THE ELECTRICAL PRECIPITATION OF
PARTICLES SUSPENDED IN GASES

BY

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THE ELECTRICAL PRECIPITATION OF PARTICLES SUSPENDED IN GASES.

I

Introduction.

The presence of heavy and obnoxious fumes in the vicinity of large manufacturing plants, such as smelters and refiners, has caused investigations to be made in order to determine an efficient means of lessening the evils attendant thereon. The growing tendency toward the universal application of electricity and the ease with which high voltages may be obtained has caused a revival of process for precipitating suspended particles from gases by means of high electromotive forces. The idea of such precipitation was first suggested by Hohlfeld in 1834, later by Guitard in 1849, and was put into practice by Sir Oliver Lodge in 1886 for clearing the air of fog.

Lodge first made use of a Wimshurst machine for charging the atmosphere, but this proved unsatisfactory and, in 1903, he employed a mercury-arc rectifier for obtaining high unidirectional voltages. In 1907, Dr. F. G. Cottrell of the University of California employed a rotating contact maker, or voltage rectifier for obtaining unidirectional from alternating voltage, and as a result of this application, succeeded in putting the process into commercial use for the precipitation of particles suspended in gases. The problems of voltage generation and rectification, of efficient forms for precipitators, and of the scope and application of the process are many, and it is these that form the context for this thesis.
II.

Theory.

A voltage applied to any system of electrodes causes charges of electricity to be given off to the surrounding medium. The number of these charges is dependent upon the potential gradient between the two electrodes, upon the temperature and atmospheric pressure, and upon the nature of the gaseous medium. These charges travel on ions, negative from the negative electrode—positive from the positive electrode, and are attracted by the electrodes of opposite polarity. A point source of discharge has a higher surface intensity, hence gives off more ions than a smooth surface. Thus, the medium between a point and a plate of opposite polarity is charged more heavily with ions of the same sign as the point, irrespective of whether that sign is positive or negative. Any insulated body, free to move, brought into this field, will travel toward the plate at a velocity proportional to its charge and to the potential gradient between the point and the plate.

Negative ions are smaller and travel with a greater velocity than the positive ones, hence, when a unidirectional voltage is applied to two similar electrodes, a strong circulation results from the negative to the positive poles. If the medium is a gas containing suspended particles, the ions strike these particles, give up a part of their charges, and cause the particles also to travel toward the pole of opposite sign. Coming into contact with one another, unlike
charges attract, agglomerate into larger particles, and fall of their own weight. Those particles which are not agglomerated travel on to the opposite pole and are deposited there. When an alternating voltage is applied, the reversals of polarity prevent a strong circulation in one direction, and hence the depositing effect is only that due to agglomeration. Accordingly, more efficient results are obtainable with unidirectional than with alternating voltage. Since the efficiency of the process depends upon the emission of the greatest number of ions, in one direction, with the highest surface tension, for the least voltage applied and power consumed, a system of points as a negative or discharge electrode and of smooth surfaces as positive or collecting electrodes is the most feasible.

A unit charge is that charge which will exert a force of one dyne upon a similar charge at a distance of one centimeter. It may also be defined as that charge which will produce one line of force per square centimeter on the surface of a sphere with a radius of one centimeter. Hence the total number of lines of force from a unit charge is $4\pi$ while the total number due to a charge $Q$ is thus $4\pi Q$. This quantity is numerically equal to the product of the force per unit area and the area, or the total electrical force acting.

If $r$ is the radius of a cylinder, or of a wire, $K$, the dielectric constant of the medium surrounding it, and $p$ the intensity of the force, the number of lines of force given off per centimeter length of the cylinder is

$$2\piKr p.$$
Equating the two equal values,
\[ 4\pi Q = 2\pi K r p \]  \hspace{1cm} (1)

Or
\[ p = \frac{2Q}{Kr} \]  \hspace{1cm} (2)

The potential of a point is defined as the amount of work required to bring a unit charge from infinity up to that point, while the difference in potential between two points is the difference in the work required to bring the unit charge from infinity to each of the points. Hence, the difference in potential between two points, \( dw \), at a distance \( dr \) from each other, is

\[ dw = p \, dr \]  \hspace{1cm} (3)

Then
\[ W = p_2 - p_1 = \int_{r_1}^{r_2} p \, dr \]  \hspace{1cm} (4)

where \( p_1 \) and \( p_2 \) are the potentials at the two points \( r_1 \) and \( r_2 \) respectively. Substituting (2) in (4),

\[ W = \frac{2Q}{K} \int_{r_1}^{r_2} \frac{dr}{r} \]  \hspace{1cm} (5)

If we consider two concentric cylinders, as shown in Figure 1, where \( r_1 \) is the radius of the smaller, and \( r_2 \) that of the larger, and with a dielectric medium whose constant is \( K \),

\[ p = \frac{2Q}{K} \int_{r_1}^{r_2} \frac{dr}{r} \]  \hspace{1cm} (6)

\[ = \frac{2Q}{K} \log_e \frac{r_2}{r_1} \]
\[
P = \frac{2Q}{K} \log_e \frac{r_2}{r_1} \quad (7)
\]

But the charge given off is proportional to the difference in potential and to the capacity, or

\[
Q = C \times P \quad (8)
\]

where "C" is the capacity per unit length, "P" is the difference in potential between the cylinders, and all quantities are expressed in appropriate units.

Solving (7) and (8) for "P", and equating results,

\[
\frac{Q}{C} = \frac{2Q}{K} \log_e \frac{r_2}{r_1} \quad (9)
\]

Or

\[
C = \frac{K}{2 \log_e \frac{r_2}{r_1}} \quad (10)
\]

expressed in electrostatic units.

Reducing the expression to farads per centimeter,

\[
C = \frac{K \cdot 10^9}{(\frac{2}{3} \times 10^{10})^2 \ \log_e \frac{r_2}{r_1}}
\]

or

\[
C = \frac{555K \cdot 10^{-12}}{\log_e \frac{r_2}{r_1}} \quad (11)
\]

The potential gradient between two charged bodies is the ratio of the drop in voltage to the distance over which the drop occurs, or

\[
\frac{dP}{dr}.
\]

Since, from (5),

\[
P = \frac{2Q}{K} \int \frac{dr}{r}
\]

\[
\frac{dP}{dr} = \frac{2Q}{K} \frac{1}{r} \quad (12)
\]
at the surface of the conductor. At any other point in the medium

\[ \frac{dP}{dr} = \frac{2Q}{Kx} \] (13)

But

\[ Q = CE \]

hence,

\[ \frac{dP}{dr} = \frac{2CE}{Kx} \] (14)

In the above development, it has been assumed that lines of equipotential are concentric and diminish regularly from the inner cylinder. Recent experiments conducted at this University have shown this to be untrue, but that the lines are more concentrated near the surface of the inner cylinder and are practically equal throughout the intervening space, until, very close to the outer cylinder, they diminish very rapidly. Figure 2 shows the comparative relation between the distance from the electrodes and the potential gradient. The dotted line follows the principle assumed in the above discussion, while the solid line is the relation recently found.

Since the velocity with which the ions travel from negative points to positive plates is proportional to their charge and to the potential gradient between the electrodes,

\[ V = kQ \frac{dP}{dr} \] (15)
where "V" is the velocity of ion travel and "k", a constant depending upon the character of the gases and upon the air pressure. Then

\[ V = k K \frac{2Q}{Kr} = k 2 \frac{Q^2}{Kr} = \frac{2k C^2 E^2}{K r} \]  

(16)

since

\[ Q = C E \]

It is thus seen that for a given system of electrodes, the velocity of precipitation is proportional to the square of the impressed voltage.

Hittorf has found that the velocity of ion travel from negative to positive point electrodes in quiescent air, is about \( 2 \times 10^5 \) centimeters per second, or about equal to the square root of the velocity of light. J. J. Thomson has found that the mechanical pressure on air at the surface of an electrode is about 400 dynes per square centimeter at an air pressure of 760 millimeters of mercury.

It has been found that ordinary air will stand a stress of approximately 100,000 volts, maximum value, per centimeter, which, then, is its potential gradient at the breaking point. In order to find the approximate flash-over point for the two concentric cylinders, substitute this value in Equation (14). Then

\[ \frac{dP}{dr} = \frac{2 C E}{K x} = 100,000 \]

or

\[ E = 100,000 \frac{K x}{2 C} \]
Substituting the value of " C " as found in Equation (10), we find that

\[ E = 100,000 \log_e \frac{r^2}{r_1} \]

and, since the maximum stress is thus greatest for the smallest value of " x ", it occurs when \( x = r_1 \) and

\[ E_{\text{max.}} = 100,000 \log_e \frac{r^2}{r_1} \]  \hspace{1cm} (17)

In considering a system of parallel wires and plates for precipitating electrodes, we might assume the wires to be close enough together to form a continuous plate. If " w " is the width of this plate and " l " the distance between electrodes of opposite polarity, the number of lines of force per centimeter length of the plate is

\[ p \cdot w \cdot K. \]

Similarly as before, the lines of force due to a charge " Q " are

\[ 4 \pi Q, \]

hence,

\[ 4 \pi Q = p \cdot w \cdot K \]

or

\[ p = \frac{4 \pi Q}{w \cdot K} \]  \hspace{1cm} (18)

The work required to move the charge from one plate to the other, or the difference in potential, is

\[ P = \int_0^L p \, dr \]

\[ = \frac{4 \pi Q}{w \cdot K} \int_0^L dr \]  \hspace{1cm} (19)

\[ = \frac{4 \pi Q \cdot L}{w \cdot K} \]  \hspace{1cm} (20)
Since
\[ Q = C P \]
\[ C = \frac{K w}{4 \pi \ell} \] (21)
in electrostatic units per centimeter length of plate, or
\[ C = \frac{0.088 \times 10^{-13}}{K w} \] (22)
farads per centimeter length of plate.

From Equation (19) we can deduce the expression for the potential gradient as
\[ \frac{dP}{dr} = \frac{4 \pi Q}{w K} \] (23)

Hence, the velocity of precipitation is
\[ V = k \frac{4 \pi Q^2}{w K} \]
\[ = \frac{k}{K} \times \frac{4}{w} \times C^2 \times E^2 \] (24)

where the same symbols are used as before, in (16).

The similarity of expressions (16) and (24) indicates that the parallel plate system is simply an extension of the concentric cylinder system. This similarity becomes more marked as the number of wires in the former system is reduced. The character of the electrode surfaces in either case greatly influences the results derived above.

The force due to the velocity of gases through a flue tends to carry along particles after they have been agglomerated and deposited. The resultant force acting upon the particles is that due to the electrical force and to the inertia of the particles, so that the importance of using long precipitation chambers and of increasing the length with an increase in the velocity of the gases, is emphasized.
III.

-APPARATUS USED-

The apparatus used in these experiments consisted of a 45 kilowatt motor-generator set, a 100 kilowatt, 500-1000-2000 / 200,000 volt, 60 cycle transformer, a rotary voltage rectifier driven by a 10 horse-power motor running in synchronism with the primary circuit, and a precipitator. Figure 3 is a diagram of the connections.

![Figure 3](image)

The motor-generator set was much larger than was necessary, but was the most available machine for the purpose. The frequency of alternation could be controlled through the field of the motor, and the voltage through the field of the alternator, both by rheostats mounted on the main switchboard.

It is noticeable that all circuits were thoroughly grounded, the center point of the high tension winding of the
transformer being grounded permanently to the core, which in turn was connected to earth.

Figure 4 is a view of the transformer, choke coils, and switchboard, all contained in a separate room. This room was lined on all sides with an iron grating which, together with all metal parts in the room, was thoroughly grounded. The rectifier was placed upon the platform shown in the rear, and the unidirectional voltage carried from here out through the rear of the room to the precipitator.
Figure 5 is a diagrammatic sketch of the switchboard and transformer connections.

Figure 5.

Power is supplied from the alternator, driven by a direct current motor, to the main switchboard shown at the left in Figure 4. Meters for measuring the voltage, current, power and frequency are contained in glass-covered drawers in the front of the board and connections so made that when the drawers are pulled out, all meter circuits are broken. A short-circuiting switch, however, leaves the other circuits complete. One single-pole and two double-pole switches control the alternating supply and distribute current to the various meters. A single-pole switch is in the alternator field.
From the main switchboard, power is carried to the auxiliary board shown at the right in Figure 4, where an arrangement of switches permits of the transformer ratio being changed from 500, 1000, or 2000 to 200000 volts.

An auxiliary winding is provided on the secondary side of the transformer to be used in voltage measurements. The connections from this winding are taken to a sorting receptacle on the auxiliary board where a ratio of 200,000 to 400, 200, or 100 volts may be obtained. This lower voltage is then taken back to the main board where the frequency, watts, current, and voltage may be read from it. An ammeter shunt gap and an auxiliary ground gap are provided in this secondary winding.

The voltage wave taken from the 45 kilowatt generator used for this work was somewhat distorted. An analysis of the wave showed that its effective value was .672 of its maximum value instead of .707 as in a sine wave. The transformer itself had practically no distorting effect on the wave. Figure 6 shows two waves taken on the secondary side when no power was being taken from the transformer, the voltages being respectively 70,000 and 150,000, effective values. An analysis of these waves shows the same ratio, .672, to exist.

When a voltage near the disruptive value is impressed on a series of electrodes, occasional flash-overs occur, and high frequency oscillations follow. In order to reduce the effect of these surges and to limit the rush of current incident to flash-overs, an air-cored inductance coil and a set of flake-graphite resistance rods were placed in each high tension line between the transformer and the rectifier. Later
tests showed the choke coils to have less effect than might be imagined, hence they were discarded. It is reasonable to believe that a very large number of turns on a coil, or the use of an iron core would be an aid in reducing the evil effects of the surges.

Effective Voltage - 70,000.

Effective Voltage - 150,000.

Figure 6.
b - Rectifiers.

Three distinct types of voltage rectifiers were used, each designed to rectify a portion of the alternating wave and each possessing its peculiar advantages. A 10 horse-power, two phase, 4 pole, 1800 R.P.M., synchronous motor (started on both phases, but operated single phase) was used to drive the rectifiers, but a much smaller motor could well have been employed. A flexible leather coupling joined the motor to the rectifier.

A sketch of the first type of rectifier is given in Figure 7.

![Figure 7](image_url)
This is of the brush-contact, disc type, alternating voltage being brought to segments on the discs through brushes which bear on slip-rings at the outside of the two discs. Unidirectional voltage is taken from two sets of two brushes each, which bear directly on the periphery of the discs and are brought into contact with the segments embedded thereon. The discs are hard poplar, thoroughly dried and cross-grained to increase their strength. They are 12 inches in diameter and 1 inch thick, and are pinned to an oaken axle which revolves in hard maple bearings. Brass segments, of such length that 90° of the impressed wave is rectified, are imbedded in the periphery of the discs, being flush with a 12 inch circle. Two wire brushes, 90° apart, bear on the discs and take off the rectified voltage.

The particular advantage of this type of rectifier lies in the fact that oscillograms may be taken on it, and its action thoroughly studied before it is actually put into practice on high voltages. Figure 8 shows an oscillogram of the rectified and impressed voltages from this machine (the two waves being to different scales, however.) It is seen that the most advantageous portion of the wave, from 45° to 135°, was taken off.

In analyzing this wave, let us assume that the impressed voltage is a pure sine wave, so that

\[ e = E \sin \phi \]  

(25)

where "e" is the instantaneous value of the electromotive force, and "E" its maximum value, while "\( \phi \)" is the angle of displacement. As is seen from the oscillogram, some higher
harmonics occur, but their effect happens to be very slight. By definition, the effective value of an oscillating wave is

$$E_{\text{eff.}} = \sqrt{\text{mean } e^2} \tag{26}$$

so the effective value of the rectified wave over 180° is

$$E_{\text{eff.}} = \sqrt{\frac{1}{\pi} \int_{\frac{\pi}{4}}^{\frac{3\pi}{4}} E^2 \sin^2 \phi \, d\phi} \tag{27}$$

But,

$$\int \sin^2 \phi \, d\phi = \frac{1}{2} \{ 1 - \cos 2 \phi \} \, d\phi$$

$$= \frac{1}{2} \{ \phi - \frac{1}{2} \sin 2 \phi \}$$

$$= \frac{\phi}{2} - \frac{\sin 2 \phi}{4}$$

$$= \frac{\phi}{2} - \frac{\sin \phi \cos \phi}{2} \tag{28}$$

Substituting (28) in (27)

$$E_{\text{eff.}} = \sqrt{\frac{E^2}{\pi} \{ \frac{\phi}{2} - \frac{\sin \phi \cos \phi}{2} \}^{\frac{3\pi}{4}}} \int_{\frac{\pi}{4}}^{\frac{3\pi}{4}}$$

$$= E \sqrt{\left( \frac{3\pi}{8} - \frac{\pi}{8} + \frac{1}{4} \right)^{\frac{1}{2}}}$$

$$= E \sqrt{.408}$$

$$= .64 \, E \tag{29}$$

Then a voltmeter of the induction type on the rectified side would read .64 of the maximum value of the wave, when the portion shown is taken off. An actual test gave a ratio of .639.

The average value of a sine wave between the same limits as considered above, is

$$E_{\text{ave.}} = \frac{E}{\pi} \int_{\frac{\pi}{4}}^{\frac{3\pi}{4}} \sin \phi \, d\phi \tag{30}$$

$$= \frac{E}{\pi} \left[ -\cos \phi \right]_{\frac{\pi}{4}}^{\frac{3\pi}{4}}$$

$$= \frac{E}{\pi} \left[ \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}} \right]$$

$$= .45 \, E \tag{31}$$
Thus a permanent field voltmeter, such as is ordinarily employed on direct current circuits, would read .45 of the maximum value of the rectified voltage. An actual test showed a reading of .437.

The highest voltage obtainable with this form of rectifier is 77,700 volts, maximum value. At this tension, flash-over occurred around the periphery of the disc, from segment to segment, and followed the rotation of the disc in such a manner as to indicate that a film of ionized air was carried along on account of its own viscosity. Radial vent holes in the discs caused freer circulation of air, and raised the flashing point somewhat.

The second type of rectifier, shown in Figure 9, consists of two brass rods, 30 inches long and 3/8 inch in diameter, fixed at right angles, 15 inches apart along the hard oak shaft which revolves in hard maple bearings. One rod is in each line of the alternating supply, receiving its voltage through brass slip rings, similarly as before.
Unidirectional voltage is taken from two sets of brass pole shoes, shown in the photograph, which are such length as to rectify $90^\circ$ of the wave. The shoes can be lowered or raised to give any desired clearance from the rotating rods, and clamped in position. A clearance of about $1/4$ inch was used in all our experiments. When the potential gradient across the gap between the rods and the pole shoes is sufficient to cause sparks to jump across, high frequency oscillations result on account of the capacity and inductance of the system. Figure 10 shows the discharge between the rods and the shoes, (a) being an instantaneous exposure, while (b) is a time exposure. It is noticeable that the spots which indicate the maximum points of the oscillations occur at about the same point in each revolution. Twelve dots can be counted over the length of the pole shoe, and as this represents $1/4$ of a complete cycle, and as the frequency of the impressed electromotive force is 50, the frequency of the oscillations is thus seen to be 2400. The results here shown checked very closely with oscillograms taken at the same time.

(a)  
(b)  
Figure 10.
The highest voltage obtainable with this machine is 106,000 volts, maximum value. At this voltage, flash-over occurs between pole shoes of opposite polarity. Figure 11 is a diagram of the connections used for taking oscillograms of the high tension voltages and currents of this machine.

Figure 11.

The auxiliary winding of the transformer is used for the alternating waves, while the rectified voltage is carried through two sets of high resistance rods, grounded at their center, and the oscillograph element shunted across a portion of the resistance. The three resulting waves of alternating voltage and current and of rectified voltage, or current, are shown in Figure 12. The high frequency oscillations are very apparent and make an analysis of the wave extremely difficult. It will be noticed that the rectified wave is in phase with the alternating current wave, which fact would be expected, since the rectifier simply turns over the negative loop of the current wave.
Figure 12.

The third form of rectifier, together with the driving motor, is shown in Figure 13. This is of the rotating disc-

non-contact type, alternating voltage being applied to two sets of discharge points, one of which is dimly seen on the
left in the picture, while the rectified voltage is taken from two similar points shown on the top of the posts at the right of the discs. These discs are of dried poplar, 18 inches in diameter, and 1 1/2 inches thick, spaced 14 inches along the axis. They are fastened to a 4 inch wooden shaft which revolves in metal bearings on metal journals. Four raised brass segments on each disc, of such length as to rectify 64° of the wave, show lighter just above the posts, and are interconnected by # 10 rubber-covered wire encased in 3/16 inch rubber sheaths. The connections are as shown in Figure 14.

From the nature of the connections, it is seen that flashover must occur around one-half the periphery of the discs, or from one discharge point to the other, as segments of opposite polarity are on opposite sides of the discs. It is this feature of the rectifier that increases its insulating value, and permits of a voltage of 184,000 volts, maximum value, being applied before breakdown occurs. The great weight of the machine is, however, objectionable, as a comparatively large amount of power is required to drive it.

From an electrical standpoint, the insulation, and
from a mechanical standpoint, the serviceability, of a rectifier are the deciding factors in its design. On this account, a combination of the second and third types, making a light, serviceable, and well-insulated machine, without the use of wooden discs, would seem desirable.

Either of the rectifiers can be adjusted to rectify any portion of the alternating wave, by shifting the relative position of the revolving parts of the rectifier and of the motor, by means of the adjustable coupling. Two methods of determining the most desirable position for the parts are plausible. The rectified voltage may be cut across high resistance rods and a low-reading ammeter, the rods being grounded at their center. The rotor may then be shifted until the ammeter reads the highest value at any impressed voltage, which indicates that the maximum portion of the wave is being rectified. An ammeter on the alternating side will indicate the same result. The second method is to adjust the parts until a uniform spark is obtained over the entire length of a pole shoe when the direct current brushes are short-circuited. The latter method is applicable only to the last two types of rectifiers.

c - Precipitators.

The first form of precipitator used consisted of an asbestos lined, wooden flue, 2 feet square and 10 feet high with a window near the top through which the process of precipitation could be watched, and access gained to the electrodes. This flue was placed over a brick fireplace in which
various materials were burned, and to which a draft of air was supplied to accelerate conflagration. Figure 15 shows a front and a side view of the apparatus with parallel wires and plates in position. The plates and wires were held in position by insulated bushings projecting through the sides of the flue. As the gases passed up the flue, they were forced between the plates and wires, received a charge, and the heavy particles precipitated.

![Diagram](image)

**Figure 15.**

The next step was to use two concentric cylinders, a small rough pipe within a smooth 10 inch pipe, supported horizontally, with one end attached to the wooden flue opposite the window. The gases were forced out this pipe from the flue, and thus the effect of various pipe lengths and of the variation of the amount of precipitate with the distance through which the gases pass in the electric field, could be conveniently studied.

The next step was to erect the concentric cylinder
electrodes vertically in order to correspond as nearly as possible with a commercial chimney. In this manner, the effect of the process on flue gases could be studied more advantageously. Both electrodes were insulated from the ground and from the fireplace beneath, by resting them on an insulating box. Figure 16 shows the method of supporting the pipes. A 2 inch pipe is shown as the inside electrode, this being used to give rigidity to the apparatus. The same principle applies to this as would apply to a smaller wire, but a lower voltage is required here than would be required with the smaller wire.

A flash-over can be seen occurring at the top of the pipe to the right. Voltage was just being applied, and a dangerous value was reached for an instant. The insulating support at the bottom is not seen.
IV. Precipitation Experiments.

The action of the three types of rectifiers insofar as the resulting wave is concerned, was practically the same, hence, more extensive use was made of the second type on account of its lower power consumption. The concentric cylinder principle was made use of for a precipitator, as the results obtained with either this or the parallel wires and plate type are practically the same, and this form was more suited to our conditions. The adaption of either form in commercial installations would depend on the local conditions actually encountered.

The character of the fumes is the deciding factor for the material of which the electrodes are composed, corrosive gases requiring special attention. The most corrosive gas encountered was that from which $\text{Hg}_2\text{SO}_4$ was precipitated, and for this, either a lead pipe and asbestos-covered wires, or tile with a stream of water flowing over it were used as electrodes.

A 3 foot pipe had very little effect on the composition with the voltage either on or off. A 10 foot pipe was next used, and with the small velocity of gases, precipitation was practically complete. The striking effect produced when the voltage is applied is shown in Figure 17, which gives two views taken a few minutes apart with the same exposure, but with the voltage respectively off and on. The length of pipe to be used is dependent upon the velocity of the gases in the flue upon which precipitation is to be
performed. A strong draft will carry along the particles even after they are agglomerated, and the pipe must be long enough that the path of the path of a particle, which is determined by the resultant of the electrical force and the force of the draft, will end within the pipe. No apparent stoppage in draft other than that due to the presence of the electrodes themselves within the pipe was noticeable when voltage was applied. The movement of the gases from the negative to the positive electrodes can be plainly seen,
being more pronounced at the end where the gases enter the field.

In order to show the relative amounts of precipitate at various points after the gases had entered the flue, strips of light paper the length of the pipe were attached to the inner surface of the larger pipe. The hydrocarbons from coal and oils gave a brown deposit on this paper, shading from a very dark brown at the point where the gases enter to an almost white at the point of leaving. The shading seems to follow somewhat a hyperbolic law, but this would evidently be influenced by the velocity at which the gases move.

As has been pointed out under II, best results are obtainable when the inside wire is used as the negative or precipitating electrode, while the outside pipe is the positive or collecting electrode. The effect of the reversal of polarity is shown in Figure 18, (a) and (b), which are samples of the paper inserted when combustion had gone far enough that almost all the hydrocarbons had been burned out of the coal. Figure 18 (c) is a sample taken a short time before (a) and (b), with the rod negative. (a) was taken when the rod was the negative electrode, and (b) when the pipe was the negative electrode. These samples were all taken near the center of the pipe with a voltage of 40,000, effective value applied for four minutes. In a similar manner, the variation of voltage and the amount of precipitate was studied, and the results seem to agree with the theory, namely, that the velocity of precipitation is proportional
Original Paper. Figure 18.
to the square of the voltage.

The power required was found to be very small, being practically equal to the corona loss. Table I gives the results of a typical loss test, while Figure 19 is a graphical representation of the same.

Figure 20 is a typical oscillogram taken from the apparatus under working conditions, showing the impressed voltage and current and the rectified voltage. Figure 21 shows the primary, secondary, and rectified voltages. It is noticeable that the high frequency oscillations set up by the spark gaps are carried back to the primary of the transformer.

Figure 20.

Figure 21.
It is often impossible to have an auxiliary winding on a transformer for reading voltages on the secondary side, and since readings taken on the primary side are not always indicative of the maximum value of voltage on the secondary side, use might well be made of a spark gap. For this purpose, an apparatus similar to that used by the Westinghouse Electric and Manufacturing Company, and described by Messrs. Chubb and Fortescue in the Proceedings of the American Institute of Electrical Engineers for February, 1913, was found very satisfactory. Ten inch (25 centimeter) spheres were used, and the results obtained were practically identical with those obtained by the above gentlemen. Table II gives the results of this test, while Figure 22 is a curve for this data.

It would seem advisable to use a condenser in parallel with the precipitator in order to maintain the rectified voltage wave and so prolong its effect, but our experiments indicated that the natural capacity of the system is sufficient, and that a separate condenser gives no better results.
V.

Conclusions.

It has been proved that the process of precipitating suspended particles from gases by means of high voltages is both theoretically and practically correct. It thus remains only to reduce the process to a smooth commercial basis. The low power loss and the possibility of reclaiming byproducts by the application of this process indicate that it can be made to not only pay for itself, but actually to return a profit. Its application to smelters and refiners for ridding their waste gases of dangerous materials seems to offer an extensive field for the process. Also, the clearing of furnace gases for use in gas engines presents a particularly lucrative field, while a solution of the smoke problem in our large cities will seem to have been found when commercial apparatus, universally applicable, has been adopted. There are still many problems in connection with the process that must needs be worked out, but it is the hope of the writer that the present thesis may form a firm ground for future development.
VI.

Bibliography.

Corona and Dielectric Strength of Air - F. W. Peek - General Electric Review - December, 1912.


The Sphere Gap as a Means of Measuring High Voltage - Peek - General Electric Review, May, 1913.


The Positive and Negative Corona and Electrical Precipitation Proceeding of A. I. E. E., June, 1913 - Strong.


Table I.

<table>
<thead>
<tr>
<th>Primary Voltage</th>
<th>Secondary Voltage</th>
<th>Core Loss Watts</th>
<th>Core Loss Line Loss Watts</th>
<th>Core-Line Precipitating Watts</th>
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<tr>
<td>24300</td>
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$f = 50$ cycles

All voltages given are maximum values.

Watts were read on the primary side.
May 20, 1914

H. C. Wolf

VOLTAGE-LOSS CURVE

Suspected in gases.

The Electrical Precipitation

Curves No. 1

Volts maximum
Table II.

Calibration of 10 inch Spheres.

<table>
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<th>Distance between Spheres (inches)</th>
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Above Values are at an average temperature of 60°F Fahrenheit.

Lower temperatures raise the required voltage.
The Electric Precipitation Curve No. 2

Volts (max. value)
- Maximum Values
- Our Values
- How
- 10 Suspended in Gases.
- Calibration Curve
- 10 Spheres

Inches

Distance Apart