

# ATMOSPHERIC ELECTRICITY AS A FACTOR OF DRY DEPOSITION OF PARTICULATE POLLUTION

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**ABSTRACT:** The electric deposition is known in case of unattached radon daughter clusters which are unipolarly charged and of high mobility. The role of the electric forces in deposition of aerosol particles is estimated comparing the fluxes of particles carried by different deposition mechanisms in a model situation. The ratio of electric and diffusion deposition fluxes

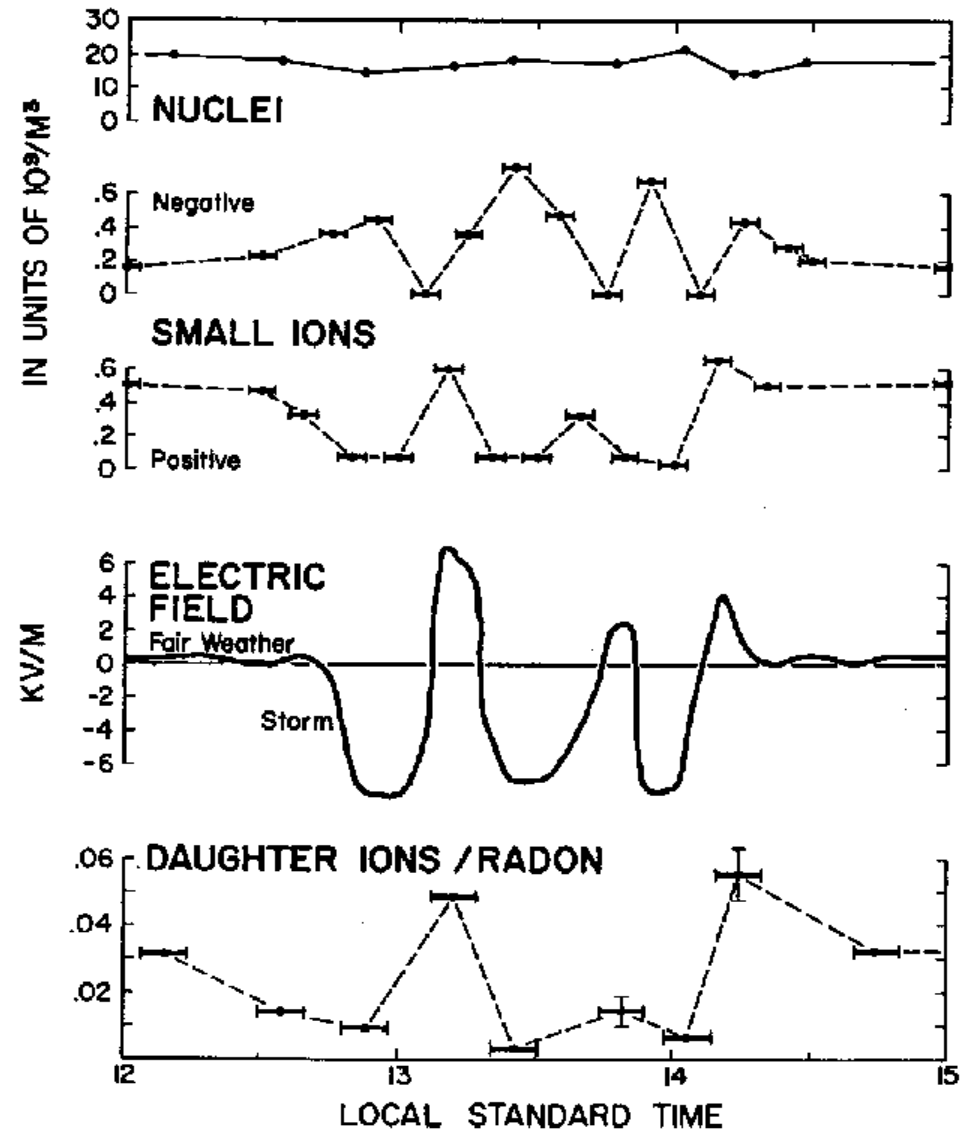
decreases about ten times only when the mobility decreases thousand times from the values characteristic for small ions to the values characteristic for large ions. The electric flux of fine particles can dominate on the tips of leaves and needles even in a moderate atmospheric electric field of few hundreds V/m as measured over the plain ground surface. Unlike the diffusion

deposition, the electric deposition is essentially non-uniform: the plate out on the tips of leaves and especially on needles of top branches of conifer trees is more intensive than on the ground surface and electrically shielded surfaces of plants. The knowledge of deposition geometry could improve our understanding of air pollution damages of plants.

# INTRODUCTION

The turbulent diffusion approaches zero on the surface of plant leaves and needles. *Porstendörfer* [1994] writes: “3.3.1. *Deposition processes*. In general, the dry deposition of aerosol particles is governed by the physical processes of sedimentation by gravity, impaction by inertial forces, interception and Brownian diffusion”. Two mechanisms, impaction and interception, are considered together below and called the aerodynamic deposition. All four non-electric mechanisms together are called the mechanical deposition. The electric mechanism of deposition is neglected by *Porstendörfer* [1994] as is common in the literature about aerosol deposition.

The electric deposition has been considered when discussing deposition of radon daughters, considerable amount of which are carried by positive small ions [*Wilkening*, 1977].



Measurements by Wilkening [1977]  
during a thunderstorm

*Willett* [1985] has created a theoretical model to describe the effect of radon daughter deposition on the near-ground air ionization. A citation: “This model predicts significant enhancements of the “surface radioactivity” under typical continental conditions.”

Heated discussion was started by *Henshaw et al.* [1996], who published an impressive demonstration of the enhanced deposition of radon daughters in the vicinity of electric power cables indoors, and explained the effect by the electric deposition of dust particles carrying the attached fraction of radon daughters. Additionally, *Henshaw et al.* [1996] pointed out the problem of the electrostatic deposition of radon daughters as a possible mechanism of the environmental effect of HV power lines.

*Tammet and Kimmel* [1998] have measured the activity of radon daughters up to 14 kBq/kg on tips of top needles of a spruce under HV power line. This activity dramatically exceeds the average level of natural radioactivity. *Tammet and*

*Kimmel* compared theoretically the Brownian and electrostatic deposition and explained the measurements by electrostatic deposition of small ions.

The electric mobilities of aerosol particles are three orders of magnitude less than the mobilities of small ions, and they are not unipolarly charged. However, the diffusion coefficient of the aerosol particles is low as well, and the relative effect of electric field could appear considerable [*Tripathi and Harrison*, 1998]. *Schneider et al.* [1994] showed how the particles are deposited on the faces and eyes of people exposed to a strong electric field e.g. near a computer display.

The hypothesis by *Henshaw* about the role of electrostatic field in deposition of aerosol particles was not accompanied by a theoretical model of the effect. A quantitative theoretical estimate is required to decide, under which conditions the electric deposition should be considered or could be neglected.

# Acknowledgements

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# THEORETICAL ESTIMATES

## THE MODEL

The deposition velocity is defined as the ratio of the deposition flux to the surface area. Specific deposition velocities caused by gravity, aerodynamic effect (impaction and interception), Brownian diffusion and electric field are denoted below as  $u_G$ ,  $u_A$ ,  $u_D$ , and  $u_E$ .

The natural ground is mostly covered by plant canopy. The electric field is strongly enhanced on the tips of leaves and on the needles of plants. Deposition to specific elements of plants depends on their geometry. The shapes and positions of leaves and needles are variable. Thus a model is required to get quantitative estimates. A simple geometrical model to compare the deposition mechanisms on these natural structures is a cylindrical wire. The field on the surface of a long wire of radius  $R$  parallel to a plane and distant  $H$  from it is

$$E = \frac{H}{R \ln(2H/R)} E_o,$$

where  $E_o$  is the undisturbed atmospheric electric field over the plane surface. The field on the surface of a short needle is enhanced when compared with the estimate above.

Electrostatic deposition is to be compared with other components of particle deposition and with the joint mechanical deposition which considers simultaneously the gravitational, aerodynamic and diffusion mechanisms. The deposition velocities characterizing different deposition mechanisms are not exactly additive. A rough approximation is used below to estimate the combined mechanical deposition velocity  $u_M$ :

$$u_M = \sqrt{u_G^2 + u_A^2 + u_D^2}.$$

The gravitational component  $u_G$  of deposition velocity over a horizontal plane is  $u_G = mgB$ , where  $g$  is the gravitational acceleration,  $m$  and  $B$  are respectively the mass and the mechanical

mobility of the particle. Other components of the deposition velocity are estimated below for the wire model.

## AERODYNAMIC DEPOSITION

### ***Symbols:***

$r$  – radius of the particle, m

$R$  – radius of the wire, m

$v$  – air flow velocity, m/s

$m$  – mass of the particle, kg

$B$  – mechanical mobility of the particle, m/(N·s)

$u_A$  – velocity of aerodynamic deposition, m/s

Stk – Stokes number of the particle  $Stk = \frac{vmB}{R}$

### ***Method:***

The theoretical models of aerodynamic deposition are roughly approximate and the experimental data are considered as better source of information. The data presented by *Fuchs* [1964] and *Wessel and Righi* [1988] are fitted with empirical equation:

$$u_A = \left[ \left( \frac{Stk}{0.6 + Stk} \right)^2 + \frac{r}{R} \right] \frac{v}{\pi}$$

## DIFFUSION DEPOSITION

### **Symbols:**

$R, d = 2R$  – radius and diameter of the wire, m

$v$  – air flow velocity, m/s

$\lambda$  – heat conductivity, W/(m·K)

$D = kTB$  – coefficient of diffusion, m<sup>2</sup>/s

$\mu$  – cinematic viscosity, m<sup>2</sup>/s

$a$  – temperature conductivity,  $a = \lambda/c_p\rho$

$h$  – coefficient of heat transfer, W/(m<sup>2</sup>·K)

$u_D$  – velocity of diffusion deposition, m/s

$Re = \frac{2Rv}{\mu}$  – Reynolds number

### **Method:**

Nondimensional heat transfer equations are translated into the diffusion deposition equations replacing [see *Eckert and Drake, 1972*]:

The Nusselt number with the Sherwood number:

$$Nu = \frac{hd}{\lambda} \quad Sh = \frac{u_D d}{D},$$

The Prandtl number with the Schmidt number:

$$Pr = \frac{\mu}{a} \quad Sc = \frac{\mu}{D}.$$

If the condition  $Re \cdot Pr > 0.2$  is satisfied (and it is well satisfied as a rule), the Churchill-Bernstein equation of heat transfer offers a good approximation:

$$Nu = \left( 0.3 + \frac{0.62 Re^{1/2} Pr^{1/3}}{\left(1 + (0.4/Pr)^{2/3}\right)^{1/4}} \right) \left( 1 + \left( \frac{Re}{282000} \right)^{5/8} \right)^{4/5}.$$

When translated into the terms of diffusion it gives the Sherwood number and the velocity of deposition [*Tammet and Kimmel, 1998*]:

$$u_D = \frac{D}{d} Sh = \frac{kTB}{2R} \left( 0.3 + \frac{0.62 Re^{1/2} Sc^{1/3}}{\left(1 + (0.4/Sc)^{2/3}\right)^{1/4}} \right) \left( 1 + \left( \frac{Re}{282000} \right)^{5/8} \right)^{4/5}$$

# ELECTROSTATIC DEPOSITION

## *Symbols:*

$u_E$  – velocity of electrostatic deposition, m/s

$Z$  – electric mobility,  $\text{m}^2/(\text{V}\cdot\text{s})$

$E$  – electric field on wire surface, V/m

$E_o$  – undisturbed atmospheric electric field, V/m

$k$  – Boltzmann constant  $1.38 \times 10^{-23}$  J/K

$T$  – temperature, K

$ie$  – particle charge,  $e = 1.6 \times 10^{-19}$  C

$p_i$  – probability to carry the charge  $ie$

$H$  – distance of the wire from grounded plain, m

## *Equations:*

$$u_E = ZE, \quad Z = \frac{ieD}{kT},$$

$$E = \frac{2H}{d \ln(4H/d)} E_o,$$

$$u_{Ei} = \frac{ieD}{kT} \frac{2H}{d \ln(4H/d)} E_o,$$

$$u_E = \sum_{i=1}^{\infty} p_i u_{Ei}$$

The probabilities  $p_i$  are calculated according to the approximation [Tammiet, 1991] improved considering the data by Reischl et al. [1996] (nondimensional charge  $i$  is denoted  $q$  in the algorithm):

```
Function pqd_bi (q{e}, d{nm}, t{Celsius}, ll{λ+/λ-} : double) : double;
Var      j : integer;
      x, sum : double;
      Nj : array [-999..999] of double;
function beta (qb : double) : double;
{NB! relative values only!}
var x, y : double;
begin
  x := 33425*qb/(d*(t+273));
  if x > 80 then y := 0 else
  if x = 0 then y := 1 else
  if x < -80 then y := -x
  else y := x/(exp(x) - 1);
  beta := y * sqrt (1 - 2 / (2 + qb * (qb - 1) + (d / 10)));
end;
```

```
Begin
j := 0; Nj [0] := 1; sum := 1;
repeat j := j + 1;
  x := beta (j-1) / beta (-j);
  Nj [j] := Nj [j - 1] * x * ll;
  Nj [-j] := Nj [1 - j] * x / ll;
  sum := sum + Nj [j] + Nj [-j];
until (j = 99) or
      ((Nj [-j] < 0.001) and (abs (j) >= abs (q)));
pqd_bi := Nj [round (q)] / sum;
End {of pqd_bi};
```



# DISCUSSION AND CONCLUSIONS

The critical field strength is defined as that which makes the velocity of electric deposition equal to the velocity of some other specific deposition. Different critical field strengths can be related to the gravitational, Brownian, aerodynamic, and joint mechanical deposition.

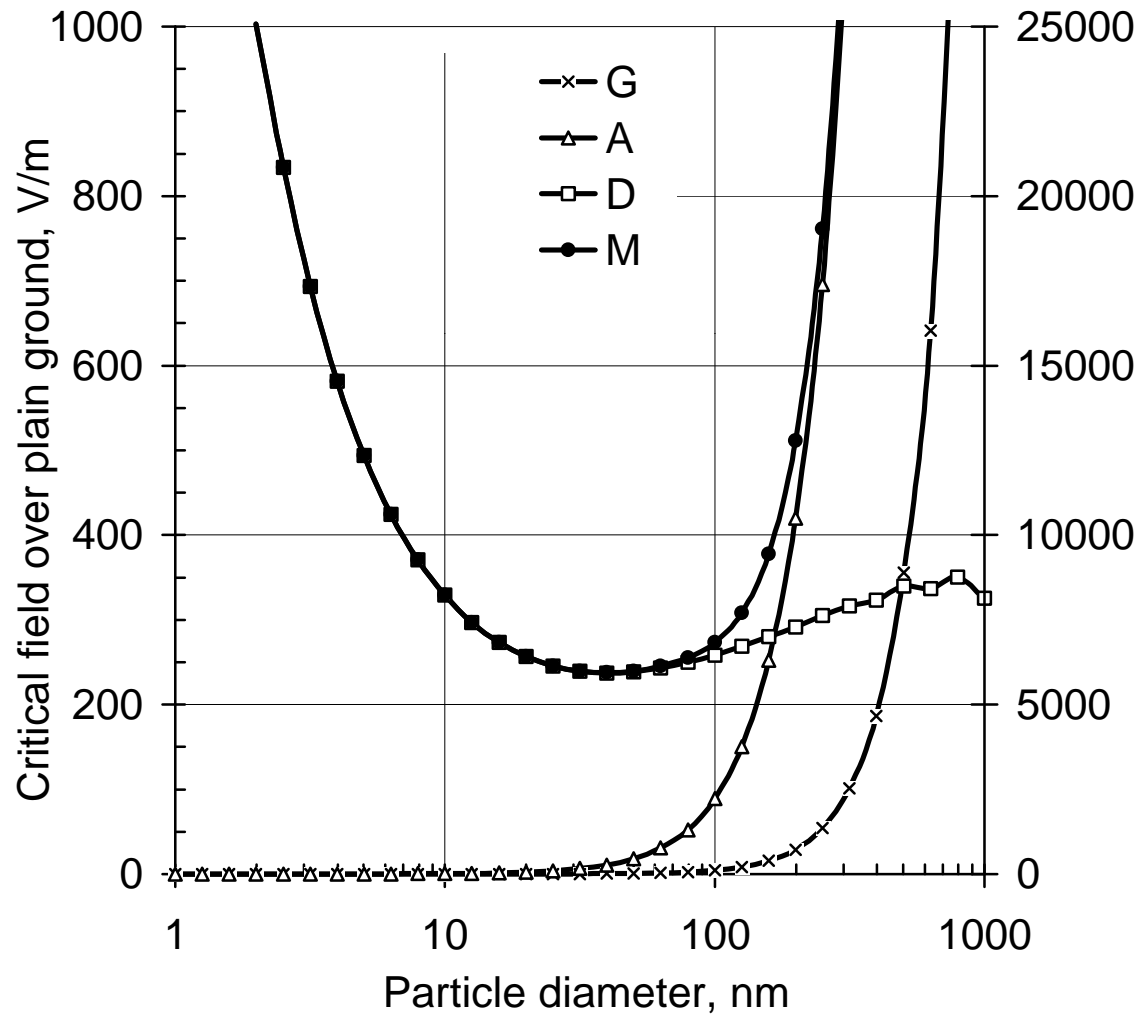


Figure 1. Critical electric field against different mechanisms of deposition:

- G – gravitational,
- A – aerodynamic,
- D – diffusional,
- M – joint mechanical.

*Assumptions:*

Standard atmospheric conditions.

Cylinder diameter 1 mm,  
height 7 cm,

particle density 2 g/cm<sup>3</sup>,

$\lambda_+/\lambda_- = 2$ .

Wind velocity 1 m/s.

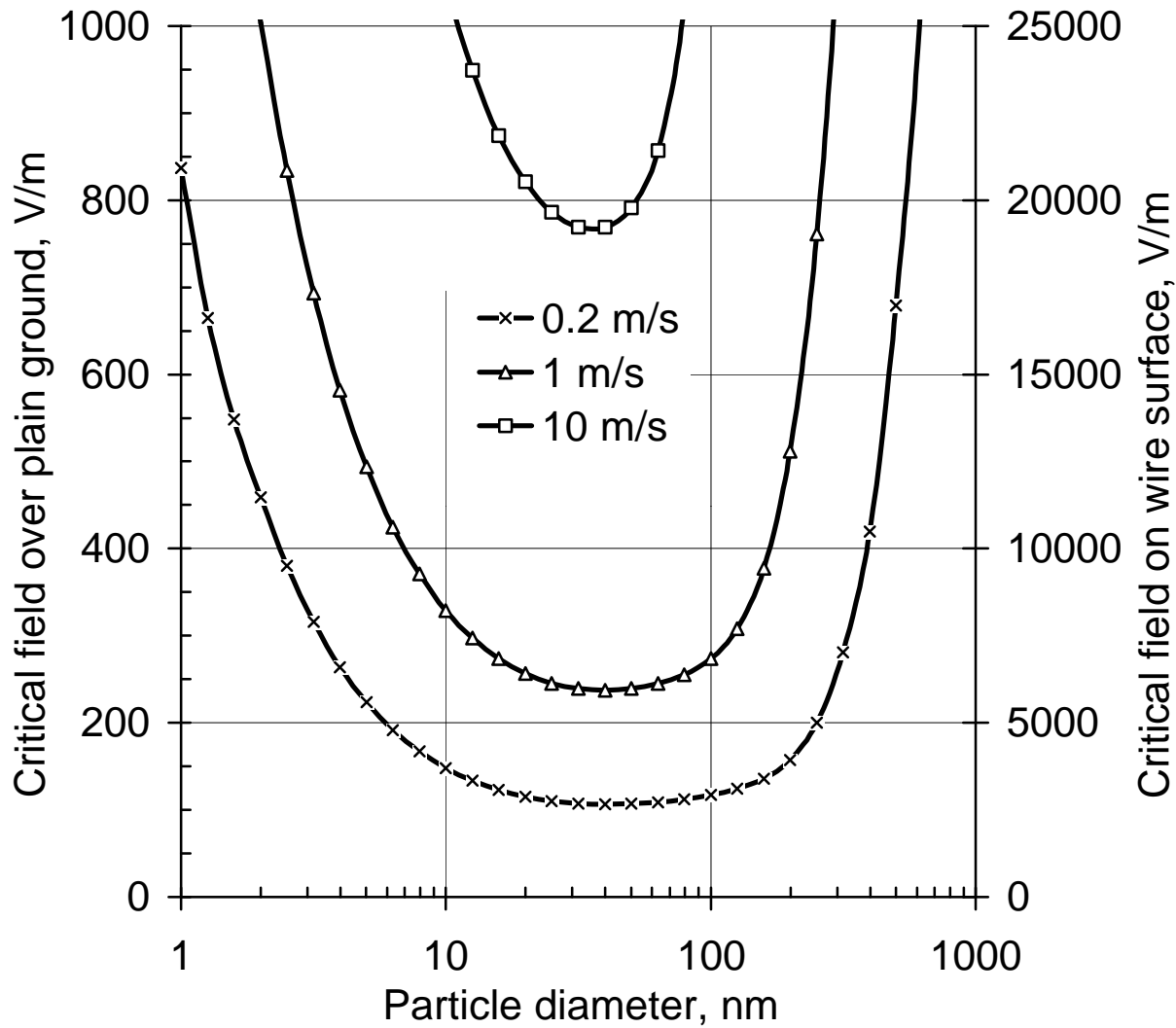


Figure 2. Critical electric field against joint mechanical deposition depending on the wind velocity.

*Assumptions:*

Standard atmospheric conditions.

Cylinder diameter 1 mm,

height 7 cm,

particle density 2 g/cm<sup>3</sup>,

$\lambda_+/\lambda_- = 2$ .

The velocity of electric deposition is proportional to the field strength. Thus the relative effect of the electric field is easy to estimate when the critical field strength is known. According to

Figure 1, the gravitational mechanism has a secondary role in aerosol particle deposition and can play some part only at extremely weak wind. Aerodynamic sedimentation and Brownian diffu-

sion are the main mechanisms of mechanical deposition of particles. The aerodynamic deposition is essential in case of particles of diameter above 100 nm. In the size range of large air ions the aerodynamic deposition is negligible and the Brownian diffusion dominates as the mechanism of mechanical deposition. In case of uniformly charged particles, the electric mobility and diffusion coefficient are proportional to each other. Thus the dependence of the critical electric field on the particle size is weak in the size range of Langevin ions.

Figure 2 illustrates the role of electric deposition compared with the joint mechanical deposition, depending on the wind velocity. The critical field strength is lowest in the particle diameter range of 10–200 nm, which contains the majority of the atmospheric aerosol particles. The role of the electric deposition essentially depends on the wind velocity. In case of a low wind of about 1 m/s or less, the critical field is comparable to the

normal atmospheric electric field, and electric deposition of aerosol particles has a considerable role as a factor of redistribution of deposit on different elements of the plants. In a strong wind of about 10 m/s or more, the electric deposition can be considerable only in a thunderstorm situation or on the top branches of trees.

The deposition of aerosol particles forced by the atmospheric electric field should be especially considered when discussing enhanced pollution damages of the top branches of conifer trees.

A subject of public discussion is the possible environmental effect of HV power lines. The AC magnetic field under the lines is often mentioned in public discussions but probably does not have any considerable biomedical effect.

A realistic environmental effect of HV power lines is the redistribution of the deposit of air pollutants between the the tips and shielded sur-

faces of leaves and needles of plants. The AC electric field does not enforce any unidirected flux of charged particles. The amplitude of oscillation of the particles is a fraction of millimetre. The time of passage of the particles carried by wind

through the critical neighborhood of the tips of leaves is less than the period of the field oscillation. Thus the effect of electrostatic deposition of particles on the leaf or needle tips should be nearly the same as in a DC field.

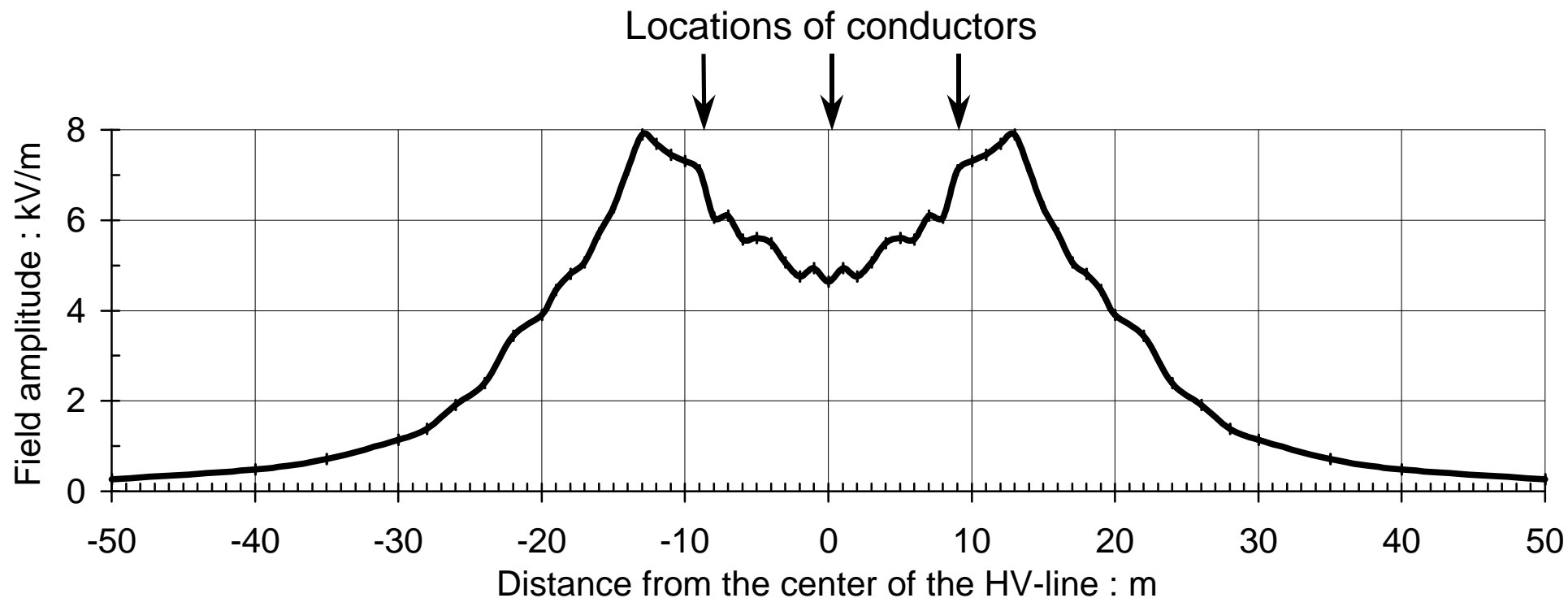


Figure 3. Electric field under a 330 kV 50 Hz AC power line having three parallel double-wire conductors at a height of 10.2 m over a flat ground. The field was measured on one side of the line and the curve is complemented for the other side by symmetry.