THE EFFECT OF ELECTROSTATIC PRECIPITATORS ON COAL PLANTS

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Abstract- Electrostatic precipitators (ESP) were invented to remove particulate matter from air [1]. They are commonly attached to coal plants to extract particulate matter from the smoke released by burning coal [2]. ESPs operate by inducing a charge on the matter, causing it to gain a negative charge [3]. Then the gas mixture enters a channel with positively charged plates, causing the matter to cling to the plates [3]. After a maximum of 200 operational hours, the plates are vibrated to disconnect the particulate matter from the plates [4]. The matter falls into a receptacle so it can be collected and disposed [4]. ESPs are incredibly important to the health of society because they remove particulate matter from the air. Particulate matter is classified into two groups: PM10 and PM2.5. Due to its microscopic size, particulate matter can enter the bloodstream and lungs which can have severe health complications [5]. Excessive exposure can cause decreased lung function, irregular heartbeat, and aggravate asthma [5]. Coal plants produce a significant amount of particulate matter through their processes, and electrostatic precipitators can remove up to 99.8% of the particulate matter [6]. Removing most of the particulate matter is vital to the health of society, because it significantly reduces the amount of particulate matter that can cause health problems.

Key Words- Coal Plants, Corona Effect, Electrodes, Electrostatic Precipitator (ESP), particulate matter

OPERATION OF ELECTROSTATIC PRECIPITATORS

How ESPs Work

An ESP is a fascinating piece of technology, but it is also an excellent demonstration of electrostatic properties. The entire function and use of an ESP relies on these electrostatic properties to collect polluted particles in the air. An industrial scale ESP is a large, mostly hollow container to allow for airflow to pass through. The container is built with long stretches of negatively charged electrodes that distribute negative charges to particles. The process that gives off these electrons is the corona effect which discharges electricity into the air that flows through the ESP. The now negatively charged particles cling to the grounded and positively charged metallic plates, which constitute the ‘walls’ inside this airflow chamber. After filtering through the ESP, the now clean air flows out of the ESP into a smokestack to be dispelled into the atmosphere. As they are now precipitated out of the air, the particles now lie on the plates as collected soot. An ESP must have this soot removed after no more than a time period of 200 hours of use [17]. In order to remove the soot, the plates can either be power washed, or as of newer ESP models, be shaken off by plates that are attached to a motor that will shake them, forcing the soot to fall off [10].

IMPORTANCE OF ELECTROSTATIC PRECIPITATORS IN THE COAL INDUSTRY

Since the start of the Industrial Age, pollution has been a major problem for the environment in which the factories are located. Before the institution of the Environmental Protection Agency (EPA), companies would simply dump their waste into a nearby river or allow smokestacks to produce clouds of pollution that would make the skies black and suffocate people with plumes of smoke. As industry grew, so did technology. Today, technology allows us to continue to generate more products and energy for consumers to use. Since coal is one of the most abundant sources of power in the United States, it is a necessity to make sure that the pollution it generates is controlled [7]. One example of a technology to use for this purpose is electrostatic precipitators (ESP). ESPs allow for coal to be a viable source of energy, while also allowing the environment to remain pollution free.
BACKGROUND ON COAL

Types of Coal and Their Compositions

Before discussing the removal of coal particulates from the air, contents that make up coal must be identified and described. According to the Office of Indian Energy, coal is a combustible, sedimentary rock that mostly consists of carbons and hydrocarbons [8]. There are different types of coal that vary in their concentration of energy output. The composition of coal depends on the amount of heat and pressure the rock was exposed to inside of the Earth and how long the rock was subjected to that heat and pressure [8]. The four types of coal (listed from lowest to highest energy output) are lignite, subbituminous coal, bituminous coal, and anthracite [8]. Lignite is brownish-black in color and has the lowest energy output out of all four species [9]. Subbituminous coal is a gray-black color [8]. Bituminous coal has a higher energy output than subbituminous coal [8]. This is the most common species of coal in the United States [8]. Anthracite has the highest energy output of the four species of coal, due to its immensely compact structure [8]. This is the most sought after coal type because it has the highest energy output. However, anthracite only makes up 1.5% of domestic coal resources [8]. Figure 1 is a picture of anthracite coal. Coal is a greatly sought after energy source in the U.S., because it is relatively cheap to extract (compared to other energy sources) and it is a domestic source of energy.

42% of coal collected in the U.S. [9]. The fact that there is an abundant amount of energy that can be harvested domestically, versus shipping energy sources from overseas, contributes to coal being the cheapest energy source available [8]. Because it is cheap, local, and relatively easy to access, coal is the most popular choice for energy in the U.S.. The energy extracted from coal is primarily used for heating homes and generating electricity [8].

At a coal plant, coal is combusted to boil water [8]. The steam that is given off turns a steam turbine, which then produces energy in the generator [8]. The steam that is given off also contains particulate matter, carbon dioxide and other compounds released from burning coal. Since these compounds are dangerous to the environment in high levels, it is often required that they are removed from the air before it is released into the environment. One of the methods to remove particulate matter from the air is by utilizing an electrostatic precipitator.

COMPONENTS OF AN ELECTROSTATIC PRECIPITATOR

High Voltage Transformer

One of the main tools in an electrostatic precipitator is the high voltage transformer. The transformer is what provides electrical energy to the electrodes [10]. The transformer is absolutely necessary for the operation of ESPs because without them, the electrodes would not be able to maintain their negative charge [10]. The high voltage is necessary to create the corona effect which allows for dust particles from the air to collect on metallic plates [10]. Electrodes are attached to the sides of the ESPs' polluted air chamber. These electrodes are then wired to the high voltage transformer to deliver charge to the electrodes. The power being supplied to these electrodes is the same power that is being generated by the plant’s generators.

Electrodes

Another key element of ESPs is negatively charged electrodes. Nazaroff and Alvarez-Cohen from Dartmouth College describe the function of the electrodes is to deliver a negative charge to particulate matter as it passes through the polluted air channel [10]. Electrodes are placed on grounded conductor plates [10]. When particulate matter touches the electrode, the electrode transfers some of its negative charge onto the particulate matter [10]. A special design feature of electrodes is the addition of sharp corners to the

FIGURE 1 [8]
Example of anthracite coal

Reliance on Coal for Energy

Since coal can be harvested domestically, it is the United States’ prime choice for energy. About 50% of the U.S. energy comes from coal, more than any other energy source [9]. The U.S. has an estimated 275 billion tons of coal buried underneath its surface [9]. Some states are rich in coal deposits while others have little to none. For example, Wyoming alone accounts for about
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electrodes. The sharp corners increase the surface area, increasing the corona effect, and thereby increasing the effectiveness of the ESP [10].

At high voltages, electrodes create a corona effect [10]. The corona effect is a phenomenon in which a significant amount of electricity can be lost to particles in the air due to arching. When a corona discharge occurs between two conductive points [11]. With nothing but air between the conductors, the particles in the air act as a continuation of the conductor [11]. Since the air is filled with many different particles, much of the electricity in this arching process is lost due to heat onto the particles [11]. However, when used properly and in a controlled setting, the corona effect can be used for practical and efficient purposes. One practical purpose for the corona effect is in ESPs, because it allows dust particles in polluted air to be negatively charged which causes them to be attracted to the positively charged metallic plates. The transfer of negative charge is caused by a large potential difference between two electrodes that causes positive and negative ions to move toward each other [11]. As the ions move toward each other, negatively charged ions collide with gas particles, transferring the charge to the particle in the air [11]. This particle is then attracted to the electrode, allowing the particles to cling onto the electrode. On a more massive, industrial scale ESP, electrodes run along grounded metal plates with a high surface area to maximize the amount of particulate matter collected [11].

Grounded Plates

In order for the electrodes to be useful, there must be grounded plates attached or nearby. Grounded plates are connected to ground, which is a for a path of electrical current to the Earth. There can be a direct or indirect connection to Earth that distributes the voltage which allows the point to act as a “zero” reference point. The purpose of having the grounded plates is to create an attraction between the particulate matter and the plates. Once the particulate matter gains a charge from the electrodes, it will be attracted to the grounded plates. The opposing charges cause the particulate matter to cling to the plates [10]. This step is what ultimately separates the particulate matter from the air. There are a variety of styles of plates available. Some examples include opzel (which has triangle-shaped pieces of metal sticking out of the grounding plates) and baffle plates (have a pattern of curved and sharp edges protruding from the grounding plates) [10]. A benefit of the baffle plate is that it is better at catching particles, due to the protuberances getting in the path of the particles [10].

Collecting Electrode Rapping Motor

After the particulate matter is removed from the air, the next step is to remove the particulate matter clinging to the grounded plates. The collecting electrode rapping motor is an instrument, connected to the grounded plates, that causes the grounded plates to shake. The motor periodically vibrates the grounded plates in order to strip the particulate matter from the grounded plates [10]. Most collecting electrode rapping motors vibrate the grounded plates after a maximum of 200 operational hours [10]. This causes the particulate matter to fall into a waste receptacle located beneath the grounded plates. This step is imperative because it prevents a build-up of particulate matter on the grounded plates. If there was no way to remove the particulate matter from the plates, the particulate matter would layer on the plates. This
would eventually lead to a decrease in efficiency because a large mass of particulate matter would clog the air channel, preventing complete airflow.

**VARIABLES TO CONSIDER IN AN ELECTROSTATIC PRECIPITATOR**

**Resistive Particles**

The U.S. Environmental Protection Agency defines the resistivity of a particle as a quantifiable number assigned to a type of particle based on its ability to conduct electricity [12]. A problem with ESPs is that some particulate matter has high resistivity. As the resistivity of a particle increases, it becomes more difficult for it to conduct electricity. For ESPs to be efficient, the particles that go through it must be able to obtain a negative charge so it can cling to the grounded plates and be removed from the air. If a particle was unable to gain a charge or not gain a large enough charge, it would continue to pass through the ESP and exit with the rest of the filtered air. Particles with high electrical resistivity slowly lose their charge after contacting the grounding plates [10]. This causes them to drift more slowly, which ultimately makes them more difficult to collect [10]. ESPs can be designed to work in a wide range of resistivity’s, however, they work best in $10^8 - 10^{10}$ ohms range [12]. Another factor that can improve the efficiency of ESPs and help combat resistivity is temperature. A study done by Barranco, Gong, Thompson, Cloke, Hanson, Gibb, and Lester found that an increase in temperature caused an increase in resistivity, but an overall increase in the efficiency of the ESP [14]. Raising the temperature should have increased the resistivity of the particulate matter, but the efficiency of the ESP also increases significantly. This implies that there may be other factors playing a role in the resistivity of particulate matter. The temperature inside an ESP should remain high in order to make the ESP as efficient as possible. This can be further explored to determine what other factors contribute to affecting a particle’s resistivity.

**Drift Speed**

Drift speed is important to calculate, because there is an ideal speed for particulate matter to pass through an ESP. The matter should not be going so slow that it takes hours to completely pass through an ESP (which can clog the pathway). On the other hand, matter should not zip through an ESP so quickly that it is unable to be removed. As particulate matter passes through the channel, it will have some drift speed that keeps it in motion until it becomes attracted to the grounded plates. Its motion is a result from a constantly changing magnitude of force. The particle is attempting to balance the electrostatic force and the drag force [10]. The electrostatic force is the force due to the particle’s charge, and the drag force comes from air resistance [10]. The electrostatic force is determined by multiplying the charge of the particle by the electric field [10]. The drag force is found by calculating Stoke’s Law then dividing by the Cunningham Slip Constant [10]. The Cunningham Slip constant can be found on a graph or computed from the formula in Figure 4. Stoke’s law is $3\pi\mu_d w_e$ and is used to find the drag force [10]. In Stoke’s Law (shown in Figure 5), $\mu_f$ is the fluid viscosity, $d_p$ is the diameter of the particle, and $w_e$ is the drift velocity [10]. This is divided by the Cunningham Slip Constant and set equal to the electrostatic force [10]. Then the equation is solved for $w_e$ to derive the equation in Figure 5 [10]. By setting the drag for equal to the electrostatic force, Equation 5 is obtained. This can then be solved for $w_e$ to find drift velocity. This equation demonstrates the relationship between particulate matter and the forces acting upon it as it enters the ESP air channel. It is an incredible resource to model the motion of different sized particles as they progress through as ESP. Since the diameter of the particle is included in this calculation, the equation can be used to compare the drift speeds of different sized particles.

$$C_e = 1 + \frac{\lambda_g}{d_p} \left[ 2.51 + 0.80 \exp \left( - \frac{0.55d_p}{\lambda_g} \right) \right]$$

**FIGURE 4 [10]**

The formula to derive the Cunningham Slip Constant

$C_e = \frac{F_e}{F_d}$

$F_e = qE$

$F_d = \frac{3\pi\mu_d w_e}{C_e}$

$w_e = \frac{C_e qE}{3\pi\mu_d}$

**FIGURE 5 [10]**

The formula to calculate the drift speed of a particle floating through an ESP
Determining the Charge Acquired by Particulate Matter

Previously, it was mentioned that particulate matter gains a charge by contacting an electrode. It is possible to determine the charge gained by the particulate matter. There are two equations that can be utilized—one simplified equation (that is slightly less accurate) and a more complicated equation (that is more accurate). The first (simplified) equation determines the charge by determining the number of electrons that the particulate matter gained and then multiplying that number by the charge of an electron, which is \( 1.6 \times 10^{-19} \) C [10]. The symbol for charge in both equations is a lowercase ‘q’ and the units of charge are Coulombs (C). For example, if a particle gained 10 electrons, the equation would be \( q = 10 \times 1.6 \times 10^{-19} = 1.6 \times 10^{-18} \) C. The second equation incorporates the fact that the number of electrons gained depends on the intensity of the corona effect and that this is equivalent to the electric field [10]. This equation also factors in the particle’s size and its dielectric constant.

The Oxford Dictionary describes the dielectric constant as a numerical representation of an object’s ability, “to store electrical energy in an electric field” [11]. The dielectric constant increases the strength of the field by a certain factor (that varies from substance to substance). With these factors included in the calculation, it will produce a much more accurate estimation to determine the actual charge of the particle.

\[
q = \frac{mf^2 \varepsilon_0}{2 + \varepsilon} E_{ch}
\]

where

\[
\varepsilon_0 = 8.85 \times 10^{-12} \text{ CV/m} = \text{permittivity of vacuum}
\]

\[
\varepsilon = 3.7 = \text{dielectric constant for the particle relative to vacuum}
\]

\[
E_{ch} = \text{charging field strength (in V/m), different from collecting field}
\]

ADVANTAGES AND DISADVANTAGES OF ELECTROSTATIC PRECIPITATORS

Highly efficient piece of machinery

ESPs are one of the most effective, efficient ways to remove particulate matter from the air. They can be designed to operate with wet and dry particulates [13]. For coal plants, the most common type of electrostatic precipitator used is the negatively charged dry precipitators [13]. This style of ESP is the most effective for coal plants because the particulates are dry and not sticky. Also, the gas and particles flowing through the ESP are not explosive, which is another condition where negatively charged electrostatic precipitators work well [13]. Since the particulates from coal match the qualities that are ideal for negatively charged electrostatic precipitators, it makes the ESP significantly more efficient.

To quantify the efficiency of an ESP, the corona power ratio can be utilized. The corona power ratio is a function of the power consumed (measured in watts) divided by the air flow (measured in cubic feet per minute) [10]. Figure 7 is an example of the corona power ratio. From the graph, it can be determined that ESPs are incredibly efficient because their collection efficiency approaches 100% [10]. Another way the efficiency can be calculated is by the percentage of removal. The efficiency can be described as the amount of particulate matter that comes out divided by the amount of particulate matter that entered the ESP. The formula for this is the concentration going in minus the quantity of the concentration going out divided by the concentration going into the ESP [10]. This can be further simplified to one minus the concentration going out minus the concentration going in [10]. Both equations described substantiate the fact that ESPs are incredibly efficient pieces of machinery.

\[
\eta = \frac{\text{amount removed}}{\text{amount entering}} = \frac{C_{in} - C_{out}}{C_{in}} = 1 - \frac{C_{out}}{C_{in}}
\]

FIGURE 6 [10]
Formula to calculate the charge a particle gains after contacting an electrode

FIGURE 7 [10]
A graph of the collection efficiency of an ESP

FIGURE 10 [10]
The formula to calculate the percent efficiency of an ESP
Particulate Size Matters

Although ESPs are very efficient in general, the size of the particles passing through them can impact its efficiency. Particulate matter that is below two micrometers in diameter (considered “small”) has a different collection rate than particulate matter that is ten micrometers long or above in diameter (considered “large”). In general, the larger the particulate matter, the easier it is for it to gain charge. Larger particles can obtain more electric charge, while smaller particles gain less charge [10]. The amount charge distributed to the particle depends on their size—larger particles have more surface area and therefore can obtain more charge. Since smaller particle matter is not able to gain as much charge, the electrostatic force between the charge and the grounded plates is weaker. This allows smaller particulate matter to exit the ESP and be released into the environment. An example of this is demonstrated from a study by Lind, Hokkinen, Jokiniemi, Saarikoski, and Hillamo. They burned wood, peat, and biomass to get different sized particulates [15]. The particulates were then put through an ESP to determine the ESPs efficiency rate [15]. Though the overall efficiency was 99.5%, the efficiency for particulate matter that was 0.1-2 micrometers was 96.5% [15]. This is an excellent example of how smaller particulates have a lower efficiency rate. Although the efficiency rate was lower, it was not significantly lower and did not greatly impact the overall efficiency of the ESP. However, the size of the particulate matter that will enter the ESP is something that should be kept in mind while designing an ESP.

![Particle Size-Efficiency Curve for ESPs](image)

**FIGURE 11 [10]**

This graph displays the particle size-efficiency of an ESP by comparing the size of a particle to the rate it is successfully collected.

Installation Costs

ESPs cost a large sum of money in order to be implemented into a coal burning facility. Depending on the size of the ESP, the materials used in the ESP, and the size of the plates in the ESP a company chooses to use, ESPs can cost upwards of one million dollars [16]. However, the cost of implementing an ESP is not only something a company should do in order to protect the environment, but it is also a requirement if a company wishes to remain in business. The Clean Air Act, initially signed into law in the 1970s, requires all companies to have the amount of waste produced to be properly disposed of and managed, or else the companies will be fined. For every repeat offense, the fines are doubled [11]. Over a period of continued negligence, higher-ups in the companies, such as CEOs, can not only face time in prison for negligence of both the law and the environment, but their companies will also be shut down. In comparison, the cost of an ESP looks much more appealing that the cost of negligence. It is a much smaller cost in the long run to install an ESP than to have to pay multiple fines over many years.

**ADVERSE HEALTH EFFECTS OF PARTICULATE MATTER**

The mission for ESPs is to remove as much particulate matter from the air as possible. But what exactly is particulate matter? According to the U.S. Environmental Protection Agency, particulate matter is a mixture of solid and/or liquid found in air [17]. Particulate matter (PM) is classified in two categories: PM$_{10}$ and PM$_{2.5}$ [17]. PM$_{10}$ consists of particulate matter that is 10 micrometers or smaller and PM$_{2.5}$ is defined as particulate matter that is 2.5 micrometers or smaller [17]. Both are fine enough to be inhaled and enter the lungs. PM$_{2.5}$ can enter the bronchioles (the smaller branches of the bronchi) due to its microscopic size [17]. Since PM$_{2.5}$ are about four times smaller than PM$_{10}$, they can penetrate deeper into the lungs. This can have disastrous health effects. If there is a significant build-up of particulate matter in the lungs, it can decrease oxygen absorption. In turn, this would cause a person to feel winded and out-of-breath more often.

Particulate matter is often released into the air when materials, such as coal or wood, are burned or when dry dirt is flung into the air [17]. Many miniscule airborne substances can be classified as particulate matter. Oftentimes, particulate matter reacts with gases in the atmosphere, like carbon dioxide and ozone to create new substances. The newly generated substances can
then negatively affect peoples’ health. For example, pollutants released from burning coal react with atmospheric gases to generate sulfur dioxide or nitrogen oxides [17]. The Queensland government classifies sulfur dioxide as an irritant that stimulates mucus secretion, coughing, and increases the risk of a respiratory infection [18]. Nitrogen oxides can reduce a person’s sense of smell, damage the respiratory tract, and increase the likelihood of respiratory infection [18]. Particulate matter can indirectly impact health by creating hazardous gases in the atmosphere. Since there are multiple ways particulate matter can cause illness or irritation, it is vital that it is removed from the air by coal plants before being released into the environment where it can cause severe damage.

ENVIRONMENTAL EFFECTS

Particulate matter is not only harmful for humans’ health but to the health of the environment as well. Particulate matter reacts with gases in the air to create a variety of harmful substances, like photochemical smog and sulfur dioxide. When in the atmosphere, particulate matter reacts with ozone to create photochemical smog. Ozone is a layer in the upper atmosphere that protects the Earth from UV radiation. However, there is ozone at ground level. The chemical formula is ozone is O$_3$. It is formed when the chemical bonds in breathable oxygen (O$_2$) are broken, forming two single oxygenes [18]. These single oxygenes then bond with O$_2$ to create O$_3$ [18]. Once ozone is generated, it can react with other atmospheric gases, like nitrogen oxides [18]. This results in the formation of photochemical smog. There are many negative side effects of photochemical smog and high concentrations of ozone. Photochemical smog can reduce visibility, making travel dangerous. Ozone can stunt vegetation growth and degrade materials like rubber and paint. Hindering vegetation growth can impact the food chain for animals. If there is less food on the bottom of the food chain, this will have a ripple effect upwards. Since there is less food, populations of animals, like deer and wolves, will decrease because there is not enough food to sustain the current population. This can put certain species in danger, especially if there are already endangered or classified as at risk.

The U.S. Environmental Protection Agency defines environmental sustainability as, “the ability to maintain or improve the standards of living without damaging or depleting natural resources for present and future generations” [19]. ESPs can improve living standards while also reducing humans’ carbon footprint. ESPs improve the standard of living by removing particulate matter from the air. Particulate matter can be hazardous for the health of the environment; it can contribute to smog formation and stunt vegetation growth. Smog, when inhaled, can cause particulate matter to build up inside the lungs of humans and animals. This can lead to a slew of health complications, including decreased lung function and an increased risk for respiratory infections [17]. In addition, stunted vegetation growth reduces the food available for consumption for animals. A limited food supply increases competition between animals and will reduce populations of many animals. Food is necessary for survival, and with less food, the population size must adjust (decrease in size) as a result. This can be dire for animals that are bordering extinction or already at risk. Since ESPs remove the
particulate matter from the air, they help to contribute to reducing health and environmental related side effects of excessive particulate matter exposure. This improves the standard of living for people and the environment, which fits in with the EPAs description of sustainability.

Another aspect of the EPAs definition of “sustainability” is the ability not to deplete natural resources. ESPs attached to coal plants fail this part of the definition. ESPs are commonly attached to coal plants to remove the particulate matter from the incinerated coal before it is released into the environment. Millions of tons of coal are burned each year in coal plants. In 2015, the U.S. burned 801 million tons of coal for energy [8]. In the same year, approximately another 100 billion tons of coal were extracted and exported [8]. With an estimated 257 billion tons of coal available in the U.S., the current rate of consumption is not sustainable [8]. Using hundreds of millions of tons of coal each year will quickly deplete the available coal resources. At this rate, there will be a limited supply or no coal at all for future generations. The EPAs definition of sustainability requires that the process/technology not deplete natural resources. Since ESPs are typically made for coal plants, they are a part of a process that consumes a significant amount of coal. Therefore, they contribute to a process that is depleting the earth of a natural resource- coal. So, ESPs do not meet this requirement for the definition of sustainability.

Economic

Though ESPs are not considered sustainable because of their excessive consumption of natural resources, ESPs are sustainable economically. As previously mentioned, an ESP’s main use is to filter particulate matter out of the air so that pollution does not enter the environment. The price to install an ESP costs upwards of one million dollars, but the value of its impact is priceless [16]. Without investing in an ESP, it would cost more money to locate and clean up pollution, and it would also result in increasing environmental fines from the EPA. Money saved from not paying fines could be allocated elsewhere within the company, making better use of their profits. Utilizing ESPs at coal facilities would sustain both companies time and money. Companies that produce energy by burning coal would receive tax cuts for using their environmentally friendly processes in their energy production. The money saved could be spent on efforts to support sustainable sources of energy such as solar or wind energy, in hopes that one day ESPs will no longer be of any use.

CONCLUSION

As seen, ESP are a necessity for power supply companies to use in order to protect our health and the environment. Many elements factor into ESP such as the types of coal used, its components of the container being the types of electrodes and plates. The science behind an ESP strongly consist of electrostatic properties and the use of the corona effect. If an ESP is not implemented, a company will face major consequences after its negligence of people’s health and the environment around the facility. ESPs must be implemented for the sake of the environment in order to preserve it for future generations use.

SOURCES

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