Mechanical & Electrical Properties

of

Large Bundled Conductors

by

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July 15, 1995

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INTRODUCTION:

The standard for bundle conductor spacing in the United States has been eighteen inches. This spacing has been applied to thousands of miles of bundled lines including twin, triple and quad bundles. This study was conducted to determine the various important numerical parameters of bundle conductors over a range of larger bundle sizes. Calculations of both electrical and mechanical parameters are presented. Conclusions favor the use of larger bundle diameters either as first design or as retrofit of spacer/dampers.

ANALYSIS:

There are three bundle configurations studied, twin, triple, and quad. Each of the configurations represent actual transmission lines that are in service today.
A summary of the initial parameters for the three cases is seen in Table 1. All of the cases employ a flat horizontal three-phase construction.

The study is broken down by mechanical and electrical parameters. For the identified parameters the sub-conductor spacing is 18, 20, 22, and 24 inches. As an illustration of the effect of smaller subconductor spacing several cases are considered with spacing from 12 to 18 inches.

Mechanical Parameters

The mechanical parameters of interest are (1) sensitivity to sub-conductor oscillation, (2) sensitivity to galloping, (3) sensitivity to bundle upset. These parameters are, in turn, dependent upon (i) spacing/diameter ratio, (ii) moment of inertia of the bundle, (iii) bundle torsional stiffness.

All of the above parameters were calculated in the three cases studies. The three references listed in the bibliography provide source information.

TWIN BUNDLES:

The calculated parameters for the twin bundle configuration are listed in the accompanying table. The S/D ratio, which is important for sub-conductor oscillation, varies from 10 to 13. The high values are recommended for the prevention of sub-conductor oscillation, [1]. The moment if inertia and the moment of inertia ratio(= ra2) are important for the prevention of galloping of the bundle. The higher the value of ra2, the higher the value of galloping wind speed, [2]. Notice that increasing the spacing from 18 to 24 inches (33% increase) has the effect of increasing ra2 by 89 percent.

The bundle stiffness increases from 110 to 165 lb-ft per radian. This is an increase of 50 percent for an increase of 33% in the bundle spacing. The ratio seen in the table is the ratio of subconductor stiffness to tension stiffness of the bundle. The total stiffness is comprised of those two parts. The large diameter conductor in this case contributes more than 55% of the tension stiffness when the spacing is 18 inches. This contribution is only 31% when the spacing is 24 inches. As the stiffness increases with bundle size, so also does the overturning angle of the bundle. It increases from 168 degrees to 215 degrees, and requires more unbalanced torque to overturn the bundle. The calculation of bundle stiffness is at the center of two neighboring subspans of length equal to 200 ft., while the calculation of overturning angle is at the center of the whole span equal to 1200 ft., [3].

TRIPLE BUNDLES:

The case study for triple bundles is based on the same span length, and the same sub-span length, and the other parameters listed in Table 1. The results are seen in the accompanying table. The S/D ratio varies from 13 to 17, while the moment of inertia ratio varies from 147 to 261. Both effects are beneficial for controlling sub-span oscillation and full-span galloping, as already noted.

The increased stiffness and the increased overturning angle are both beneficial for bundle stability. Notice that the ratio of subconductor stiffness to tension stiffness is at a lower level compared to the twin conductor. This is mainly due to the smaller diameter of the subconductor in the triple bundle. It is clear that increasing the size of the triple bundle is beneficial.

QUAD BUNDLES:

The case study for quad bundles is based on the same span length, and the same sub-span length, and the other parameters listed in Table 1. The results are seen in the accompanying table. The S/D ratio varies from 13 to 17, while the moment of inertia ratio varies from 238 to 424. The stiffness increases from 113 lb-ft./rad to 177 lb-ft./rad. The overturning angle increases from 200 degrees to 231 degrees. All of these effects are in the direction of improving the quad bundle stability. The static stability is improved by increased bundle torsional stiffness, while the dynamic stability is improved by increased S/D ratio and increased moment of inertia ratio.

As another example of these effects, three additional case studies were carried out and are reported in Table 4. Only the quad bundle was considered. It is clearly seen from the calculated results that all properties of the bundle that were improved by increased spacing are worsened by decreased spacing. One could expect more trouble from subconductor oscillation, more frequent occurances of galloping, and more bundle upset problems when the spacing between subconductors is diminished.

Finally, an analysis was performed to relate the increase of galloping wind speed to the increase of bundle moment of inertia. The results are seen in

Figure (1). The galloping wind speed at which galloping starts to occur is plotted as a dimensionless parameter vs. the dimensionless moment of inertia parameter, ra2. These are defined as follows:

Uo = minimum wind speed for gallop / frequency x diameter ....(1)

ra2 = bundle weight moment of inertia / bundle weight x diameter ^{2}......(2)

The diameter is the subconductor diameter and the frequency is the gallop frequency expressed as radians per second.

Applications of Fig. (1) to the three cases studied show that the minimum wind speed for gallop would increase by 59% for the twin, by 39% for the triple, and by 38% for the quad, if the bundle spacing is increased from 18 inches to 24 inches.

CONCLUSIONS:

Mechanical properties of bundles are improved if the spacing of the subconductors is increased. The more the spacing increases, the more the properties improve. These properties all relate to either static or dynamic stability of the bundle.

[1] EPRI, Transmission Line Reference Book, Wind-Induced Conductor Motion, EPRI Project No. 792, 1980, p.215.

[2] Richardson, A.S., Designing Quad Bundles Against Galloping, University of Liege, Belgium, AIM Study Day on Galloping, 10 March, 1989.

[3] O. Nigol, et al, Torsional Stability of Bundle Conductors, IEEE paper no. F 77 224-9, IEEE/PES Winter Meeting, New York, NY, January, 30, 1977.

Table 1. Parameters for electrical & mechanical study of bundle spacing

item	TWIN	TRIPLE	QUAD
Reference design:	PPL	FPL	AEP
Voltage:	500 kV	500 kV	765 kV
Conductor:	ACAR 1.82in. Dia.	AAAC 1.382in. Dia.	ACSR 1.386in. Dia.
Tension:	12,600Lb.	8360Lb.	7,240Lb.
Right of way width:	200 ft.	200 ft.	200 ft.
Ground clearance (120deg)	34 ft.	35 ft.	45 ft.
Phase spacing:	34.5 ft.	34.5 ft.	45.7 ft.
Bundle configuration:	Hor. TWIN	Inv. Delta	Sqr. QUAD

Table 2. Effect of Spacing on Twin Bundle Mechanical Properties

SPACING (inches)	S/D Ratio	Inertia (Lb-in2)	Ratio*	Stiffness (Lb-ft/Rad)	Ratio*	Twist Angle (Degrees)
18	10	384	49	110	0.559	168
20	11	474	60	127	0.453	189
22	12	574	73	145	0.375	204
24	13	683	87	165	0.315	215

* Inertia ratio is referred to weight per ft. x diameter squared.
* Stiffness ratio is subconductor stiffness / tension stiffness.

Table 3. Effect of Spacing on Triple Bundle Mechanical Properties

SPACING (inches)	S/D Ratio	Inertia (Lb-in2)	Ratio*	Stiffness (Lb-ft/Rad)	Ratio*	Twist Angle (Degrees)
18	13	377	147	94	0.342	210
20	14	465	181	111	0.277	222
22	16	563	219	128	0.229	230
24	17	670	261	148	0.192	237

* Inertia ratio is referred to weight per ft. x diameter squared.
* Stiffness ratio is subconductor stiffness / tension stiffness.

Table 4. Effect of Spacing on QUAD Bundle Mechanical Properties

SPACING (inches)	S/D Ratio	Inertia (Lb-in2)	Ratio*	Stiffness (Lb-ft/Rad)	Ratio*	Twist Angle (Degrees)
18	13	697	238	114	0.396	200
20	14	861	294	133	0.321	214
22	16	1042	356	154	0.265	224
24	17	1240	424	177	0.223	231

* Inertia ratio is referred to weight per ft.. x diameter squared.
* Stiffness ratio is subconductor stiffness / tension stiffness.

Table 4a Effect of Small Spacing on QUAD Bundle Mechanical Properties

SPACING (inches)	S/D Ratio	Inertia (Lb-in2)	Ratio*	Stiffness (Lb-ft/Rad)	Ratio*	Twist Angle (Degrees)
12	9	310	106	68	0.892	82
14	10	422	144	82	0.655	147
16	12	551	188	97	0.501	180

* Inertia ratio is referred to weight per ft. x diameter squared.
* Stiffness ratio is subconductor stiffness / tension stiffness.

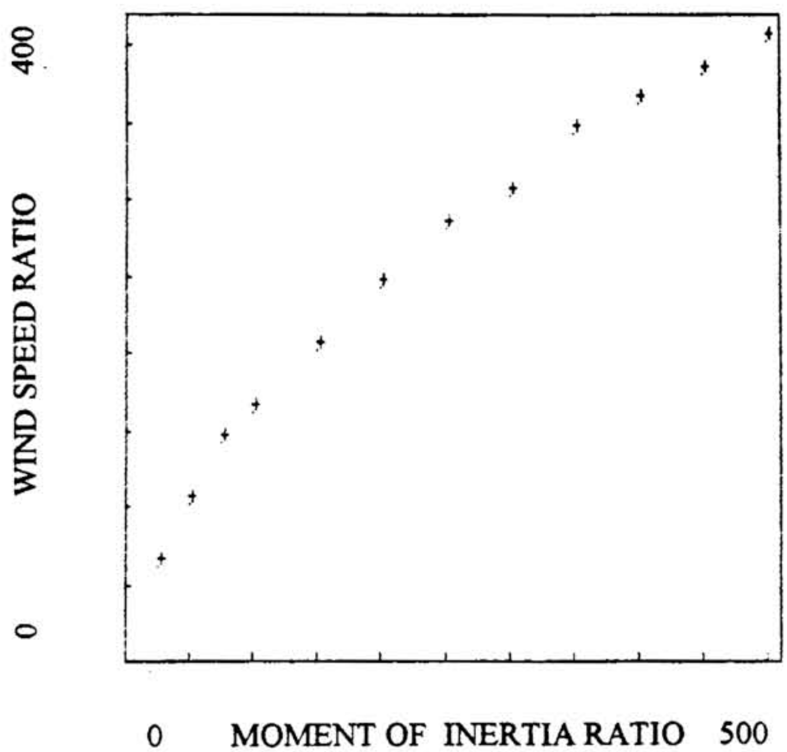

FIG. (1) Lowest wind speed for galloping
vs.
Bundle moment of inertia ratio.

Electrical Properties

Electrical properties of the enlarged bundle diameter are seen in Table 5. The properties considered are: (i) foul weather audible noise, (ii) foul weather radio noise, (iii) heavy rain corona loss, and (iv) reactance. The primary concern is how these properties vary as the diameter (spacing) is increased from 18 inches to larger spacing.

TWIN BUNDLE:

The table lists the numerical values of the above properties for subconductor spacing of 18in., 22in., and 24in. The audible noise increases from 49.9dB to 50.3dB, an increase of less than one percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. The profile of audible noise may be seen in Fig. (2). The cited increase of audible noise would be obtained by a person standing at the edge of the right-of-way who would take about one step toward the center of the line.

The radio noise increases from 56.5dB to 56.9dB, an increase of less than one percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. The profile of radio noise may be seen in Fig. (3). The cited increase in radio noise would be obtained by a person standing on the edge of the right-of-way who would take less than one step toward the center of the line.

The corona loss increases from 143 Watts/mile to 152 Watts/mile, an increase of six percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. For a one thousand mile line the **increase** of corona loss is nine kilowatts. At a cost of five cents per kilowatt-hour the value of the **increase** of lost energy is forty-five cents per hour for a one thousand mile line, and this occurs **only** during episodes of heavy rain rate equal to one inch per hour over the entire line. The probability of this occurance is very low.

The reactance **decreases** from 0.605 to 0.587, a decrease of three percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. This trend has different benefits for new lines being designed from old lines already in service whose worn-out spacers are being considered for replacement. For new lines being designed the benefits could be realized from reduced costs for compensation capacitors. For old lines considered for spacer replacement the accompanying Table 6 will help to explain.

Spacer forces were calculated for an assumed 25,000 ampere fault current. The forces applied to the spacer **decrease** by twelve percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. Clearly, this benefit results in less wear and tear on the spacer itself over the life of the spacer.

TRIPLE BUNDLE:

The table lists the numerical values of the above properties for subconductor spacing of 18in., 22in., and 24in. The audible noise increases from 42.9dB to 43.8dB, an increase of less than one percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. The profile of audible noise may be seen in Fig. (4). The cited increase of audible noise would be obtained by a person standing at the edge of the right-of-way who would take about one step toward the center of the line.

The radio noise increases from 51.1dB to 51.9dB, an increase of less than one percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. The profile of radio noise may be seen in Fig. (5). The cited increase in radio noise would be obtained by a person standing on the edge of the right-of-way who would take less than one step toward the center of the line.

The corona loss increases from 76 Watts/mile to 85 Watts/mile, an increase of 12 percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. For a one thousand mile line the **increase** of corona loss is nine kilowatts. At a cost of five cents per kilowatt-hour the value of the **increase** of lost energy is forty-five cents per hour for a one thousand mile line, and this occurs **only** during episodes of heavy rain rate equal to one inch per hour over the entire line. The probability of this occurance is very low.

The reactance **decreases** from 0.550 to 0.521 a decrease of five percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. This trend has different benefits for new lines being designed from old lines already in service whose worn-out spacers are being considered for replacement. For new lines being designed the benefits could be realized from reduced costs for compensation capacitors. For old lines considered for spacer replacement the accompanying Table 6 will help to explain.

Spacer forces were calculated for an assumed 25,000 ampere fault current. The forces applied to the spacer **decrease** by eleven percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. Clearly, this benefit results in less wear and tear on the spacer itself over the life of the spacer.

QUAD BUNDLE:

The table lists the numerical values of the above properties for subconductor spacing of 18in., 22in., and 24in. The audible noise increases from 55.2dB to 56.2dB, an increase of less than one percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. The profile of audible noise may be seen in Fig. (6). The cited increase of audible noise would be obtained by a person standing at the edge of the right-of-way who would take about one step toward the center of the line.

The radio noise increases from 63.8dB to 64.7dB, an increase of less than one percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. The profile of radio noise may be seen in Fig. (7). The cited increase in radio noise would be obtained by a person standing on the edge of the right-of-way who would take less than one step toward the center of the line.

The corona loss increases from 364 Watts/mile to 411 Watts/mile, an increase of 13 percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. For a one thousand mile line the **increase** of corona loss is 47 kilowatts. At a cost of five cents per kilowatt-hour the value of the **increase** of lost energy is $2.35 per hour for a one thousand mile line, and this occurs **only** during episodes of heavy rain rate equal to one inch per hour over the entire line. The probability of this occurance is very low.

The reactance **decreases** from 0.538 to 0.511, a decrease of five percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. This trend has different benefits for new lines being designed from old lines already in service whose worn-out spacers are being considered for replacement. For new lines being designed the benefits could be realized from reduced costs for compensation capacitors. For old lines considered for spacer replacement the accompanying Table 6 will help to explain.

Spacer forces were calculated for an assumed 25,000 ampere fault current. The forces applied to the spacer **decrease** by twelve percent corresponding to an increase in spacing equal to 33 percent from 18 inches to 24 inches. Clearly, this benefit results in less wear and tear on the spacer itself over the life of the spacer.

In line with the mechanical properties study, it is appropriate to consider the effect of **reducing** subconductor spacing in the quad bundle. Here, in Fig. (8) the spacer forces are plotted as a function of spacing distance from 10 to 26 inches. The forces **decrease** as spacing distance **increases** from 18 inches. In the event that spacing distance is decreased to 14 inches, the spacer force increases to 185 pounds from 165 pounds. At a spacing of 12 inches the force rises rapidly to more than 200 pounds. This is a counter-benefit and results in **more** wear and tear on the spacer.

CONCLUSIONS:

Larger bundled conductor spacing will increase foul weather audible noise and foul weather radio noise by less than one percent. It will increase foul weather corona loss by nine kilowatts on 1,000 miles of either twin or triple bundled 500 kV, and by 47 kilowatts on 1,000 miles of a quad bundled 765 kV line. The foul weather conditions are based on edge of right-of-way for audible and radio noise, and on a heavy rain rate of one inch per hour for corona loss. In all cases, increasing the subconductor spacing **reduces** the inductive reactance and reduces the spacer forces due to a fault current.

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ACKNOWLEDGEMENT:

The calculation of electrical properties was performed by Mr. Jim Stewart of Power Technologies, Inc., Schenectady, NY.

TABLE 5. ELECTRICAL PROPERTIES AS FUNCTION OF BUNDLE SPACING

Edge of right of way values for foul weather audible and radio noise.
Corona loss total for all 3 phases at heavy rain rate of 1 inch/hour.
Positive sequence inductive reactance.

500 kV Twin Bundle

Bundle Spacing Inches	Foul Weather Audible Noise dB(A)	Foul Weather Radio Noise dB Above 1 uV/m	3-Phase Corona Loss Watts/mile	Reactance Ohms/mile
18 Inches	49.9	56.5	143	0.605
22 Inches	50.2	56.7	148	0.593
24 Inches	50.3	56.9	152	0.587

500 kV Triple Bundle

Bundle Spacing Inches	Foul Weather Audible Noise dB(A)	Foul Weather Radio Noise dB Above 1 uV/m	3-Phase Corona Loss Watts/mile	Reactance Ohms/mile
18 Inches	42.9	51.1	76	0.550
22 Inches	43.4	51.6	82	0.528
24 Inches	43.8	51.9	85	0.521

765 kV Quad Bundle

Bundle Spacing Inches	Foul Weather Audible Noise dB(A)	Foul Weather Radio Noise dB Above 1 uV/m	3-Phase Corona Loss Watts/mile	Reactance Ohms/mile
18 Inches	55.2	63.8	364	0.538
22 Inches	55.9	64.4	393	0.519
24 Inches	56.2	64.7	411	0.511

The PTI and BPA programs give the same trend for audible and radio noise as a function of bundle spacing within 0.2 dB from 18 to 24 inches. Such small differences are beyond the ability to measure. When complete calculations are used, the electric field at the subconductor surface increases slightly with increase in bundle spacing over the range investigated.

TABLE 6. SPACER FORCES AS FUNCTION OF BUNDLE SPACING

Approximate Maximum Bundle Spacer Forces, assuming:

25,000 amperes fault current at source
Fault 10 miles from the source

500 kV Twin Bundle

Bundle Spacing Inches	Subconductor Current RMS Amperes	Force Pounds	Ratio of Force to 18 Inch Spacing
18	8201	484	1.0
22	8258	444	0.917
24	8286	428	0.884

500 kV Triple Bundle

Bundle Spacing Inches	Subconductor Current RMS Amperes	Force Pounds	Ratio of Force to 18 Inch Spacing
18	5644	230	1.0
22	5717	213	0.926
24	5741	206	0.896

765 kV Quad Bundle

Bundle Spacing Inches	Subconductor Current RMS Amperes	Force Pounds	Ratio of Force to 18 Inch Spacing
18	4790	165	1.0
22	4830	152	0.921
24	4847	146	0.885

Wider bundle spacing reduces the reactance and increases the fault current. Magnetic force is inversely proportional to bundle spacing, so increasing the bundle spacing decreases the force for the same current. Larger numbers of subconductors divides up the fault current among more subconductors and gives less current per subconductor. These calculations are too approximate to use for spacer design, but do give the relative effect of changes in bundle spacing.

FIG. 2

500 KV TWIN BUNDLE
L50 FOUL WEATHER AUDIBLE NOISE

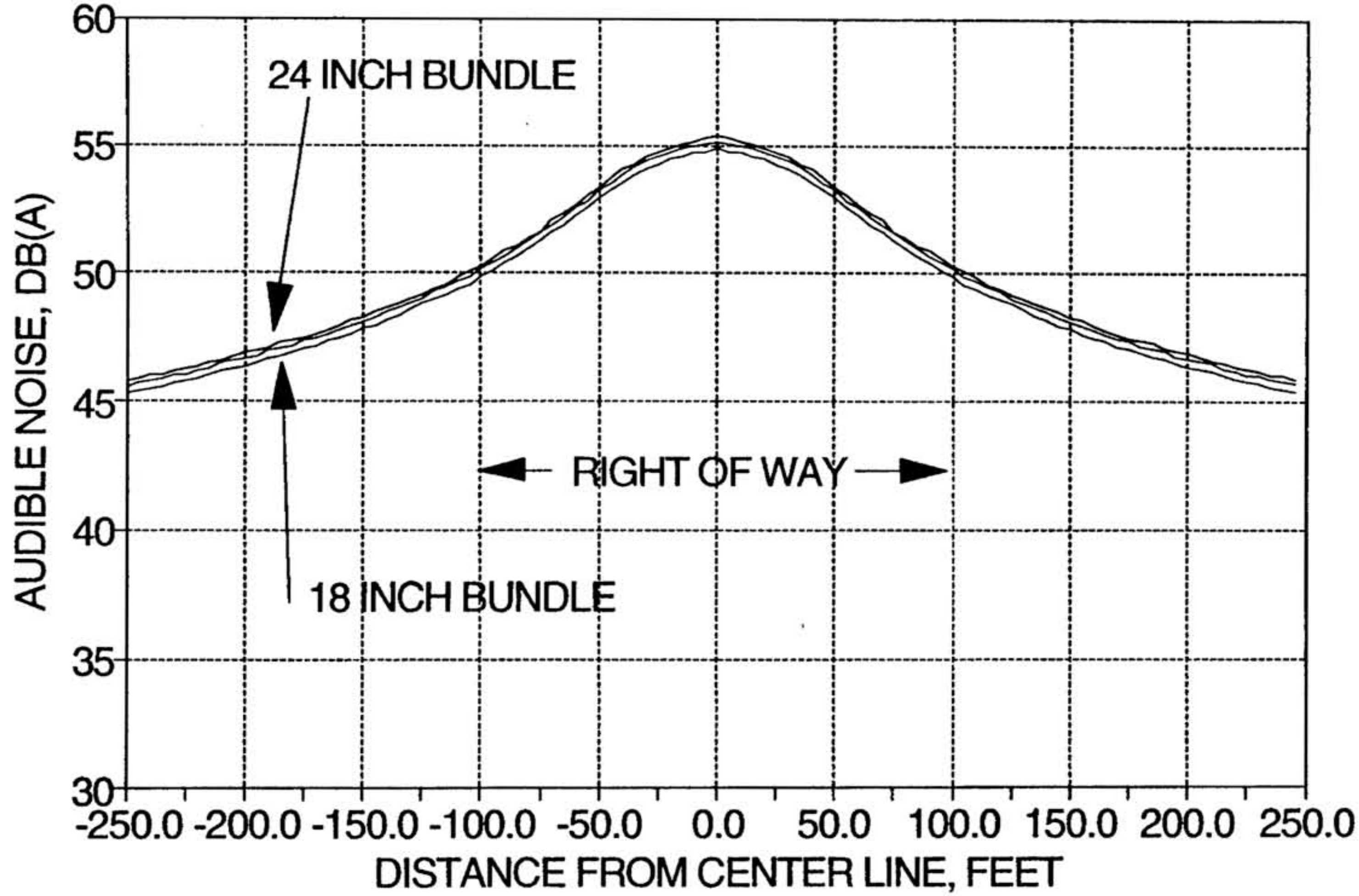


FIG. 3

500 KV TWIN BUNDLE
FOUL WEATHER RADIO NOISE

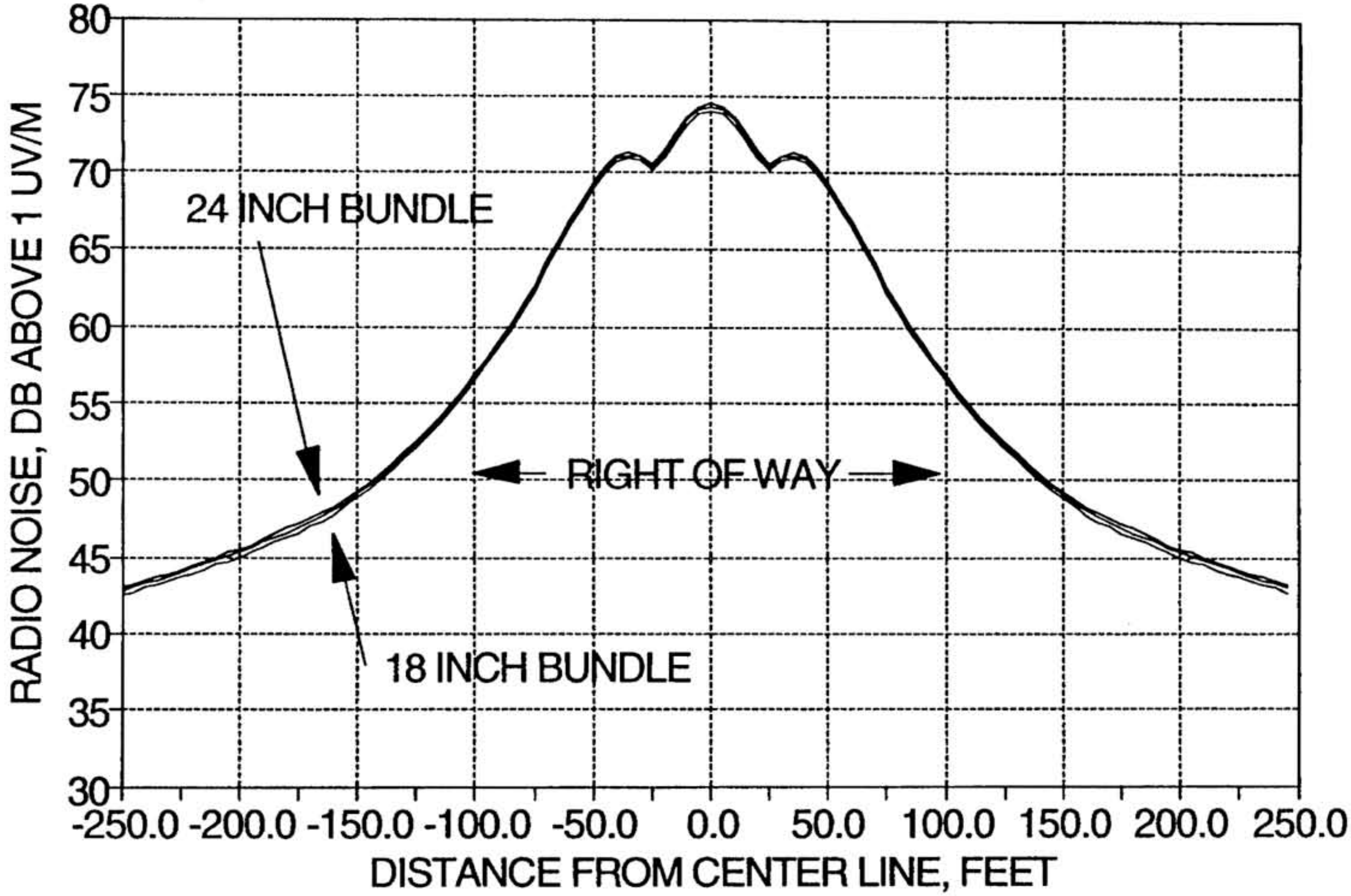


FIG. 4

500 KV TRIPLE BUNDLE
L50 FOUL WEATHER AUDIBLE NOISE

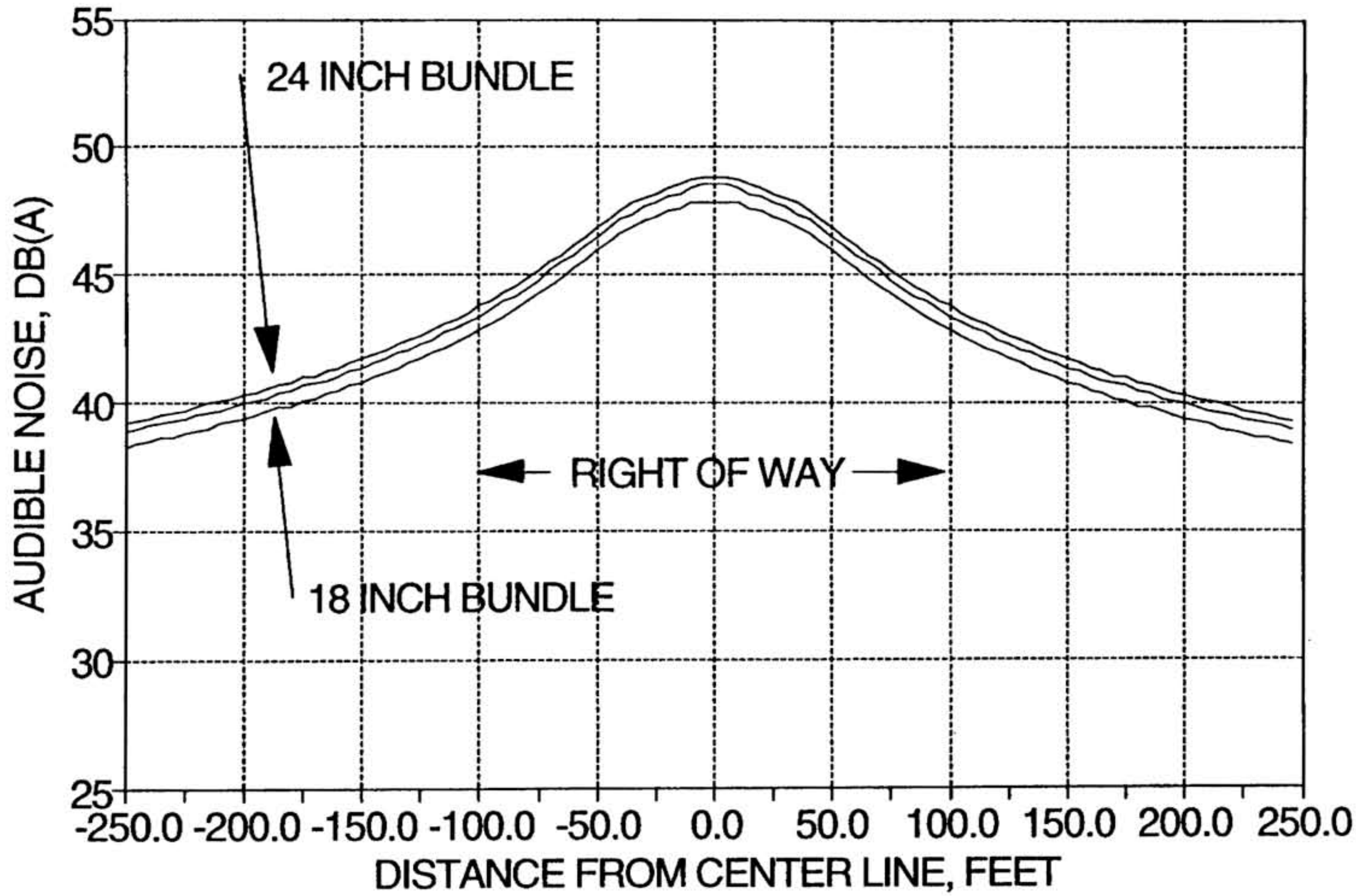


FIG. 5.

500 KV TRIPLE BUNDLE
FOUL WEATHER RADIO NOISE

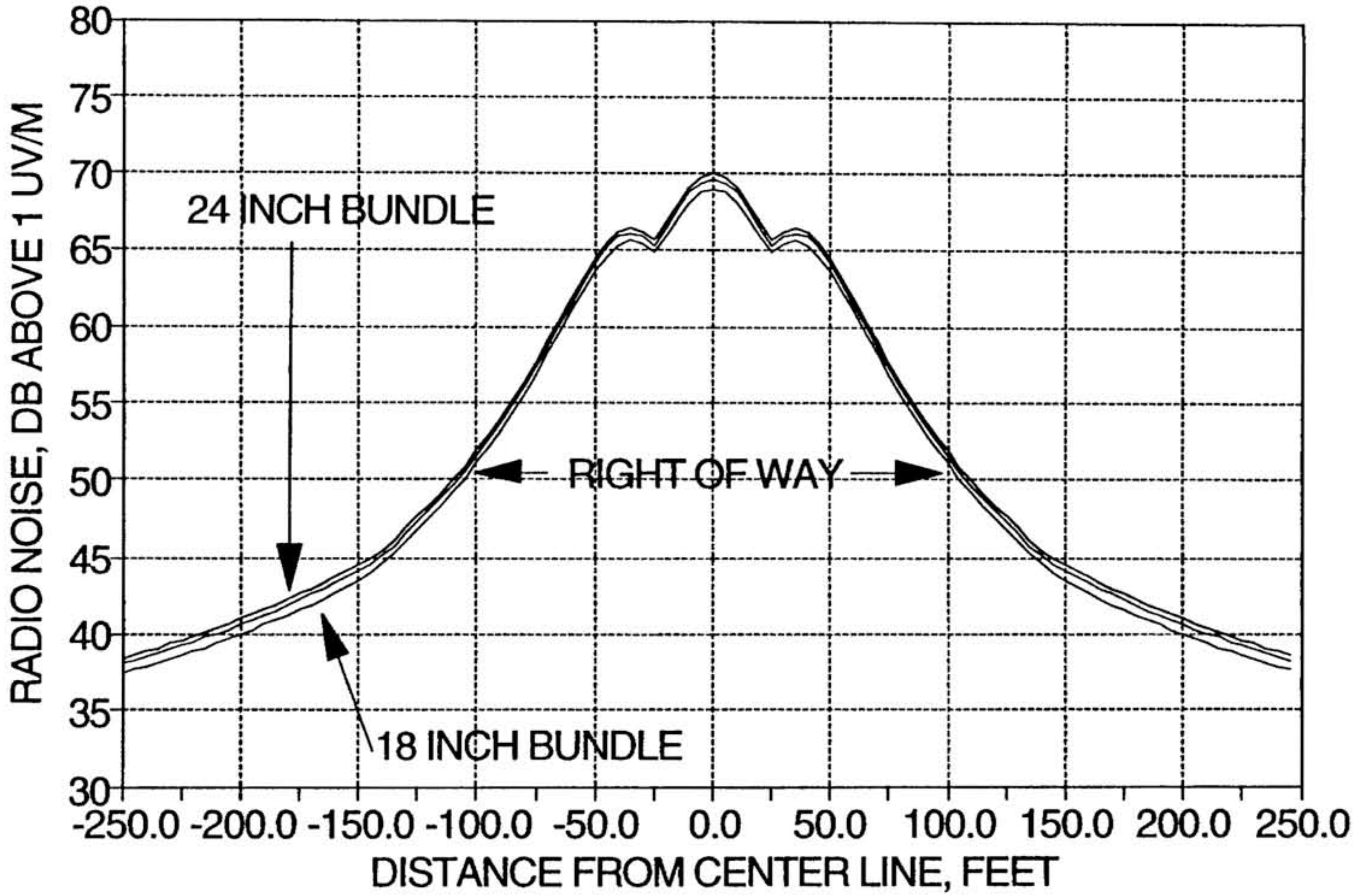


FIG. 6.

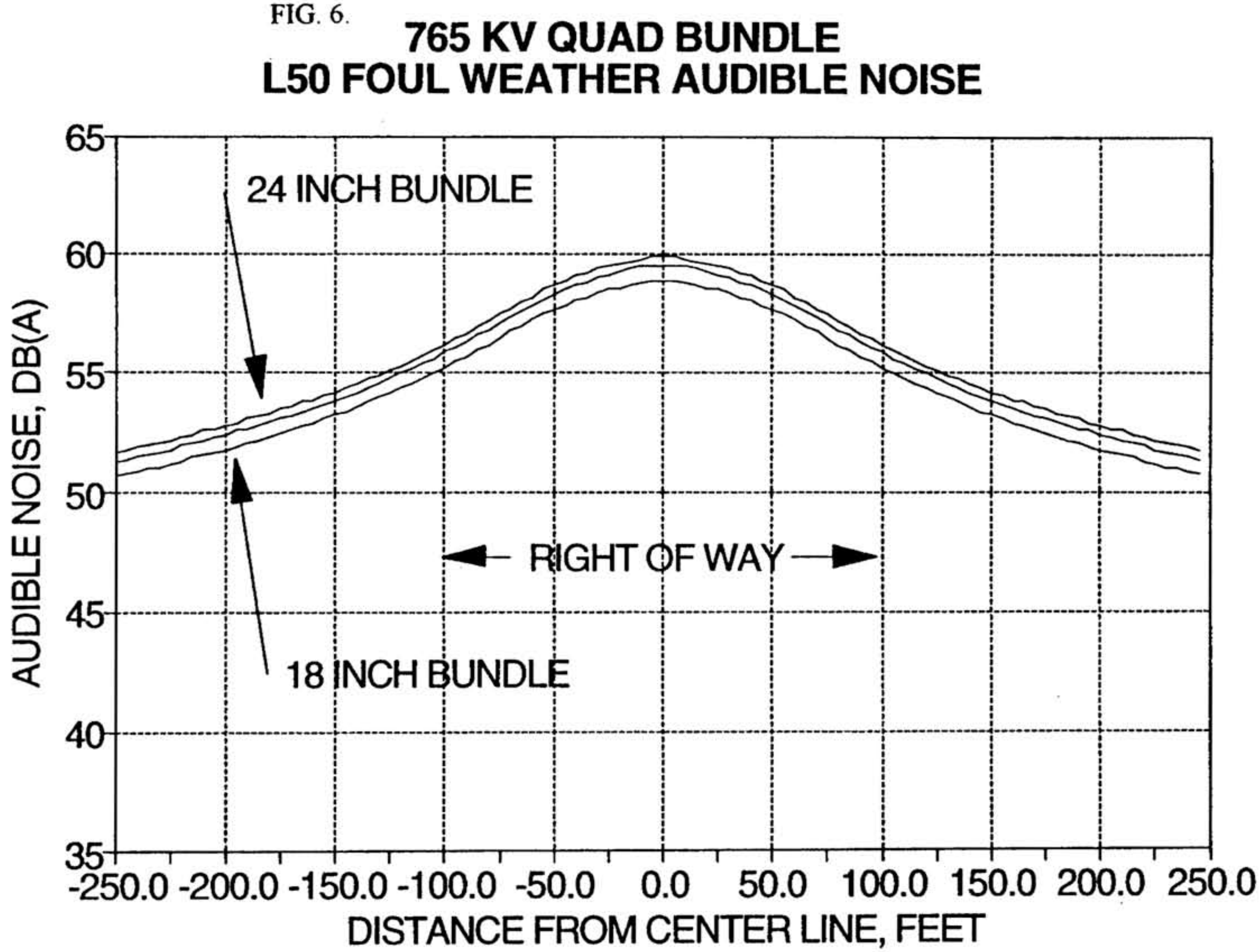
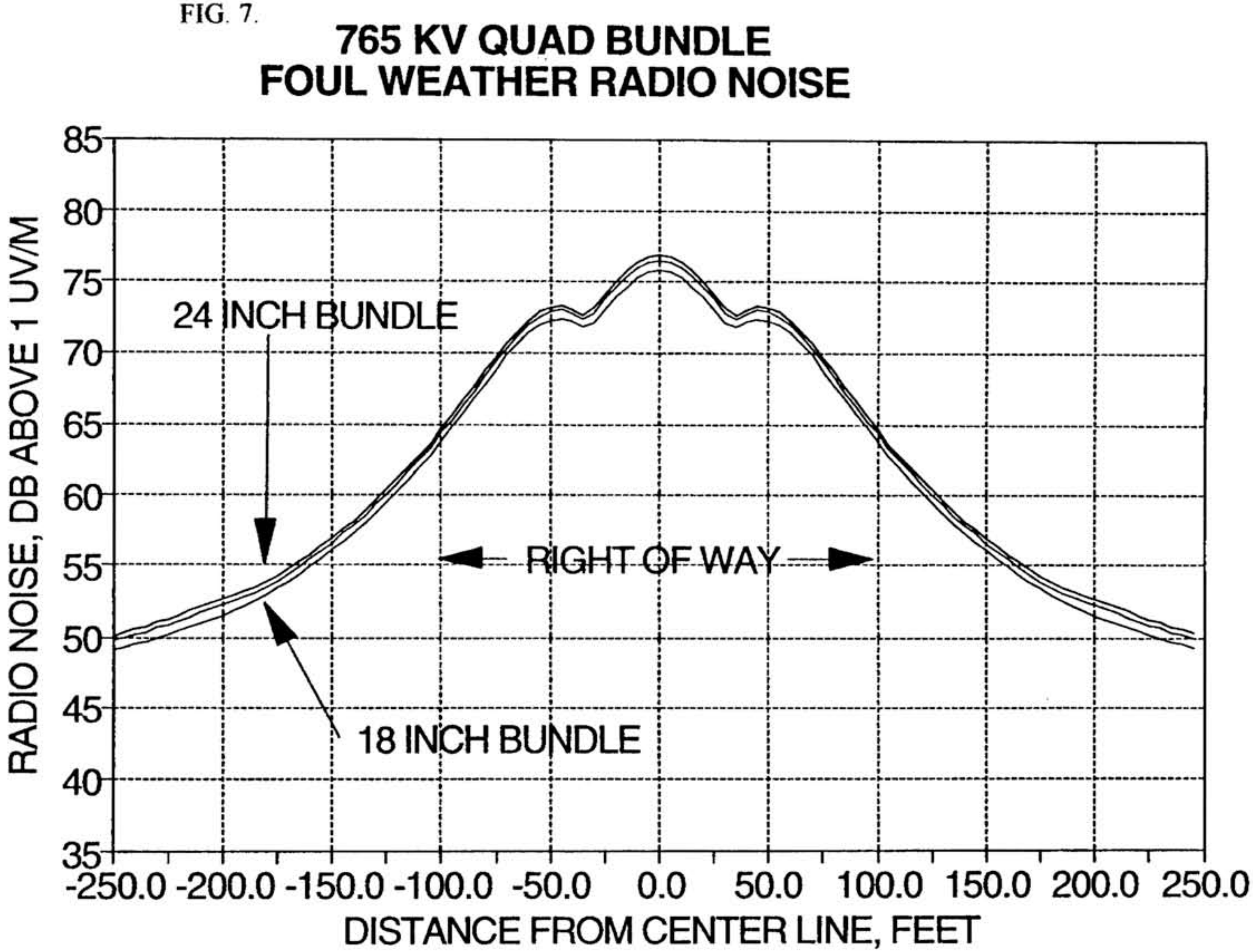

765 KV QUAD BUNDLE
L50 FOUL WEATHER AUDIBLE NOISE
AUDIBLE NOISE, DB(A)
65
60
55
50
45
40
35
24 INCH BUNDLE
18 INCH BUNDLE
RIGHT OF WAY
-250.0
-200.0
-150.0
-100.0
-50.0
0.0
50.0
100.0
150.0
200.0
250.0
DISTANCE FROM CENTER LINE, FEET

FIG. 7.


765 KV QUAD BUNDLE
FOUL WEATHER RADIO NOISE
RADIO NOISE, DB ABOVE 1 UV/M
85
80
75
70
65
60
55
50
45
40
35
24 INCH BUNDLE
18 INCH BUNDLE
RIGHT OF WAY
-250.0 -200.0 -150.0 -100.0 -50.0 0.0 50.0 100.0 150.0 200.0 250.0
DISTANCE FROM CENTER LINE, FEET

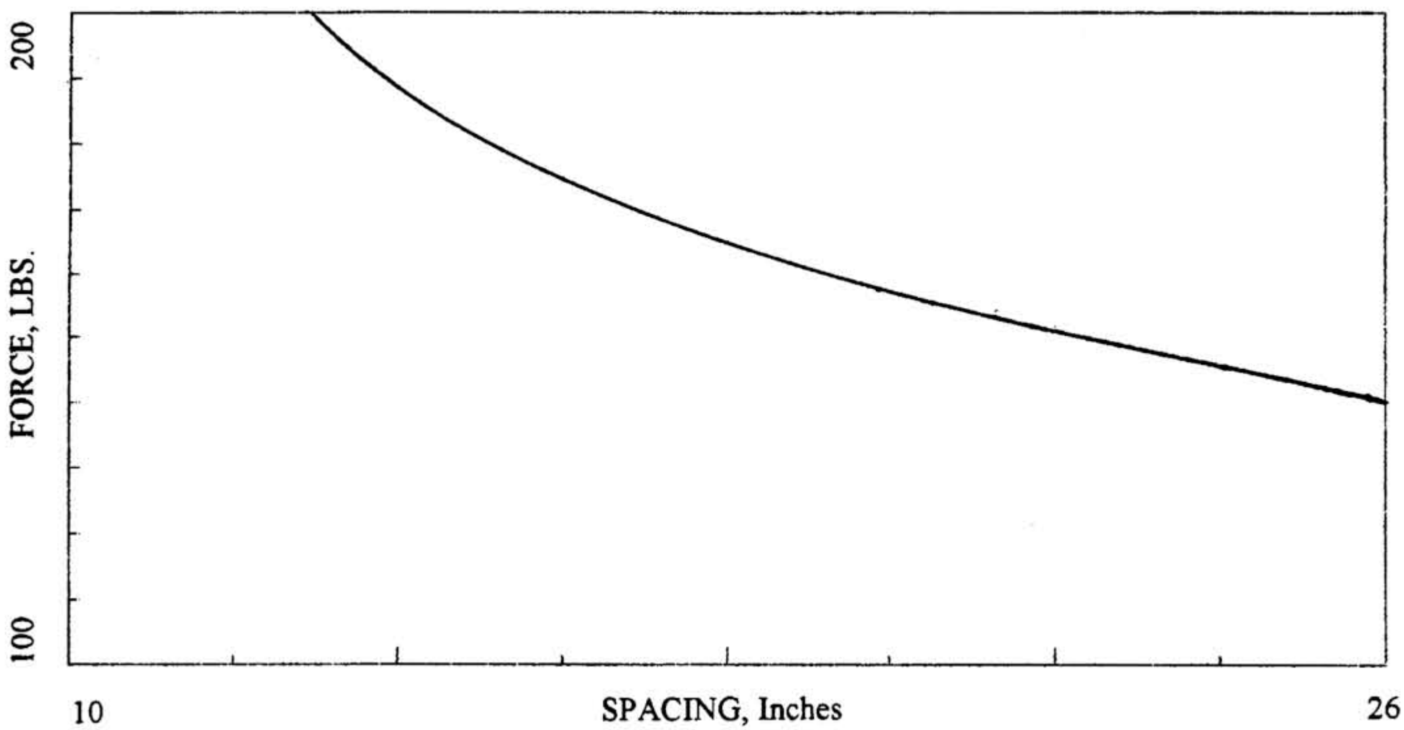


FIG. (8) Spacer force vs. bundle spacing for 25,000 ampere fault current.