A Proof-of-Concept Test for Separation Efficiency of an Electro-Cyclone

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Naveen Kunapareddy
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This thesis titled
A Proof-of-Concept Test for Separation Efficiency of an
Electro-Cyclone

by
NAVEEN KUNAPAREDDY

has been approved for
the Department of Mechanical Engineering
and the Russ College of Engineering and Technology by

________________________________________
Gregory Kremer
Associate Professor of Mechanical Engineering

________________________________________
Dennis Irwin
Dean, Russ College of Engineering and Technology
ABSTRACT

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This research is aimed at making coal gasification a more cost-competitive technology by reducing the enormous costs associated with hot gas clean up. To achieve this an electrostatic cyclonic separator was designed, which is capable of concentrating particulate matter from very high temperature gas streams into small slip streams thus enabling the bulk gas to flow particulate free through the outlet.

Approved: _____________________________________________________________

Gregory Kremer

Associate Professor of Mechanical Engineering
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CHAPTER 1: INTRODUCTION

1.1: Coal

The use of coal by humans dates back to second and third century, and it is also the most used fossil fuel by mankind. Coal has played such a dominant factor in our quest to a mechanized world. 92% of the coal mined in America is used in generation of electricity. The power plants that use this coal generate about 50% of the nation’s electricity (Energy information administration, 2008). Such high usage of coal comes with a lot of environmental challenges attached to it. Some of the major environmental concerns raised are emission of particulates, NOX, SOX, CO$_2$ and trace elements. Our primary focus for this project is on particulate emissions or particulate pollution.

1.2: Particulate Pollution

The pollution of ambient air by suspended fine particles has become a serious global concern in recent years. Particulate pollution can be termed as a heterogeneous mixture of aerosols sourced from many naturally occurring events like volcanoes, dust storms, forest fires etc and human generated sources include waste gases from power plants, by products of automobile combustion etc. Particulates also referred as particulate matter are normally denoted as PM with a number suffix attached to it, indicating the size. For example PM$_{10}$ denotes a particle with a size of 10 micrometers. Of these fine particulates PM$_{2.5}$ have a history of easy retention in human body and are known to be one of the root causes for various allergies and diseases like asthma, lung emphysema etc (Schwartz, 1996).
The Clean Air Act of 1990 identified 189 chemical compounds known to cause air pollution and classified them as Hazardous Air Pollutants (HAPs). Environmental Protection Agency (EPA) was entrusted with the responsibility of evaluating the health risks and determining an acceptable emission rate for emission of these particles. Combustion of coal at power plants or combustion systems releases HAPs into the flue gas stream. As these HAPs are primarily in a solid phase except for mercury and selenium, various particulate cleaning technologies are used to capture their solid phase particles (Altman et al., 1997).

1.3: Particulate Pollution Control

Particulate control from coal combustion is a relatively mature technology, but significant amount of research and commercial work is underway to improve the performance, cost effectiveness and applicability of these particulate control systems. Different particulate cleanup technologies include Electro-Static Precipitators (ESP), fabric filters, wet scrubbers and cyclones. The relative costs of operation vary based on cleaning efficiency. Cyclones are considered the cheapest form of particulate control, but their cleaning efficiency is not enough to meet the strict emission standards set for power plants and combustion systems. This is one of the major reasons why we see cyclones often setup as pre-cleaners to a much finer cleaner technology such as ESPs.

1.4: Current Control Technologies for Particulate Matter

Two popular technologies that are most frequently employed for fine particulate cleanup are Electrostatic Precipitators also known as ESPs and fabric filters also known as bag houses.
1.4.1: Electrostatic Precipitators

Electrostatic precipitators are the most used particulate cleanup technology in the industry today. These devices are capable of treating gas volumes ranging from 10,000 cfm to 300,000 cfm at temperatures ranging from 400 F to 1000 F (Tavoulareas et al., 2005).

An ESP consists of an external device which generally forces air to pass though an enclosed shell. The gas which is passing through the shell gets ionized with the help of high voltage discharge electrodes placed in the shell. As the gas further moves though shell the negatively charged particles are then attracted to the grounded electrode plate where the particles are collected. Various rapping mechanisms are used to remove the particles from the grounded electrode plate.

![Figure 1.1. Schematic of an ESP. (Environmental Protection Agency, 1998)](image-url)
1.4.2: Fabric Filters

A bag house or a fabric filter consists of an array of upside down suspended bags which are shaped long and narrow and have a diameter of 10 inches. Air is blown from the bottom of the bag house and as it passes through the fabric the particles collect and fall down into the hoppers. This form of cleaning proves to be a very expensive because these bags houses are not designed to operate at high temperature and as a result the dirty flue gas should be cooled significantly before it enters the bag house and this increases the overall cleanup cost (Britannica, 2008).

1.5: Uniqueness of the Research

“Coal gasification is a process that converts solid coal into a synthetic gas composed mainly of carbon monoxide and hydrogen.” (Tavoulareas et al., 1995). Gasification of coal can be done by controlling coal, oxygen and steam mixture inside a gasifier. This gasified coal should be cleaned of particulates and sulfur compounds (Tavoulareas et al., 1995). There are basically two types of flue gas cleaning systems. One is cold or wet gas cleaning system and second is the hot gas cleaning system. The wet gas cleaning system comes with a high cost because of the post treatment involved in cleaning the liquid affluent. The hot gas cleanup offer more cost benefits and at the same time keeps the overall cycle efficiency high (Fathom et al., 1998). One very popular method of hot gas clean up is usage of cyclonic separators which separate a dense charged particle entrained flow through a grounded slip stream while the clean bulk gas can go through the outlet with out losing any temperature. This would enable more efficient offline cleaning of the small volume of particles entrained gas. After the gas from the slip stream
is cleaned, it is merged back with the bulk gas flow without significantly lowering the bulk gas temperature.

The cyclonic separation unit in this test system would be simulated to be used at the outlet of the gasifier. Since we do not have a working gasifier, we had to simulate this by mixing particulates injected from a particulate injection system into a high temperature gas created by a burner. This mixture will be electrically charged by the discharge electrodes placed inside the cyclone. The problem of particle agglomeration at the collecting surface is eliminated in this design because of the self cleaning mechanism kicking in because of high stripping velocity and swirl caused by the particulates, preventing them from adhering to the collecting surface. The 5% of the gas stream with nearly 95% of particles is then passed through an extremely high efficiency cooling and collection unit and after that the cleaned gas stream is combined with bulk clean gas exiting through the outlet of the cyclone. In this arrangement the bulk gas (95% of flow) will barely be affected in temperature.

1.6: Objective of the Research

The objective of this research is to develop a low cost particulate cleanup device capable of operating at very high temperature for synthesis gas cleanup, occurring after the coal gasification process. This research is aimed at making coal gasification a more cost competitive technology by reducing the enormous costs associated with hot gas clean up. To achieve this objective an electrostatic cyclonic separator was designed, which is capable of concentrating particulate matter from very high temperature gas streams into small slip streams thus enabling the bulk gas to flow particulate free through the outlet.
The focus of the research was to develop an electro cyclone as a proof of concept model and to quantify the collection efficiency at the slip stream with and without the use of voltage. In order to achieve this, two sets of experiments were performed as follows.

1) 3 EPA standard method 5 experiments were performed with voltage.

2) 2 EPA standard method 5 experiments were performed without voltage.
CHAPTER 2: LITERATURE REVIEW

2.1: A Brief History of ESP’s and Cyclones

The first practical simulation of electrostatic precipitation occurred in 1878, when R Nahrwold in a laboratory style experiment using an electrified needle point placed in a tin cylinder, showed that with an increase in electric discharge, there was a noticeable increase in the collection of the dust particles (White, 1977). In 1906 Fredrick Cottrell applied electrical energy to an ESP using high-voltage ratified alternative current and collected sulfuric acid mist in his Berkeley, CA laboratory. The success of alternative current technology finally led to a construction of 1,000,000 CFM ESP to collect dust from a cement kiln at Riverside, CA (White, 1977).

Dust separation using inertial forces was used by many industrially advanced countries since the early 1800s. In 1885 the first cyclone was made commercially available by the Knickerbacker Company (Kirk-Othmer, 1978). Cyclones were initially used in the food industries to process and clean the ingredients. Later, in synthetic detergent production, fast reactor cyclones were used to separate the cracking catalyst from vaporized reaction products (Coker, 1993). Cyclones are currently an excellent means for particulate cleanup from high temperature and high pressure gases (Cortes et al., 1999). Cyclones today are mostly used as pre-cleaners i.e. to clean coarser particles from heavy particle laden streams of flue gases and subsequently finer particle cleaning is done by other collecting devices.
2.2: Basic Operation of the Electro Cyclone

A cyclone is an inertial separator used to separate medium sized and coarse particles emitted from power plants, cement industries etc. An electro cyclone is a device which incorporates electrostatic technology into a cyclone. Here the particles are made to enter the main chamber through a tangential inlet. As the particle laden gases swirl down they are charged by electrodes which are hung from the ceiling of the cyclone (Kerdonfag et al., 2004). The actual dust separation in an electro cyclone is achieved in two forms, first the inertial forces acting on the particles due to swirling motion inside the cyclone performs mechanical cleaning, and at the same time the charging of the particles by the electrodes creates a number of gas ions in the space and this results in an voltage gradient between the electrode and the cyclones. These charged particles are then attracted and drawn though a tangential grounded exit pipe located at a certain height from the bottom. The particles with sizes smaller than 10 um are collected at the tangential exit pipe also called the slip stream and particles greater than 10 um are collected at the bottom plate by the inertial forces acting on the particles (Crane et al., 2001).

2.3: Variables/Factors Affecting Electro cyclone Performance Operation

2.3.1: Precipitation Mechanism

Discharge electrodes in electro cyclones are used to create a corona which helps in charging the particles. Corona charging proves to be the best method for particle collection and retention in heavy gas cleaning applications (White, 1977). This is achieved by application of high negative voltage to the discharge electrode using the
transformer rectifier set. Precipitation of the particles is when these negatively charged particles are attracted and then collected at the grounded surface.

2.3.2: Corona Discharge and Gas Molecule Ionization

Corona discharge is produced when a high voltage is applied onto the electrode and this is seen as a luminous blue glow around the electrode tip. In this region the electric field becomes so high that it exceeds the breakdown voltage of the gas. Any ions that enter this region are then accelerated to speeds high enough to detach an electron when it bumps into an atom, thus leaving a positive ion and an additional electron (Cross, 1981). This process continues creating many more electron/ion pairs which finally result in a process called Avalanche multiplication as illustrated in the figure 2.1

![Figure 2.1. Corona Discharge and Avalanche Multiplication. (Environmental Protection Agency, 1998).](image)

Now the fast moving free positive ions and electrons start to leave the corona area and eventually slow down as they enter the inter electrode region i.e. the region near the grounded plate. In this region they undergo collision with many neutral atoms and lose all
the gained charge and get captured. These negatively charged ions start to move to the grounded plate, where they are collected (Environmental Protection Agency, 1998).

2.3.3: Particle Charging and its Mechanisms

The particle charging is basically achieved in two forms, one by field charging and second by diffusion charging. Field charging is a process where electric field is applied on the ions, which in turn directs the ionic movement towards the particles thus charging the particles, this collision of the ions onto the particles takes place till the charge on the particles builds up strong enough to divert the electric field lines around them. The diverted electric field lines now prevent these charged particles from coming in contact with the newly charged particles (Alisoy et al., 2004). The saturated particles i.e. particles which no longer can take any more charge, tend to migrate to the grounding electrode as shown in figure 2.2.

![Field Charging Diagram](Environmental Protection Agency, 1998)

Figure 2.2. Field Charging. (Environmental Protection Agency, 1998)

Random thermal motion of ions occurring in the gas due to the collision between ions and particles tend to impart a charge on the ions leading to a phenomenon called
diffusion charging. According to (Cross, 1981) diffusion charging becomes very important when the radius of the particles reduces to less than 1.5 um. Since diffusion charging is only applicable to very small particles, these sub micron particles do not cause any disturbances in the electric field lines as with the case of field charging (Environmental Protection Agency, 1998).

Depending on the particle size either one of these charging mechanisms occur. Field charging dominates for particles with a diameter greater than 1 micron, because particles must be large enough to capture gas ions. For particles with 0.1 micron diameters or less, diffusion charging acts as a dominant force (Woodard, 1998). In most cases when particle diameters range 0.1 to 1 microns, combinations of field and diffusion charging mechanism tend to act on the particles. Another type of charging mechanism less frequently seen is electron charging, where free moving electrons impart a charge on contact with the particles. The net combined charging effect of diffusion charging and field charging would appear as in figure 2.3

\[\text{Figure 2.3. Net Combined Charging Effects (Flagan, 1988)}\]
2.3.4: Electric Field Strength and Spark Over

When a dielectric is disrupted between two conductors placed parallel to one another then a phenomenon known as spark over is seen. Earlier we have discussed how a corona is produced when a high voltage is applied to a conductor. When this voltage is increased gradually, at some point the corona tends to further extend from the surface. If we start to further increase the voltage, then at some point sparking occurs i.e. the corona turns to a spark and bridges with the parallel conductor (Peek, 1915). A short term collapse is noticed in the electric field when the spark over occurs. Efficiency of an ESP according to Deutsch Anderson’s equation varies by the square of its electric field strength. Maintaining this field strength as high as possible at all times gives us the optimal efficiency. Care should also be taken to prevent sparking from occurring too frequently because this collapses the electric field resulting in improper charging of particles. 50 to 100 sparks per minute is the optimum sparking rate for a ESP (Environmental Protection Agency, 1998)

2.3.5: Electrode Geometry

Electrode design and placement also play an important role in the overall efficiency as they are responsible for the corona discharge. According to (Parker, 1996) the basic requirement of a discharge element is to provide field intensity on the surface when electrically energized. This field intensity is responsible for the ionization of the gas. Best electrode model is that which has a physical model to allow for maximum migration velocity and maximum field intensity on the surface. (Jedrasisk et al., 2001). Out of the most commonly used electrode configurations shown in the figure 2.4, a lot of research
results have shown that the barbed tube is the most effective and useful corona discharge electrode in respect of effective transportation of solid particles towards the collection electrodes. This type of electrode is widely used in ESP’s.

*Figure 2.4. Different Electrode Configurations Used for ESP’s. (Jedrasisk et. al., 2001)*

### 2.3.6: Collection Surface

Collection surfaces occur in many forms and sizes, and they play a fundamental role in achieving maximum collection efficiency for the ESP. Ideal collection surface would have a relatively flat profile and should be mechanically stable at all temperatures and gas flow conditions (Parker, 1996). The charged particles which reach the collection surface partially lose the charge, the rest of the charge that is present on the particle is responsible for various cohesive and adhesive forces that are built up and eventually are responsible for coagulation of the particles. In general, particles are attracted and held to each other molecularly. But when the dust layer builds up beyond the desirable thickness, particle removal becomes a necessity (McKenna et. al., 1995).
2.3.7: Particle Resistivity

The resistance of a material (e.g. fly ash) to electrical conduction is termed as particle resistivity. This phenomenon has an immense effect on the overall collection efficiency of the ESP. Ideal particles for electrostatic collections are those which have a medium resistivity. If the particles are very good electric conductors, i.e. those with little or no resistivity, they tend to lose their charge too soon to the collection plate and when this happens there is a very high chance the particles will re-entrain in the bulk gas stream. If the particles are very good insulators the charge does not drain off at the collecting plates. When this happens then a back corona builds up starting to repel newer particles from being collected at the collection plate (University of Delaware College of Engineering, 2008).

“Resistivity decreases with increased coal sulfur content because of increased adsorption of conductive gases by the fly ash.”(Wang et. al., 2004). Particle resistivity can be controlled by a technique called flue gas conditioning. Use of moisture and chemicals to reduce particle resistivity is very popular (White, 1977).

2.3.8: Particle Removal

Over a period of time the collection plates become too thick with layers of particles accumulated on them and they have to be removed in order to maintain efficiency of the collection surface. The removal of these particles is done by a process called rapping wherein some physical force is applied on the particle to dislodge them into dust
collection bins. The usual techniques applied here are mechanical hammers, electrical impulses, magnetic impulses, electric vibrators and sonic horns.

### 2.3.9: Particle Size

Particle size and distribution play a key role in the performance of an electro cyclone. Many factors like migration velocity, centrifugal forces, gravitational forces and electrical forces decide the charging mechanism and eventually also decide the collection efficiency. The functioning of the cyclones or ESP with respect to the variation in particle size actually brings us to major design modifications and implementations of better control technologies for the particulate control. The larger sized particles are easily collected in most technologies like settling chambers, cyclones etc, but the fine particles have very peculiar behavior and are difficult to collect as they are easily re-entrained. In addition to the particle size, the shape of the particles also greatly affects the amount of charge that can accumulate on it as well as the collection efficiency.

### 2.4: Previous Work Done in the Field of Electro Cyclone

Significant amount of research has been performed on increasing the efficiency of a cyclone. A small amount of it concentrates on the use of electrostatic forces as an additional medium for enhancing the particle filtration in a cyclone, which is also called an electro cyclone. Dietz early electro cyclone experiments reveal a significant increase in overall collection efficiency when radial forces are employed on pre-charged particles (Dietz, 1982). Lim discusses various performance factors for an electro cyclone. In their
experiment, 0 to 9 KV was applied to an electro cyclone by a central discharge wire running through the cyclone and the following conclusions were made: (Lim et al., 2001)

1) With an increase in the voltage to the discharge electrodes an increase in collection efficiency was clearly noticed.

2) The collection efficiency of the smaller particles increased with the decrease in the flow rate and this was attributed to longer retention time for the particles in the cyclone resulting in more efficient charging and collection at the grounded electrode (Lim et al., 2001). This conclusion was further augmented by Chi Jen Chen who used an electro cyclone with an applied voltage of 25 KV and varying flow rates of 15.75, 28.75, 44.26 m3/min respectively. The results show that, at low flow rates the grade efficiency of an electro cyclone was much higher than a normal cyclone (Chen, 2000). (Kim et. al., 2001) used various particle types like Titanium dioxide (TiO2), Zinc Powder (ZN) and pulverized fly ash with diameters ranging from 10 um to 180 um. The results showed that, for particles with size less than 38 um, a two fold increase was noticed in the overall collection efficiency. They conclude “In particular for small particles, of the order of a micron, electro statically assisted cyclone separation could be an efficient method to clean fine particles from gas steam and /or extend the range of separated particles sizes from existing cyclone designs” (Crane et al., 2001).

As we see from above that little research has been performed to see the effect of particle size, electric discharge, and flow rate on collection efficiency of the electro cyclone but no work has been actually done on the method of collection of the charged particles. In most of the research performed on an electro cyclone, the charged particle collection method is generally a dust trap which is grounded and located at the bottom of the
cyclone. But in this research we are using a tangential slip stream which acts as grounded electrode and this is connected to a vacuum assisted filter box. As the particles entering the cyclone are charged and attracted to slipstream and thus are drawn into the filter box and collected.
CHAPTER 3: EXPERIMENTAL METHODOLOGY

3.1: Model & Design of Current Electro-Cyclone setup

The main components of the rig are the cyclone body, burner/blower, slip stream, and transformer rectifier set. The overall picture of the electro cyclone is shown in figure 3.1.

In the electro cyclone experiment we are simulating a high temperature particle laden gas cleaning system. The high temperature gas is pumped using a gas burner and as the gas comes out of the burner it gets mixed with particles injected into it with the help of a
fluidizer and a blower. The gas then tangentially enters the cyclone through the inlet. The electrodes hanging from the flange in the inside of the cyclone electrically charge the particle laden gas entering the cyclone. This charged gas undergoes two types of separation, one is the mechanical separation of particles due to the cyclonic forces acting on the particles and another is the electrostatic force which guides the particles to move towards the grounded slipstream. The clean gas escapes out of the cyclone through the vortex finder. The particle laden gas flows through the slip stream and is cooled as it passes through the water jacket and particles get collected in the filter holder.

The schematic of the entire gas flow is shown in figure 3.2.

*Figure 3.2. Schematic of the Experimental Setup and Gas Flow.*
3.2: Cyclone Main Structure

The interior surface area of the cyclone is completely covered with mica sheets to provide electrical insulation between the electrodes and cyclone body. The surface of the mica inside the cyclone had a coating of alumina paint to prevent the mica surface from abrading due to particles in the gas. The top of the cyclone was capped off with an iron flange which has a provision for the vortex finder to fit securely right through it. The flange also has provisions to provide electrical connection to the electrodes. These characteristics are shown in figure 3.3.

*Figure 3.3. Vortex Finder Attached to the Flange of the Cyclone.*
The vortex finder is essentially the outlet of the cyclone through which the clean air exits the rig. In our test set up we have a mica tube coated with layers of alumina paint as a vortex finder which was attached to the cyclone flange. Mica was selected as the material for use inner lining of the cyclone and as the vortex finder because of its excellent electrical insulation property. This layer of mica inner liner was necessary to prevent sparking between the inner walls of the cyclone and electrodes. A thin layer of alumina was applied on to the surfaces of the inner liner and mica tube to prevent the iron oxide particles from sand blasting the mica’s very flaky surface. The dimensions of the vortex finder are 14” long and 5” in diameter. The tube runs through the flange such that 11” of the tube length is below the flange. To prevent leakage of the gases from the cyclone a high temperature seal is used to close the space between the mica tube and the flange. A Garlock rope arrangement made on the flange and tightens on to the mica tube making the required seal. Figure 3.4

*Figure 3.4. Mica Tube being Held in Position and Sealed with a Garlock Rope.*
3.3: Collection Surface

The collection surface used in the electro cyclone is the slip stream. The slip stream provision was made at a height of about 13 inches below the center line. The height was determined after trying various heights and stream size diameters as follows, first a 3D solid model of the cyclone with electrodes was modeled in a solid modeling software called GAMBIT and then this solid model was exported to an computational fluid dynamics analyzer called FLUENT, where the finite element analysis was performed until about 5% of the total flow was noticed going through the slip stream. The comparisons for various slip stream diameters are given below (Prashant, 2005).

<table>
<thead>
<tr>
<th>Slip Position (inches from center)</th>
<th>Inlet Velocity (m/s)</th>
<th>Percentage Flow through Slip</th>
<th>Mesh Size</th>
<th>No. of Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>25</td>
<td>4.75%</td>
<td>0.5</td>
<td>4486</td>
</tr>
<tr>
<td>13</td>
<td>25</td>
<td>4.32%</td>
<td>0.5</td>
<td>4132</td>
</tr>
<tr>
<td>11</td>
<td>25</td>
<td>4.46%</td>
<td>0.5</td>
<td>4000</td>
</tr>
<tr>
<td>12.5</td>
<td>25</td>
<td>4.32%</td>
<td>0.5</td>
<td>4175</td>
</tr>
</tbody>
</table>
3.4: Specific Power and Corona Discharge

The voltage connection to the electrodes inside the cyclone was established using electrode connecting unit. This unit electrically insulated the electrodes from the thickness of the flange. It consisted of an all thread wrapped with a mica tape and onto which a ceramic sleeve was inserted and on the ceramic sleeve sat the mica bushing which supported the weight of the electrodes on the flange. The open end of the all thread inside the cyclone was coupled to the electrodes using an all thread coupler. The open end of the all thread outside the cyclone was used for connecting to the voltage supply as shown in figure 3.5.

Figure 3.5. Electrode Connecting Unit.
These electrodes are positioned in between the inner and outer mica tubing providing maximum particulate contact and thus enabling maximum amount of particulate charging. Co-axial cables connect the electrodes to the transformer set as shown in figure 3.6.

![Transformer Rectifier Set](image)

*Figure 3.6. Transformer Rectifier Set.*

**3.5: Injection System**

Another component of the experimental setup is the iron oxide feeder. This was used to feed the iron oxide particles into the cyclone. As shown in figure 3.7 this setup consisted of three parts-first is the screw feeder whose feed rate could be adjusted by a motor control, second is a fluidizer section where the particulates are mixed with a stream of air to get fluidized and third is the blower which sucked in the fluidized air coming out of the fluidizer and channeled it into the cyclone inlet stream where it is mixed with the very high temperature gas coming from the burner before entering the cyclone.
3.6: EPA Method 5
EPA method 5 (The Active National Directory of Source Emissions Testing, 2008) is an EPA standard procedure which determines the amount of particulates emitted by stationary sources.

The various instruments used for the method are as follows:

- **Sampling Probe** - The sampling probe is used to collect the air sample from the gas stream.
• **Filter heating system**- This box is used to heat the filter to a temperature which prevents condensation of water on the surface of the filter.

• **Filter**- This is a circular porous paper which fits into a filter holder and filters the sample air passing through it.

• **Filter holder**- This is borosilicate glass enclosure, with an airtight seal to make sure all air passes through the filter and nothing escapes out. It also provides structural support to the filter paper.

• **Flexible vacuum line**- This is white Teflon tubing which connects the filter holder to impinger section.

• **Impingers** – These are a series of special nozzle glass bottles which help in drawing out the moisture out of the sample air before it enters the sampling meter boxes. These are four bottles/impingers, the first two consisting of distilled water and the next one being empty and the last one containing silica gel in it.

• **Vacuum gauge**- Method 5 sampling procedure mandates leak checks at the sampling nozzles. A 15 in Hg vacuum is pulled through a plugged nozzle to check to see if there is a leak, the vacuum gauge reading should not exceed .02 mark in the 60 sec procedure.

• **Volume meter** – Also called the dry gas meter, this is used to accurately measure the flow rates of the sample volume.

• **Dual inclined manometer** – Used to velocity and orifice differential reading.

The sampling at the slipstream will not be Method 5, but a filter collection method will be used. Here the entire flow will be run through a cooler, over the filter and at the back end, a vacuum pump will keep the velocity at the level that would have been there without the cooler and filter as shown in figure 3.8 and 3.9.
3.7: Test Procedure

All experiments were conducted keeping safety as the highest priority, so for this reason before the start of the experiments an extensive amount of time was spent on charting the Standard Operating Procedure (SOP) for the entire test setup and it was also approved by Environmental Health and Safety department (EHS). All experiments were performed by strictly following the SOP defined for Electro-Cyclone. For further insight into the testing procedure followed please refer to the Electro-Cyclone SOP attached in Appendix (1).
CHAPTER 4: TEST RESULTS

4.1: Review of Objective

The focus of the research was to develop an electro-cyclone as a proof of concept model and to quantify the collection efficiency at the slip stream with and without the use of voltage. In order to achieve this, two sets of experiments were performed as follows.

3) 3 method 5 experiments were performed with voltage.

4) 2 method 5 experiments were performed without voltage.

Section 4.2 deals with all the general experimental parameters used in the experimentation and discussion of the results achieved.

4.2: General Test Parameters Achieved During Experimentation

4.2.1: Temperature

Electro cyclone is intended to be a hot gas cleanup device. All efforts were made in order to achieve a maximum stable temperature of 850 F throughout the experiment, but since the burner had no electronic control to set the exact temperature, the burner air inlet plate was to be adjusted before every experiment until the required temperature was achieved. As this was a manual adjustment, it was not possible to always set it to exactly 850 F and always some slight variations were noticed. This problem was overcome by taking a temperature reading once every 5 minutes of the experiment and later averaging the readings. Table 4.1 shows the average temperature for each experiment.
Table 4.1

Temperature Achieved During the Test

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>Average temperature(F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>845±5</td>
</tr>
<tr>
<td>2</td>
<td>855±5</td>
</tr>
<tr>
<td>3</td>
<td>840±5</td>
</tr>
<tr>
<td>4</td>
<td>845±5</td>
</tr>
<tr>
<td>5</td>
<td>855±5</td>
</tr>
</tbody>
</table>

4.2.2: Voltage

The voltage provided to the electrodes inside the cyclone is a direct measure of the strength of corona, which in turn is responsible for the ionization of the particles and hence collection efficiency. According to Jedrusik a minimum of 20kv was needed to establish an onset of corona for barbed tube electrode geometry, which is very similar to the geometry of the electrodes used in the electro cyclone (Jedrusik, et al. 2001). The upper range of voltage selection was limited by the sparking in the experimental rig. So the electro-cyclone was designed for a voltage range of 35 kv. All efforts were made to maintain a steady voltage of 35kv throughout the experiments. It was seen that the voltage tended to flutter by 1 or 2kv below 35kv towards the last ten minutes of the 30 minute experiment.
4.2.3: Hot Gas Flow Rate
The average gas flow rate entering any hot gas cleanup is around 1100 acfm (Clelanda
and Purvi, 1999). At the inlet the flow rate was maintained at around 600 acfm. The flow
rate was first calculated for the cold air and then converted to hot gas.

4.2.4: Particle Size Distribution and Concentration
Atlantic equipment engineers were the suppliers for the iron oxide particles. The size
variation specified by the supplier was 0.13 – 3.87 µm. In the experiments tested, we
were more interested in knowing the behavior of the particles after they were properly
charged rather than when they were being charged. So a value of 1 gm/min was chosen
for particle feed rate to avoid space charge effect on the particles, which in theory states
that with a higher number of particles, the overall charge efficiency decreases. Although
we did not have any significant results that show 1g/min concentration would have
minimized the effect of space charge, it was our best estimate with which to start.

4.3: Test Results for Electro-Cyclone Experiments

4.3.1: Test Matrix for Electro-Cyclone Experiment
Table 4.3 shows the test matrix for the elector-cyclone experiments. A total of five
experiments were performed, out of which three experiments were performed with
voltage, and the other two were performed without voltage. Of the three voltage
experiments, one was performed by a different operator in order to establish repeatability.
Although method 5 is an EPA approved standard method, if not performed correctly, a
different set of results can appear. Having a second operator perform the method to see
repeatable results gives us additional confidence in the method 5 analysis being performed for all the experiments.

### Table 4.2

<table>
<thead>
<tr>
<th>#</th>
<th>Approx. Voltage (kV)</th>
<th>Approx. Iron oxide Conc. (g/min)</th>
<th>Approx. Gas temp. (°F)</th>
<th>Approx. Gas vel. (CFM)</th>
<th>Approx. Size distribution (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>1</td>
<td>850</td>
<td>900</td>
<td>2±1.87</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>1</td>
<td>850</td>
<td>900</td>
<td>2±1.87</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>850</td>
<td>900</td>
<td>2±1.87</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1</td>
<td>850</td>
<td>900</td>
<td>2±1.87</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>1</td>
<td>850</td>
<td>900</td>
<td>2±1.87</td>
</tr>
</tbody>
</table>

### 4.3.2: Electro-Cyclone Experiments Results Summary

Experiment number 1, 2 and 5 were performed with voltage. After the first experiment it was noticed that there was very little particle collection on the filter paper in the slip stream. Some investigation on the rig revealed that there were a lot of particles being collected on the interior of the cooling tube running through the water jacket. Therefore, we had to remove the water jacket, completely rinse away all the particle, and replace it. From next experiment onwards, the rinse was collected and the particle weight was added to that of the total slip stream particle weight. The reason for not collecting the rinse volume for the first experiment was that there were a couple of test runs performed before the first experiment was run and this led to the suspicion that the particles
collected would not be representative of the particles for just the first test. Hence the efficiency calculations were not performed for the first test, but the test acted as a base to establish the particle collection in the water jacket inner tube. The inlet weight and outlet weight were determined by running method 5 sampling at both the inlet and the outlet.

Table 4.3

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>Inlet Wt (gms)</th>
<th>Outlet Wt (gms)</th>
<th>Slipstream Wt (gms)</th>
<th>% of particle mass through outlet</th>
<th>% of particle mass through slipstream</th>
<th>% of particles mass retained in the electrocyclone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.51</td>
<td>2.11</td>
<td>---</td>
<td>28.0</td>
<td>---</td>
<td>71.9</td>
</tr>
<tr>
<td>2</td>
<td>8.73</td>
<td>4.07</td>
<td>0.45</td>
<td>46.5</td>
<td>5.15</td>
<td>48.2</td>
</tr>
<tr>
<td>3</td>
<td>9.22</td>
<td>5.37</td>
<td>0.04</td>
<td>58.2</td>
<td>0.43</td>
<td>41.3</td>
</tr>
<tr>
<td>4</td>
<td>12.6</td>
<td>7.07</td>
<td>0.11</td>
<td>55.9</td>
<td>0.87</td>
<td>43.2</td>
</tr>
<tr>
<td>5</td>
<td>10.0</td>
<td>3.09</td>
<td>0.51</td>
<td>30.7</td>
<td>5.07</td>
<td>69.1</td>
</tr>
</tbody>
</table>

Method 5 sampling was not possible at the outlet as the temperature of the gas was very high for sampling equipment to withstand, even after passing the gas though the water jacket. The water jacket here reduced the temperature from around 800º F to 300º F as this temperature reduction was essential for glass micro fiber filter paper used in our filter box to withstand the temperature while it was rated for a maximum of 400º F. Although the water jacket worked as intended as far as the temperature reduction was concerned, there was a flaw in the construction. Use of black pipe instead of stainless steel resulted
in the formation of rust as explained in detail in the first part of this section and also in
the recommendation section. The gas entered the filter box from the exit of the water
ejacket. The role of the filter box was to provide structural support to the glass micro fiber
filter paper and also provide an airtight environment inside the box, thus making sure the
entire gas stream flows though the filter paper. The filter box did work for what it was
designed, as in the post experiment sample collection it was noticed that the particles
were uniformly collected on the entire collection surface, and minimal tear was noticed
on the filter. But as explained in the slip stream sampling section of Standard Operating
Procedure (SOP) for the cyclone, it can be seen that the filter paper cannot be accessed
very easily and requires a lot of caution and care. It is a very long and tedious procedure
to delicately remove all the outer sections of the filter box so that we do not disturb the
particles settled on the filter paper.
CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations for electro cyclone design and experiments are discussed in the following chapter.

5.1: Conclusions

Conclusions for the voltage experiments are discussed first, followed by the non voltage experiments.

5.1.1: Electro Cyclone Experiments with Voltage

Three experiments, the first two and the last, were performed with voltage. This order was chosen in order to check the repeatability of the system. The first experiment conducted with voltage did not yield much quantitative data, but it did show us a very important observation of the particles being trapped inside the cooling tube as discussed in chapter 4.

Figure 5.1. Hot Gas Cooling Setup.
From the second and fifth experiment (Voltage), it can clearly be seen that there was a significant increase in the particles passing through the slip stream when compared to the tests conducted without voltage. Averaging experiments 2 and 5 (Voltage) and experiments 3 and 4 (Non-Voltage), then calculating a percentage difference between these sets shows an 87% increase in particle flow through the slip stream when voltage was applied.

Table 5.1

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>% of particle through slip stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>5.15</td>
</tr>
<tr>
<td>3</td>
<td>0.43</td>
</tr>
<tr>
<td>4</td>
<td>0.87</td>
</tr>
<tr>
<td>5</td>
<td>5.07</td>
</tr>
</tbody>
</table>

Before the post experimental cleaning it was baffling to see such low percentage of particles being collected at the slip stream filter, but during the post experiment’s cleaning of the cyclone, it was noticed that a significant amount of particles was deposited at the entrance of the slipstream because of a small cup like formation as shown in figure 5.2, which aided the particles to settle down in large numbers and resulted in a significant amount of particles not being accounted for at the slip stream filter.
Thus from the voltage experiments, we can conclude that there was an increase in the total flow of particle into the slipstream when compared with those experiments when no voltage was applied, but the exact number could not be got be quantified because of the above-mentioned reason.

5.1.2: Electro Cyclone Experiments without Voltage

Two experiments were conducted without voltage, and in these experiments very few particles were collected at the slip stream filter when compared to experiments performed with voltage. The collection efficiency for a conventional cyclone cleaning PM 2.5 is around 40% (Environmental Protection Agency, 2008). we see from Table 4.3, for the non-voltage experiments performed; the mechanical cyclone efficiency is around the expected area of 40 %. From the non voltage experiments, it can also be seen that the total percentage of particle retained in the cyclone is about 34% less when compared to the experiments conducted with voltage, indicating that when particle were not being charged, fewer were retained inside the cyclone.
5.1.3: Total Particle Weight Balance

The total weight of particles entering the cyclone over five experiments quantified through method 5 is 48 gm, the total weight of the particles exiting the cyclone quantified by method 5 is 21 gm, and the total weight of particles at the slipstream was quantified to be 1 gm. So over a period of five experiments, 26 gm of particle should have been settled in the cyclone. Since a couple of test runs were conducted on the rig before the start of the experiment, it can be assumed that more than 26 gm is present inside the cyclone. But during the post experiment cleanup of the inside of the cyclone, a total of 23 gm of particles were collected at the dust trap and 1.5 gm of particles was collected at the slipstream entrance. Since there was no standard method to get an exact weight of particles inside the cyclone, the weight is considered only an approximation. The majority of deficit in particle weight can be attributed for the particles that are left inside the piping at the inlet to the cyclone. What the above discussion means for our experiments is although we did see a significant increase in particle separation at the slipstream with the application of voltage, still, overall the dominant force of separation remains to be the mechanical cyclonic forces acting on the particles.

From the above discussion we see that about 21 gm of particulates have escaped though the outlet without being caught either by the cyclonic forces or the electrostatic forces, and if we break it down per experiment, we see about 4 grams of particles have escaped for each experiment. This amount would have been a much smaller if not for the particles settling down at the cup like formation at the entrance of the slipstream and then reentering into the air, and thus eventually making their way out instead of flowing smoothly into the slipstream filter box. This has also prevented us from coming to an
effective conclusion regarding the slipstream location. Although we do see a lot of particles being deposited at the slipstream entrance and an increase in particle collection on application of voltage, it will be premature to say that this is the best location or to recommend that it be moved to a different location until we are able to quantify every particle that is flowing through it. From my overall experience on working with this rig in all stages, starting from design to construction and finally experimentation, I believe the proof of concept set of experiments performed gave us some very crucial information about the rig behavior under operating conditions and thus gave us the ability to draw a fair amount of recommendations in order to proceed from a proof of concept stage to the next. Since these recommendations also come with a lot of uncertainty attached and in order to proceed efficiently into the next phase without getting bogged down, I have divided the recommendation section into two parts, first being the most important and that need to be addressed before performing the next set of experiments, which I am confident will help us in achieving the objective from a proof of concept stand point. The second set of recommendations would then be auxiliary to the recommendations drawn from the next set of testing.

5.2: Recommendations

A proof of concept design experiments were performed on the electro cyclone. The objective of this thesis was to perform a set of experiments to quantify the collection efficiency of the slipstream with and without the use of a voltage. Since this was a proof of concept testing for the slipstream efficiency and we did not have any efficiency range to start with, we aimed for a particle collection efficiency of about 95% at the slipstream. But as we have seen from discussions in results summary and conclusions, the desired
results were not achieved. Therefore, the following recommendations have been suggested based on the conclusions from the experimental results and post rig conditions investigated.

5.2.1: Recommendations Specific to My Thesis Objective

- The most important observation yielding from the experiments performed was the design of the slip stream entrance. This happens to be important because of the dominant role it has played in allowing the bulk of particles to settle down at the lip of the slip stream entrance, thus preventing them from being able to be quantified at the slipstream filter. As explained in section 5.1.3, we can see that a bulk of particles settled at the slip stream entrance. In the existing design, the cross sectional area of the slip stream entrance decreases from 2.5 inches in diameter to 0.75 inches in a very rapid transition, and this causes formation of a cup like area at the transition which aids the particles to settle down. The design of the slip stream entrance needs to be improved in order to promote uniform flow throughout the entire section. The improved design should have much slower transition to help particles flow smoothly without settling down around entrance area. As previously discussed, electrostatics play a much bigger role in separation of particles, than the actual shape of the slipstream. But the present slipstream shape was greatly affecting the path of flow for the charged particles such that the electrostatic forces were being dominated over the physical hindrance caused by the slipstream, due to abrupt transition in its profile.
• The existing slipstream design does not have a provision to remove the slipstream without having to remove the top flange of the cyclone, and this prevented collection of the rinse volume for quantification of the particles present inside of the slipstream tube due to highly adhesive nature of the charged particles towards a grounded surface. Thus future design should strongly take that into consideration and design a slipstream entrance which can be easily and carefully removed for sampling at the end of each experiment by not disturbing the particles settled inside.

• After the first experiment, it was observed that particles were being stuck along the inside surface of the slipstream cooling tube. This was attributed to the fact that the charged particles became attracted to the grounded surface and stick to the surface. In order to account for these particles, a method 5 rinse procedure was used to wash out the particles from the inside of the cooling tube, and this rinse volume was added along with filter paper rinse volume to calculate the total particulates collected at the slipstream. The rinse procedure could have been avoided if all the particles flowed smoothly into the filter. This can be achieved by the following two methods: one, having a mirror polished inside surface of the cooling tube which helps in the particles flowing smoothly, and secondly, using a mechanical rapper or vibrating device which would at regular intervals strike or generate vibration pulses to clear the inside of water jacket cooling tube, thus helping all the particles to flow out of the water jacket tube and eventually be collected at the slip stream filter paper.
• In order to accurately quantify the effect of cyclonic forces on the particles, the test plan should also incorporate the method of quantifying the amount of particles collected at the dust trap after each experiment. This can be done by unscrewing the dust trap and carefully collecting all the particles and quantifying them.

• Since the existing test plan does not have a procedure to quantify the volumetric flow rate at the slip stream, the new test plan should incorporate this procedure.

5.2.2: Recommendations for Future Work

• During the post experiment investigation, a slight wear was noticed on the surface of the mica tubing coated with a layer of alumina paint. To avoid this problem and to make the rig last for more experiments, use of ceramic material instead of mica sheets to electrically insulate the interior of the cyclone would greatly reduce the wear by the particles and temperature. This solution also would be the ideal choice when considering voltage optimization on the rig because in this setup we could accommodate more tests ranging from 25 kv to 45 kv to determine the optimal voltage where maximum collection of particle is seen. Since the present design has a max operating voltage of 38kv, use of ceramic material to provide electrical insulation should give us an opportunity to test for voltage optimization at 40 and 45 kv.

• A standard EPA method 5 sampling procedure was used for inlet and outlet sampling. At the slipstream the same method could not be followed as the temperature of the gas to be sampled was very high for the method 5 sampling
equipment. Use of water cooled method 5 probes, as shown in figure 5.3 should be a good solution to sample high temperature air flowing though the slip stream.

*Figure 5.3. Method 5 Water Cooled Probe (www.envirosupply.com)*
REFERENCES


Ohio Coal Research Center (OCRC)

Standard Operating Procedure

For

“Electrocyclone”

Document No: SOP_Electrocyclone _100702

Last Updated 10/02/2007 by Naveen Kunapareddy, based on work by previous OCRC researchers
1. TEST SYSTEM DESCRIPTION

FIGURE 1.1: ELECTRO CYCLONE SET-UP

FIGURE 1.2: SCHEMATIC OF ELECTRO CYCLONE SET-UP
The main components of the rig are the cyclone body, burner/blower, slip stream, and transformer rectifier set. The overall picture of the current electro cyclone is shown in Fig 1.1. Critical inside areas of the cyclone are electrically insulated with mica material. This was done in order to provide the necessary electrical insulation to prevent sparking between the conductive interiors of the cyclone and the discharge electrodes. The conical section of the cyclone body narrows down in diameter from 12 inches at the point where it is welded to the cylindrical section to 2 inches, where the bottom cap is fitted. The top of the cyclone is closed using a flange arrangement which has necessary provisions to fit the vortex finder and the electrodes. The vortex finder is essentially the outlet of the cyclone through which the clean air comes out of the rig. A natural gas burner/blower provides the flue gas into the cyclone. A fluidizer is setup to provide the necessary particulates injection into the flue gas stream. A slip stream is connected at the lower side of the conical section, where the bulk of the particles laden gases are expected to be collected using a slip stream filter apparatus.

(Environmental Protection Agency) EPA method 5 will be used for iso-kinetic sampling and thereby detecting the efficiency of the unit.
II. PERSONAL PREPARATION

A. Required Personal Training:

<table>
<thead>
<tr>
<th>No.</th>
<th>Required Training for Operators</th>
<th>Offered by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Occupational Safety and Health Administration (OSHA) laboratory chemical hygiene training</td>
<td>Environmental Health &amp; Safety (EHS) at Ohio University</td>
</tr>
<tr>
<td>2</td>
<td>EPA Method 5 Test Facility</td>
<td>OCRC</td>
</tr>
<tr>
<td>3</td>
<td>Malvern Mastersizer</td>
<td>OCRC</td>
</tr>
<tr>
<td>4</td>
<td>HiPotronics Model 850-20 Transformer Rectifier</td>
<td>OCRC</td>
</tr>
<tr>
<td>5</td>
<td>Airdata Multimeter - Model ADM 850 and Pitot Tube</td>
<td>OCRC</td>
</tr>
<tr>
<td>6</td>
<td>Industrial Scientific Model M40 Gas Monitor</td>
<td>OCRC</td>
</tr>
<tr>
<td>7</td>
<td>Night hawk carbon monoxide/Explosive detector</td>
<td>OCRC</td>
</tr>
<tr>
<td>8</td>
<td>Laboratory Tool Training</td>
<td>OCRC</td>
</tr>
<tr>
<td>9</td>
<td>Digital Millimeter</td>
<td>OCRC</td>
</tr>
<tr>
<td>10</td>
<td>Analytical Instrument safety and usage guidelines</td>
<td>OCRC</td>
</tr>
<tr>
<td>11</td>
<td>Metler Toledo balance</td>
<td>OCRC</td>
</tr>
</tbody>
</table>
### Required Safety Equipment:

<table>
<thead>
<tr>
<th>No.</th>
<th>Required Safety Equipment</th>
<th>Purpose/Condition</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tyvek disposable lab coat</td>
<td>With chemicals</td>
<td>Lab 045</td>
</tr>
<tr>
<td>2</td>
<td>Nitrile gloves</td>
<td>With chemicals</td>
<td>Lab 045D</td>
</tr>
<tr>
<td>3</td>
<td>Goggles</td>
<td>With chemicals</td>
<td>Lab 045</td>
</tr>
<tr>
<td>4</td>
<td>Safety Glasses</td>
<td>With tools</td>
<td>Lab 045</td>
</tr>
<tr>
<td>5</td>
<td>Synthetic Work Gloves</td>
<td>With tools</td>
<td>Lab 045</td>
</tr>
<tr>
<td>6</td>
<td>Insulated Rubber Boots</td>
<td>With high voltage</td>
<td>Lab 045D</td>
</tr>
<tr>
<td></td>
<td><em>(Minimum 17kV Rating)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Insulated Rubber Gloves</td>
<td>With high voltage</td>
<td>Lab 045D</td>
</tr>
<tr>
<td></td>
<td><em>(Minimum 15kV Rating)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Dust Mask N 95 Style</td>
<td>With particulates as precautionary measure</td>
<td>Lab 045</td>
</tr>
<tr>
<td>9</td>
<td>Insulated Grounding Stick</td>
<td>With high voltage</td>
<td>Lab 045D</td>
</tr>
<tr>
<td>10</td>
<td>M40 Multi Gas Monitors</td>
<td>To be worn by operators</td>
<td>Lab 045D</td>
</tr>
<tr>
<td>11</td>
<td>Night Hawk CO detector</td>
<td>CO Detection</td>
<td>Lab 045D</td>
</tr>
</tbody>
</table>
### C. Required Tools/Analytical Equipment:

<table>
<thead>
<tr>
<th>No.</th>
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<th>Purpose/Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EPA Method 5 recommended test equipments and supplies</td>
<td>For particulates sampling</td>
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<tr>
<td>2</td>
<td>Malvern Mastersizer</td>
<td>For checking Particulates Distribution</td>
</tr>
<tr>
<td>3</td>
<td>Digital Millimeter</td>
<td>For Ensuring proper grounding</td>
</tr>
<tr>
<td>4</td>
<td>Air Data Meter</td>
<td>Differential pressure reading</td>
</tr>
<tr>
<td>5</td>
<td>TR Set (850 – 20)</td>
<td>Voltage application</td>
</tr>
<tr>
<td>6</td>
<td>Laboratory Hand Tools</td>
<td>Misc. Operations</td>
</tr>
</tbody>
</table>

### D. Required procedures:

1. All operators are required to follow EPA Method 5 for particulates sampling.
   
   EPA Method 5 manuals are available at following location:

   X:\OCRC Main Directory\Analytical\EPA Methods
III. PROJECT/SITE PREPARATION

A. Required Services:

1. 120V/20A Electrical service with Ground Fault Circuit Interrupt (GFCI) protection for each of the following:
   
   a. TR Controller
   
   b. DC Controller for K-Tron particulate injection system
   
   c. Meter boxes for EPA Method 5
   
   d. Malvern Mastersizer test cart.
   
   e. Control module for natural gas burner/blower.

2. Natural gas supply for each of the following:

   a. Natural gas burner

3. Water supply for water jacket cooling system.

4. Compressed Air

B. Required Equipment/Supplies:

1. Required quantity of substance to inject into ESP

   a. Iron Oxide – Max 1.2lbs/hr and particle size of 2±1.87

2. Filters for particle collection

   a. 25 mm size glass fiber filters for inlet and outlet sampling.

   b. 13 cm size alstorm glass fiber filters for slip stream sampling.
C. Required Number of Operators:

1. A minimum of three operators are required to operate the cyclone ESP and conduct the EPA method 5 sampling.

D. Date of Final Safety Review Board Evaluation and Certification of Project/Site

Safety Certification Completed: ____________________________________________

Signature and Date
IV: OPERATION

A. RIG PREPARATION

Ensure that the work area is clean and clutter free. Make sure that surroundings of the rig are free from unnecessary tools and equipment. The OCRC Chemical Hygiene Plan applies to all aspects of the operation. Get CONFIRMATION from lab personnel before running the test. Before starting totally new set of experiments, go through each and every step of the SOP (dry run) without actually turning on the water circulation, burner, blower, injection system and voltage supply.

a) Differential Pressure (ΔP) readings (At inlet and outlet and slip stream):

1. Connect the standard pitot tube to the air data meter for taking differential pressure readings.
2. Connect the burner/blower to the 120V/20A Electrical service GFCI outlet.
3. In order to run only the blower in the burner/blower assembly, make sure that all the manual gas valves on the burner supply pipe train are in the closed position. (Fig 4.1A) and only the burner/blower ON/OFF switch is set to ON position as shown in Fig 4.1 B.

FIGURE 4.1 A: BURNER SUPPLY PIPE TRAIN
4. Power the particulate injection blower by turning the blower power switch to ON position.

5. Using the S-type pitot tube, record the $\Delta P$ values for the sampling location at inlet as shown in Fig 4.2 A. Once the readings have been taken and the probe removed, replace the plug at inlet differential pressure reading port.
6. Power down the burner/blower by setting the ON/OFF switch on the control box to OFF position as shown in Fig 4.1 B.

7. Power down the particulate injection blower by setting the switch on the variac control to OFF position.

b) Water Circulation:

1. Ensure that the water jackets drain pipe is securely connected to the buildings floor drain in the Stocker 045 D lab (Fig 4.3 A). Turn on the main water valve which is situated on the left side of the research tower entrance. Fig 4.3 B
2. Open the secondary water valve connected to the rotameter situated above the water jacket. Fig 4.3 C.

3. Check all plumbing for water leakage. All leaks must be repaired before continued operation.

4. Check for any spilled water around the unit. Spilled water must be cleaned and dried before continued operation.

c) Natural Gas Burner :

1. All operators are required to have an M40 multi gas meter worn at all times during testing.
2. Check the Nighthawk Carbon Monoxide/Explosive Gas detector for functionality. Fig 4.4 A.

   a. Observe the initial reading displayed on the detector. It should initially be at a value of 0.

   b. Test the detector by pressing the test/reset button below the display screen (Fig 4.4 A). The detector should go through a series of displays and beeps before returning to the initial value of 0 in approximately 15 seconds. If the functional test does not return to the display value of 0, immediately notify the problem to the shop supervisor.

![Nighthawk Carbon Monoxide/Explosive Gas Detector]

**FIGURE 4.4 A: NIGHTHAWK CARBON MONOXIDE/EXPLOSIVE GAS DETECTOR.**

3. Check to see that the grounding wire which is green in color is properly connected to a ground as shown in Fig 4.4 B.
4. Keep the area around the burner/blower clear and free of combustible materials, gasoline or other flammable liquids or vapors. Do not obstruct burner air openings or ventilation grilles for combustion air. If the burner is to be shut down for an extended time, the main manual gas valve (Building gas valve) should be closed as a precaution. Main manual gas valve is located in research tower next to the torch booster.

5. Open all manual gas valves located on the burner/blower pipe train.

6. Turn burner/blower ON-OFF switch to the ON position.

7. Wait 30 seconds, if the burner has failed to light or if the burner lights and then goes out turn the burner/blower ON-OFF switch to OFF position for 30 seconds and repeats steps 6 again.

8. To shut down the burner, set the burner ON/OFF switch to OFF position and close all the manual gas valves on the burner pipe train.

9. For trouble shooting or any additional instructions please refer to the online burner manual (www.waynecombustion.com/manuals/EGH%20Manual%20Rev%20D.pdf) or a hard copy located at the rig along with the SOP.
B. METHOD 5 PREPARATION (For sampling at inlet and outlet):

a) Filter Paper:

1. The filter paper should be dried and desiccated in an oven at 105°C for about two hours and weighted every six hours until there is no significant change in the weight of the filter paper prior to the experiment. This is done to remove the moisture from the filter paper [EPA Method 5-section 8.1.3]. Use Mettler Toledo 290759 weighing machine placed in Stocker 045A lab to weigh the filter. This procedure should be done prior to setting up the unit for experiment.

b) Impinger set:

1. Prepare the impinger set of four for the inlet and the outlet sampling positions. Fill up the first two impingers with 100 ml distilled water, keep the third one empty and the fill last one with silica gel. [EPA Method 5-section 8.3.1]

2. Record initial weights of all the impingers on “Method 5_Spreadsheet”.

3. Put all impingers in the impinger bucket as shown in Fig 4.5A.
4. Use the U-connectors as shown in Fig 4.5B to seal the impingers.

c) Connections (same for the inlet and outlet)

1. Fix the filter in the filter holder after weighing.

2. For EPA Method 5, connect the heating box at the down end of probe and only nozzle at the front end of probe. Then put filter holder in the heating box [EPA Method 5-figure 5-1).

3. Make all the required connections from the nozzle to the probe to the filter to the impingers to the umbilical’s to the meter box by following figure 5-1 of EPA Method 5 in case of Method 5. Some tips are given below

   i. The blue connector (Fig 4.6A) is used to connect the outlet of the impinger train to the meter box umbilical (Fig 4.6B)

   ii. The white Teflon tube (Fig 4.7) is used to connect the probe to the inlet of the impinger train.
iii. A picture of the meter box and some connections is shown in Fig 4.8.

4. While making connections double check that they are sealed properly otherwise moisture could enter the meter box and cause malfunction.

5. Perform a leak test as described in EPA Method 5 Section 8.4.

6. In the event of a leak, check the connections and repeat the leak test until the setup is sealed properly.
7. For EPA Method 5, turn on the oven used for heating the filters and set the required temperature in the thermostat on the meter box (Fig 4.8).

8. Fill out the required data and the initial readings from the Method 5 Meter Boxes on the data sheets. Meter box number and correction factor should be included.

C. TESTING

a) Injection System – For Particulates:

1. If desired don NIOSH approved dust masks N95 style. **NOTE USE OF THE DUST MASK IS VOLUNTARY.**

2. Load iron oxide into the particulate injection system.

3. To hookup the particulate injection system, connect the outlet of the fluidizer to the particulate injection inlet of the ESP, as shown in Fig 4.9 A. Connect a compressed air line from the building supply to the fluidizer as shown in Fig 4.9B. Open the compressed air valve from the building supply which is located next to the gasifier as shown in Fig 4.9 C.

4. Control the particulate feed rate by adjusting the feed rate control knob of the K-Tron DC controller on the particulate injection system as shown in Fig 4.9 A.

5. Conduct a feel test for air leakage around the fluidizer. In an event of leakage, notify the shop technician immediately and commence system shutdown.
b) Voltage Supply:

1. Voltage will always be the last subsystem to be initiated. All other subsystems must be operational before voltage is supplied to the electrodes.
2. This operator will wear all necessary PPE, including insulated (minimum 15kV rated) rubber gloves, (minimum 15kV rated) rubber gloves and insulated (minimum 17kV rated) rubber boots while energizing the rig. Before donning the PPE, operators are required to check for proper functioning (checking to see for any cuts, holes or worn out material) of the equipment.

3. Ensure that all safeties are in place and operable before charging the ESP. All safety chains must be secured to prevent accidental contact.

4. Make sure the insulated grounding stick is connected securely to the ground and is placed outside the safety chain before the start of the test. After the test is over and before entering the secured area, this is used to dissipate any charges that might have built up on the Cyclone ESP or its components.

5. Make sure that the co-axial cables between the electrodes and the power pack are connected properly.

6. Connect the power pack (Fig 4.10) to the control unit. While doing so make sure that the orientation of the plug is correct as shown in the figure (Fig 4.10). **The key hole in the plug should properly mate with the key of the power pack.**

Note: For any unexpected shutdown or emergency, proceed with the rig shutdown section.
7. Connect the transformer to the electrode and tighten a nut above the connection to make sure the electrode connection is secured.

8. Turning on the Voltage

a. Plug the TR set to power outlet.

b. The TR-Set is turned on using the power switch followed by the backup switch. (Fig 4.11)

c. Press the on button. (Fig 4.11)

d. Now increase the voltage using the black voltage knob gradually till you reach the required voltage or detect the sparking point. (Fig 4.11)

e. In case the voltage drops to zero due to sparking to restart the voltage,

   1. Turn the voltage knob to zero

   2. Press the reset button (Fig 4.11)

   3. Next press the on button
4. and proceed to apply the required voltage

![Transformer Rectifier Control Module](image)

**FIGURE 4.11 TRANSFORMER RECTIFIER CONTROL MODULE.**

c) **Sampling (same for inlet and outlet):**

1. Run the test for EPA Method 5 for max of half hour by following section 8.5 of EPA Method 5.

2. One operator will monitor the Method 5 Meter Boxes and will be responsible for recording all necessary results.

3. All operators are required to stay out of the chained area, while the rig is being energized.

4. Make sure that the insulated grounding stick is plugged to a GFCI outlet.

5. Probe should be accurately positioned using the levels (Fig 4.12) as well as the markings on the probes.
Some tips for sampling are as follows:

1. During sampling, the gas is drawn through a set of impingers loaded as per EPA Method 5/17 to the Method 5 Meter Box. This is necessary to absorb the moisture in the gas sample.

2. Record differential pressure and stack temperature readings at every sampling point using the “Method 5_Spreadsheet” to find the value of delta H at that particular point.

3. Maintain filter temperatures in the range of 200 to 220F throughout the experiment.

4. Record probe and meter box temperatures, vacuum pressures, and dry gas meter readings on the “Method 5_Spreadsheet.” These parameters are used to calculate the capture efficiency of the ESP.

d) Slip Stream filter paper and filter box setup.

1. The slip stream filter paper should be dried and desiccated in an oven at 105°C for about two hours and weighed every six
hours until there is no significant change in the weight of the filter paper prior to the experiment. This is done to remove the moisture from the filter paper [EPA Method 5-section 8.1.3]. Use Mettler Toledo 290759 weighing machine placed in Stocker 045A lab to weigh the filter. This procedure should be done prior to setting up the unit for experiment.

2. The filter paper is then placed on the filter gouge bracket and an O ring is then placed on filter paper and the support bracket is then assembled on top by tightening all the bolts on the brackets as shown in the Fig 4.13A, Fig 4.13 B and Fig 4.13 C.
3. Now the filter support assembly is placed into the bottom half of the filter housing with the filter paper side facing up as shown in Fig 4.14. **NOTE: MAKE SURE THE BOTTOM HALF OF THE FILTER HOUSING GOES ON TO THE FILTER SUPPORT STAND.**

4. Now the upper half of the slip stream filter is assembled by placing an O ring on the lower half filter housing lip and then tightening the upper half of the filter housing using nuts and bolts.

**FIGURE 4.13 C: FILTER SUPPORT ASSEMBLY.**

**FIGURE 4.14: BOTTOM HALF OF FILTER HOUSING**
5. This entire assembly is removed from the filter support stand and the upper half filter housing side is connected to the slip stream water jacket, the bottom half filter housing side is connected to the vacuum pump, while the entire filter housing rests on the filter housing holder.

6. NOTE: SLIP STREAM FILTER IS CONNECTED ONLY AFTER THE COMPLETION OF DIFFERENTIAL PRESSURE READING AT THE SLIPSTREAM LOCATION.

e) Sampling at the slip stream

1. This operator will wear all necessary PPE, including insulated (minimum 15kV rated) rubber gloves, rubber gloves and insulated (minimum 17kV rated) rubber boots

2. Before contact with the vacuum pressure gauge valve, operators must first use the insulated grounding stick to contact (ground) the probes to dissipate any charge that may have built up.

3. Every 15 min of experimentation the operator should adjust the pressure of vacuum pump (Fig 4.15) by turning the vacuum manual valve to match that of the pressure at the start of the experiment.
V. PROJECT/SITE CLEANUP

1. Shut down all subsystems in the reverse of their startup.

2. Close the sampling valves to the Method 5 Meter Boxes. Leave connections intact as a post leak test will be performed per Method 5.

3. Turn off the TR set. Use the insulated grounding stick to dissipate any charges that have built up on or around the ESP or its components. Give special attention to the electrodes and make sure that they have been properly grounded.

4. Only after the TR set is turned off and charges dissipated open the secured chain to access the ESP.

5. For particulate injection system, first turn off the K-Tron DC screw feeder control, close the valve that supplies the building compressed air. Uncouple the system if needed.

6. Power down the natural gas burner/blower by closing the manual gas valves located on the burner supply pipe train.
7. Visually check to see if the water flow rate on the rotameter is still at the required flow rate.

8. Close the valve of the residential gas valve (Building gas valve).

9. Close the main water supply valve at the entrance of the research tower. Remove the sample probes from the ESP sample ports and complete the post leak test per EPA Method 5- section 8.4.4.

10. Remove all the connections and recover the filter paper and store it carefully per Method 5- section 8.7.6.1.

11. Clean the probes and the sampling lines by following section 8.7.6.2 of EPA Method 5 and collect and seal the samples in glass bottles. Glass bottles must be labeled with the appropriate experimental information.

12. Treat the impingers by following section 8.7.6.3 of EPA Method 5.

13. Slip stream

   a. Using a themocouple reader make sure the temperature of the slipstream has come down to room temperature and then uncouple from the cyclone and carefully set it on the slip stream filter stand making sure that the bottom half of the filter housing goes into the stand.

   b. Remove the bolts and take off the upper half of the filter housing.

   c. Now carefully remove the filter support assembly and remove the top bracket. Now follow section 8.7.6.2 of EPA
Method 5 and collect and seal the samples in glass bottles. Glass bottles must be labeled with the appropriate experimental information.

14. Return the probes, nozzles, and umbilical cords to storage.

15. Download the data from the Industrial Scientific M40 gas monitor and supply with the Method 5_spreadsheet for each test. These data should be documented in the lab note book for future references. Return the M40 unit to the charger base.

16. Return all tools and analytical supplies to their designated locations.
APPENDIX B: FAILURE MODE EFFECTS ANALYSIS (FMEA)

Ohio Coal Research Center
Initial Safety Certification - Failure Mode and Effects Analysis Worksheet (Adapted from Cincinnati Machine PFMEA)

<table>
<thead>
<tr>
<th>Name / Description of Test System, including SOP</th>
<th>Key Contact / Phone</th>
<th>Date of Initial FMEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolysis precipitator</td>
<td>Naveen Konapareddy</td>
<td></td>
</tr>
<tr>
<td>Electrolysis precipitator is a device which would be used in the clean up of the hot gases coming out of the power plant</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. A written step-by-step experimental procedure or standard operating procedure (SOP) must exist in order to judge its safety; so that has to be completed before the FMEA can be completed. Consider including scheduled safety inspections or checks in the experimental procedure. The SOP must be included in the DFSR or appropriately referenced.

Hazard Identification Discussion (Details for the "description of test subsystem or operating procedure" and "potential failure mode") columns:
- Note the procedure used to identify all potential hazards, including who was involved and what was done to insure completeness.
- All aspects and modes of operation of the system must be evaluated, including system setup, actual testing, post-test cleanup, etc.
- Strive to design your system and procedures to completely avoid dangers whenever possible. For guidance, review the design for safety guidelines, especially with respect to avoidance, protection and warnings.

The standard operating procedure is in process, keeping all the safety procedures in mind. The Experimental Setup was divided into various parts such as structural, mechanical and electrical. All subsystems like forcing, burner, vacuum pump, TR set were analysed. The dangers associated with each part was assessed. The hazards were also identified by using HZOP (Hazard and Operability studies), which is a structured method for systematically investigating each element of the system for all the ways in which important parameters can deviate from the intended design conditions to create hazards and operability.

The potential dangers were identified, but proper precautionary measures have reasonably lowered the SEV and OCC values, hence there was no need of including an FMEA for:
- Umbilical cords and wires: Tripping danger can be avoided by bundling up most of the cords and wires and marking them with fluorescent tapes.
- Particulate matter: Possible dangers while handling particulates will be prevented by using a proper face mask and gloves.
- Electrical sparking: FMEA for sparking within the rig is not considered, as the test rig will be properly grounded all the time and will be sealed completely.

The FMEA was included for the following:
- Electric shock
- Gas Leakage
- Particulate exposure
- High noise levels
1) FMEA description and ratings for Hazard 1

<table>
<thead>
<tr>
<th>Category</th>
<th>Potential Failure</th>
<th>Potential Effect</th>
<th>S</th>
<th>Potential Case(s) of Failure</th>
<th>C</th>
<th>Current Controls</th>
<th>D</th>
<th>R</th>
<th>Recommended Action</th>
<th>Person</th>
<th>Action Taken</th>
</tr>
</thead>
<tbody>
<tr>
<td>test subsystem</td>
<td>Mode</td>
<td>of Failure</td>
<td>E</td>
<td>(Mechanism(s) of Failure</td>
<td>F</td>
<td>Detection / Prevention</td>
<td>E</td>
<td>P</td>
<td>Action 5</td>
<td>Completion</td>
<td>Date</td>
</tr>
<tr>
<td>or section of SOP</td>
<td>T</td>
<td>Failure</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

2) Include some discussion/justification for the rating for severity (SEV)

Electric Shock will cause severe burn injuries and sometimes even death. So there is very serious danger. Also no test would stop completely since the operator is affected. Note that the current would go up drastically when a person gets a shock and this could lead to tripping of the TR Set. Hence a SEV value of 10 is used.

3) Include some discussion/justification for the rating for probability of occurrence (OCC)

Direct contact with electrodes is not possible since they are enclosed inside the rig. All parts of the rig are grounded with very experienced shop technicians, so a likely event of charge building on the frame is very less. The only potential parts of the rig with which the user can get a shock are the bolts at the top of the rig to which the electrodes are connected and the ends of the wires which are connected to them. The chances of touching these are really low since they are too far away from the place the operator is working. Also all operators on the core team have considerable experience in handling the tests, they are generally very observant and keep an eye on each other as well, the SOP requires insulation gloves and boots at all times during experimentation and also a locked fenced area separating the operator from the rest of the system.

4) Include some discussion/justification for the rating for probability of detection (DET)

The operators are experienced and following the SOP correctly would give the operator a good room to detect and avoid the hazard.

5) Recommended actions: Make specific recommendations for action and include some discussion of the alternatives that were considered.

Installation of a fence which separates the operator from the system.

2) FMEA description and ratings for Hazard 2

<table>
<thead>
<tr>
<th>Category</th>
<th>Potential Failure</th>
<th>Potential Effect</th>
<th>S</th>
<th>Potential Case(s) of Failure</th>
<th>C</th>
<th>Current Controls</th>
<th>D</th>
<th>R</th>
<th>Recommended Action</th>
<th>Person</th>
<th>Action Taken</th>
</tr>
</thead>
<tbody>
<tr>
<td>test subsystem</td>
<td>Mode</td>
<td>of Failure</td>
<td>E</td>
<td>(Mechanism(s) of Failure</td>
<td>F</td>
<td>Detection / Prevention</td>
<td>E</td>
<td>P</td>
<td>Action 5</td>
<td>Completion</td>
<td>Date</td>
</tr>
<tr>
<td>or section of SOP</td>
<td>T</td>
<td>Failure</td>
<td>C</td>
<td></td>
<td></td>
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</tbody>
</table>

2 Include some discussion/justification for the rating for severity (SEV)

A gas leak can lead to a very unsafe testing environment, even a small spill can trigger a very dangerous fire hazard and inhalation of gas can lead to potential health problems like nausea and dizziness. Hence a SEV value of 10 was used.

3) Include some discussion/justification for the rating for probability of occurrence (OCC)

All the joints and connections will be completely snoot tested before the start of experimentation and providing proper ventilation as per SOP.

4) Include some discussion/justification for the rating for probability of detection (DET)

Can smell the gas and also a feel test as well as snoot testing is done to ensure proper sealing of all the lines. SOP is required to ensure proper working of the gas alarm before experimentation.

5) Recommended actions: Make specific recommendations for action and include some discussion of the alternatives that were considered.

Installation of a gas monitor which would alarm in case the leak reaches a value of 10% of LEL (Lower explosion limit)

6) Notes on actions taken:
3) FMEA description and ratings for Hazard 3

<table>
<thead>
<tr>
<th>Category</th>
<th>Potential Failure</th>
<th>Potential Effect</th>
<th>S</th>
<th>Potential Cause(s)</th>
<th>O</th>
<th>Current Controls</th>
<th>D</th>
<th>R</th>
<th>Recommended</th>
<th>Person</th>
<th>Action Taken</th>
<th>Person</th>
<th>Action Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate exposure</td>
<td>Leakage</td>
<td>Faulty results or inhalation</td>
<td>6</td>
<td>Improper or worn out sealings on the test set-up and regular inspection</td>
<td>3</td>
<td>Detection / Prevention</td>
<td>E</td>
<td>P</td>
<td>Action</td>
<td>T</td>
<td>N</td>
<td>Completion</td>
<td>Date</td>
</tr>
</tbody>
</table>

2 Include some discussion/justification for the rating for severity (SEV)
Health problems like asthma, bronchitis and other respiratory diseases. The exposure time is very small and use respirators while handling iron oxide is required.

3 Include some discussion/justification for the rating for probability of occurrence (OCC)
Chances of exposures is very less during ordinary operating conditions. Exposures generally occur during intermittent inspections and while feeding the screw feeder. SOP requires to use protective face masks which prevent inhalation of the particles during the exposure time.

4 Include some discussion/justification for the rating for probability of detection (DET)
Particulates leakage is normally visible as we know the potential sites of leakage and since iron oxide is black in color so it can be easily seen when it deposits on anything.

5 Recommended actions: Make specific recommendations for action and include some discussion of the alternatives that were considered.

6 Notes on actions taken

4) FMEA description and ratings for Hazard 4

<table>
<thead>
<tr>
<th>Category</th>
<th>Potential Failure</th>
<th>Potential Effect</th>
<th>S</th>
<th>Potential Cause(s)</th>
<th>O</th>
<th>Current Controls</th>
<th>D</th>
<th>R</th>
<th>Recommended</th>
<th>Person</th>
<th>Action Taken</th>
<th>Person</th>
<th>Action Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Pump</td>
<td>Noise</td>
<td>Cause deafness and head aches</td>
<td>4</td>
<td>Compressed air in the vacuum pump</td>
<td>8</td>
<td>Noise is an inherent part of the system</td>
<td>T</td>
<td>N</td>
<td>Action</td>
<td>T</td>
<td>N</td>
<td>Completion</td>
<td>Date</td>
</tr>
</tbody>
</table>

2 Include some discussion/justification for the rating for severity (SEV)
Short exposure causes head ache and fatigue and prolonged exposure could cause deafness.

3 Include some discussion/justification for the rating for probability of occurrence (OCC)
Chances of exposures is very high as the manufacturers note on the vacuum pump suggest high decibel noise levels.

4 Include some discussion/justification for the rating for probability of detection (DET)
There is no chance to avoid as the noise is a part of the system.

5 Recommended actions: Make specific recommendations for action and include some discussion of the alternatives that were considered.
Usage of ear plugs or if there is a possibility for isolating or sound proofing the the vacuum system by using a baffle box to muffle the sound.

6 Notes on Actions taken: