Dual Flue Gas Conditioning  
Processes, Technology and Experience

Henry V. Krigmont, James J. Ferrigan

1 Allied Environmental Technologies, Inc. P.O. BOX 3826, Seal Beach, CA, 90740 USA
2 Fuel Tech, Inc. Fuel Tech, Inc. 27601 Bella Vista Pkwy, Warrenville, IL 60555 USA

Corresponding author: JFerrigan@ftek.com

Keywords: Electrostatic Precipitator, Gas Cleaning, PM Removal, Flue Gas Conditioning, Ammonium Conditioning, Dual FGC, Ammonium Bisulfate, ABS

1 INTRODUCTION

Altering the flue gas environment through gaseous additives (flue gas conditioning or FGC) is a common technique to improve ESP performance. The deposition of layers of liquid on the surfaces of fly ash particles is the most common mechanism for altering the behavior of these particles during precipitation [1].

Over the years, SO3 flue gas conditioning (FGC), demonstrated its ability to modify the fly ash resistivity via surface conductivity modification. On the other hand, Dr. Dismukes clearly demonstrated that fly ash shows no significant change in resistivity as a result of ammonia conditioning[3]. However, it does improve the efficiency of fly ash precipitation through two mechanisms: a space-charge effect and an increase in the cohesive energy of fly ash.

In fact, ammonia works as a scavenger, hunting down each free molecule of the SO3 and/or H2SO3 producing several ammonium salts. Consequently, the reaction of ammonia with sulfur trioxide to produce ammonium sulfate or ammonium bisulfate appears to have been a key event in the occurrence of either type of conditioning process.

Ammonium bisulfate, generated on fly ash particle surfaces during conditioning with ammonia in the presence of SO3, has been shown to be effective in field applications for reducing resistivity and increasing cohesivity. The effectiveness of this compound for increasing cohesivity is linked to the fact that it melts at 146.67°C (296°F). Since it may exist as a liquid at the flue gas temperatures encountered in many particle control devices, it could be collected at the contact points between particles through capillary action. When this occurs, liquid bridges are formed between adjacent particles. These liquid bridges form strong bonds between particles and significantly increase the bulk cohesivity of the ash. This is the most common mechanism for increasing ash cohesivity. Water adsorbed from the flue gas can also form these liquid bridges.

Since fly ash resistivity and cohesivity are key parameters in determining electrostatic precipitators (ESP) performance, the Dual FGC, which had been defined as simultaneous but independent injection of ammonia and SO3, presents the best way to influence these key parameters.

2 SO3 FLUE GAS CONDITIONING

By far, the largest body of work in the art of flue gas conditioning has been devoted to attempts to lower the dust resistivity[1,4,5,6]. FGC is as old as the art of precipitation itself. As early as 1912, it was discovered that copper converter dust precipitation was considerably enhanced by the presence of SO3 or increased moisture of exhaust gases.

Acceptance of the process called FGC as an engineering solution to a common environmental problem has come slowly. To begin with, the process is misnamed; it is not the gas which is conditioned, but the particles of dust in the gas, e.g., the fly ash. Adjusting the resistivity of fly ash particles by application of a dilute acid solution to their surfaces is an easily understood and straightforward task. The very idea that the behavior of a gas stream might be manipulated by adding a few parts per million of a reagent boggles the mind.

Sulfur occurs in coal as organic and inorganic compounds. When coal is burned, more than 95% of the sulfur becomes SO2. A small fraction is converted to gaseous SO3. When the flue gas temperature drops below approximately 600°F (316°C), SO3 begins to react with water vapor to produce sulfuric acid vapor. The reaction is essentially complete when the temperature drops to about 300° - 350°F (149°-177°C), where precipitators normally operate. Thus, in a strict sense, conditioning results from sulfuric acid vapor (H2SO3), rather than SO3 being absorbed onto the surface of the fly ash particles (Figure 1).

SO3 may come from two sources: (a) combustion, i.e. native or indigenous conversion of the SO2 formed during the combustion of the sulfur contained in the coal to SO3 and (b) as the SO3 flue gas conditioning (FGC), which is SO3/air mixture injected to assist in electrostatic precipitators (ESP) performance enhancement.

2.1 INDIGENOUS SO3 FGC

SO3 content has a significant impact on particle resistivity, which is one of the most important parameters in ESP collection efficiency. For high resistivity ashes, SO3 reduces the back corona phenomena. SO3 is generated inside the boiler, but the SO3 quantity in the flue gas changes along the path from the furnace to the stack [1]. SO3 concentration is modified from the boiler to the ESP: in the SCR, if present, and in the regenerative air preheater.

Another approach to creating SO3 is to utilize “native” SO3 formed during combustion of sulfur contained in fossil fuels as a feedstock for its subsequent conversion to SO3. Extensive experiments at Lehigh University[12] confirmed
that, at conditions typical for coal-fired applications, a substantial portion of the "native" SO$_2$ could be oxidized to SO$_3$. The rate of such process will depend on specific factors including catalyst's properties, the temperature and the concentrations of SO$_2$, O$_2$ and water vapors. Systems implementing this technique have been proposed, but none were free of major deficiencies$^{13,14,15}$.  

![Electrostatic Precipitator](image)

**Figure 2. Indigenous FGC (iCON®)**

The Indigenous Flue Gas Conditioning (iCON®) concept$^{16}$ (Figure 2) consist of the following: withdrawing a portion of the clean flue gases containing sulfur dioxide (SO$_2$) generated by a combustion process from a location downstream of electrostatic precipitator (FGC process carrier gas flow), preheating process carrier gases, passing the process carrier gases through the catalyst bed where a portion of the SO$_2$ is converted into sulfur trioxide (SO$_3$), and returning the carrier gases with the additional SO$_3$ to a location ahead of the electrostatic precipitator. The amount of process carrier gas is governed by the SO$_3$ injection rate required$^{17}$, sulfur content of coal fired (boiler exhaust gases SO$_2$), and type/efficiency of the catalyst used in the iCON® catalyst bed. A sample calculation using medium S coal and moderate sulfuric acid catalyst efficiency resulted in the approximate one to two percent (1 to 2%) exhaust gas flow. The iCON® process of generating the SO$_3$ for the FGC and subsequent carrier gases delivery, distribution, and mixing is very simple and straightforward.

### 2.2 SO$_3$ FLUE GAS CONDITIONING

With very few exceptions all commercial SO$_3$ FGC systems installed to date are based on catalytic conversion of sulfur dioxide (SO$_2$) which is supplied either in liquid form or obtained by burning elemental sulfur$^{2,10}$. Elemental molten sulfur used to be the preferred feedstock for long-term permanent operations because its operating costs are lower. However, it has now been surpassed by the systems based on the use of granular (pelletized) dry sulfur.

The catalytic conversion process was chosen over other methods of making SO$_3$ because of its flexible and easy control, but also because it minimizes the quantity and the difficulty of handling hazardous materials in the system.

#### 2.2.1 Molten Sulfur Feedstock

Elemental molten sulfur is the preferred feedstock for long-term permanent operation because of lower operating cost, however, liquid SO$_2$ may be used for trials and small or short-term situations where reduced capital costs can offset increased feedstock expense.

#### 2.2.2 Dry Sulfur Feedstock Technology (Molten Sulfur on Demand)

Dry sulfur configuration combines the advantages of dry sulfur storage, transfer of dry sulfur to the melter vessel, and molten sulfur metering.

Sulfur is delivered in dry form and then melted for use in various processes (Figure 3). Using this tried and true proven method, dry sulfur is melted via the use of saturated steam to molten sulfur for conventional process metering. This takes advantage of dry sulfur storage and handling while maintaining the good burn characteristics of molten sulfur and accurate reliable metering. With the proper provisions, a permanent system could accept both dry and molten sulfur feed stock so that the process is not dependent on one source or method of sulfur delivery.

![Dry SO$_3$ FGC System Layout](image)

**Figure 3. Dry SO$_3$ FGC System Layout**

#### 2.2.3 SO$_2$ to SO$_3$ Conversion

In conventional FGC systems, the catalyst for conversion of SO$_2$ to SO$_3$ is usually chosen from any of the types developed for the manufacture of sulfuric acid and similar applications. Vanadium pentoxide is the active ingredient in these catalysts, and is classified as a hazardous material. Care should be taken to remove dust and water from the air intake to the maximum extent possible and to service the air intake filter on a regular basis.

The hot air stream containing the generated SO$_3$ exits the SO$_2$ to SO$_3$ converter at temperatures from 390 °C (750 °F) to about 538 °C (1,000 °F), depending on the production rate of SO$_3$. It is essential that this stream be held above its acid dew point temperature throughout the delivery manifold and injection probes. For this reason the distribution manifolds are heavily insulated; the injection probes, if installed on the cold side of the air preheater, are also thermally insulated from the flue gas.

#### 2.2.4 Injection Probes or Lances

Since installation of injection probes is easily accomplished in the ESP-type ductwork on the cold side of the air preheater rather than in the boiler-type construction on the hot side, most of the present FGC installations inject on the cold side.

As more and more power generating stations install SNCR and SCR systems for NOX reduction the potential for NH$_3$ slip at the air heater inlet has resulted in system suppliers revisiting the cold side injection strategy. This has led to unique innovations in the use of a "biased dense grid" design with biased injection probes. This approach has greatly enhanced the injection of SO$_3$ after the air heater with no further concern for retention time.

### 3 AMMONIA FLUE GAS CONDITIONING

The value of ammonia as a conditioning agent was reportedly discovered in 1942 in efforts to deal with high resistivity of catalyst dust in the petroleum industry$^{12,13,4,5}$. The use of the ammonia for treating fly ash in coal-fired power plants, on the other hand, is "comparatively" new.

First reports of the *intermittently* successful use of the ammonia as a conditioning agent were reported in Australia by Watson and Blecher in 1966. The study demonstrated positive results while using the ammonia as a conditioning agent. There, the SO$_3$ flue gas conditioning was proved to be ineffective due to the highly acidic ash (pH of 3.5–4) and, thus, speculations were that conditioning with a basic rather than acidic agent might prove more effective.
3.1 PROCESS AND CHEMICAL REACTIONS

Fundamental explanations of ammonia conditioning effects have assumed that the chemical compounds formed when ammonia is injected, either concurrently with injection of sulfur trioxide (Dual FGC) or when the latter is formed by "natural" (combustion) processes in sufficient quantities, are ammonium bisulfate \( \text{NH}_4\text{HSO}_4 \) or, if the stoichiometric ratio is appropriate, the normal sulfate \( \text{NH}_4\text{SO}_4 \).\(^{[12,3,4,5,6]} \) Besides these, the existence of intermediate chemical compounds is possible. The melting points change continuously according to the \( \text{H}_2\text{SO}_4/\text{NH}_3 \) stoichiometric ratio, and there is a possibility that compounds with very low melting points may be formed in the process. In addition, the compounds which are stable in solid form at temperatures above 150 °C (300 °F) are those with stoichiometric ratios 1.2 and above.

The chemical reactions postulated by Rendle and Wilson teach that ammonia will react with any natural sulfur trioxide present and moisture to produce ammonium bisulfate (Eq. 1). In the presence of excess ammonia, this reaction will slowly continue to produce ammonium sulfate (Eq. 2).

Melting point of ammonium bisulfate \( \text{NH}_4\text{HSO}_4 \) is 146.9°C (297°F). Therefore, lacking excess ammonia or as cooling occurs, the liquid ammonium bisulfate will freeze at temperatures below 147°C (297°F) into a sticky solid. It is this adherent nature of the resultant that has been thought to play a major role in the precipitator performance improvement.

When flue gas temperatures are 140.9°C (284 °F), \( \text{NH}_4\text{HSO}_4 \) will become solid. Melting points of \( \text{NH}_4\text{HSO}_4 \) are 513°C.

In the Eq. (2), \( \text{NH}_4\text{HSO}_4 \) dissociated at higher than 200°C temperatures. When flue gas temperatures are above 200°C, \( \text{NH}_4\text{HSO}_4 \) produced will decompose into \( \text{NH}_2\text{HSO}_4 \). Reactions taking place in this equation are usually slower than those in equation (3).

\[
\text{NH}_3(\text{gas}) + \text{SO}_3(\text{gas}) + \text{H}_2\text{O}(\text{gas}) \rightarrow \text{NH}_4\text{HSO}_4(\text{liquid, solid}) \\
\text{NH}_3(\text{gas}) + \text{NH}_4 + \text{H}_2\text{O}(\text{liquid}) \rightarrow \text{NH}_4\text{HSO}_4(\text{solid, sulphuric ammonia}) \\
\text{SO}_3 + 2\text{NH}_3 + \text{H}_2\text{O} \rightarrow \text{(NH}_4\text{)}_2\text{SO}_4 \\
\text{NH}_4\text{HSO}_4 + 2\text{NH}_3 \rightarrow \text{(NH}_4\text{)}_2\text{SO}_4
\]

The ammonium sulfate shown as the product of the Eq. (2) would exist as a solid in a wide range of flue gas temperatures, as indicated in the equations (2 – 3). The ammonium bisulfate shown as the product of the first Eq. (1) would exist as a liquid above 144°C (291°F) or as a solid below this temperature; hence, the physical state is indicated in the equation as either liquid or solid. (There is some uncertainty about the temperature where ammonium bisulfate solidifies. The indicated temperature is based on the data of Kelley et al. Thermodynamic information indicating that either of the two reactions can occur under flue-gas conditions is also included in the data published by Kelley.)

While ammonium bisulfate has been studied fairly extensively in the context of atmospheric aerosols, very little fundamental work has been conducted at conditions relevant to the electrostatic precipitators in coal based power generation. Since ammonium bisulfate is a sticky material, an accurate determination of its formation temperature can help accurately determine its impact on the ESP operation as well as its operational limitations.\(^{[7,8]} \)

Wei et al.\(^{[7]} \) experimentally investigated the formation (i.e. condensation) temperature of ammonium bisulfate to determine how much \( \text{NH}_3 \) slip an air preheater can tolerate given the flue gas sulfur content and temperature.\(^{[7]} \)

Johnson et al.\(^{[9]} \) noted especially the importance of one of, perhaps, the most important principle chemical reaction for the formation of ammonium bisulfate (Eq. 5):

\[
\text{SO}_3 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{SO}_4
\]

Eq. (5) is important because the presence of \( \text{H}_2\text{SO}_4 \) reduces the amount of \( \text{SO}_3 \) available in the flue gas to react with \( \text{NH}_3 \), which tends to reduce the ammonium bisulfate formation temperature.\(^{[8]} \) Alternatively, however, Eq. (5) can be viewed as governing the equilibrium concentrations that control whether Eq. (1) or Eq. (2) is the dominant pathway to ammonium bisulfate formation at any particular temperature.

Matsuda et al.\(^{[10]} \) on the other hand, took an experimental approach and defined the vapor pressure of ammonium bisulfate as the product of vapor pressures of \( \text{H}_2\text{SO}_4 \) and \( \text{NH}_3 \) based essentially on Eq. (2) under the assumption that at ammonium bisulfate formation temperatures equilibrium favors \( \text{H}_2\text{SO}_4 \) over \( \text{SO}_3 \) as the sulfur repository.

Wei et al.\(^{[7]} \) concluded that, in commercial practice, most operators tend to use ammonium bisulfate formation temperature close to the Johnson et al. while catalyst manufacturers tend to use the Matsuda et al. to set minimum SCR operation temperatures. The Wei et al. results suggest that the ammonium bisulfate may be forming at much lower temperatures than predicted by the Johnson et al.

From our point of view, one of the most important points of the Wei et al. work was that the study has shown that \( \text{SO}_3 \) remains an important contributor to the ammonium bisulfate formation.

3.2 AMMONIA FLUE GAS CONDITIONING AND FLY ASH RESISTIVITY

Generally, the volatility of a gas can be roughly correlated with the ease of adsorption of the gas on a solid. Ammonia is highly volatile, having a boiling point of -33°C (-27.4°F), and its adsorption on fly ash at elevated temperatures would require high partial pressures of the gas. Moreover, adsorption of ammonia on fly ash would be greatly aided if the surface of the ash is acidic. Thus, in Dual FGC case when the occurrence of an acidic surface material is the result of the adsorption of sulfur trioxide, the resistivity of the ash had been already modified.

The reaction of ammonia with sulfur trioxide to produce ammonium sulfate or ammonium bisulfate appears to have been a key event in the occurrence of either type of conditioning process.

Dismukes\(^{[2,10]} \) investigated concentrations of ammonia, sulfur oxides, and water vapor found at the inlets to field ESPs (Table 1). In each instance, the injection of ammonia lowered the concentration of sulfur trioxide. This observation is consistent with the occurrence of increased adsorption of sulfur trioxide on the surface of the fly ash as the acid on the surface is neutralized by ammonia. It is also consistent with the reaction of ammonia and \( \text{SO}_3 \) (actually present as sulfuric acid) to produce particles of ammonium sulfate or ammonium bisulfate, as shown by the chemical Equations 1 through 4 above.

Direct measurements of resistivity were made with a point-to-plane probe in situ as described by Mr. Harry White. Comparative values of the data obtained with ammonia injected at concentrations of 7 to 20 ppm by volume show no significant change in resistivity as a result of ammonia conditioning.

The pH data indicate that ammonia injection produced mildly acidic slurry but that the samples collected during ammonia injection were less acidic than those collected without injection. The ammonia concentrations appear to postulate that ammonia was present either in the form of a discrete particulate (such as ammonium sulfate) or a surface
deposit on the fly ash. The sulfate concentrations apparently varied randomly as changes were made in ammonia injection.

Therefore, the Dismukes'2,10 experiments proved that ammonia conditioning altered the electrical properties of the flue gas rather than the fly ash resistivity.

It should be noted that Indian researchers (Kumar et al.11) reported diametrically opposite results claiming "...a considerable reduction in the resistivity of fly ash in the temperature range between 120°C and 180°C. It was also observed that the resistivity has not shown any further reduction beyond critical amount of ammonia dosage."

<table>
<thead>
<tr>
<th>REAGENT/TEST No.</th>
<th>14-1</th>
<th>14-2</th>
<th>15-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO3 Injected, ppm</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>SO3 Exiting Stack, ppm</td>
<td>1.8</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>NH3 Injected, ppm</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>NH3 Exiting Stack, ppm</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
</tbody>
</table>

### 3.3 SPACE-CHARGE EFFECT

Dual FGC improves the ESP performance due to an additional space charge, which alters the electrical characteristics of the flue gas in a precipitator. Specifically, it produces a space charge enhancement of the electric field by which fly ash particles are:

i. initially charged and collected or

ii. recollected following rapping reentrainment.

Indeed, the most probable process by which the space-charge effect occurs is reaction of the ammonia with the sulfur trioxide and water vapor normally present in flue gas to produce fine particles of ammonium sulfate or ammonium bisulfate and subsequent charging of the particles of reaction product in the precipitator.

### 3.3.1 Creation of Ultrafine Particles

Injection of ammonia (NH3) into the flue gases in the presence of SO3 results in the formation of submicron particles of ammonium sulfates.

Particle formation due to chemical reaction between NH3 and SO3 species is a complex phenomenon. When the molar ratio between NH3 and SO3 is less than 1.0, ammonium bisulfate (HSO4) is created which is semi-liquid at the operating temperature range, hence, it promotes ash agglomeration. However, when the molar ratio between NH3 and SO3 is more than 1.0, there is an increase in the ammonium sulfate production, resulting in the creation of fine particles.

Ultrafine particle creation is a recognized problem arising, for example, when an SCR device is added in the flue gas path. SO2 to SO3 conversion levels in the SCR are indeed a guaranteed value given by SCR manufacturers in order to lower submicron particle creation and opacity increase due to the presence of SO3.

On the other hand, fine particles increase the space charge load and yield enhanced voltage-current curves of the electrostatic precipitator. However, to maintain the same level of current as existed without the fine particles, the voltage must be increased.

Numerical ESP Performance (NEP) model simulations on a 600 MW power plant (utilizing the full possible power output of the power supplies), show that particles concentration at the ESP could increase as little as from 13 mg/Nm3 to 15 mg/Nm3. However, although the ultrafine particles do not significantly contribute to the mass based outlet emission of an ESP, they might become extremely important if stricter regulations concerning PM2.5 (particle smaller than 2.5 micron) would be imposed. The NEP model is based on the EPA’s ESP-VI Windows version18. The ESP-VI 4.0W Performance Prediction Model (ESP-VI 4.0W) is an advanced ESP model capable of accurately predicting the performance of an ESP.

Sample calculations shown that with 10 ppm of ammonia added to the flue gas, the ammonia sulfate creation is estimated close to 30 mg/Nm3. This value is compared to approximately 12,000 mg/Nm3 of coal ash at the ESP inlet. Therefore, un-optimized Dual FGC (incorrect SO3/NH3 injection stoichiometry) may produce excess submicron particles which are harder to collect, thus altering particle size distribution at the ESP outlet impacting ESP performance.

### 3.3.2 Experimental Validation

Occurrence of the space-charge effect was suggested by the electrical behavior of the precipitators investigated. From a theoretical point of view, postulation of this effect is warranted on the basis of the available thermodynamic data for the indicated reactants and products, as published by many authors. Experimentally, the occurrence of the effect is supported not only by the precipitator electrical data but by certain additional experimental data discussed by Dismukes2 and Dahlin et al.14.

If injected ammonia were to react to produce a particulate of ammonium sulfate or bisulfate, the concentration of ammonia as a gas downstream from the plane of injection would have to be lower than the concentration injected and the concentration of SO3 would have to be lower than the normal concentration of this gas. The ammonia and sulfur trioxide concentrations as tested indicate that both of these predictions were satisfied.

### 3.4 INCREASED COHESIVENESS OF FLY-ASH PARTICLES

Dual FGC by producing ammonium bisulfate increases the cohesiveness of fly ash particles and thus lowers the reentrainment of ash deposited on the collection electrodes.
3.4.1 Cohesion

As discussed previously, depending on the NH$_3$ to SO$_3$ (H$_2$SO$_4$) stoichiometric rates, ammonia can produce low melting point substances. Low stoichiometric rates produce substances with a high tendency to absorb moisture, promoting cohesion between particles. To simplify the cohesion mechanisms, only the ammonium bisulfate is being considered. Since it has a melting point around 150°C it is in a semi-liquid state at the typical operating temperatures of an electrostatic precipitator and therefore it acts as a particle-bonding agent. Cohesion has a positive effect on the electrostatic precipitator efficiency by:

i. Increasing the average particle size (the larger particles are easier to collect in the electrostatic precipitator)

ii. Reducing the re-release of particles on the plates.

In order to quantify the particle cohesion effect on ESP, simulation using NEP model was carried out with the same configuration described as above. A 10% decrease in reentrainment parameter reduces particle concentration at the ESP outlet from 13 mg/Nm$^3$ to about 10 mg/Nm$^3$.

3.4.2 Experimental Validation

This effect should be of greater consequence in improving the overall collection efficiency of low resistivity ash compared to high resistivity ash because the greater electric force across a deposit of the latter material will prevent excessive reentrainment. There were numerous types of qualitative observations indicating that an increase in cohesiveness indeed occurred.

Observations of fly ash collected in a Brink impactor indicated that conditioned ash scatters/disperses less than unconditioned ash on the impaction surfaces. Finally, photomicrographs of ash have shown that conditioned ash particles are bridged by feather-like material thought to consist of ammonium sulfate.

4 DUAL FLUE GAS CONDITIONING

A Dual FGC system, by providing the independent and simultaneous injection of SO$_3$ and NH$_3$ in strictly controlled stoichiometric ratios allows for a further collection efficiency improvement when compared to SO$_3$ injection on its own. The mechanisms responsible for improved precipitator performance appear to include such phenomena as space-charge effects, agglomeration and increased cohesiveness of the fly ash. Additionally, some evidence suggests that the injection of ammonia promotes improved attachment of the available sulfuric acid to fly ash particles, making it more effective for resistivity control.

Generally speaking, when SO$_3$ and NH$_3$ are concurrently injected into a gas stream, a fine fume consisting of a variety of ammonium sulfate particles, all much less than 1 micron in size, is produced. These particles alter the electrical characteristics of the flue gas between the discharge electrodes and the collecting plates and produce a space-charge enhancement of the electric field. The higher field strength increases the overall collection efficiency of the ESP. DFGC creates a thin conductive film on the surface of the fly ash believed to consist of low melting point ammonium sulfate products which contributes to the resistivity modification. It has been suggested that the addition of ammonia improves upon the efficiency of the SO$_3$ conditioning by an additional charge carrier, the NH$_4^+$ ions.

Figure 4 depicts a conceptual Dual FGC system layout. When design for joint operation, both SO$_3$ and ammonia injection systems may share a number of the system components. For example, a slipstream of process air from the SO$_3$ system blower could be used for dilution of the ammonia gas stream. An ammonia storage container which houses the one-ton cylinders of NH$_3$ is equipped with internal racks for the stabilization of the cylinders, electric space heaters for vaporization of the NH$_3$ as well as the manifold and necessary connectors required for the vaporization and transportation of the gaseous NH$_3$ to the SO$_3$ production skid where it combines with the dilution air. The vaporized ammonia mixes with the slipstream air from the SO$_3$ process air blower. The diluted ammonia/air mixture travels through piping to the injection probes located downstream of the air preheater and upstream of the ESP. All equipment is factory assembled and incorporated into the SO$_3$ system central control cabinet, air inlet filter/silencer, and process air blower.

5 CASE STUDIES

5.1 SHENHUA ZHUNGEER POWER PLANT

Zhungeer Power Station is a 1,570-megawatt (MW) coal-fired power plant located at the suburbs of Junggar, Ordos (E’erduosi) Prefecture, Inner Mongolia Autonomous Region. The local coal is being delivered from the Zungeer mine. It is thought that Zhungeer coal ash gives the most difficulty with respect to ESP performance [18,20,21].

The plant’s first two units of 125 MW each, known as Zhungeer-II, were commissioned in 1992-1993 and retired in 2013. The units 1 and 2 are 330 MW tangentially fired boilers. Zhungeer-II is a four-unit coal-fired power plant with a total capacity of 1,320 MW, completed between 2002 and 2007. There is one (1) ESP with two (2) chambers, two (2) cells per each unit. Each cell houses forty seven (47) gas passages on 305 mm (12 inches nominal) centers. Each ESP has five (5) mechanical fields in the direction of the gas flow: first three fields are 3.00 m (9.85 ft.) in length and last two fields are 3.5 m (11.47 ft.) each. Collecting plates are 15.24 m (50.00 ft.) tall. The SCA is 151 m$^2$/kacfm.

Figure 5. NEP Model Projected Performance

Original ESP dust concentrations were 25 g/Nm$^3$ at the inlet for Unit 1 and 15 g/Nm$^3$ at the inlet for Unit 2, and 116
mg/Nm³ for Unit 1 and 85 mg/Nm³ for Unit 2 at the outlet. Based on extensive numerical modeling, Dual FGC was proposed to improve the outlet emissions.

Figure 5 presents NEP model projected performance for the Zhungeer Units 1-2 electrostatic precipitators.

![Figure 6. Stack Testing Results](image1)

Figure 6 depicts the results of the stack testing with and without the SO₂ FGC. The project was completed in 2014-2015 and the results were as follows (the final emissions were tested with SO₂ FGC only):

- Unit 1 achieved 18 mg/Nm³ at ESP outlet
- Unit 2 achieved 17 mg/Nm³ at ESP outlet

5.2 NRG ENERGY – MORGANTOWN POWER STATION

Morgantown Generating Plant is located in Newburg, MD. Its capacity is 1,492 megawatts at base load. It was designed to burn both coal and oil. Unit 1 was placed in service in 1970 with the Unit 2 following in 1971. Each of the two (2) boilers, manufactured by Combustion Engineering (CE), are rated at 640 MW. Each boiler is a tangentially coal fired supercritical unit with a superheater, single reheat and economizer. Units 1 and 2 are each equipped with Low NOX burners (LNBs), Electrostatic Precipitators (ESP), Selective Catalytic Reduction (SCR), Over Fire Air (OFA) and Flue Gas Desulfurization (FGD) and exhausted through a 400-foot high stack. When the FGD systems are not in use, the flue gas is exhausted through a 700-foot high bypass stack. The Units also have the capability of firing on No. 6 oil as an alternative primary fuel.

Existing electrostatic precipitators (ESP) are marginal at best with the design SCA of 38 m³/m²/s (193 ft³/kacfm) at the design load and 31-33 m³/m²/s (158-169 ft³/kacfm) at the boilers’ current maximum load. One of the potential upgrades that were identified early in the project definition phase was to improve the stack emissions which, when implemented, will serve to improve the overall APC equipment effectiveness and ultimately the performance of the precipitators.

![Figure 7. NEP Model ESP Projected Performance](image2)

Figure 7 depicts the NEP model ESP projected performance and Figure 8 presents as tested stack emissions comparison.

5.3 MINNESOTA POWER COMPANY - TAÇONITE HARBOR ENERGY CENTER

Taconite Harbor Energy Center located near Schroeder, Minnesota, is a coal-fired steam generating power plant consisting of three (3) identical tangentially-fired coal-burning units located on the north shore of Lake Superior.

Each unit is capable of a heat input of 900 MBtu/hr, with net generating capacities of 79 MW (Boiler 1) and 76 MW (Boiler 2). The plant uses western subbituminous coal which is received by boat and stored in an outdoor storage pile. Ash is pneumatically conveyed to and collected in a storage bin, then wetted and disposed of.

Due to the installation of a Lime Based Sorbent and other agents used to lower SO₃ and NOₓ emissions, particulate load had increased. The exiting precipitator was not able to handle the speed of gas flow to effectively collect the excess and highly resistive fly ash. Government regulations required the facility to reduce opacity.
The equipment upgrade also resulted in an improved reliability and performance. The successfully performed hot-to-cold retrofit augmented by the use of Dual FGC, enabled the plant to outperform the 0.03 lbs./MBtu outlet emissions (Figure 9). The equipment upgrade also resulted in an improved reliability and performance.

6 SUMMARY
In conclusion, in properly designed and implemented Dual FGC system (at appropriate stoichiometric ratio), ammonia will, in effect, scavenge SO\textsubscript{3} thus creating certain ammonia salts. While SO\textsubscript{3} will be working on improving the fly ash resistivity, the ammonia salts will be working on improving particles agglomeration and cohesivity, eliminating rapping losses, and the enhancing the electric field to further improve the particle migration velocity.

7 REFERENCES
4. Dahlin, R.S., et. al., "A field study of combined NH\textsubscript{3} and SO\textsubscript{3} conditioning systems on a cold-side precipitator at a coal-fired power plant". 77th Annual Meeting of APCA, San Francisco, Paper 84-96.3, (June 1984)
18. Parker, Kenneth, et.al. EPA-600/R-04/072. EPA Contract No. 68-C-99-201