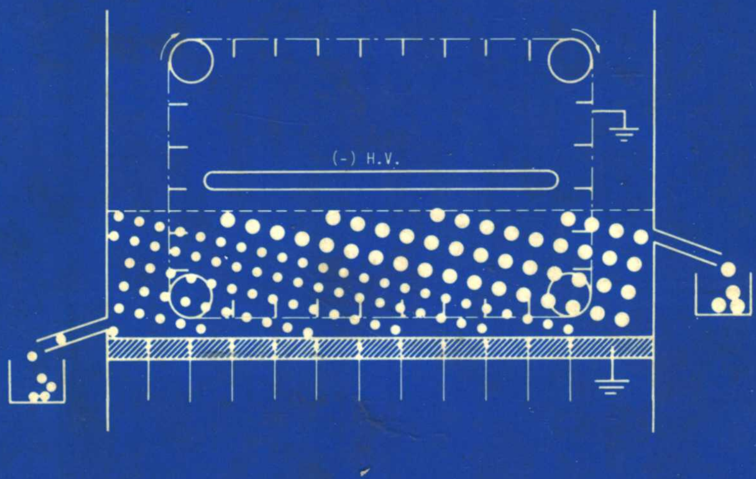
# Electrostatic Mineral Separation

Ion I. Inculet

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# EDITORIAL FOREWORD

Electrical charging and manipulation of particulates play an increasingly important role in many modern electrostatic processes. The most rapid development has probably been in the field of electrophotography, and this application has been described in detail in Scharfe's book entitled, 'Electrophotography Principles and Optimization' which is available as the preceding volume in this series. Titles on other particle handling processes, such as precipitation and powder coating, will be added to the series soon.

In this volume on mineral separation, Professor Inculet has to his great credit achieved an excellent combination of sufficient mathematical treatment, ensuring adequate and useful design-guide data, while at the same time maintaining a logical descriptive approach to both fundamental phenomena and practical systems. Chapter 4 on electrification processes is particularly interesting, offering an invaluable source of information for applications requiring a basic knowledge of particle charging. The concluding chapter relates to techniques for separation of ores in outer space, indicating future trends in applications. Above all, the monograph is very readable and is a welcome addition to the Series on Electrostatics and Electrostatic Applications.

J.F. Hughes, Ph.D., M.I.E.E., F.Inst.P.
April 1984

# PREFACE

As we look around us and examine the air we breathe, the food we eat, the various industrial processes which improve our standard of living, the coal-fired power plants which provide energy, or the future plans for building solar power stations from materials extracted out of the lunar soil, finely divided matter in liquid or solid form appears omnipresent.

Since the beginning of this century and the work of Frederick Cottrell, it has become increasingly obvious to industry that finely divided matter can be best handled by means of electrostatic forces. Electrostatic forces can be made to act on individual particles without affecting the medium in which such particles are present. The same forces may be made to act along certain designed field lines, and, furthermore, depending on the direction of the electric field or the polarity of the charge, the forces may be made to reverse direction at high speeds.

While contemplating the two main landmarks in the development of the industrial applications of electrostatics: 1) the electrostatic precipitator, and 2) the electrophotography, we cannot help but see the crystallization of a third major industrial activity as represented by the electrostatic processes for the separation or beneficiation of finely divided matter in various forms such as mineral ores, ore tailings, pulverized coal containing clay particles, or, in the food industry, flour containing impurities, etc.

The electrostatic processes, in addition to doing the job well and competitively with other methods, have the great advantage of being environmentally clean. Compared to conventional separation processes involving horrendous water pollution problems, such as flotation to extract mineral values or washing to extract the clay before burning the coal, the electrostatic methods are or may be made harmless to the air environment with modest expense.

Furthermore, as one thinks of future projects to develop power stations in space by building the units with materials taken from the moon surface, where water is not available, and where the raw materials are already in the form of fine particles ideally suited for electrostatic processing, the incentives for improving and developing the electrostatic separation processes on earth become that much more attractive.

The work presented in this monograph has been based in part on the research and development work carried out in the Applied Electrostatics Laboratory of the Faculty of Engineering Science at The University of Western Ontario over the 1973-1983 decade.

The author is much indebted to his colleagues in the Faculty of Engineering Science, who singly or through interdisciplinary collaboration, have, and continue to set, a firm foundation to research and development work in the applications of electrostatics: Dr. G.S. Peter Castle, Electrical Engineering, with whom he has worked together on many projects; Dr. Maurice A. Bergougnou, Chemical Engineering; Dr. James D. Brown, Materials Engineering; Dr. Terry E. Base, Mechanical Engineering; and Dr. Robert M. Quigley, Civil Engineering.

A great deal of recognition is also due to the many graduate students who have, through hard work, energy and enthusiasm, contributed so much to the advancements realized in the Applied Electrostatics Laboratory of The University of Western Ontario.

Finally, as the book begins to take shape, the author is grateful to Miss Elizabeth Milliken, Assistant to the Editor of the Canadian Geotechnical Journal and Secretary in the Faculty of Engineering Science, for having accepted the task to help to see this monograph completed.

*"In old folklore, a young prince, for the conquest of his bride, had to prove to the king his talents and forces in a variety of trials. In one of the more subtle trials, the king's men prepared a bushel of a mixture of fine flour and salt and locked it together with the prince in a room. The prince had to separate the mixture back into its original constituents in the dark, before next morning, when the king's quality control inspectors armed with double sampling tables would ascertain that the separation of the billions of small particles in the μm range was completed at a high level of confidence.*

*In the story, it also happened that the good and observant prince, during his travels to that far land, rescued the queen of the ants from drowning. In lieu of proceeding to separate the flour from the salt, he called for help and the grateful queen of the ants sent two armies: one to collect the salt and the other to collect the flour. The work was completed before morning....*

*Men have long contemplated the problems of selectively handling very small particles, and to our ancestors one of the simplest solutions was the training of ants..." (Inculet, 1977-1978).*

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# CHAPTER I

# OVERVIEW

In the ultimate analysis of any physical separation process, be it manual, gravitational, mechanical, magnetic and/or electrostatic, one finds forces at work. Such forces must be selective and sufficiently large to extract the fraction to be separated.

If one tries to crystallize the common denominator of industries which owe their success to electrostatics, one invariably finds **very small forces at work on very small particles** of a diameter in the order of a few micrometres. While such forces appear insignificant on our scale, they are very large when compared with those of gravity acting on the same particles.

The separation of minerals is economically justifiable for beneficiation purposes. In general, one has to deal with either a mixture of particles in which the various components are chemically pure or a mixture of particles in which some of the particles contain several elements to be separated. In the second case, one must comminute the material to a sufficiently small size such that the individual particles in the mixture become practically pure for a physical separation process.

Should the comminution process fail to produce particles of an acceptable chemical purity, any electrostatic separation process becomes ineffective.

The electrostatic forces are generated by the action of an electric field on a charged particle. Consequently, in any electrostatic separation process one needs a source of electrical potential to generate the electric field and a process by which the individual particles are charged electrically.

Once the charging has been accomplished, the electrostatic separation processes have substantial advantages over any other processes. These advantages are:

1. The electrostatic forces work on the particles to be separated only; they do not affect the medium in which the particles are located.

2. The trajectories of the particles under the influence of the electric field follow the electric field lines. The electric field lines may be shaped to suit the particular application.

3. The direction of the electrostatic forces may be reversed by either changing the polarity of the charge or the direction of the external electrostatic field.

4. The electrostatic forces may be arranged to work in combination with other forces such as gravitational or centrifugal forces.

5. The electrostatic separation forces are independent of the substrate of the material on which the surface electric charge is generated. They are determined solely by the product of electric field and charge. In magnetic separators the forces are considerably greater, yet such forces work on magnetic materials only. The electrostatic forces do not differentiate between magnetic and non-magnetic materials. A charged magnetic particle placed in an electric field will be subjected to forces practically equal to those acting on a similar particle made out of non-magnetic material and charged with the same charge.

The generation of the necessary electric fields is a well established technology. In any industrial development of electrostatic mineral separation, most of the attention must be devoted to generation of the electrical charges on the various particles to be separated. Every application requires custom design of the system which will generate the necessary charges and charge polarities.

Perhaps the only disadvantage of the electrostatic force is the limitation on the maximum mass that it can effectively work upon. However, as in most mineral separation processes the material must be comminuted to a fairly small size in order to liberate the sought fractions, quite often the sizes of the particles to be separated come well within the realm of electrostatic forces.

When electrostatic forces are used to selectively deflect or change particle trajectories, such forces do not need to be as large as those needed to effectively lift a certain mass against gravitational forces. The limitations of electrostatic forces are documented and presented in more detail in the respective chapters of this monograph.

It is important to notice that in addition to the forces which result from the interaction of an electric field with an electric charge, dielectrophoretic forces can also be generated. Such forces are the result of polarization of the material under the influence of an electrostatic field. They are generally smaller and their application to large scale mineral ore beneficiation is practically non-existent.

The material handled in this monograph deals primarily with systems which are of immediate industrial importance. The description of the processes is given in sufficient detail to enable one to plan and estimate a particular application.

The following is a brief overview of the various chapters.

**Chapter 2** deals with electrostatic forces in air and motion of charged particles. As a large number of industrial processes for beneficiation or separation of mineral values from finely comminuted materials are carried out in air, both the electrical forces on charged particles as well as the air drag forces which determine the steady-state velocities of the motion of particles, are analyzed on the basis of the classical theory.

**Chapter 3** covers the fundamental principles at the basis of practical measurements of electric fields and charges. The methods shown are expected to be of help in both R and D work for new processes as well as for field work.

**Chapter 4** deals with the three main industrial processes for the generation of electric charges on particles. Tribo-electrification, corona charging and induction charging are analyzed from the point of view of controlling parameters.

**Chapter 5** describes some of the key procedures for the preparation of the raw material prior to electrostatic beneficiation or separation. In particular, the surface condition, as well as temperature and humidity effects, are reviewed for industrial application.

**Chapter 6** describes one of the electrification processes with considerable promise in the industrial field - the tribo-electrification in fluidized beds, as applied to electrostatic beneficiation of coals.

**Chapter 7** shows the versatility of the electric fields acting on fine particles electrified in a fluidized bed. It deals with the separation and collection which may be achieved by means of a conveyor with troughs running above a fluidized bed of particulate materials to be beneficiated.

**Chapter 8** shows the influence of vibratory energy introduced in a fluidized bed on the triboelectrification of very fine particles. Examples are given of separation of synthetic materials.

**Chapter 9** describes the electrostatic separation of very fine particles in a dilute phase continuous loop. Possible industrial applications are presented in the beneficiation of fly ash.

**Chapter 10** describes a novel method of combining gravity separation with electrostatic forces in a counter-current gas fluidized bed with particular application to the beneficiation of coals.

**Chapter 11** describes a novel separator developed at The University of Western Ontario for beneficiation or sizing of particulates by means of alternating, curvilinear electric fields.

**Chapter 12** looks at possible future application of the electrostatic beneficiation principles to the beneficiation of ores in outer space.

# CHAPTER 2

## ELECTROSTATIC FORCES IN AIR AND MOTION OF CHARGED PARTICLES

At the basis of all electrostatic forces on a charged particle is the relationship:

$$F = E\, q \qquad (2.1)$$

where F is the force on the particle, E is the electric field intensity at the particle, and q is the charge on the particle (assumed to be a point charge).

In practical applications, the electric charges are not point charges but rather distributed over the surface of an irregular particle and the acting electrostatic field is generally non-uniform. Furthermore, because the particles to be separated are of finite size and of a dielectric permittivity different from that of the medium, the local electric fields are altered as shown in the following cases.

Considering a few simple examples, let us take the case of an uncharged, spherical particle of conductive material placed in a uniform electric field $E_o$ as shown in Fig. 2.1.

The electric field at the surface of the particle is altered substantially and varies according to the sinusoidal function

$$E_r = 3E_o \cos\theta \qquad (2.2)$$

where θ is the angle between the point radius on the sphere and the direction of the uniform electric field vector $E_o$.

From equation (2.2), one can see that the maximum electric field at the surface of the uncharged conductive sphere is three times the value of the ambient field.

Due to the symmetry of field lines on the two halves of the spherical particle, the particles are subjected to an equal horizontal pull, $F_R$, from both sides.

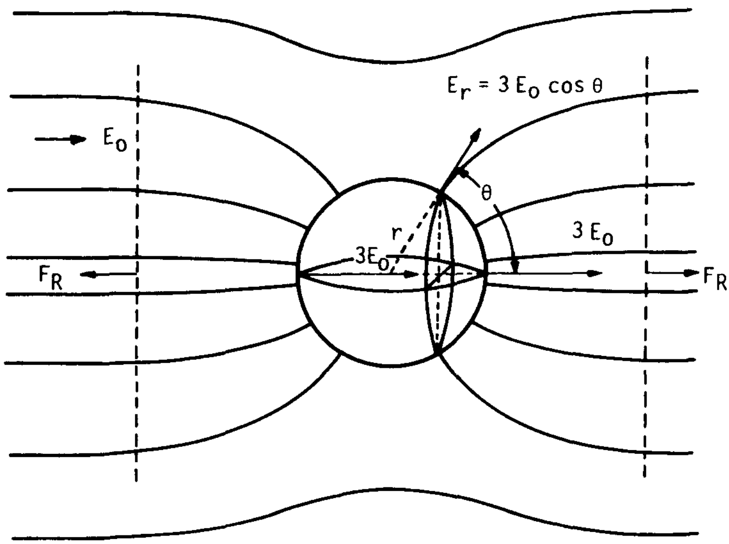


Fig. 2.1 Uncharged, conductive spherical particle in a uniform electric field $E_0$

In a second example, let us consider a conductive spherical particle of radius **r**, with a **saturation** charge **q** uniformly distributed over its surface and obtained by ionic bombardment in a uniform electric field $E_0$. It has been shown theoretically that in such a case the electric field intensity on the surface of the spherical particle can be described by the sinusoidal expression

$$E = 3\,E_0\,(1 + \cos\theta) \qquad (2.3)$$

where θ is the same angle defined in the previous example.

It is obvious from equation (2.3) that the maximum field at the surface of the spherical particle is equal to 6 times the value of the uniform electric field; also, that the maximum is located "downstream" at the farthest point on the surface of the sphere. Depending on the polarity of the charge, the field, $E_0$, will subject the particle to an attraction or repulsion force, $F_R$, (in the direction of the field) equal to $24 \pi \varepsilon_0 r^2 E_0^2$.

This theoretical finding is of importance in considering the design of the working electric fields. The choice of the working field in a particular application should be considerably less than one-sixth of the electric field intensity which gives breakdown in that medium.

Further safety margins have to be considered in the case of particles with sharp edges or points.

Let us assume now that a charged spherical particle is allowed to fall in vacuum in a gravity field such that its trajectory is perpendicular to the electric field lines used in the separation process.

The electrostatic force will accelerate horizontally the mass of the particle to be separated. The law governing the horizontal component motion of the particle is given by the formula

$$m \frac{d^2 \bar{s}}{dt^2} = Eq \qquad (2.4)$$

$m$ = mass of particle

$\bar{s}$ = horizontal displacement vector

$t$ = time

If one rewrites equation (2.4) in the form of equation (2.5),

$$\frac{d^2 \bar{s}}{dt} = E\left(\frac{q}{m}\right) \qquad (2.5)$$

where $\frac{q}{m}$ = charge to mass ratio

one sees that the charge-to-mass ratio is a very important parameter in determining the law of motion of the particle in the separation process.

If we assume further that the medium in which the falling spherical particle of radius a is accelerated horizontally is air, of viscosity $\eta$, the horizontal motion is given, equation (2.6):

$$m\frac{d^2\bar{s}}{dt^2} + 6\pi\eta a\frac{d\bar{s}}{dt} = E\,q \qquad (2.6)$$

or

$$\frac{d^2\bar{s}}{dt^2} + 6\pi\frac{\eta}{m}a\frac{d\bar{s}}{dt} = E\left(\frac{q}{m}\right) \qquad (2.7)$$

where, again, one sees the importance of the $\left(\frac{q}{m}\right)$ = charge-to-mass parameter in the horizontal acceleration of the particle.

The solution of equation (2.7), which gives the velocity of the particle as a function of time is

$$\frac{d\bar{s}}{dt} = \frac{Eq}{6\pi\eta a}\left(1-e^{-\frac{t}{m/6\pi\eta a}}\right) \qquad (2.8)$$

Equation (2.8) allows the calculation of the horizontal terminal velocity component of the falling particles by making $t = \infty$.

$$\left(\frac{d\bar{s}}{dt}\right)_{terminal} = \frac{Eq}{6\pi\eta a} \qquad (2.9)$$

As can be seen, the horizontal terminal velocity is independent of the mass. However, the mass does play an important part in the vertical motion of the particle, and hence in the resultant trajectory.

For a more accurate calculation of the terminal velocity of spherical particles moving in air, one must calculate the Reynolds number for each diameter and make use of experimental data on drag coefficients (Schlichting, 1968).

A final example with practical applications for force calculations on charged particles involves electric fields generated by a uniformly distributed space charge in a conductive enclosure.

In the case of a large fluidized bed of uniformly and unipolarly