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ADVANCES IN FINE PARTICLE CONTROL TECHNOLOGY

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ABSTRACT

Currently the technologies of choice for the control of fine particle emissions from large combustion sources are fabric filters and electrostatic precipitators (ESPs). As these two technologies compete, advances in both technologies and their hybridization hold promise for significantly reduced fine particle emissions from both new and existing sources. Recent improvements in fabric filtration include flue gas additives and electrostatic augmentation. ESP improvements include separation and optimization of particle charging and collection, fast-rise time pulsed energization, and hybrid ESP/fabric filtration concepts. Mathematical models which allow diagnosis of problems on existing systems and optimized design of new systems are also discussed.

INTRODUCTION

Recent studies in the United States point to fine particles as being a major environmental concern. These studies have focused on areas where the primary sources of ambient submicron particles are combustion and metallurgical operations. If regulations to reduce fine particle emissions are forthcoming, mandated additional control of combustion source particles is possible.

In view of the perceived need for better fine particle control technologies, it is important to review the more recent advances and their market status. Because the major combustion sources of fine particles are almost wholly controlled by either electrostatic precipitation (ESP) or fabric filtration (FF), the focus of this paper will be upon recent improvements and innovations in these two technologies.

NEW AND RETROFIT ESP IMPROVEMENTS

In recent years improvements in the ability to design new ESPs, upgrade existing ones, and to diagnose ESP problems and apply cost-effective solutions have been realized through the development of mathematical models for ESP simulation, simultaneous with the development of personal computers. One noteworthy model, ESPVI4.0, has been published by the U.S. Environmental Protection Agency (EPA) and is available (in English) worldwide for public domain use.[1] With this model, the user can simulate practically any ESP and use its output to assist in determining causes and potential solutions to poor performance, as well as assist in design of new ESP's. A training course is being prepared under U.S. EPA guidance for developing a core group of instructors which can train ESP operators in use of ESPVI4.0 in their native language. The first course to be taught will be to ESP experts from India.

Flue Gas Conditioning

The collection efficiency of an ESP is governed primarily by two characteristics of the particles to be collected,size distribution and their electrical resistivity. The particle size distribution exiting coal fired utility boilers is influenced by the coal, coal grind, combustion conditions and, perhaps, particle agglomeration. The opportunity to promote particle agglomeration in a typical flue gas stream prior to collection is quite limited because the particles are separated by several diameters with a low probability for particle collisions. There is a reasonable probability for agglomeration when the particles are collected as they form a distinct layer on the collection electrodes. The tendency for particles to agglomerate after collection (cohesivity) is related to the surface conditions of the individual particles. Small particles adhere to other particles by van der Waals forces. Particles with rough surfaces and those with surface layers of adhesive materials will tend to remain as agglomerates when removed from the plates. Therefore, the amount of material reentrained during rapping and from the normal vibrations associated with plant operation can be reduced if the surface of the particles can be modified to result in a cohesive ash.

The electrical resistivity of the particles directly influences the electrical conduction through the collected dust layer, and is the primary factor in the electrical behavior of the ESP. During normal operation of the ESP, the corona system generates free electrons (in negative corona) that quickly attach to electronegative gas molecules to form negative ions. Some small portion of these ions attach to the particles to provide the charge for interacting with the electrical field and being collected, while the remainder flow through the interelectrode space through the dust layer to complete the electrical flow path.

The flow of ions through the collected dust layer together with the applied voltage on the system establishes an electric field in the collected dust layer. The electric field in the layer can be expressed as the product of the electrical current density and the resistivity of the particles:

$$E = jp$$

where E is the electric field, j is the current density, and p is the resistivity of the collected dust layer.

When the resistivity of the particles is high, the electric field in the layer for a given current density increases. When the electric field in the layer increases above some critical value, on the order of 10 to 20 kV/cm, the field strength is sufficient to establish an electrical breakdown in the gas residing between the dust particles analogous to the corona around the discharge electrode. This electrical discharge in the layer limits the electrical operation of the ESP. First, if the resistivity is in the intermediate range (mid 10^{11} ohm-cm) the breakdown occurs when the applied voltage is sufficiently high to cause a spark to propagate across the interelectrode space from the positive to the negative electrode. Repeated sparking causes the automatic spark rate function to reduce the operating voltage to maintain the appropriate spark rate. A reduction in operating voltage leads to a reduction in collection efficiency in the ESP. Thus, the first limitation in performance from higher resistivity is sparking at reduced voltage.

If the resistivity of the particles is increased further to the high 10^{11} or 10^{12} ohm-cm range, the breakdown in the dust layer occurs at an operating voltage that is too low to propagate a spark. For this condition, the electrical breakdown in the layer is sustained and grows across the collected dust layer. This condition, termed back corona, generates positive ions across the dust layer providing an additional ion source for electrical conduction in the ESP gas stream. This positive ion conduction in addition to the negative ions from the corona electrode causes the power supply to operate at high currents and low voltages with a severe limitation on the collection efficiency of the ESP. The positive ions flow to the negatively charged dust particles, leading to a net reduction in their charge and therefore a reduction in the collection efficiency.

Sulfur Trioxide

The primary purpose for the use of flue gas conditioning is to reduce the electrical resistivity of the particulate matter, to allow the ESP to operate at higher voltages and electric field strengths. The most common flue gas conditioning agent for coal fly ash installations is sulfur trioxide (SO_3). The electrical resistivity of fly ash is a function of the chemical composition of the fly ash material; principally the concentrations of sodium, calcium, and iron, and the temperature and composition of the flue gas. Usually the coal contains some amount of sulfur in addition to the other customary constituents. When the coal is burned in the furnace, the sulfur is converted to sulfur dioxide (SO_2). Some percentage of this SO_2 is further oxidized to SO_3 (somewhere around 0.5%). If the sulfur content of the fuel is greater than about 1.5 to 2%, the native SO_3 is usually adequate to provide a resistivity in the appropriate range for efficient collection.

When the natural sulfur is insufficient to provide the amount of conditioning needed, SO_3 can be generated at the plant site for injection into the gas stream prior to the ESP. The more common conditioning system burns sulfur to generate SO_2 which is then passed through a catalyst where approximately 96% is converted to SO_3. This gas stream is then injected into the flue gas stream ahead of the ESP to provide a concentration of SO_3 that will reduce the electrical resistivity of the fly ash particles to provide good electrical operating conditions. The concentration of SO_3 required in the ductwork is on the order of about 10 parts per million (ppm) for operating temperatures of about 150^0C.

Ammonia

Ammonia has also been used for conditioning fly ash to improve ESP collection efficiency. It has been used successfully for conditioning hot-side ESPs that have exhibited the "sodium depletion" phenomenon that leads to the formation of a high resistivity dust layer that adheres tenaciously to the collection electrodes until severe cleaning occurs. The severe cleaning can be water washing, or either sand or wheat blasting. The mechanism by which ammonia conditioning improves performance is not yet determined, but there is conjecture that the ammonia molecule, which is electropositive, attaches to the positive ions generated in back corona and reduces their influence on ESP performance. The action of ammonia when injected is essentially instantaneous resulting in an immediate increase in operating voltage. Reversal is also very fast after the ammonia is removed from the system.

Ammonia has also successfully reduced rapping reentrainment from a unit burning high sulfur coal that generated a very low resistivity ash. The ammonia quickly combines with the native SO_3 to form ammonium sulfate-bisulfate which is very "sticky." This "sticky" ash helps to reduce ash reentrainment which occurs during rapping.

Combined Sulfur Trioxide and Ammonia

Both ammonia and SO_3 have been used in combination as conditioning agents. They have been applied to a lignite ash that did not respond readily to conditioning with SO_3 alone. Upon examination with an electron microscope, the appearance of the ash was very smooth (in contrast with most ashes) and the interaction between the SO_3 and ash was minimal. The combined injection of ammonia and SO_3 served as an effective conditioning agent, resulting in a reduction in resistivity and causing the material to become more cohesive. This combination of conditioning agents was successfully applied to fabric filter installations reducing both "bleed through" and the pressure drop across the fabric/dust layer combination.

Ammonium Sulfate

Ammonium sulfate has also been used as a conditioning agent. The net effect is approximately the same as the co-injection of ammonia and SO_3. The material is injected at temperatures of 350°C, which is sufficient to dissociate the ammonium sulfate. Once dissociated, the constituents act as if they were injected separately.

Moisture

Moisture conditioning also effectively reduces the resistivity of fly ash. Water is injected with two fluid nozzles with a size distribution and loading sufficient to humidify and cool the flue gas to decrease particle resistivity while avoiding droplet impingement on surfaces. The successful application of moisture conditioning at a utility plant in the U.S. has provided the motivation for other installations to consider this option[2].

Sodium

Sodium conditioning can be effective in restoring proper electrical resistivity to fly ash that is experiencing the development of high resistivity from sodium depletion. The application is primarily for hot-side units where the sodium oxide content of the fly ash is usually less than 1%. There is also the potential for use in cold-side units that may have very low amounts of sulfur in the coal and sodium in the fly ash. Sodium carbonate, or other sodium bearing compounds, is distributed on the coal prior to milling and fed into the furnace with the coal. The amount of material that is customarily injected is that necessary to bring the equivalent total sodium oxide concentration in the ash to about 1.5%.

Proprietary Agents

Proprietary conditioning agents have been marketed for several years. These materials have been formulated to provide changes to specific characteristics of the particles to be collected. These materials are sometimes combinations of some of the chemicals that are described above with an additional compound added to provide a modification to some other aspect of the particles. Ammonium sulfate and sodium compounds are common components of proprietary conditioning agents.

One of the more recent developments for conditioning has been developed by ADA Technologies in Englewood, Colorado. The material referred to as ADA-23 or FGC-23 was developed under the sponsorship of the U.S. Department of Energy and ADA Technologies. The material is reported to reduce the electrical resistivity of fly ash particles from both cold side (150°C) and hot-side (300°C) precipitators as well as increasing the cohesivity of the ash. The increase in cohesivity reportedly reduces the rapping reentrainment from the collecting electrodes in the precipitators and will also improve the performance of fabric filters by decreasing the pressure drop across the dust cake and reducing the particle penetration through the fabric dust cake system. This additive is currently undergoing full scale tests in the U.S. It is reported to effectively condition both eastern and western U.S. coal fly ashes[3].

Separation of Charging and Collection (Cold Pipe Precharging)

The cold pipe precharger (Figure 1) consists of a charging wire for high voltage and a pipe for the ground electrode, through which cooled water is circulated. The concept is intended to reduce the resistivity of dust collected on the cold pipe surface and achieve a very high level of charge on the entrained dust particles in a very short distance along the direction of gas flow. In laboratory, pilot and field pilot tests, the addition of cold pipe technology effectively overcame the negative effects of back corona, and significantly improved collection efficiency of ESPs operating with high resistivity dust.[4,5]

A simple application proposed for cold pipe technology is to minimize reentrainment emissions. Because reentrainment dust typically represents 70% of particle mass emissions from an ESP, and these emissions tend to be agglomerated into larger particles, placement of a cold pipe section at the ESP exhaust results in significant ESP performance improvement.[6]

By placing prechargers in front of each collection section, this new ESP concept is referred to as a multistage ESP. The high level of ESP performance by the multistage concept is mainly due to the separation of the charging and collection functions, and the optimization of each.

The SUPER ESP

The concept of the SUPER ESP (Figure 2) evolved from the multistage ESP by examining the performance predictions of ESPVI4.0 for conventional and multistage ESP sections of varying lengths and numbers of wires. As shown in Figure 3, a wire-pipe section containing 3 or 4 wires is capable of equal performance to that of a 7- or 8- wire conventional ESP section for low resistivity ash, or to a 12- to 14- wire section for high resistivity. This implies that a SUPER ESP can be constructed at one-half to one-fourth the size of conventional ESPs at the same performance level. In summary, multiple pairs of individually energized prechargers with short collector sections have replaced the long, individually energized sections of conventional ESPs.

In addition to cost advantages due to a smaller ESP, another benefit of using SUPER ESP is elimination of the need for flue gas conditioning.[7,8]

Electrical Energization

Historically the conventional precipitator power supply controls have been equipped with current and voltage limits to protect the transformer-rectifier assembly and a spark rate control to maintain as high an average operating voltage as possible. These controls attempted to optimize the performance of each power supply independently. They were effective for maintaining the operation of the ESP except the case of reverse ionization or "back corona" caused by collecting high resistivity particles.

The limitations in performance caused by back corona are associated with the formation of positive ions in the dust layer on the collection electrodes. The current flow through the collected layer establishes an electric field in the layer that is proportional to the product of the resistivity and current density. When the electric field in the layer exceeds the electrical breakdown field strength in the layer, a localized corona forms in the interstices of the dust layer. For the case of negative corona, the back corona generates positive ions that flow into the interelectrode space and tend to discharge the previously negatively charged particles, reducing collection efficiency. In order for the power supply controls to function properly with high resistivity dusts, an additional control parameter was needed.

Computer Based Control Systems

The development of the modern personal computer (PC) provides an additional capability for power supply controls for ESPs. The computer can be programmed to search through the various measured parameters and work to optimize performance based on items other than those in conventional systems. The computer can identify the existence of back corona and establish a current and voltage setting that would either avoid or minimize the influence of the back corona. The shapes of the V-I curve and the secondary voltage waveform provide the information necessary to maintain the secondary current density at a level low enough to minimize the deleterious effects of back corona.

The PC-based control system also provides the opportunity to use non-conventional energization techniques. The Mitsubishi Company in Japan has developed an approach to energization that they term "Intermittent Energization." In intermittent energization the rectifier circuit is programmed to pass one or two half cycles of energization and then skip some number of cycles. The computer searches through a number of alternatives to determine the appropriate number of cycles to energize and the number to skip to maintain the maximum value of the average voltage with a current density low enough to avoid back corona. This capability exists in almost all PC-based control systems.

Pulse Energization

Pulse energization provides a high operating voltage with a low average current density and provides for a more nearly uniform current density distribution on the collection electrodes. Conventional negative corona consists of individual tufts of corona distributed along the corona electrode, while positive corona is very uniformly distributed over the corona electrode. The more uniform corona causes a more nearly uniform current distribution on the collection electrode. If the voltage waveform used for energization has a very fast rise time, on the order of a few microseconds, the negative corona exhibits the appearance of positive corona. The entire corona electrode glows uniformly, rather than developing the tufts characteristic of fully developed negative corona. A typical pulse energization system will operate with pulse voltages on the order of 100 kV rather than the 50 kV value expected for conventional energization. The pulse repetition rate is set to provide an operating current density low enough to avoid the formation of back corona.

HYBRID FABRIC FILTRATION/ESP

COHPAC I and COHPAC II

The Electric Power Research Institute has developed an upgrade retrofit technology for utility installations operating with an ESP currently not meeting the U.S. New Source Performance Standards (NSPS) for atmospheric discharge of any gases which contain particulate matter in excess of 13 ng/J (0.03 lb/10^6 Btu) heat input derived from the combustion of solid, liquid, or gaseous fuel. The technology can be applied to an older installation installed before the new emission limits were required, or one meeting NSPS for particulate matter, but for which changing the fuel supply to a low sulfur coal to meet the SO_2 emission limits is being considered. The technology is known by the acronym COHPAC, from COmpact Hybrid PArticle Collector.[9] The retrofit installation consists of a pulse jet fabric filter system operating at very high gas-to-cloth ratios to remove the uncollected particles that pass through the lower efficiency ESP.

The less than optimum operating ESP is expected to provide collection efficiencies in the high 90% range with outlet particulate emissions on the order of 43 to 86 ng/J (0.1 to 0.2 lb/10^6 Btu). Thus the ash loading into the COHPAC unit is low. This low loading allows the pulse jet fabric filter to operate at very high face velocities without rapidly developing a very thick dust layer on the fabric filter material[10]. In addition, the particles that are to be collected are electrically charged, having previously passed through the ESP. Electrically charged particles form highly porous dust layers in fabric filters[9] that exhibit very low pressure drops for a given dust loading. The particle loading and dust layer characteristics provide the conditions for effective operation of a relatively small pulse jet fabric filter.

Two versions of COHPAC are in various stages of development. COHPAC I involves the installation of the fabric filter assembly downstream from the ESP in a separate structure. The original ESP remains in its normal condition and the COHPAC I assembly is added. Pilot scale testing of this concept has been conducted[11,12] and the results of these pilot tests indicate that COHPAC I will operate reliably with face velocities of 3 to 3.6 m/min (10 to 12 ft/min).

The COHPAC I concept has been pilot scale tested at a large utility. The favorable test results guided the utility to a decision to install a full scale COHPAC I unit at that site. The station is equipped with hot-side ESPs that have been in operation since the late 1960s. The COHPAC I retrofit is currently in progress and scheduled to be completed by December 1996.

A second version of the technology is known as COHPAC II. In this variation, the outlet field of the existing ESP is removed and replaced with the internals of a pulse jet fabric filter.

This installation should be somewhat less expensive to build than COHPAC I and lends itself to installation in power stations without available space to construct a fabric filter. The COHPAC II arrangement results in placing a greater particulate loading on the fabric filter assembly, which may limit the allowable face velocity and increase the required cleaning frequency of the unit. An existing EPRI pilot scale ESP was converted to the COHPAC II configuration for testing on a slip stream from a pulverized coal boiler. The unit operated very well on both U.S. eastern bituminous and Powder River Basin sub-bituminous coals[13].

Electrostatically Stimulated Fabric Filtration (ESFF)

Fabric filtration, in the form of baghouses, is a major technology in the control of particle emissions. The two categories of baghouses, shown in Figure 4, are the reverse air (inside to outside flow) and pulse-jet (outside to inside flow). Because of the ability to handle higher gas volumes for a given bag surface area, pulse-jet fabric filters have become more popular. Dust is emitted from baghouses due either to leaks, holes in the fabric or improper seals between the bag and bag support cage; or to penetration of the fabric by a particle. Another negative aspect of fabric filtration is the high pressure drop across the dust cake, compared to that of ESPs.

Previous work in the application of electrostatics to improve fabric filter performance included charging particles prior to collection, collecting particles in an electric field, and combining charging and collection.[14] Most efforts reported significant pressure drop reduction. Recent work by the U.S. EPA has hybridized ESP and fabric filtration with the two concepts shown in Figures 5 and 6. Figure 5 shows a conventional reverse-air baghouse which has:(1) corona discharge wires axially inside each bag, (2) bag fabric made somewhat conductive by adding conductive fibers to the woven bag, and (3) an electric field developed between the electrode and bag surface by a conventional ESP power supply.[15]

Figure 6 shows the same principles applied to a pulse-jet baghouse, wherein the corona wire is located at the centerline of each four-bag array, within the baghouse, external to the bags. An innovation involves placing a pulse-jet ESFF array within the last section of an ESP, shown in Figure 7. Mathematical models developed on bench-scale data indicate that this concept can improve ESP efficiency by increasing particle capture and reducing fabric penetration, by greater than 90% over base performance with the pressure loss of 10 to 30% of a fabric filter.[16]

CONCLUSIONS

A number of promising new concepts have been identified which promise to improve performance and cost-effectiveness of current technologies. Hybrid fabric filter/ESP concepts have the most potential to lower emissions of fine particles significantly.

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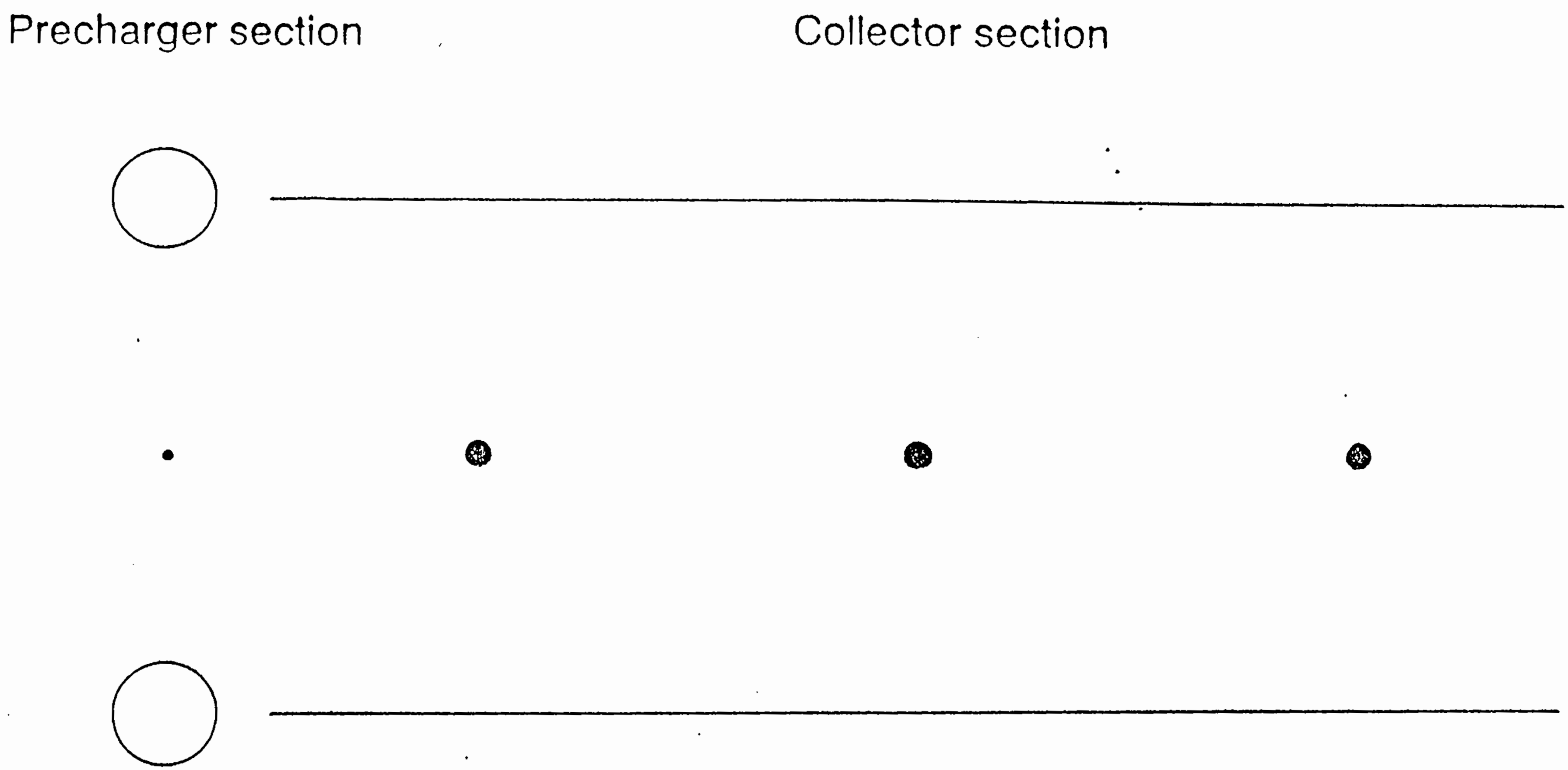

Figure 1. ESP Section with Cold Pipe Precharger

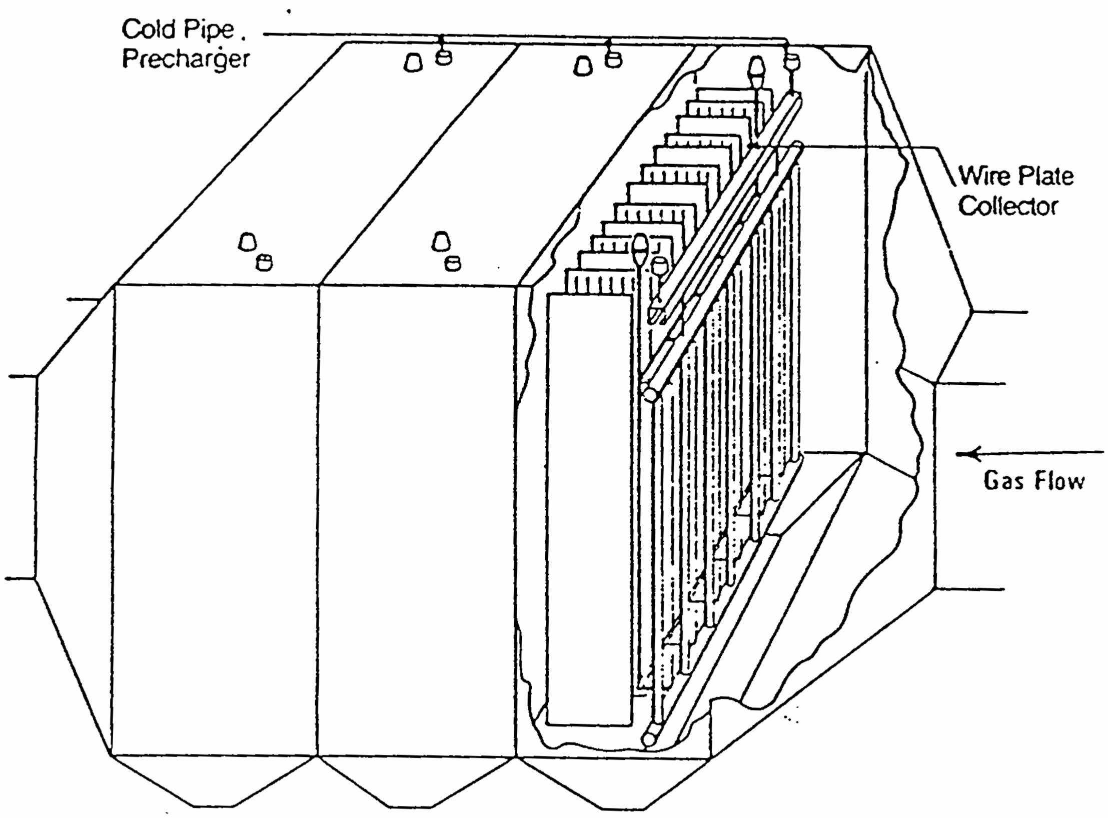

Figure 2. Multi-Stage Electrostatic Precipitator

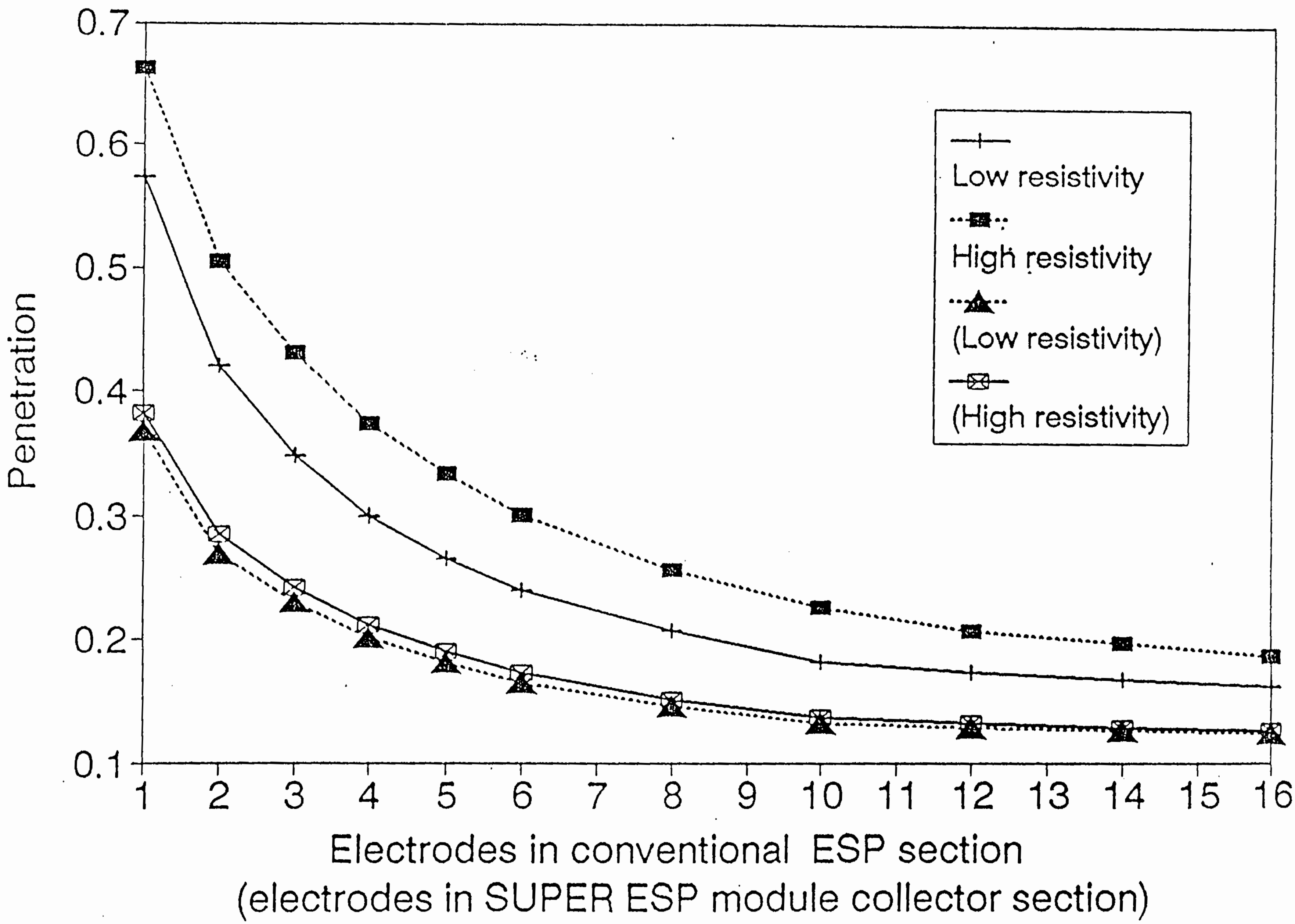

Figure 3. Predicted Super ESP and Conventional ESP Performance

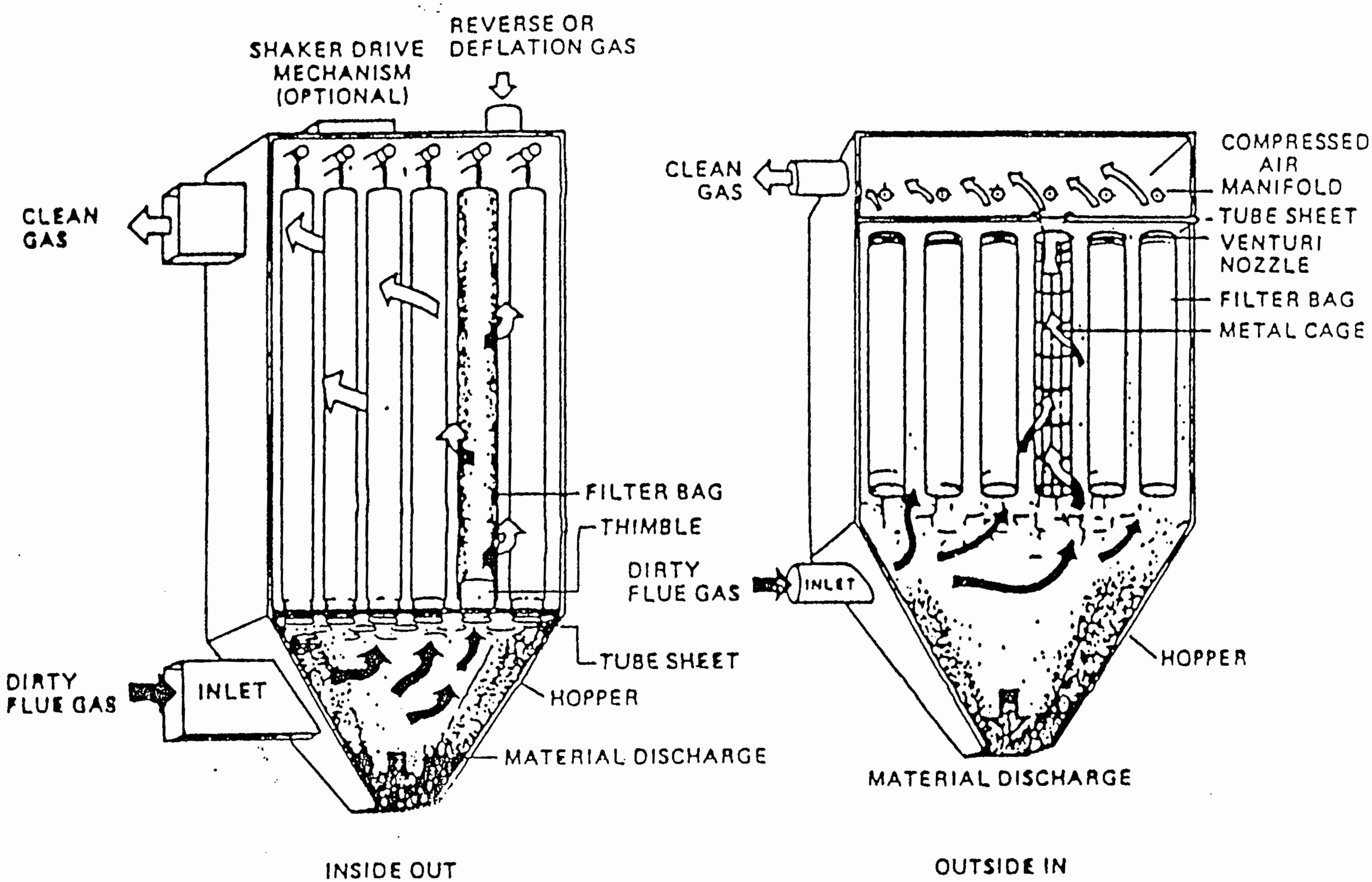

Figure 4. Reverse Air and Pulse Jet Baghouses

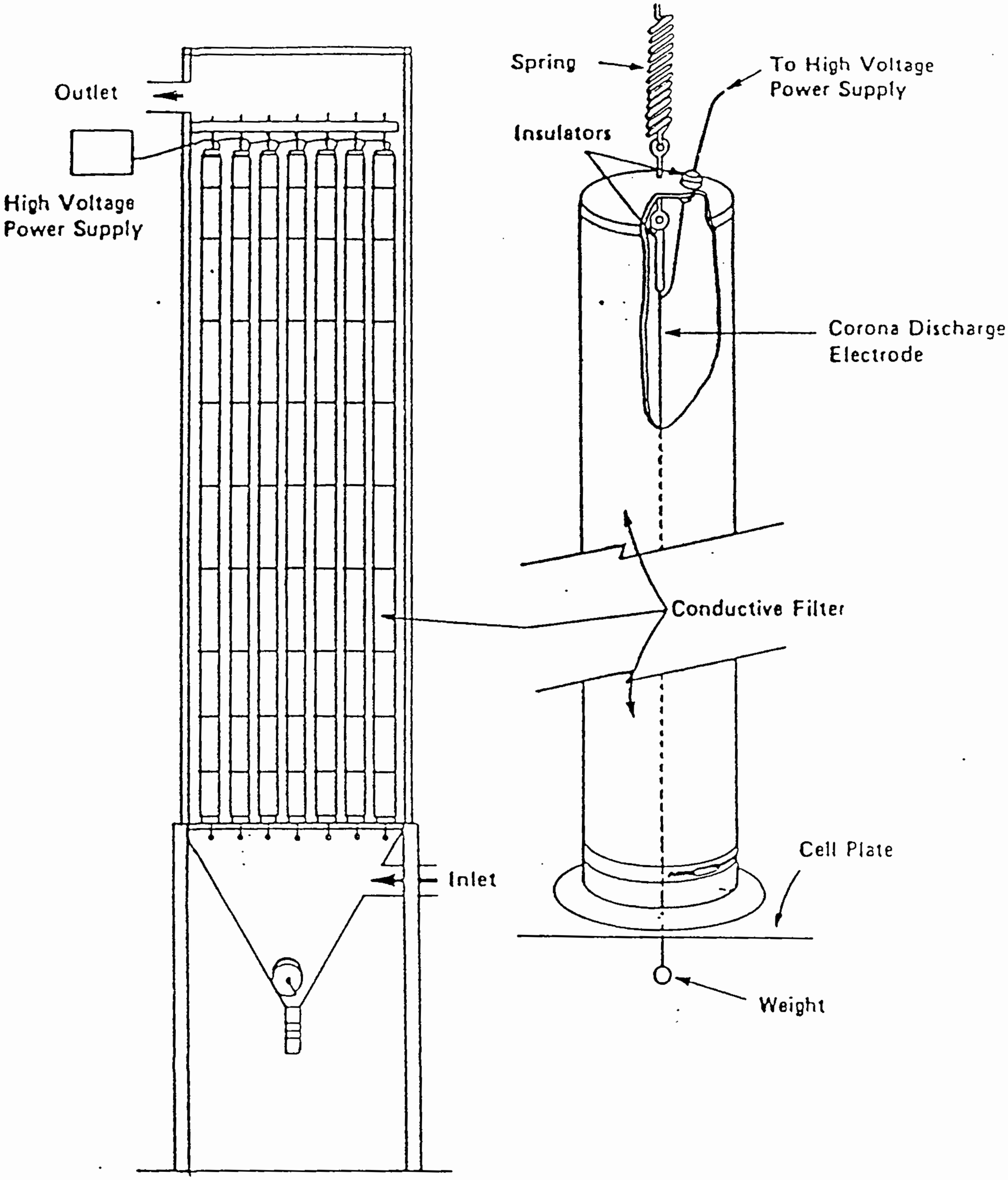

Figure 5. Electrostatically Augmented Reverse Air Baghouse

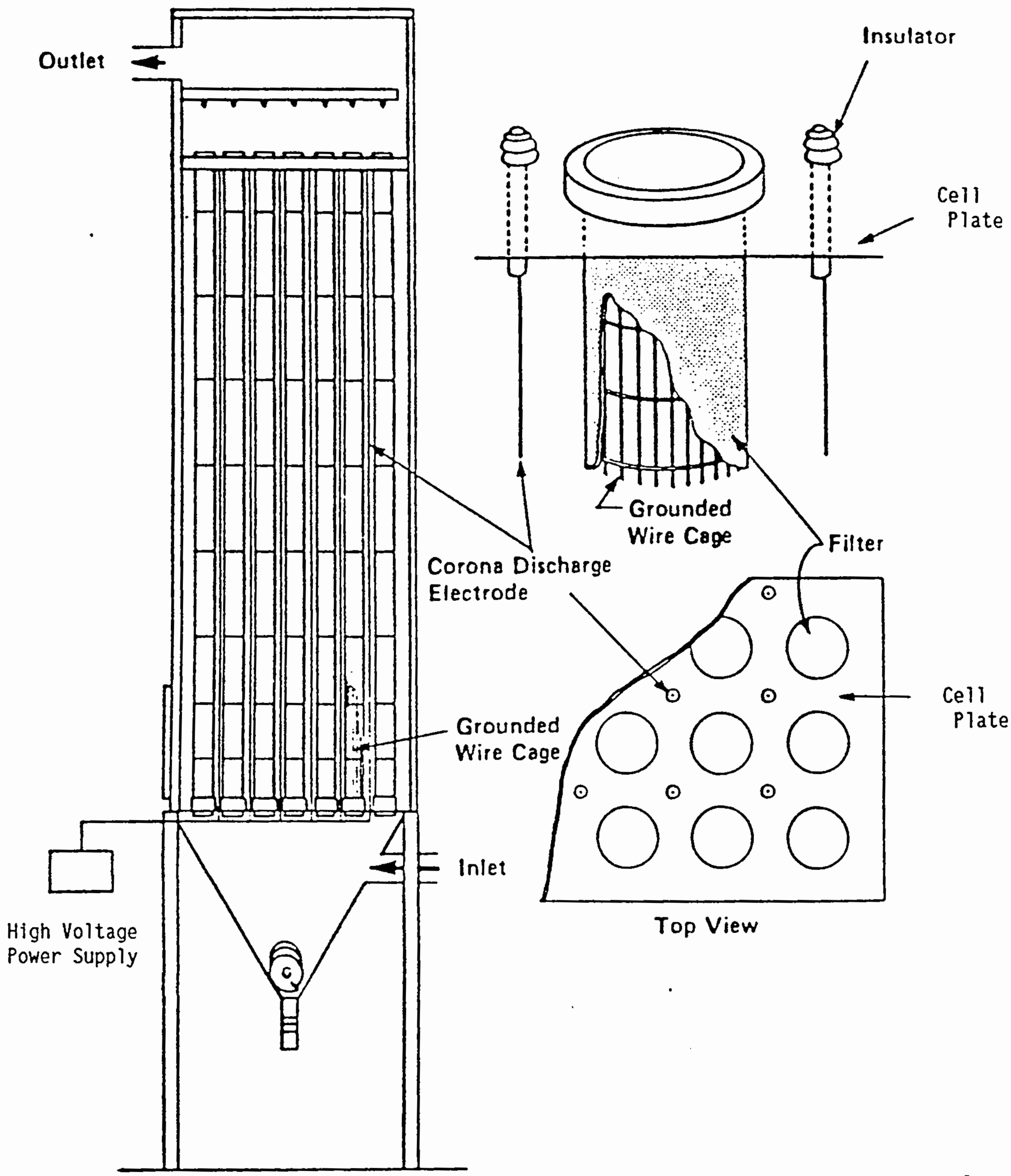

Figure 6. Electrostatically Augmented Pulse Jet Baghouse

1. PARTICLE LADEN GAS
2. ESP FIELDS
3. EXIT DUCT
4. INLET DUCT
5. INLET TRANSITION SECTION
6. ESP HOUSING
7. T/R UNITS
8. DIFFUSION PLATES
9. TUBE SHEET
10. T/R POWER SUPPLY
11. ESFF SECTION
12. PLENUM
13. OUTLET TRANSITION SECTION
14. BAFFLE PLATE
15. ESFF HOPPER
16. ESP HOPPERS

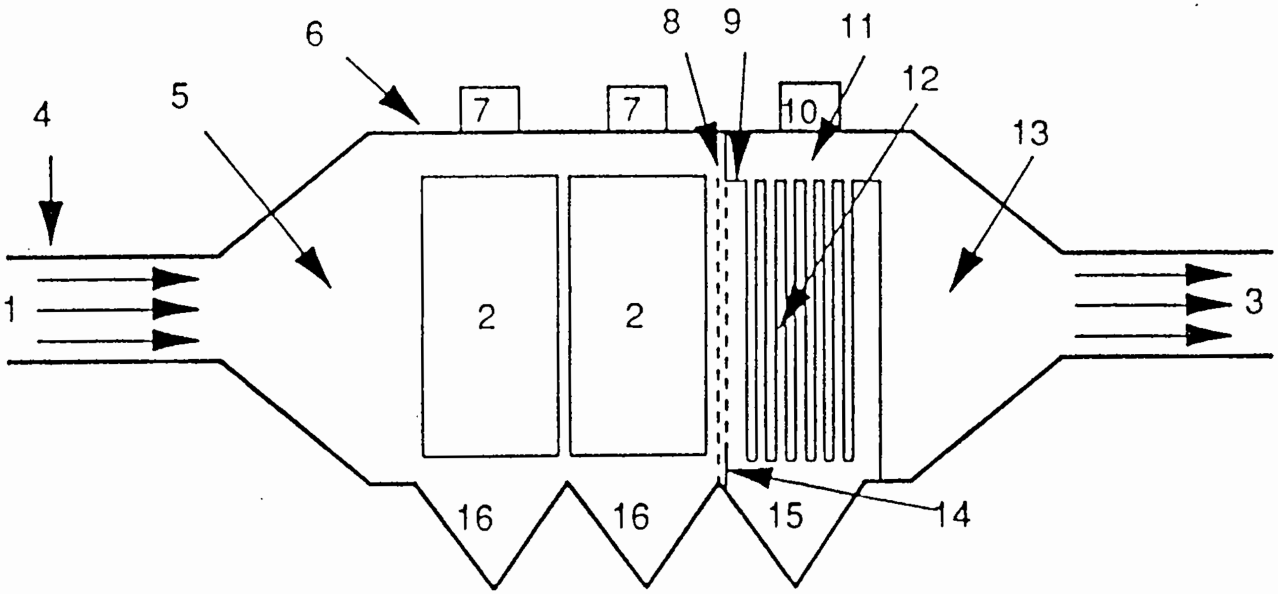

Figure 7. Hybrid ESP/ESFF

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Combustion		Particulate	21B
Filters		Fabric Filters	
Fabrics			11E
Electrostatic Precipitators			13I

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