2	45.14	25.9	23.31	41.76
14	0.234	36.2	32.58	38.56	31.4	28.26	33.45
8	0.368	38.5	34.65	27.82	38.3	34.47	27.68
6	0.47	43.2	38.88	25.36	41.1	36.99	24.13
0	0.955	60.9	54.81	19.74	53.3	47.97	17.28

Table 5-1b. Corona onset, data rms values, Forestport, 1985 (corrected for air density).

D outer = 3.2 m Vert cor = 0.89		Wet Cor = 0.97 Freq = 28 kHz Vertical Onset			Dry Cor = 0.99 Freq = 57 kHz Vertical Onset		
Wire Number	Diameter (cm)	V onset (kV)	V onset cor (kV)	E onset (kV/cm)	V onset (kV)	V onset cor (kV)	E onset (kV/cm)
Smooth dry							
18	0.106	23.3	20.95	49.32	22.5	20.23	47.63
14	0.167	31.5	28.32	44.87	30.4	27.33	43.30
8	0.33	43.4	39.02	34.38	43.2	38.84	34.23
3/8 inch	0.952	91.6	82.35	29.74	91.6	82.35	29.74
1 1/2 inch	3.795	200	179.80	21.37	NA	NA	NA
Stranded dry							
16	0.145	27.5	24.72	44.29	25.8	23.19	41.55
14	0.234	34.2	30.75	36.39	33.3	29.94	35.43
8	0.368	40.9	36.77	29.53	38.7	34.79	27.94
6	0.47	45.2	40.63	26.51	42.1	37.85	24.69
0	0.955	84.2	75.69	27.26	86.5	77.76	28.1
Smooth wet							
18	0.106	22.9	21.01	49.48	22.7	20.83	49.04
14	0.167	31.6	28.99	45.94	29.1	26.70	42.31
8	0.33	42	38.54	33.96	39.9	36.61	32.26
3/8 inch	0.952	59.5	54.59	19.71	59.5	54.59	19.71
1 1/2 inch	3.795	107.7	98.82	11.74	NA	NA	NA
Stranded wet							
16	0.145	28	25.69	46.02	25.9	23.76	42.57
14	0.234	36.2	33.21	39.32	31.4	28.81	34.10
8	0.368	38.5	35.32	28.37	38.3	35.14	28.22
6	0.47	43.2	39.64	25.86	41.1	37.71	24.60
0	0.955	60.9	55.88	20.13	53.3	48.90	17.61

Onset gradients are shown in table 5-2, which also includes 60 Hz valves from Cobine and calculated values using the formulas at the bottom of the table. Electrical gradients at the wire surface are calculated using the formulas.

$$E = 2 \times V/(d \times 1n(4 \times h/d) \text{ for horizontal wires,} \quad (5\text{-}1)$$

and

$$E = 2 \times V/(d \times 1n(D/d)) \text{ for vertical wires,} \quad (5\text{-}2)$$

where E is in kV/cm if
V is in kV,
d is the wire diameter in cm,
h is the height above the ground in cm, and
D is the diameter of the test cell in cm.

Table 5-2. Corona onset gradients at Forestport, NY.

Data taken in Sept. 1985
vertical rms value Go = 24.4 kV/cm
Drel = 0.98 rel air dens
Freq = 28 kHz Kstrand = 0.9 stranding factor

Wire Dia (cm)	Dry E Cor (kV/cm)	Wet Ons E Cor (kV/cm)	60 hZ Ons Cobine (kV/cm)	Dry CALC (kV/cm)	K Freq	K Wet	Wet CALC kV/cm
Smooth sample							
0.106	49.38	48.5	48.94	48.09	0.9699	0.9890	47.5
0.167	44.9	45.1	43.30	42.15	0.9655	0.9736	41.0
0.33	34.4	33.3	36.93	35.18	0.9576	0.9106	32.0
0.952	29.8	19.3	30.46	27.64	0.9418	0.6778	18.7
3.795	21.4	11.5	25.84	21.59	0.9119	0.5168	11.1
Stranded samples							
0.145	44.3	45.1	44.92	43.46	0.9578	0.9901	43.0
0.234	36.4	38.6	39.87	37.83	0.9464	0.9796	37.0
0.368	29.6	27.8	36.09	33.40	0.9328	0.9598	32.0
0.47	26.5	25.3	34.38	31.30	0.9241	0.9420	29.4
0.955	25	19.7	30.45	26.15	0.8918	0.8320	21.7

CALC are calculated values based on the formula

$$Ecalc = 0.707 \times GO \times Drel \times (1 + 0.72/d^{\wedge} 0.44) \times Kfreq \times Kwet$$

where $Kfreq = 1 - 0.008 \times F^{\wedge} 0.6 \times d^{\wedge} 0.3$ smooth

$Kfreq = 1 - 0.015 \times F^{\wedge} 0.6 \times d^{\wedge} 0.5$ stranded

$Kwet = 1 - 0.5 \times d^{\wedge} 2/(0.5 + d^{\wedge} 2)$ smooth = 1 if dry

$Kwet = 1 - 0.18 \times d^{\wedge} 1.5$ stranded = 1 if dry

d = wire diameter, cm

F = frequency, kHz

The electric field values at the surface of the wire at which corona starts decreases with increasing wire diameter since corona only occurs when a minimum energy distance or volume is exceeded. Figure 5-1 shows this reduction in onset gradient that occurs as the diameter of the sample is increased. These vertical data appear to show a larger reduction in onset gradient for wet conditions at the larger diameters than at the smaller diameters.

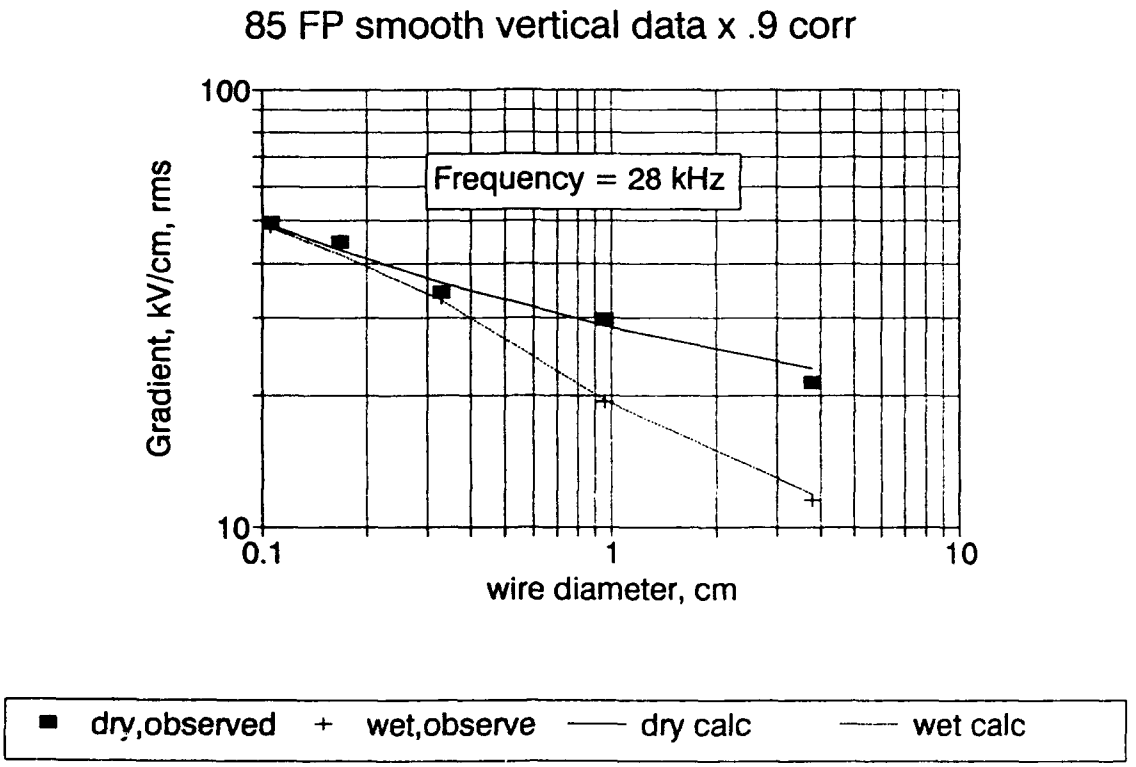

Figure 5-1. Corona onset gradients.

Onset values for the 1989 data are shown in table 5-3 for both horizontal and vertical tests. The correction factor employed for the 1989 vertical data is 0.94 since smaller corona shields were used at the ends of the test sample. The visual onset values for the horizontal tests done during the day are not as precise as those for the vertical tests that were performed indoors where the room could be darkened to see corona onset.

Table 5-4 compares onset gradients from the 1985 and 1989 data. For comparison, calculated values are given using the preliminary formula at the bottom of the table. The amount of reduction in corona onset gradient from dry to wet conditions appears to depend on whether the sample is vertical or horizontal. The vertical data show little dry to wet difference at the small diameters, while there is a greater difference for all diameters for the horizontal tests. The six columns on the right side show calculations using preliminary formulas for calculating onset gradients as a function of wire diameter, smooth or stranded, frequency, wet or dry, and for wet if the sample is vertical or horizontal.

Table 5-3. Corona onset at VLF, 1989 Forestport data.

		Freq = 28 kHz Vertical V correction = 0.94 D outer = 3.2 m			Horizontal H correction = 1 Wire height = 2.4	
Wire Number	Diameter (cm)	Observed V Onset (kV)	Corrected V Onset (kV)	E ons cor (kV/cm)	V Onset (kV)	E Onset (kV/cm)
Smooth dry						
18	0.106	21.3	20.02	47.14		
14	0.167					
8	0.33	41	38.54	33.96		
6	0.47					
3/8"	0.952	88	82.72	29.87		
1"	2.54				115	26.40
Stranded dry						
16	0.154				27	42.33
10	0.228				34	35.69
8	0.368	41	38.54	30.95	42	29
6	0.47				47	26.24
Smooth wet						
18	0.106					
14	0.167					
8	0.33					
6	0.47					
3/8"	0.53					
1"	2.54					
Stranded dry						
16	0.154				25	39.2
10	0.228				30	31.5
8	0.368	28	26.32	21.14	35	24.2
6	0.47				44	24.6

Table 5-4. Corona onset gradient at VLF.

Wire Dia cm	Vertical Data ****Observed rms Values**** Forestport 85 28 kHz Dry E Cor Ons kV/cm	Wet E Cor Ons Onset kV/cm	Forestport 89 28 kHz Dry E Cor Ons kV/cm	Calculated Values Go = 24.4 D_{rel} = 0.98 Kstrand = 0.9 Dry CALC kV/cm	K Freq	Smooth K Wet Vert	Wet CALC kV/cm	****Observed Stranded**** Stranded Dry Vert kV/cm	Stranded Wet Vert kV/cm	Forestport 89 Stranded Wet Hor kV/cm	Kwet Hor	Wet Hor CALC kV/cm
Frequency												
Smooth												
0.106	49.4	48.5	48.9	47.71	0.96	0.99	47.19				0.93	38.29
0.145				43.50	0.96	0.98	42.62	44.3	45.1	39	0.92	34.41
0.167	44.9	45.1		41.77	0.96	0.97	40.67				0.91	32.81
0.234				38.06	0.95	0.95	36.18	36.4	38.6		0.90	29.33
0.3				35.65	0.95	0.92	32.93				0.89	27.05
0.33	34.4	33.3	34.7	34.79	0.95	0.91	31.68				0.88	26.22
0.368				33.84	0.95	0.89	30.24	29.6	27.8	24.2	0.88	25.32
0.4				33.15	0.94	0.88	29.13				0.88	24.65
0.47				31.88	0.94	0.85	27.00	27	25.3	24.5	0.87	23.41
0.6				30.11	0.94	0.79	23.81				0.85	21.66
0.8				28.24	0.93	0.72	20.31				0.84	19.76
0.952	29.8	19.3	29.9	27.21	0.93	0.68	18.44				0.82	18.70
0.955				27.19	0.93	0.68	18.41	25	19.7		0.82	18.68
1				26.93	0.93	0.67	17.95				0.82	18.41
3.795	21.4	11.5		21.07	0.89	0.52	10.89				0.69	11.69

Table 5-4. Corona onset gradient at VLF (cont).

Frequency	Vertical Data ****Observed rms Values**** Forestport 85 28 kHz		Forestport 89 28 kHz		Calculated Values Go = 24.4 D_{rel} = 0.98 Kstrand = 0.9				****Observed Stranded**** Forestport 89 Stranded			
Wire Dia cm	Dry E Cor Ons kV/cm	Wet E Cor Ons Onset kV/cm	Dry E Cor Ons kV/cm	Dry CALC kV/cm	K Freq	Smooth K Wet Vert	Wet CALC kV/cm	Stranded Dry Vert kV/cm	Stranded Wet Vert kV/cm	Wet Hor kV/cm	Kwet hor	Wet Hor CALC kV/cm
Stranded			Forestport 89 wet horizontal									
0.145	44.3	45.1	39.00	37.6	41.66	0.96	0.96	39.90				
0.234	36.4	38.6			35.75	0.95	0.94	33.59				
0.368	29.6	27.8	24.20	30.4	30.97	0.95	0.91	28.33				
0.47	26.5	25.3	24.50	26.24	28.62	0.94	0.90	25.70				
0.955	25	19.7			22.46	0.93	0.83	18.56				

CALC values use provisional formula

$$Ecalc = 0.707 \times Go \times D_{rel} \times (1 + 0.72/d\,\hat{}\,0.44) \times Kfreq \times Kwet$$

where: $Kfreq = 1 - 0.01 \times F\,\hat{}\,0.6 \times d\,\hat{}\,0.3$

$Kwet\ vert = 1 - 0.5 \times d\,\hat{}\,2/(0.5 + d\,\hat{}\,2) = 1$ if dry

$Kwet\ hor = 1 - 0.12 \times d\,\hat{}\,0.4$

d = wire diam, cm

F = frequency, kHz

Figure 5-2 shows the reduction in onset gradient with increasing diameter observed at 28 kHz for smooth dry wires. Figure 5-3 shows the results for wet smooth vertical wires. Figure 5-4 shows the results for stranded cables at 28 kHz for several conditions. It is instructive to note that the observed dry onset value at 0.95 cm for the Forestport 1985 data is above the curve, but that the Forestport, 1989 data point shown is below the curve.

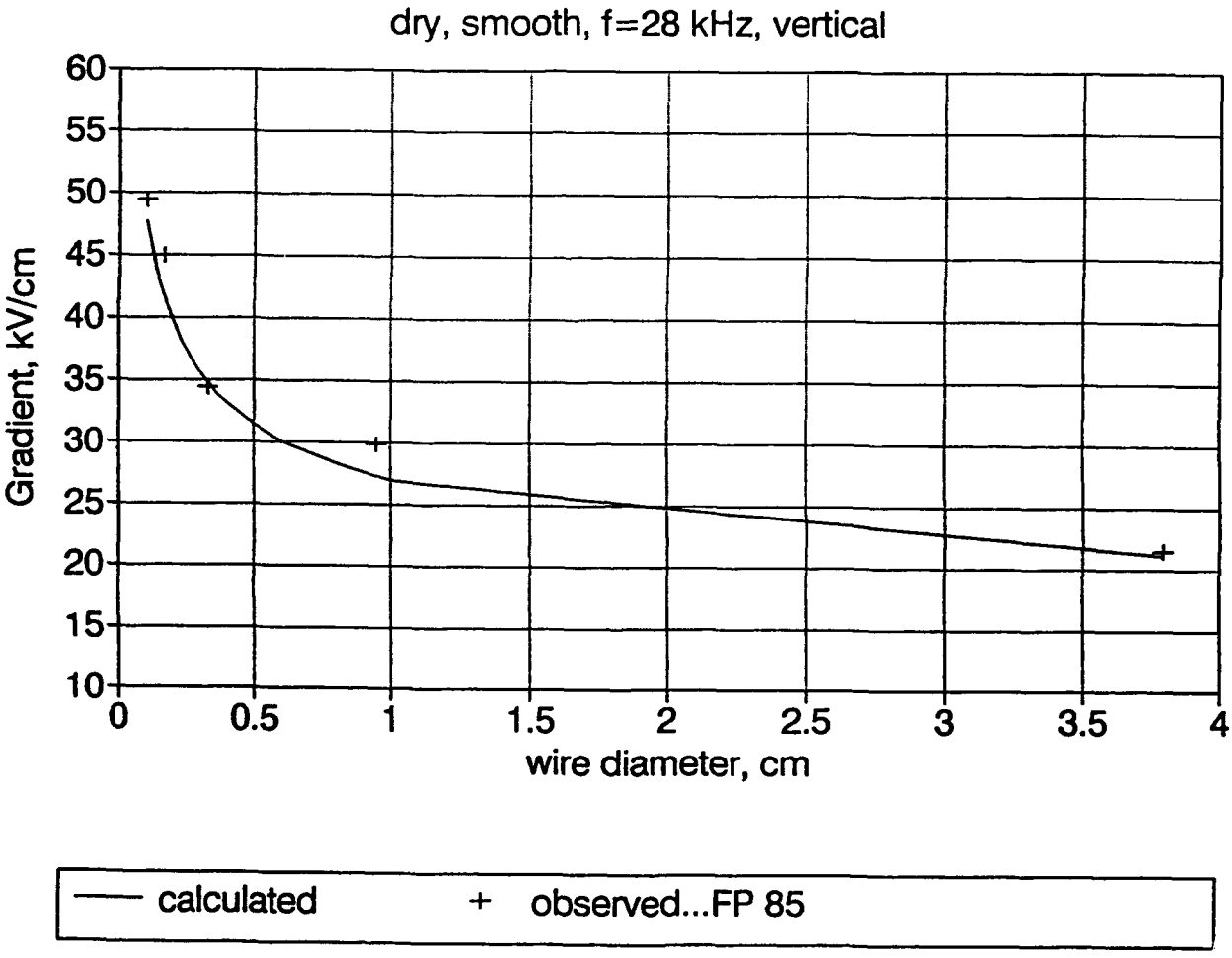

Figure 5-2. Corona onset gradient (dry, smooth, f = 28 kHz, vertical).

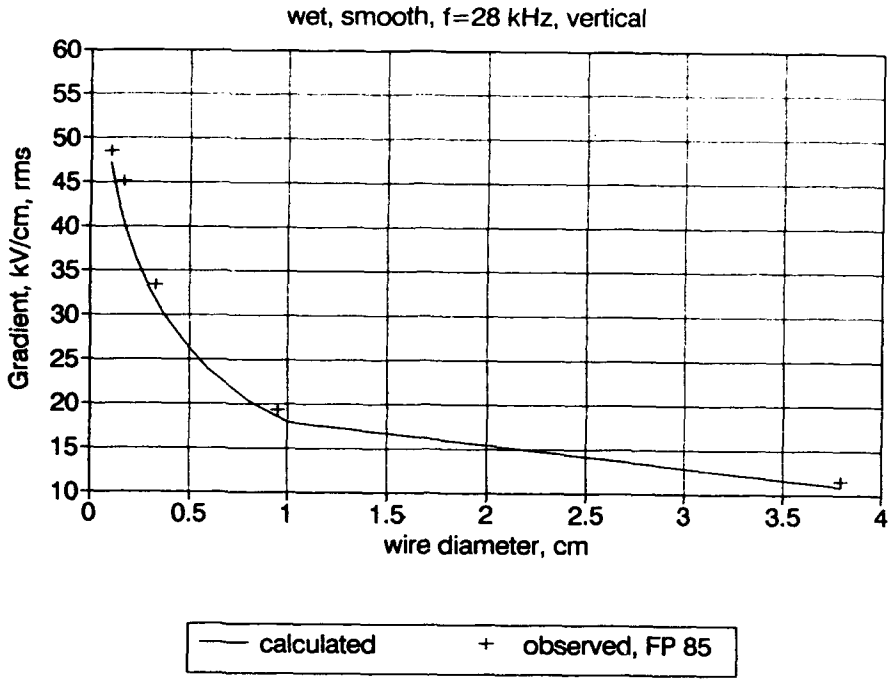

Figure 5-3. Corona onset gradient (wet, smooth, f = 28 kHz, vertical).

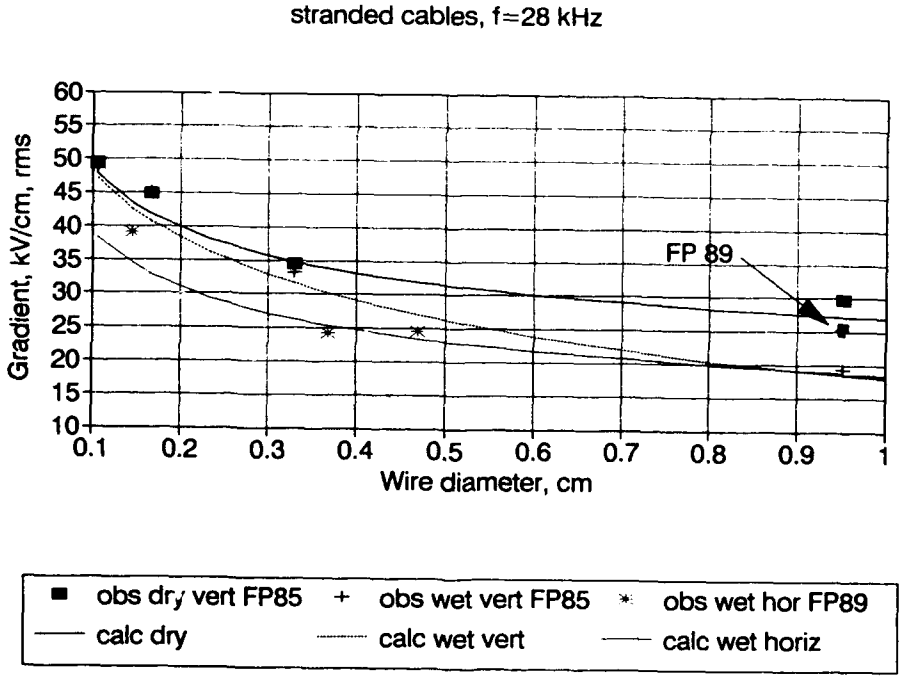

Figure 5-4. Corona onset gradients (stranded cables, f = 28 kHz, several conditions).

5.1 STRANDING FACTORS

Cables made of a number of individual strands have gradients at the outer surface of the individual strands larger than that on the surface of a smooth wire of the same overall diameter. The actual gradient on the strand surface can be calculated using the cage formula in the section on cage effects. The exact gradients are dependent on the height of the cable above ground and the number of strands in the cable.

Take for example a seven-strand cable having six outer strands of 2 cm diameter at a height of 100 meters. The ratio of E fields on the surface of a smooth wire, whose diameter is equal to that of the stranded cable, is 0.745 that on the surface of the stranded cable. This assumes that the smooth wire diameter is 2.59 times the strand diameter, i.e., the minimum cable diameter. This ratio becomes 0.684 if the overall diameter of 3 times the strand diameter is used. In addition, the gradient for the cable relative to that of a single strand at the same voltage is 0.548. The corresponding values for a 19-strand cable with 12 outer strands are 0.768 and 0.695. The reduction relative to a single strand is 0.344.

It should be pointed out that the factors determined above are not the exact stranding derating factor "K strand." This is because the corona onset is related to the way the field decreases with distance from the surface and not just on the surface values. This is the well-known energy distance factor required on corona formation. The exact K strand factor will generally be greater than the calculated values just quoted.

An examination of corona onset values from Smith (1963) give K strand factors of about 0.88 to 0.90 for seven-strand cables. From table 5-3, the corona onset gradients for #8 stranded and smooth wires are 30.5 and 33.96 kV/cm. The ratio of these gradients is 0.91, which is close to the ratios observed in Smith's 1963 data. Observations by Miller (1957) show that for clean stranded cables the stranding factor observed ranges from 0.88 to 0.95. He also shows that for weathered cables the stranding factor ranges from 0.7 to 0.86.

5.2 FREQUENCY EFFECTS

The exact amount of reduction in onset gradients with increasing frequency is difficult to obtain. The reduction from 60-Hz values as frequency increases into the audio range is described by Whitehead and Gorton (1914). Their actual onset voltage or gradient values are not readily apparent in their paper; however, it is possible to use their results related to the 60-Hz onset values. Their results indicate a few percent reduction for frequencies up to several thousand hertz. These values along with values from Smith (1963), Kolechitskii (1967), and Forestport 1989 data are shown in figure 5-5. The reduction in the 50-kHz region of about 15 percent is greater than was expected.

The provisional frequency law listed in this figure is

$$K_{freq} = 1 - 0.015 \times F^{0.6} \times d^{0.3} \qquad (5\text{-}3)$$

where F is in kHz, and
d is in cm.

The provisional relationship is believed to be good over the frequency range shown, but should not be extrapolated too far as it is known that eventually as frequency increases (and also for short impulses) that there is a turn up in K frequency.

There is a definite change in corona appearance that appears to be related to both frequency and wire diameter. Kolechitskii (1967) reports a critical frequency effect shown in figure 5-6. Below the critical frequency, the onset of corona has the form of a rather uniform bluish brush discharge that likely corresponds to negative corona. Above the critical frequency, the corona appears to go directly into reddish white flares extending far out from the wire surface as the voltage is increased.

This type of behavior was seen at the Forestport tests, and similar results are seen in Smith's 1963 data, where the onset of corona appeared on the negative half cycle first for small wires and on the positive half cycle for the larger wires. It is believed that rain may have some influence on the frequency effect.

It is possible that the frequency effect is dependent to some extent on the impedance of the wire or test cell. For example, a larger diameter wire has a lower line impedance and as a result, the reactive to resistive component ratio across the corona zone may change with both frequency and wire diameter. It is also possible that the critical frequency is dependent on test cell outer diameter or wire height. In fact, the large flaring seen in the vertical coaxial cell did not appear as great in the outdoor horizontal wire tests.

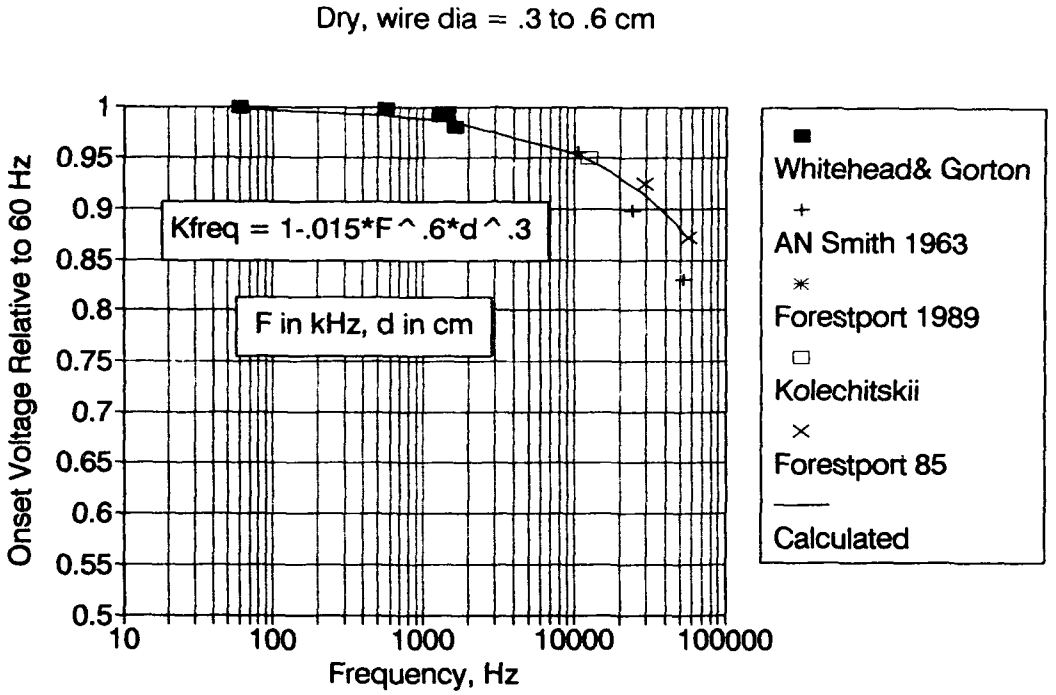

Figure 5-5. Corona onset versus frequency (dry, wire diameter = 0.3 to 0.6 cm).

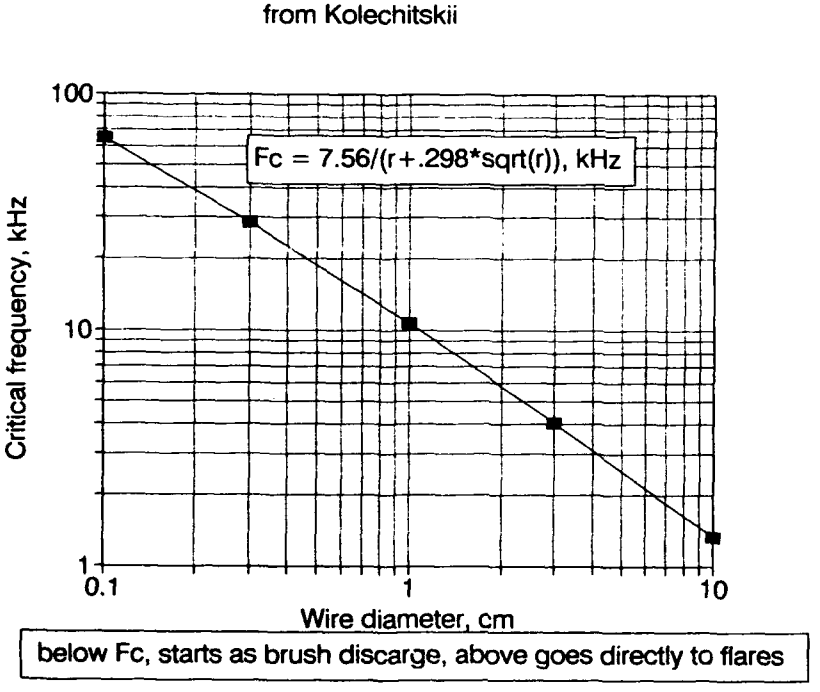

Figure 5-6. Critical frequency (from Kolechitskii, 1967).

5.3 CAGE EFFECTS

The use of parallel wire in cages to increase the corona onset voltage is well known. An excellent approximate formula for the effective surface gradient as a function of wire diameter and spacing, i.e., cage diameter is available, Hansen (1992). This formula has the form:

$$Em = V/N \times (2/d + (N-1)/(D/2+d/4)) \times (1/1n(4 \times H/deq)) \qquad (5\text{-}4)$$

where Em is the maximum surface gradient in volts/meter
V is in volts,
N is the number of wires,
d is the wire diameter in meters,
D is the cage diameter in meters,
H is the height of the cage above ground in meters,
and deq is an equivalent diameter given as
deq = 2 $\times$ (N/2 $\times$ d $\times$ (D/2)^(N - 1)^(1/N).

This formula is used in calculating the ratio of the gradients for a cage of two to six wires relative to the gradient for one wire of the same diameter and at the same height. The results are given in tables 5-5 and 5-6 for #8 stranded wires and 1-inch (2.54 cm) wires at heights of 2 and 100 meters. It should be noted that the reduction obtained at the lower heights is not as great as that for the 100-meter case.

Figure 5-7 shows the effects of changing cage diameter and shows that the optimum cage diameter is smaller for two wires than is true for the six-wire case. Figure 5-8 shows the results of the calculations for #8 stranded wire at a height of 2 meters. The observed point from the 1989 vertical tests was for dry conditions at a frequency of 29 kHz. As might be expected, the observed point shows less reduction than calculated since it is in a cylindrical test cell with an effective height that would be less than the 2 meters for the calculated values.

Table 5-5. Cage gradient calculations, h = 2 meters (CAGECALC, P. M. Hansen formula).

Wire dia, cm = 0.368 Height above ground, 2 m

Dia Cage	Ratio of En to E1					
(cm)	N = 2	N = 3	N = 4	N = 5	N = 6	DC/DW
0.74	0.7694	0.6725	0.6199	0.5869	0.5644	2.0
2.21	0.6882	0.5470	0.4684	0.4187	0.3845	6.0
3.68	0.6802	0.5273	0.4402	0.3845	0.3458	10.0
5.15	0.6825	0.5244	0.4327	0.3734	0.3321	14.0
6.62	0.6873	0.5265	0.4318	0.3701	0.3269	18.0
8.10	0.6928	0.5305	0.4338	0.3702	0.3254	22.0
9.57	0.6984	0.5353	0.4370	0.3719	0.3259	26.0
11.04	0.7039	0.5404	0.4408	0.3745	0.3275	30.0
12.51	0.7092	0.5456	0.4449	0.3777	0.3297	34.0
13.98	0.7143	0.5507	0.4492	0.3810	0.3323	38.0
15.46	0.7191	0.5557	0.4536	0.3846	0.3351	42.0
16.93	0.7237	0.5606	0.4579	0.3882	0.3381	46.0
18.40	0.7281	0.5654	0.4622	0.3918	0.3412	50.0
19.87	0.7323	0.5700	0.4664	0.3955	0.3443	54.0
21.34	0.7363	0.5745	0.4705	0.3991	0.3474	58.0
22.82	0.7401	0.5788	0.4746	0.4027	0.3505	62.0
24.29	0.7438	0.5831	0.4785	0.4062	0.3536	66.0
25.76	0.7474	0.5872	0.4825	0.4097	0.3567	70.0

Ratio of wire surface gradients for a cage of N wires relative to 1 wire DC/DW is ratio of cage diameter to wire diameter.

Wire dia, cm = 2.54 Height above ground, 2 m

Dia Cage	Ratio of En to E1					
(cm)	N = 2	N = 3	N = 4	N = 5	N = 6	DC/DW
5.08	0.7959	0.7009	0.6475	0.6135	0.5898	2.0
10.16	0.7459	0.6207	0.5490	0.5029	0.4709	4.0
15.24	0.7359	0.5982	0.5174	0.4650	0.4283	6.0
20.32	0.7363	0.5922	0.5059	0.4491	0.4092	8.0
25.40	0.7404	0.5927	0.5026	0.4427	0.4004	10.0
30.48	0.7461	0.5964	0.5034	0.4411	0.3968	12.0
35.56	0.7524	0.6016	0.5065	0.4422	0.3962	14.0
40.64	0.7589	0.6077	0.5109	0.4449	0.3974	16.0
45.72	0.7654	0.6142	0.5161	0.4487	0.3999	18.0
50.80	0.7719	0.6210	0.5219	0.4532	0.4033	20.0
55.88	0.7782	0.6278	0.5279	0.4581	0.4072	22.0
60.96	0.7843	0.6347	0.5341	0.4634	0.4115	24.0
66.04	0.7903	0.6416	0.5404	0.4689	0.4161	26.0
71.12	0.7961	0.6484	0.5468	0.4745	0.4210	28.0
76.20	0.8017	0.6551	0.5533	0.4803	0.4260	30.0
81.28	0.8072	0.6618	0.5597	0.4861	0.4312	32.0
86.36	0.8125	0.6683	0.5661	0.4920	0.4364	34.0
91.44	0.8176	0.6748	0.5725	0.4979	0.4418	36.0

Ratio of wire surface gradients for a cage of N wires relative to 1 wire DC/DW is ratio of cage diameter to wire diameter.

Table 5-6. Cage gradient calculations, h = 100 meters (CAGECALC, P. M. Hansen formula).

Wire dia, cm = 0.368 Height above ground, 100 m

Dia Cage (cm)	Ratio of En to E1 N = 2	N = 3	N = 4	N = 5	N = 6	DC/DW
0.74	0.7445	0.6462	0.5944	0.5625	0.5409	2.0
2.21	0.6462	0.5037	0.4277	0.3807	0.3488	6.0
3.68	0.6288	0.4746	0.3914	0.3396	0.3042	10.0
5.15	0.6242	0.4644	0.3774	0.3229	0.2857	14.0
6.62	0.6233	0.4604	0.3710	0.3147	0.2762	18.0
8.10	0.6240	0.4590	0.3679	0.3104	0.2708	22.0
9.57	0.6254	0.4589	0.3665	0.3080	0.2677	26.0
11.04	0.6271	0.4596	0.3661	0.3067	0.2658	30.0
12.51	0.6289	0.4606	0.3662	0.3062	0.2647	34.0
13.98	0.6308	0.4618	0.3667	0.3061	0.2642	38.0
15.46	0.6326	0.4632	0.3675	0.3063	0.2640	42.0
16.93	0.6344	0.4646	0.3683	0.3067	0.2640	46.0
18.40	0.6362	0.4661	0.3693	0.3073	0.2643	50.0
19.87	0.6380	0.4676	0.3704	0.3080	0.2646	54.0
21.34	0.6397	0.4690	0.3715	0.3087	0.2651	58.0
22.82	0.6413	0.4705	0.3726	0.3095	0.2656	62.0
24.29	0.6429	0.4719	0.3737	0.3103	0.2662	66.0
25.76	0.6444	0.4734	0.3748	0.3112	0.2668	70.0

Ratio of wire surface gradients for a cage of N wires relative to 1 wire DC/DW is ratio of cage diameter to wire diameter.

Wire dia, cm = 2.54 Height above ground, 100 m

Dia Cage (cm)	Ratio of En to E1 N = 2	N = 3	N = 4	N = 5	N = 6	DC/DW
5.08	0.7541	0.6562	0.6042	0.5719	0.5499	2.0
10.16	0.6848	0.5557	0.4864	0.4434	0.4142	4.0
15.24	0.6620	0.5198	0.4428	0.3948	0.3620	6.0
20.32	0.6524	0.5030	0.4213	0.3702	0.3352	8.0
25.40	0.6481	0.4940	0.4092	0.3559	0.3193	10.0
30.48	0.6463	0.4890	0.4019	0.3469	0.3091	12.0
35.56	0.6458	0.4863	0.3974	0.3410	0.3023	14.0
40.64	0.6462	0.4848	0.3945	0.3371	0.2975	16.0
45.72	0.6470	0.4843	0.3927	0.3344	0.2941	18.0
50.80	0.6481	0.4843	0.3917	0.3326	0.2917	20.0
55.88	0.6494	0.4847	0.3912	0.3314	0.2899	22.0
60.96	0.6507	0.4853	0.3911	0.3307	0.2887	24.0
66.04	0.6522	0.4862	0.3913	0.3303	0.2879	26.0
71.12	0.6537	0.4872	0.3916	0.3301	0.2873	28.0
76.20	0.6552	0.4882	0.3922	0.3302	0.2870	30.0
81.28	0.6567	0.4894	0.3928	0.3304	0.2869	32.0
86.36	0.6582	0.4906	0.3936	0.3308	0.2869	34.0
91.44	0.6597	0.4918	0.3944	0.3312	0.2871	36.0

Ratio of wire surface gradients for a cage of N wires relative to 1 wire DC/DW is ratio of cage diameter to wire diameter.

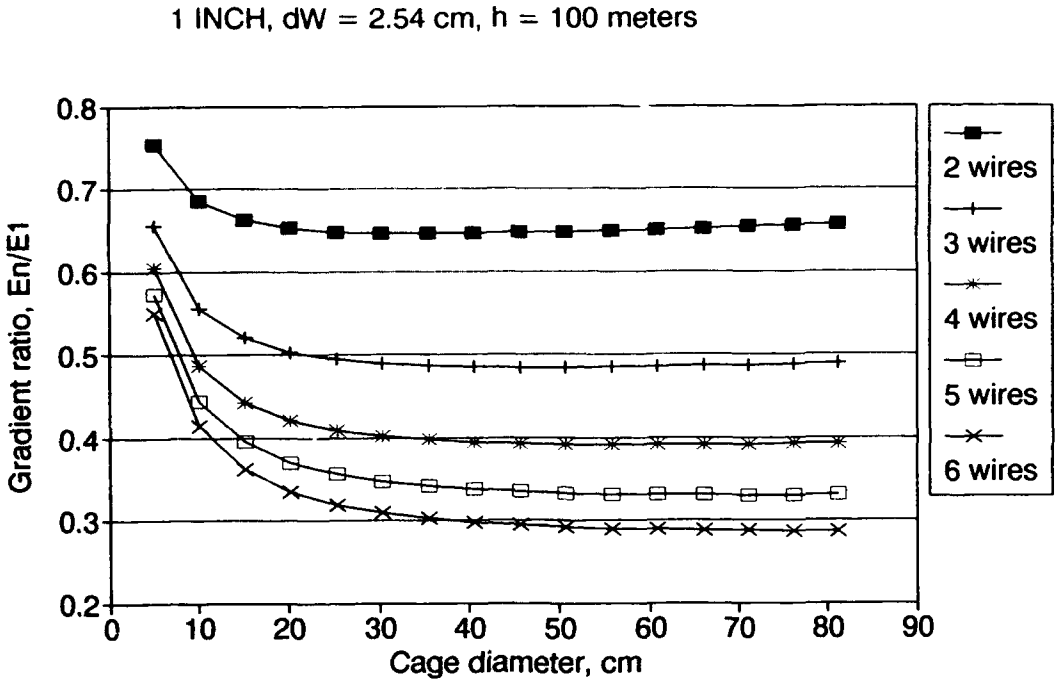

Figure 5-7. Cage gradients, (1 inch, dw = 2.54 cm, h = 100 meters).

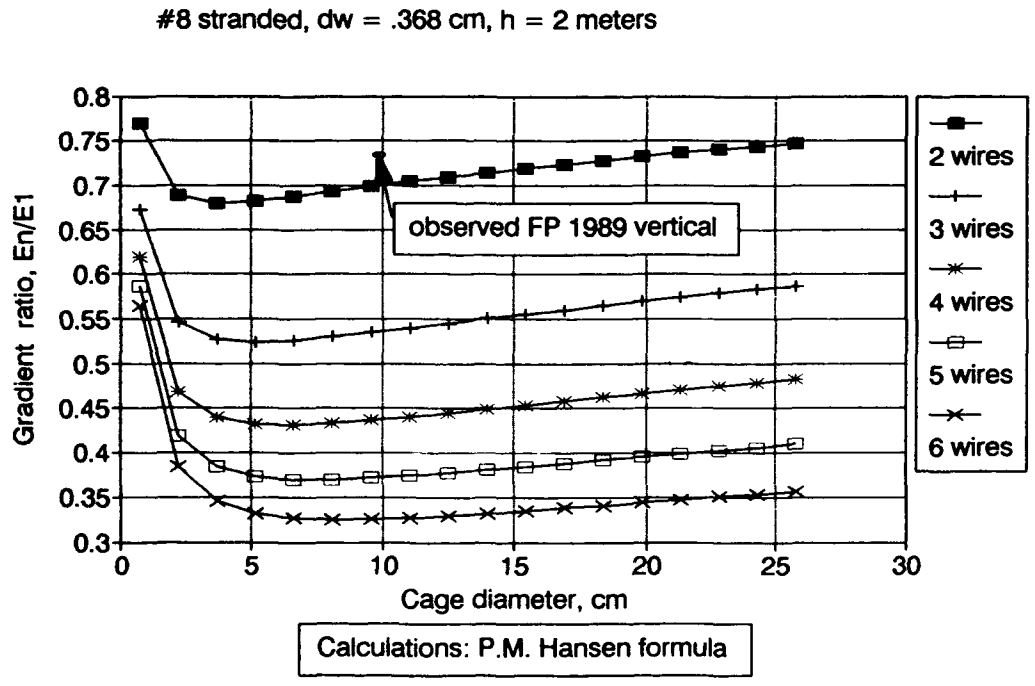

Figure 5-8. Cage gradients, (#8 stranded, dw = 0.368 cm, h = 2 meters).

5.4 CORONA ONSET FORMULA DEVELOPMENT

Data on the DC breakdown gradient of air from Cobine (1958), and Meek and Crags (1953) are shown in figure 5-9. These data show that the breakdown gradient is very large for short distances and decreases to the critical breakdown value of 24.3 kV/cm, which is the point where the ionization and recombination coefficients are equal for standard temperature and pressure conditions. The large increase at small spacings results from the fact that an initial ionization event does not have sufficient length and volume to form a positive avalanche unless the field is very large. Peek's formula also shown on this figure shows that the surface field on a wire of diameter equal to S is greater than the breakdown gradient of a uniform field. This is to be expected since the field drops off rapidly from the surface of small wires. For large diameters, breakdown gradient and corona onset should approach each other.

The Peek equation, which is valid in the 0.01- to 10-cm range, is not likely to be valid for either very small or large diameters. This results since it uses a value 30 kV/cm for the breakdown gradient of air instead of 24.3. This was necessary to fit wire data over the nominal range of diameters with a $1\sqrt{(d)}$ relationship. Also shown on this figure is the formula derived to provide a better fit to data at larger diameters.

Figure 5-10 shows the corona onset gradients as a function of wire diameter at 60 Hz. The values up to 1 cm diameter are from Peek (1929), page 56. The values at larger diameters are from Miller (1956), page 1032. Miller's original values show a definite discontinuity between Peek's larger diameters and Miller's smaller diameters. This may have resulted from the structure surrounding Miller's test facility. As a result, Miller's values were all multiplied by a 0.95 correction factor.

A formula having the form

$$E_{onset,max} = Go \times Dr \times (1 + a/(Go \times Dr)^{b}) \qquad (5\text{-}5)$$

where Go = 24.3, kV/cm
Dr = 1 at STP i.e., relative air density,
a = 0.717 and
b = 0.423

was found to fit the data well when a and b values were adjusted to the values shown. This formula approaches the Go value for large diameters and also fits the 60-Hz values down to 0.01 cm.

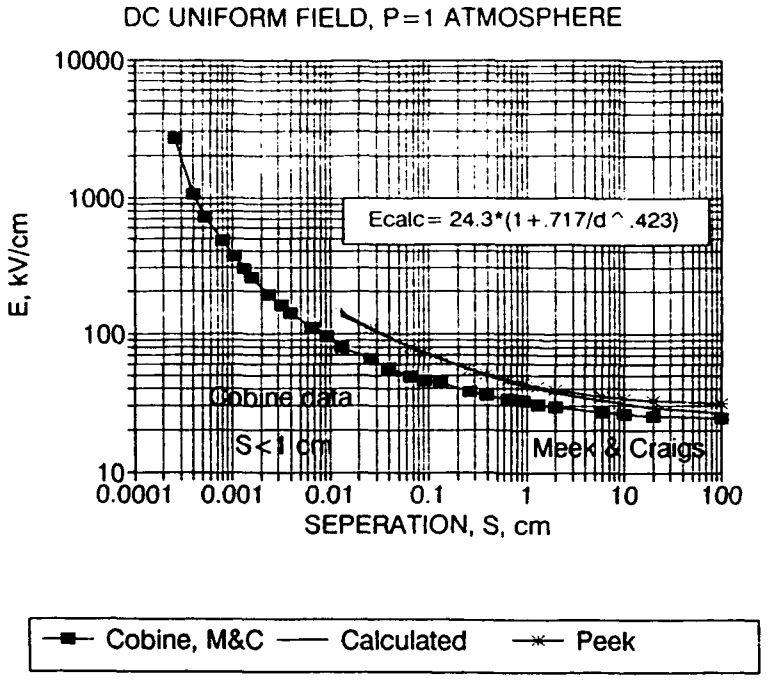

Figure 5-9. Breakdown gradient in air (DC uniform field, P = 1 atmosphere).

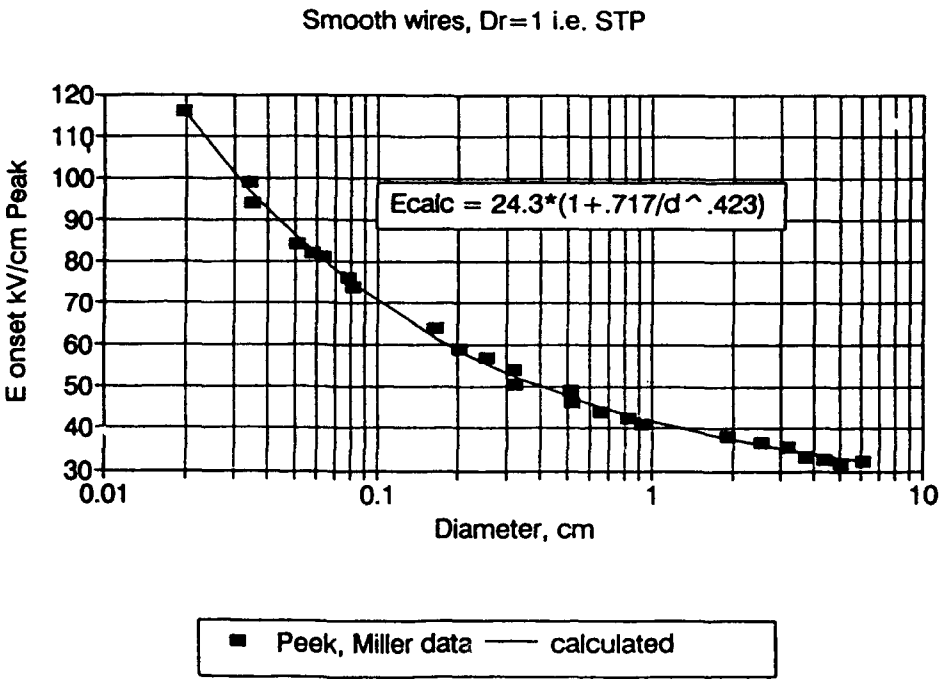

Figure 5-10. 60-Hz corona onset (smooth wires, Dr = 1, i.e, STP).

Onset gradients can now be calculated using the following formulas:

$$\text{Eonset} = 24.3 \times (1 + 0.717/(d \times Dr)^{\wedge} 0.423), \text{ kV/cm crest} \quad (5\text{-}6)$$

where Eonset is for smooth dry wires,
d is the wire diameter in cm, and
Dr is the relative air density

For stranded wires, a stranding factor K strand is required. Its value will depend on the number of strands in the cable and surface conditions. In general, the larger number of strands results in a factor nearer 1 as described previously. Of great importance are the surface conditions of the wire. Clean and smooth K strand values can be as high as 0.95 or more. Weathered cables may be as low as 0.8 or even less for wires with scratched surfaces. It should be mentioned that it is not clear at this point if a value of 24.3 or 24.4 should be used for the critical breakdown strength of air. Some of the data reported here are fitted best with 24.4 and some with 24.3.

Frequency effects are given by the provisional relation,

$$Kfreq = 1 - 0.015 \times F^{\wedge} 0.6 \times d^{\wedge} 0.3, \quad (5\text{-}7)$$

where F is in kHz and
d is the wire diameter in cm.

The correction factors for wet conditions appear to be different for vertical and horizontal configurations. Wet conditions have a smaller reduction for small vertical wires, while horizontal wires appear to have a greater reduction for all wire diameters. Preliminary equations that fit the 1989 measurements have the form

$$K \text{ wet } V = 1 - 0.5 \times d^{\wedge} 2/(0.5 + {}^{*} d^{\wedge} 2) \quad (5\text{-}8)$$

and

$$K \text{ wet } V = 1 - 0.12 \times d^{\wedge} 0.4 \quad (5\text{-}9)$$

Some of the data indicate that K wet for stranded horizontal wires should be

$$K \text{ wet str} = 1 - 0.18 \times d^{\wedge} 1.5 \quad (5\text{-}10)$$

When designing antennas, it is often useful to have an initial view of what voltages can be used for different wire diameters as a function of height. Figures 5-11 and 5-12 give onset values expected for a range of wire sizes heights of 3 to 300 meters above ground for dry and wet conditions.

In actual cases, the diameters used are often greater than shown in this figure. The 1989 data do not include data for large-diameter stranded cables. If possible, data on diameters of at least 2- to 3-cm stranded cables should be obtained. The voltages required will be quite large.

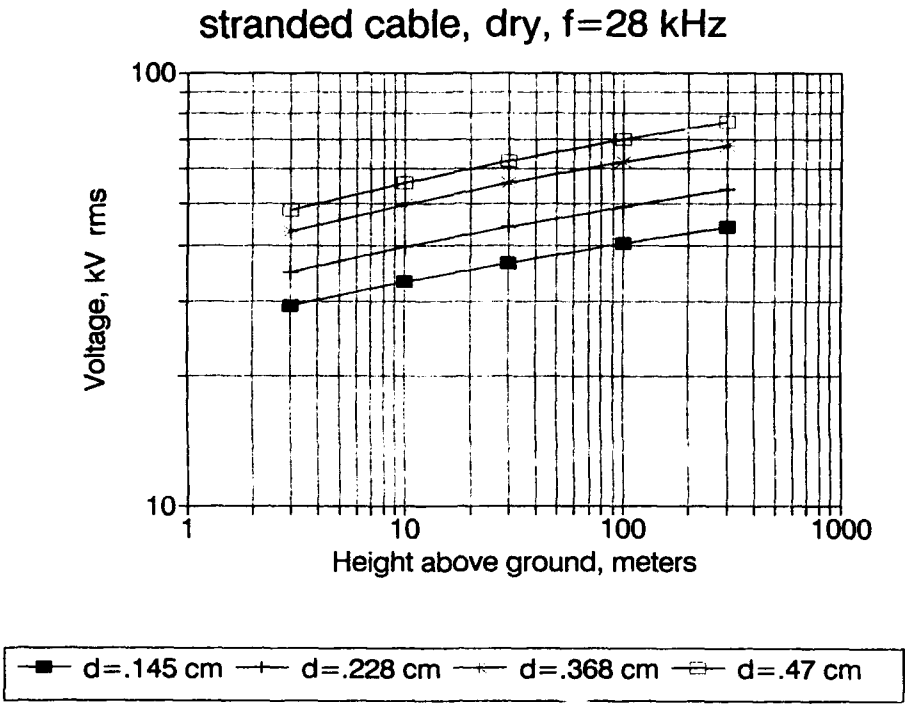

Figure 5-11. Corona onset voltages (stranded cable, dry, f = 28 kHz).

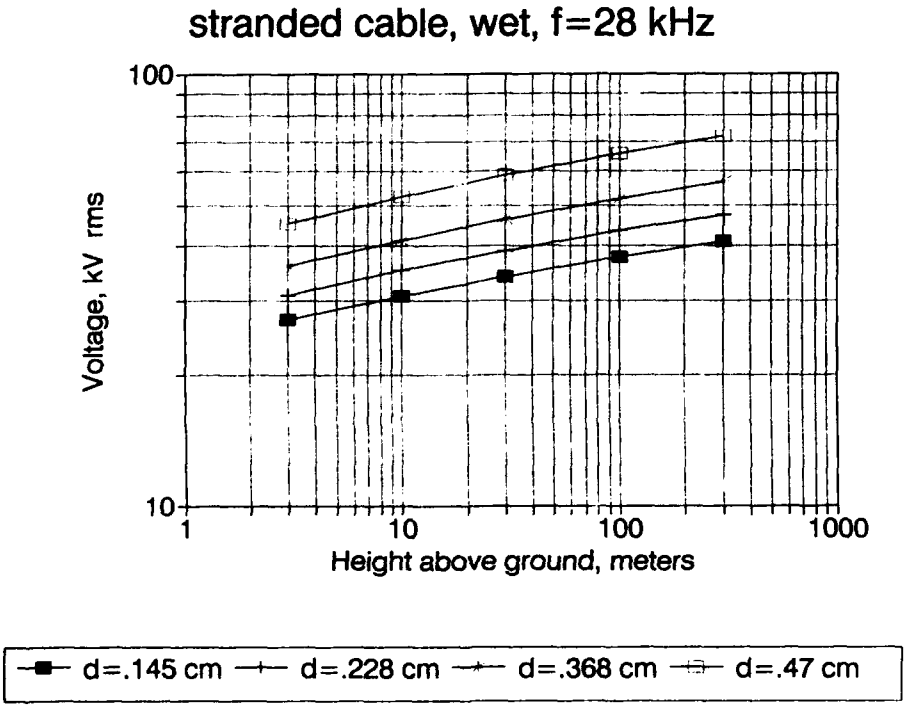

Figure 5-12. Corona onset voltages (stranded cable, wet, f = 28 kHz).

6.0 CORONA POWER VERSUS VOLTAGE

Corona power was measured during the 1989 tests using the circuit and equipment described in section 1. First, the circuit losses were measured so that they could be substracted from the total power measured. Figure 6-1 compares observed and calculated cell loss power. The test circuit power loss appears to vary as Ploss = K × V^(2.03). The value of K is dependent on frequency and the amount of helix and capacitance in place at the time. Nominal values for F = 29.5 kHz are K = 0.276, and for F = 57.4 kHz, K = 0.98. In the data sheet calculations, the exponent of 2.03 is always used, but the K value is sometimes changed slightly to fit the pre-corona values of K required since the circuit loss appeared to vary from one test to another even at the same frequency.

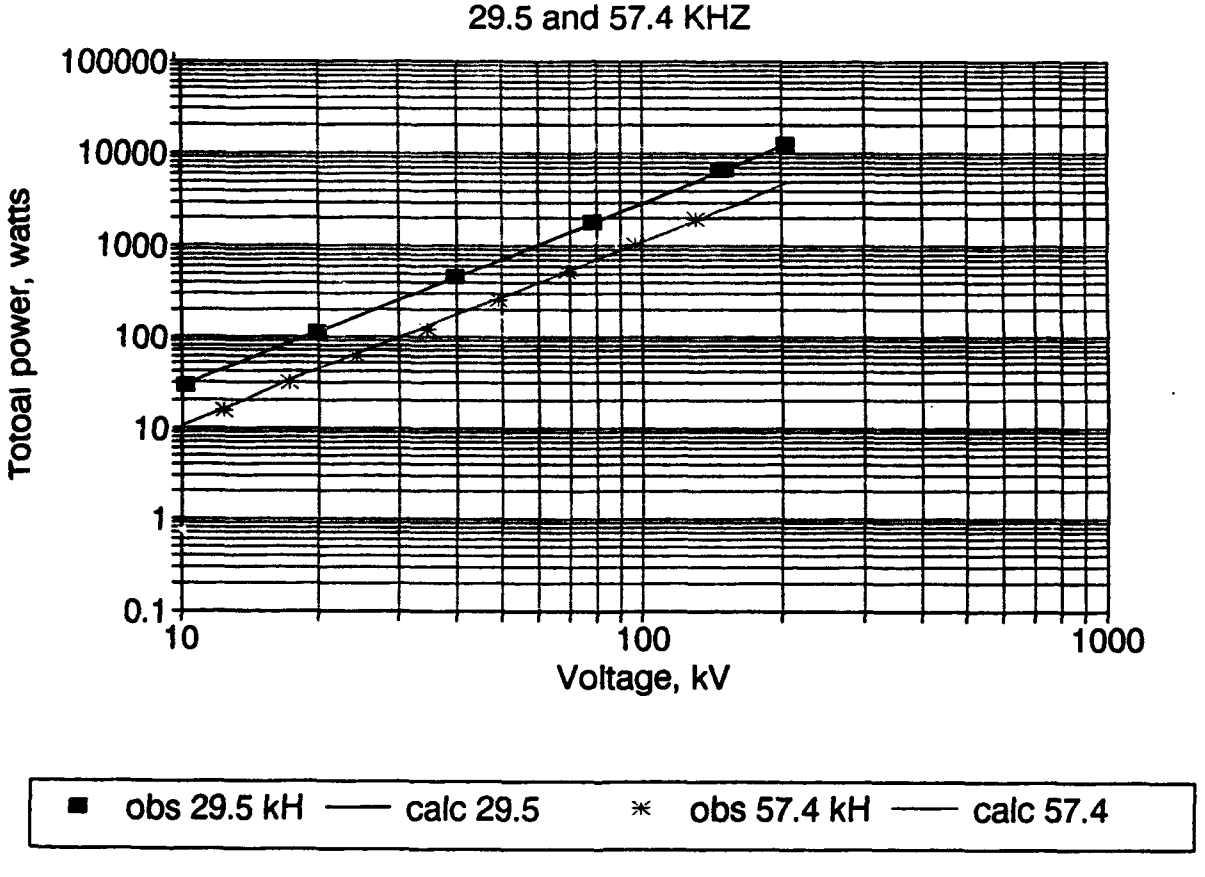

Figure 6-1. Vertical cell calibration (29.5 and 57.4 kHz).

Corona power calculations are based on a formulation originally done by Ryan and Henline (1924). Their equation is

$$P = 4 \times f \times C \times V \times (V - Vo) \qquad (6\text{-}1)$$

where P is power in watts,
f is frequency in Hz,
C is the cable capacitance in farads,
V is the crest voltage in volts, and
Vo is the corona onset crest voltage in volts.

If V is rms, the constant 4 becomes 8. This formula appears to fit the power observed at power frequencies rather well. The actual power will usually be less than the formula indicates since it is based on an idealized rectangular hysteresis loop. In fact, they show an alternate approximation assuming that the losses are in a resistive sheath around the conductor and that the current is equal to the voltage divided by the capacitive reactance. In this case, the power is

$$P = 2 \times \pi \times f \times C \times V \times (V - Vo) \qquad (6\text{-}2)$$

if Vs are rms values.

This means that the initial constant, which we will define as K1, is 6.28 instead of 8. It is important to note that at power frequencies the corona starts near the voltage maximum, although it does shift away from the maximum at higher over-voltages. At VLF on the other hand, Smith (1963), corona starts near current maximum, i.e., at voltage minimum. This means that if power is calculated as $P = V \times I \times \text{Cos}(a)$ that "a" will not be 0, and as a result, the power will be less than indicated in the above formula.

Figure 6-2 shows the observed and calculated corona power per meter length of a #8 smooth wire as a function of voltage. The observed power is divided by an effective length, and the calculated power uses a calculated capacitance per meter of length in an assumed long cylinder. The power in watts per meter is now

$$P/m = K1 \times f \times C \times V \times (V - Vo) \qquad (6\text{-}3)$$

The constant that appears to fit this data fairly well is K1 = 3.5. It should be observed that the data values increase faster initially than the calculated values. This may result from the effective length calculated being too small at the start.

Often it is desirable to obtain results in terms of the gradient at the wire surface since this makes results largely independent of the test cell configuration. To do this requires converting the voltages to gradients.

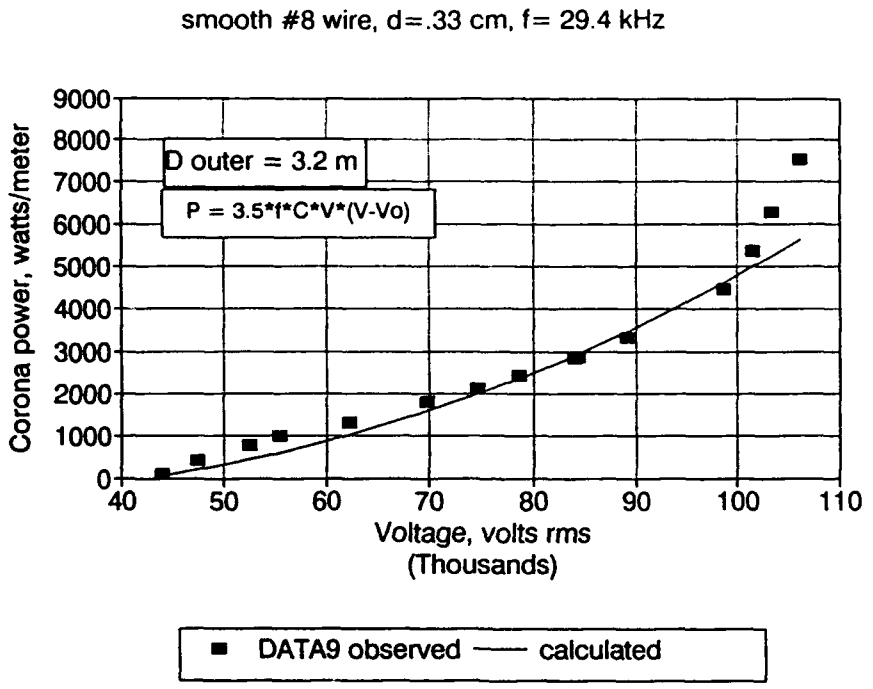

Figure 6-2. Corona power (vertical, dry, smooth #8 wire, d = 0.33 cm, f = 29.4 kHz).

The surface gradient is given as

$$G = 2 \times V/(d \times 1n(D/d)) \tag{6-4}$$

for a concentric cylinder of outer diameter D and a wire diameter d.

Solving for V yields

$$V = G \times (d \times 1n(D/d))/2 \tag{6-5}$$

The capacitance per meter for this case is

$$C = 56.63E - 12/1n(D/d) \text{ Farads/m} \tag{6-6}$$

The constant is $2 \times \pi \times Eo$, where Eo = 8.8543E - 12. Substituting the above values of V and C in the power equation results in

$$P/m = K1/4 \times 56.63E - 12 \times 1n(D/d) \times d\hat{}\ 2 \times f \times G \times (G - Go). \tag{6-7}$$

where f is in Hz, d in meters, and G in V/m.

If F is in kHz, d in cm, and G in kV/cm, the equation becomes

$$P/m = K1 \times 0.0139 \times 1n(D/d) \times d\hat{}\ 2 \times f \times G \times (G - Go). \tag{6-8}$$

For the case of a wire above a ground screen, the log term is $1n(4 \times h/d)$ where h is the height of the wire above ground, provided that $h >> d$.

Figure 6-3 shows the observed and calculated powers as a function of gradient for a #8 stranded wire in both vertical and horizontal test cells. It is instructive to note that the observed vertical cell values increase rapidly at about 80 kV/cm and are much greater than the calculated values. On the other hand, the horizontal values above 70 kV/cm show powers less than calculated. Up to about 60 kV/cm, the observed and calculated values are in close agreement. The K1 value that fits this stranded wire data is 2.6, which is less than the 3.5 that appears to fit the #8 smooth wire. Both of these tests are at 28 kHz.

It should be pointed out that reducing the results to gradient values assumes that these are the gradients that would occur without corona. In essence, this gives effective over voltages, i.e., above corona onset in a way that is essentially independent of the wire height.

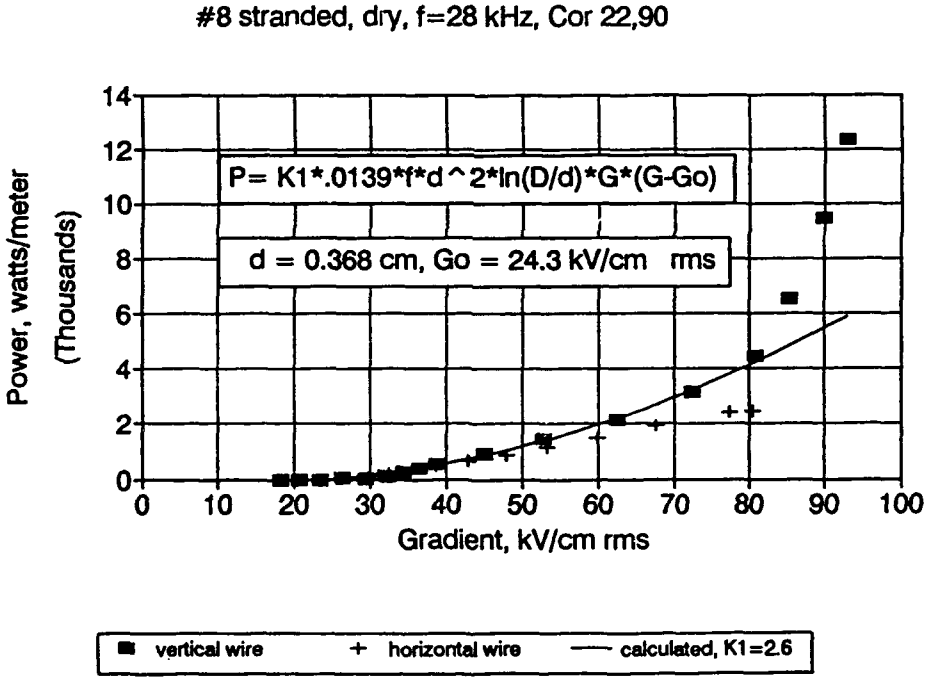

Figure 6-3. Corona power versus gradient (#8 stranded, dry, f = 28 kHz, Cor 22,90).

Figure 6-4 shows the observed corona power for #6 stranded wire (0.47-cm diameter) in the horizontal test cell. Three different frequencies are shown. The power for 27.8 kHz for some reason did not show as much increase from the 17.9-kHz values as expected. The 48.6-kHz values do on the other hand show about the amount of increase above the 27.8-kHz value expected. The K1 values of 2.6 and 2.4 for 27.8 and 48.6 kHz are in agreement with the previous values. The K1 = 3.8 required to fit

the 17.9 data seems high at first, and it is possible that the 17.9 observed values are higher than they should be. It is also possible that this is a real phenomenon in that the critical frequency for this size wire is near 20 kHz. In view of this, it is possible that the K1 to use below the critical frequency is greater than the K1 to be used above the critical frequency. This change would be in the right direction, since at power frequencies, K1 is greater, i.e., about 7 or 8.

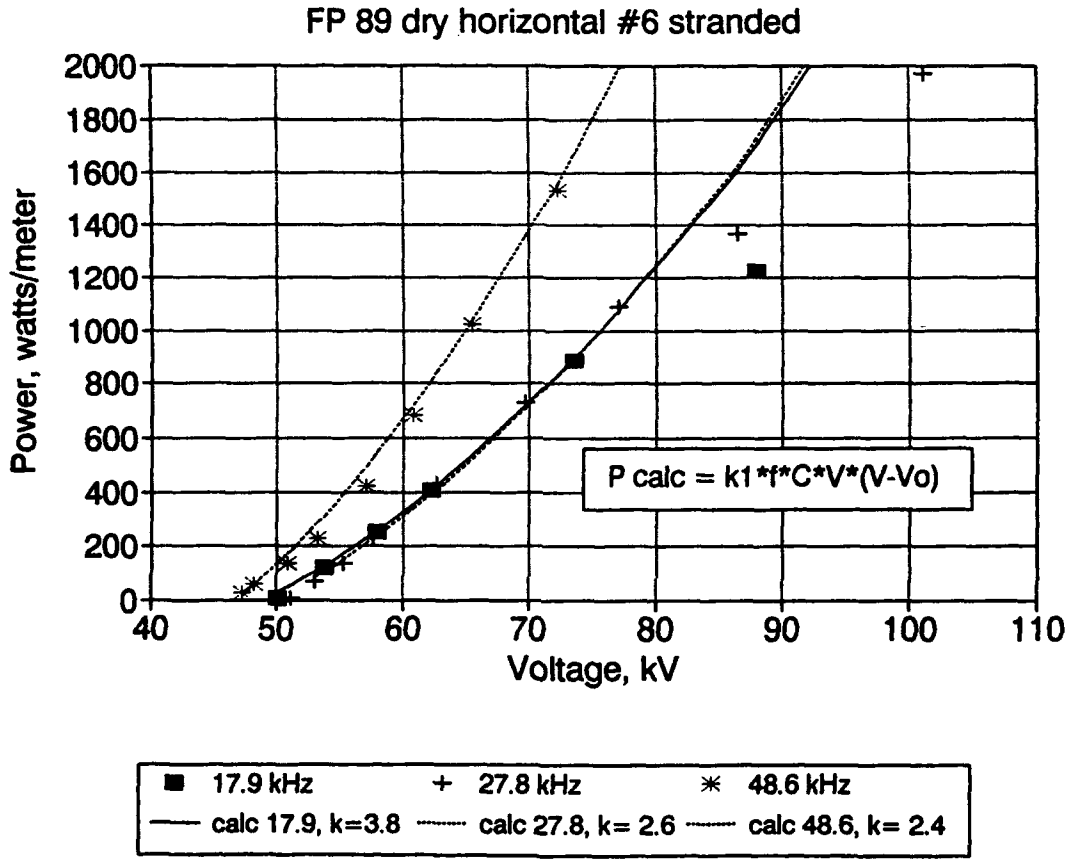

Figure 6-4. Corona power (dry, horizontal, #6 stranded).

Table 6-1 shows the way that the corona power is calculated for the case of #6 wire in the horizontal test cell. Table 6-2 shows observed and calculated values for three wire sizes, #18, #8, and #6, under wet horizontal conditions. Corona power versus gradient is shown in figure 6-5 for these three different stranded wires under horizontal wet conditions. The observed results appear to follow rather closely to the calculated values using K1s of 4.8, 4.3, and 4.8 as shown. These K1 values appear to be larger than those of the dry wires in the previous figures. Figure 6-6 shows the results of #8 wire in the horizontal cell with dry conditions at 17.9 and 27.8 kHz. As with the #6 wire, there does not appear to be much difference between the 17.9 and 27.8 power levels.

Table 6-1. Corona power per unit length calculations (#6, horizontal).

#6 Stranded, Horizontal, Dry, 17.9, 27.8, 45.0 kHz — Capacitance/Length 7.3E-12 Farads/m

d #6 = 0.47 cm — Height = 2.4 Meters — V onset = 48.95833

										*******	K1*E6	*******
							50	46.875	3800000	2546500	2400000	

		Measured				Measured			Calculated		
V Meas kV	Density V Cor kV	Corona Data 88 17.9 kHz	Power Data 87 27.8 kHz	Watts Data 86 48.6 kHz	Equiv Gradient kV/cm	Corona 17.9 kHz	Power 27.8 kHz	Per 48.6 kHz	Unit 17.9 kHz	Length 27.8 kHz	Watt/m 48.6 kHz
25.77	26.84115			0.00	14.99						
27.30	28.4375		0.00		15.88						
34.03	35.44271	0.00			19.79						
34.80	36.25		0.00		20.24						
36.80	38.33333			0.00	21.40						
38.00	39.58333	0.00			22.10						
39.10	40.72917		0.00		22.74						
40.98	42.68229			0.00	23.83						
43.30	45.10417	0.00			25.18						
43.95	45.78125		0.00		25.56						
44.28	46.11979				25.75						
45.40	47.29167			75.96	26.40			25.32			16.78
46.30	48.22917			171.17	26.93			57.06			55.61
48.13	50.13021	24.00			27.99	8.00			29.17		138.95
48.85	50.88542			407.75	28.41			135.92	48.69		173.76
49.05	51.09375		18.55		28.53		6.18		54.18		183.54
50.95	53.07292		199.75		29.63		66.58		108.43	84.28	280.08
51.15	53.28125			694.36	29.75			231.45	114.37	90.35	290.64
51.55	53.69792	361.00			29.98	120.33			126.37	102.62	311.96
53.03	55.23438		410.72		30.84		136.91		172.13	149.41	393.15

Table 6-1. Corona power per unit length calculations (cont).

#6 Stranded, Horizontal, Dry, 17.9, 27.8, 45.0 kHz — Capacitance/Length 7.3E-12 Farads/m

d #6 = 0.47 cm — Height = 2.4 Meters — V onset = 48.95833

										*******	K1*E6	*******
							50	46.875	3800000	2546500	2400000	

		Measured				Measured			Calculated		
V Meas kV	Density V Cor kV	Corona Data 88 17.9 kHz	Power Data 87 27.8 kHz	Watts Data 86 48.6 kHz	Equiv Gradient kV/cm	Corona 17.9 kHz	Power 27.8 kHz	Per 48.6 kHz	Unit 17.9 kHz	Length 27.8 kHz	Watt/m 48.6 kHz
54.78	57.05729			1268.18	31.85			422.73	229.46	208.46	494.68
55.35	57.65625		684.59		32.19		228.20		249.01	228.13	529.28
55.63	57.94271	764.00			32.35	254.67			258.49	237.84	546.04
58.40	60.83333			2046.41	33.96			682.14	358.58	340.58	723.01
59.73	62.21354	1230.00			34.73	410.00			409.48	392.68	812.53
60.18	62.68229		1304.68		35.00		434.89		427.15	410.82	843.67
62.88	65.49479			3066.07	36.57			1022.02	537.79	524.45	1038.37
66.95	69.73958		2186		38.94		728.90		719.63	711.42	1357.73
69.35	72.23958			4619.32	40.33			1536.60	835.10	830.26	1560.18
70.55	73.48958	2560.00			41.03	885.27			895.17	892.10	1665.39
73.98	77.05729		3278.15		43.02		1091.43		1709.14	1077.48	1980.32
82.93	86.38021		4752.35		48.23		1366.93		1605.09	1624.02	2905.62
84.45	87.96875	4333.02			49.11	1228.55			1074.00	1726.10	3078.04
97.08	101.1198		7472.37		56.45		1970.51		2619.06	2671.39	4670.51

Table 6-2. Corona power versus gradient (28 kHz, wet, horizontal).

	d, cm	G onset
#18	0.145	31 kV/cm
#8	0.368	23 kV/cm
#6	0.47	22 kV/cm

Freq = 28 kHz
K1 = 4.8, 4.3, 4.8

Gradient kV/cm	Obs #18 Watts/m	Obs #8 Watts/m	Obs #6 Watts/m	Calc #18 Watts/m	Calc #8 Watts/m	Calc #6 Watts/m
16.00						
18.00			0.00			
21.50		0.00				
21.73			0.00			
23.12		33.18			2.04	32.21
24.19			2.28		21.34	66.06
24.48		72.14			26.84	75.68
25.91		115.57			55.77	126.19
26.50			38.14		68.61	148.55
27.34		163.00			87.72	181.77
27.60			124.71		93.95	192.61
29.09		202.26			131.05	256.94
30.07			320.18		157.17	302.16
32.51	5.93			8.07	228.48	425.28
32.80		302.18		9.70	237.46	440.77
33.32			518.38	12.76	254.33	469.84
35.34	20.45			25.23	322.18	586.62
36.84			764.38	35.44	376.91	680.69
37.67		442.67		41.35	408.33	734.63
37.88	40.64			42.91	416.61	748.83
40.85	52.46			66.24	538.87	958.45
42.86		631.89		83.73	629.25	1113.18
43.40			1235.29	88.64	654.48	1156.34
44.95	116.59			103.23	729.12	1283.98
49.49		920.99		150.65	968.79	1693.30
49.89	179.55			155.24	991.81	1732.58
50.75			1837.17	165.04	1040.88	1816.28
55.91		1352.14		229.42	1360.38	2360.85
56.11	250.58			232.06	1373.38	2382.97
60.88			2687.08	299.53	1704.39	2946.43
62.28		1802.46		320.81	1808.20	3123.01
63.50				339.88	1901.03	3280.87
64.59	350.56			357.34	1985.84	3425.07
70.14		2311.62		452.05	2443.73	4203.19
74.03		2620.30				

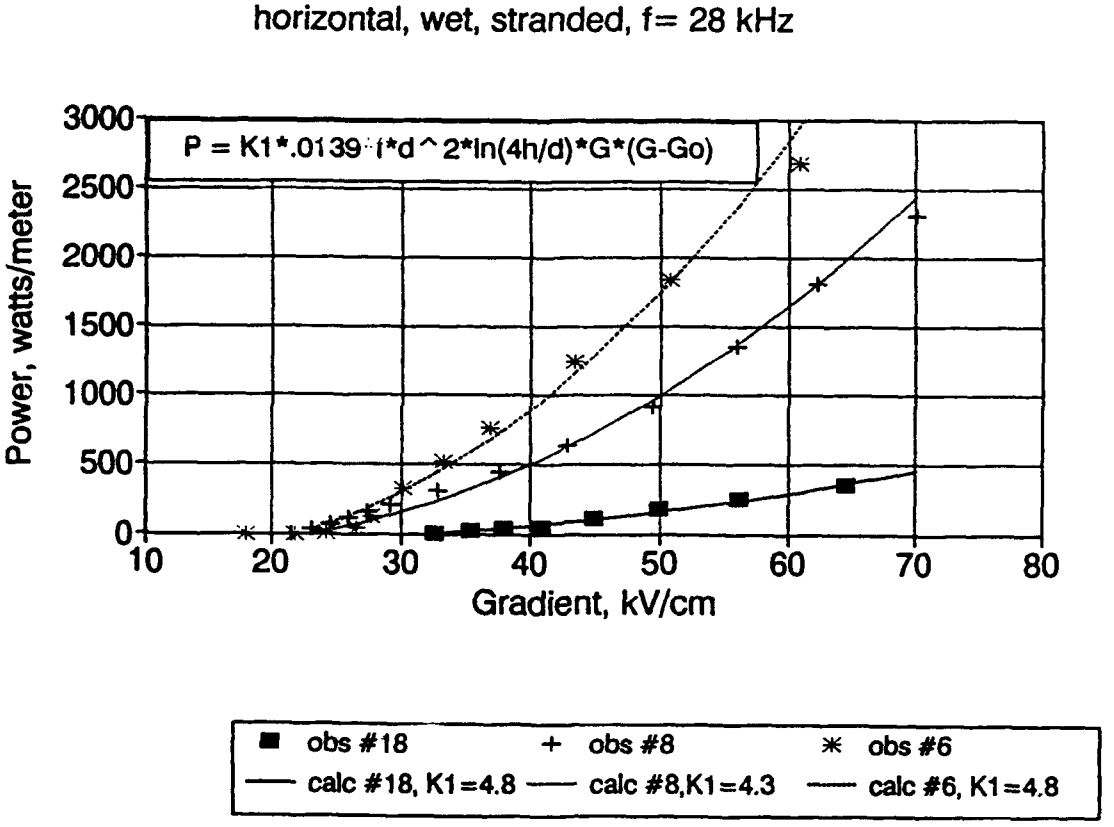

Figure 6-5. Corona power versus gradient (horizontal, wet, stranded f = 28 kHz).

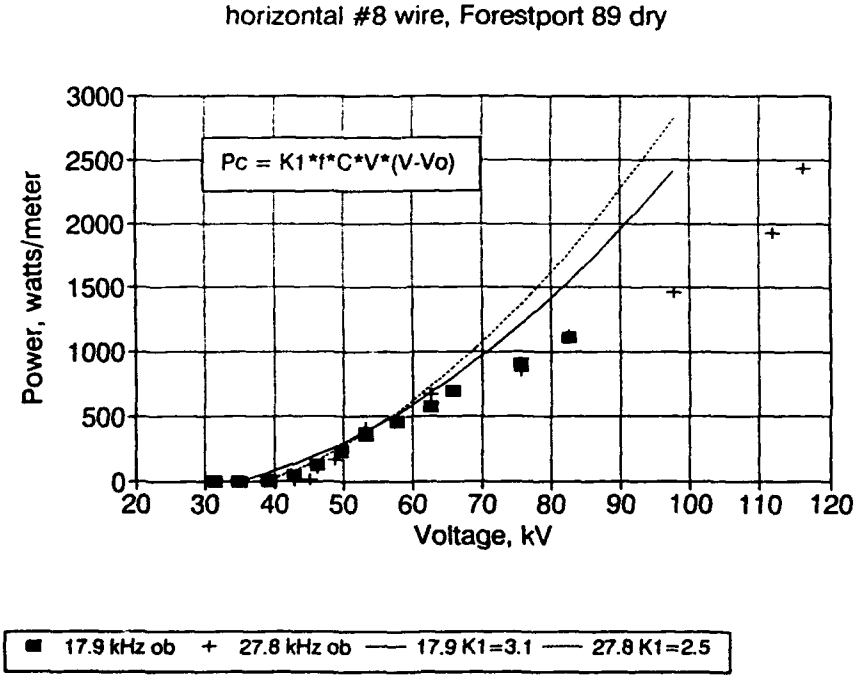

Figure 6-6. Corona power (horizontal, #8, dry).

The effects of rain or wet conditions on corona power are seen in figure 6-7 for a #8 stranded horizontal wire. It is apparent that the major change occurs by the wire going into corona at about 22 kV/cm when wet, instead of at about 26 kV/cm when dry. By the time the voltage is increased to 55 kV/cm, the powers are seen to be almost the same.

Based on the results observed this far, it is clear that VLF and LF corona power follow the general form given in the preceding formulas. It is not clear as yet how the scaling constant K1 varies with frequency, wire diameter, and wet or dry conditions. Tests over a larger range of frequency and with larger stranded conductors may be required to determine more exact values for K1. In fact, it is likely that it should be replaced with some function that is related to frequency, wire diameter, wet or dry, and the amount of over voltage.

It is likely that some discontinuity occurs in the corona power as frequency is changed through the critical value. Below critical, the wire is fairly well covered with a small sheath of plasma. Above critical, the flares extend our farther, but have relatively large spacing between flares. This may be the reason the value of K1 appears to change, i.e., decrease as frequency increases through this region. The results of figure 6-5 seem to show a larger value of around 4 for wet horizontal wires. On the other hand, the data in figure 6-7 seem to fit a much smaller value of around 2. A closer look at the initial dry onset shows a more rapid increase in corona power with increasing voltage for the dry case. This could mean that the initial value of K1 would be around 4 where the initial glow is increasing in diameter. Beyond this region, there may be a transition to small flares with a corresponding loss of glow discharge in the region between flares.

One definite conclusion that can be drawn from these studies is that large amounts of power are consumed in VLF and LF corona if the gradients are much above the inception point. For example, at 28 kHz and #8 wire, if the inception gradient is exceeded by 20 percent the power reaches 300 to 400 watts per meter of wire in corona. From this, it is clear that corona should be avoided at VLF and LF where antennas use large lengths of cable.

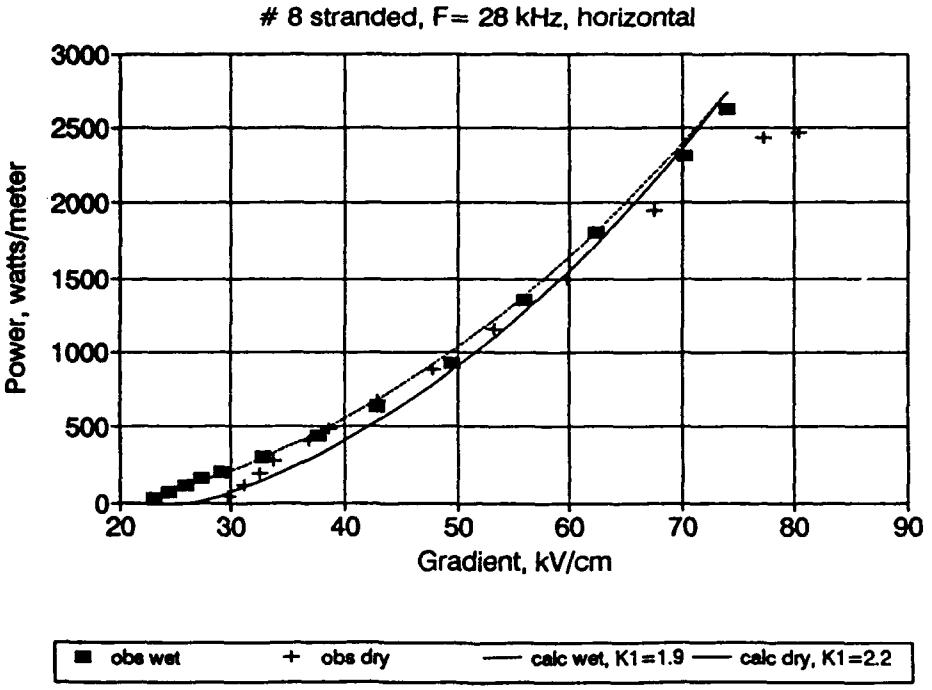

Figure 6-7. Corona power (horizontal, #8, wet and dry, f = 28 kHz).

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To determine corona power for given sets of typical conditions, tests were performed at the Forestport, NY, high-voltage test facility during 1985 to determine onset conditions, and in 1989 to measure corona power at VLF and LF. A discussion of the results of these tests is presented in this report.

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