Technical Evaluation of an Ammonia-Based SO_2 Scrubbing Technology's Potential Applicability to Vectren's A.B. Brown Generating Station

Prepared for

Frost Brown Todd, LLC

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Executive Summary

Trimeric investigated the alternative of retrofitting Vectren's A.B. Brown coal-fired generating units with an ammonia-based SO_2 scrubber technology that could eliminate or materially reduce the wastewater discharge from the scrubbing process and produce commercially saleable agricultural fertilizer as a byproduct of the process. For this investigation, Trimeric gathered information about A.B. Brown Station and about ammonia-based scrubbing technology, reviewed publically available data, and held several conversations with engineers from Marsulex Environmental Technologies (MET) and Jiangnan Environmental Technology (JET). Trimeric also visited three operating coal-fired plants with ammonia-based SO_2 scrubbing technology installed and operating.

Trimeric found that ammonia-based scrubbing is a commercially-available technology that can achieve high levels of SO_2 removal. The technology can produce a saleable fertilizer byproduct. If implemented, an ammonia-based scrubber could eliminate the concern that Vectren has about complying with U.S. Steam Electric Power Generating Effluent Limitations Guidelines (ELG) regulations. The technology has been successfully deployed in Poland and China at coal-fired power plants at a scale comparable to the A.B. Brown units and using similar equipment design to what would be used at A.B. Brown. Other technical aspects of the ammonia-based scrubber were evaluated, including process availability/reliability/maintenance, ammonia and ammonium sulfate handling safety, effect on the generating plant's water balance and byproducts, impact on ability to install carbon capture technologies, effect on other air emissions, and a preliminary economic analysis. With respect to these aspects, no adverse information was identified in Trimeric's investigation that would be likely to prevent the ammonia-based scrubbing technology from being a potentially viable candidate for an SO_2 removal technology for A.B. Brown. As to mercury emissions and particulate matter emissions, further investigation would be required to determine if additional mercury removal processes and/or particulate control technologies, both of which are commercially available, would need to be deployed along with an ammonia-based scrubber at A.B. Brown to meet current emissions limits.

1. Introduction

Vectren has proposed to retire its coal-fired generating assets at A.B. Brown and replace them with natural gas-fired generating assets. The coal-fired assets operate with dual alkali scrubbers that remove SO_2 from the flue gas to enable compliance with regulatory limits on SO_2 emissions. Vectren reported that these existing dual alkali scrubbers were expensive to operate and were beyond their expected useful life. Vectren evaluated the economics of replacing the existing dual alkali flue gas desulfurization (FGD) systems at A.B. Brown Units 1 and 2 with a limestone-based technology which is widely deployed across the United States. Vectren determined that the economics of scrubber replacement with a limestone forced oxidation system were not favorable because of the scrubber's capital cost and the likelihood of needing additional wastewater treatment equipment for compliance with future Effluent Limitation Guidelines.[1] However, Vectren did not report considering other FGD options in their decision to retire the coal-fired assets at A. B. Brown. Ammonia-based SO_2 scrubbers are one such FGD option; they have been widely deployed in Poland and China, and they have the potential to provide economic advantages over limestone scrubbing.

Trimeric Corporation was engaged by Frost Brown Todd, LLC to determine whether an ammonia-based scrubbing technology is a commercially-available SO_2 emissions control technology and whether the technology has potential technical viability as a replacement for the existing SO_2 emissions control technology at Vectren's A.B. Brown Generating Station. Trimeric evaluated key performance criteria for the ammonia-based scrubbing technology: its SO_2 removal performance, its ability to generate a saleable ammonium sulfate product, and its elimination of the need for wastewater treatment under the U.S. Steam Electric Power Generating Effluent Limitations Guidelines (ELG). Trimeric assessed the technology's availability at commercial-scale by assessing its deployment history with respect to the scale, process equipment fidelity, and application environments that are similar to A.B. Brown. Finally, Trimeric evaluated other technical considerations relevant to the technology's potential deployment at A.B. Brown, such as its reliability, effect on other air emissions and plant byproducts, its compatibility with the installation of future CO_2 controls, and a preliminary economic analysis.

The remainder of this report is structured as follows:

- Section 2: Methodology for Technology Assessment
- Section 3: Ammonia-based scrubbing Technology Discussion
- Section 4: Technology Assessment

2. Methodology for Technology Assessment

The objective of Trimeric's analysis for Frost Brown Todd, LLC was to determine whether ammonia-based scrubbing is a technically-viable, commercially-available SO_2 removal technology option for A.B.

[1] Verified (Public) Direct Testimony of Wayne D. Games, Vice President of Power Supply. Cause NO. 45052 (March 20, 2018).

Brown. Trimeric's analysis was limited to the technical performance and commercial readiness of ammonia-based scrubbers; Trimeric did not determine whether installation of ammonia-based scrubbers is the best option for A.B. Brown.

Trimeric assessed the ammonia-based scrubbing technology for (1) its ability to meet key performance criteria for the successful technical and economic operation of the technology at Vectren's A.B. Brown Generating Station, and (2) its deployment history relevant to A.B. Brown's scale, expected process equipment configuration, and operating environment.

Key performance criteria critical to the technology's success as a potential replacement for the existing FGD scrubbers at A.B. Brown include (1) its SO_2 removal performance, (2) its ability to generate a saleable ammonium sulfate product, and (3) its elimination of the need for wastewater treatment under the U.S. Steam Electric Power Generating Effluent Limitations Guidelines (ELG). Other technical aspects of the ammonia-based scrubber were evaluated, including process availability/reliability/maintenance, ammonia and ammonium sulfate handling safety, effect on generating plant's water balance and byproducts, impact on ability to install carbon capture technologies, effect on other air emissions, and a preliminary economic analysis.

Data for Trimeric's evaluation were obtained from the following sources.

- Testimony of Wayne D. Games of Vectren Energy Delivery of Indiana, filed on March 20, 2018 with the Indiana Utility Regulatory Commission. This testimony includes the Revision 1 report that was issued on July 8, 2017 by Burns & McDonnell Engineering Company, Inc. entitled "A.B. Brown FGD Condition Assessment & Retrofit Cost Estimate." The A.B. Brown plant design parameters used as the basis for Trimeric's analysis were mostly obtained from this testimony, including the Burns & McDonnell report. The plant design criteria assumed for this analysis are summarized in Appendix A.
- Information obtained from the public domain including papers and presentations at technical conferences, company websites, and brochures.
- Information provided in conversations with engineers from Marsulex Environmental Technologies (MET) and Jiangnan Environmental Technology (JET) , suppliers of ammonia-based SO_2 scrubbing technology.
- Information provided in test reports from JET, which JET authorized to be cited in this report.
- Plant tours of three sites which operate JET's ammonia-based SO_2 scrubbers.

3. Ammonia-based Scrubbing Technology Discussion

Ammonia-based scrubbing is a technology for reducing SO_2 emissions from the flue gas effluent of a coal-fired power plant. In this section of the report, the US suppliers for this technology are first discussed. Then, a basic process description is provided.

Suppliers of Ammonia-based Scrubbing Technology

Trimeric obtained information from two well-established companies selling ammonia-based SO_2 scrubbers to the United States' coal-fired power market: Marsulex Environmental Technologies and Jiangnan Environmental Technology.

Ammonia-based scrubbing for flue gas desulfurization was developed by General Electric Environmental Services in the 1990s and later acquired by Marsulex Environmental Technologies (MET). MET offers multiple technologies for flue gas desulfurization, including ammonium sulfate, limestone, lime, and sodium hydroxide. MET has over 150 wet FGD systems installed in 22 countries. MET conducted the first field pilot of the ammonium sulfate technology at Dakota Gasification Company's (DGC) SynFuels Plant, which then led to installation of 350-MWe ammonia-based scrubbing unit at DGC in 1997. This scrubbing unit still operates today. MET's second installation was a 315-MWe unit that started operation in 2006 at an oil sand processing facility in Canada. MET has designed and installed scrubbers for applications with high to low sulfur loadings from oil refiners, coal-fired boilers and non-traditional sulfur-containing streams. MET considers its experience list proprietary, but MET did share that most of its recent installations have been concentrated in Poland and China. MET is in the process of constructing a small ammonia-based scrubber in the state of Louisiana.[2]

Jiangnan Environmental Technology (JET) is a US based subsidiary of Jiangsu New Century Jiangnan Environmental Protection Inc., Ltd (JNEP). JNEP began research on ammonia-based scrubbing technology in 1998 and licensed the technology to JET in 2014. JET markets the technology under the name Efficient Ammonia Desulfurization (EADS). JET has more than 300 ammonia-based flue gas desulfurization absorbers installed at over 150 different sites, all in China.[3] Over 85% of the EADS installations are on coal-fired units. EADS can be applied to units firing coal with sulfur content of 0.3% to 8%. JET's current technology configuration is labeled as a "4th generation" EADS system, which incorporates "ultra-sound enhanced deSO_X and PM-removal." The 4th generation EADS system was first deployed in 2015, and has since been deployed at over 50 installations.[4]

Process Description

Basic process flow diagrams for the MET and JET systems can be found at their respective websites.[5,6] Flue gas is conveyed from the outlet of a particulate control device by an induced draft fan into the

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[2] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[3] Repp, David, Ke Zhang, Peter Lu, JET-Inc. "Ammonia-Based Desulfurization Technology." *Power-Gen International.* Las Vegas, NV, December 5-7, 2017.

[4] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.

[5] Evans, Amy P., Claudia Miller, Steve Pouliot. "Operational Experience of Commercial, Full Scale Ammonia-Based Wet FGD for Over a Decade." *www.met.net.* August 20, 2009. http://www.met.net/Data/Sites/35/assets/Information-Library/Technical%20Papers/Operational%20Experience%20of%20Commercial,%20Full%20Scale%20Ammonia-based%20Wet%20FGD%20for%20Over%20a%20Decade%20-%20August%202009%20-%20Presented%20at%20Coal-Gen%202009.pdf (accessed July 31, 2018).

bottom of the absorber tower. The flue gas counter-currently contacts saturated ammonium sulfate slurry that is introduced into the absorber. Good contact between the gas and liquid is achieved through engineering design of the spraying system and the design of absorber column internals intended to direct the flow path of the gas and liquid. Contact with the slurry cools the flue gas close to its adiabatic saturation temperature. The heat from the flue gas evaporates water from the ammonium sulfate slurry, resulting in the production of ammonium sulfate crystals which will become the product of the scrubbing process. The reaction chemistry can be summarized in the following two reactions.

$$SO_2 + 2NH_3 + H_2O \rightarrow (NH_4)_2SO_3$$
$$(NH_4)_2SO_3 + \frac{1}{2} O_2 \rightarrow (NH_4)_2SO_4$$

The actual chemistry is more complicated, involving several intermediate steps: (1) absorption of SO_2 into water to form sulfurous acid, (2) the reaction of sulfurous acid with ammonium sulfate and sulfite to form ammonium bisulfite and bisulfate species, (3) the reaction of ammonia with the sulfurous acid, ammonium bisulfite and bisulfate to form ammonium sulfite and ammonium sulfate, (4) the addition of O_2 to oxidize ammonium sulfite to ammonium sulfate, and the addition of heat from the flue gas to evaporate water and crystallize ammonium sulfate solids. These reactions are described in a paper by MET.[7]

The scrubbed flue gas exits the top of the absorber after passing through mist eliminators and other equipment engineered to remove entrained liquid droplets and particulate matter from the gas. The scrubbed flue gas is exhausted through a chimney/stack.

The ammonium sulfate slurry flows down the absorber tower into a reaction tank. An oxidation air fan delivers air for the oxidation of ammonium sulfite to ammonium sulfate. The ammonia feed rate to the reaction tank is controlled to maintain the desired pH in the reactor slurry. Ammonia is supplied either as aqueous ammonia (typically about 30% NH_3 in water) or as anhydrous ammonia.

The contents of the reaction tank are called the reaction tank slurry. The slurry consists of a mixture of ammonium sulfate solids (approximately 10-15 weight% of the slurry, according to JET[8]) and an aqueous phase liquid containing ammonium sulfite, sulfate, bisulfite, and bisulfate species. The reaction tank slurry is conveyed to the top of the absorber tower via slurry recirculation pumps. In a spray tower design, this slurry is continuously fed from the reaction tank to the spray headers in the absorber tower.

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[6] "Application of EADS (Efficient Ammonia Desulfurization)." http://jet-inc.com/wp-content/uploads/2017/03/JET-Inc-EADS-Application-in-Coal-Fired-Boiler-FGD.pdf (accessed July 31, 2018).

[7] Evans, Amy P., Claudia Miller, Steve Pouliot. "Operational Experience of Commercial, Full Scale Ammonia-Based Wet FGD for Over a Decade." *www.met.net.* August 20, 2009. http://www.met.net/Data/Sites/35/assets/Information-Library/Technical%20Papers/Operational%20Experience%20of%20Commercial,%20Full%20Scale%20Ammonia-based%20Wet%20FGD%20for%20Over%20a%20Decade%20-%20August%202009%20-%20Presented%20at%20Coal-Gen%202009.pdf (accessed July 31, 2018).

[8] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.

The reaction tank slurry can be further processed into an ammonium fertilizer product. An ammonia-based scrubber is typically designed to produce one of three types of product: a diluted slurry of ammonium sulfate fertilizer, a standard crystalline form of ammonium sulfate, or a hard granular production formed by compaction. The granular product can be blended with other fertilizers to form a specialty blend that is optimized for specific crops.

While the scrubbing of SO_2 from the flue gas is a continuous process, the production of fertilizer can be operated in a batch mode by periodically sending a bleed stream of slurry to the fertilizer processing area.

If the slurry form of ammonium sulfate product is desired, no further processing of the ammonium sulfate stream is required.

If a solid ammonium sulfate fertilizer is desired, then the slurry is first dewatered through a hydrocyclone in which the ammonium sulfate solids exit the bottom of the hydrocyclone along with some of the slurry liquid. The ammonium sulfate solids from the hydrocyclone bottoms are further dewatered in a centrifuge. The ammonium sulfate solids from the centrifuge are then dried to less than 0.5%-1% moisture in a dryer, and the dryer exhaust gas is treated to remove particulate matter before being exhausted to the atmosphere. The dried fertilizer product is cooled and then stored. At this point, the "standard" fertilizer product (it looks like crystals of sugar that are slightly rectangular in size) has been produced and can be packaged for sale. If a granular product is desired, then the standard product is formed into sheets and milled into the rounded, compacted product. This additional processing requires significant capital investment as it requires several pieces of equipment including conveyors and hammer mills.[9]

The majority of the slurry's liquid phase exits the top of the hydrocyclone and is typically combined with the centrifuge's liquid reject stream called the centrate. The combined stream can be returned in its entirety back to the reaction tank slurry and/or processed through a filter press. MET typically includes a filter press in its process design, while JET only uses the filter press when upstream particulate control devices provide insufficient removal of ash from the flue gas. The solids in the centrate consist primarily of fly ash captured in the ammonia scrubber, and the filter press reduces the moisture content of the fly ash cake to 30-40%. This fly ash cake can be mixed with other solids streams and landfilled; according to MET, this fly ash cake does not trigger hazardous waste classification.[10] The water removed by the filter press is either returned to the absorber or sprayed onto the ammonium sulfate product as it enters the dryer.

[9] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[10] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

Process water is stored in a process water tank and conveyed to the absorber to make up for water lost through evaporation of the reaction tank slurry liquid to the flue gas and through water that leaves with the ammonium sulfate product and with the fly ash filter cake.

4. Technology Assessment

The technology assessment is organized into the following three subsections: key technical performance criteria, commercial availability, and other considerations.

Key Performance Criteria for Ammonia-Based Scrubbing Technology

Trimeric assessed the key technical performance criteria for the ammonia-based scrubbing technology: SO_2 removal efficiency, the generation of a saleable ammonium sulfate fertilizer product, and the elimination of ELG-regulated streams.

SO_2 Removal

The requirements for SO_2 removal per A.B. Brown's Title V permit specify 0.426 lb SO_2/MMBtu when Unit 1 and Unit 2 operate simultaneously; the permit also specifies at least 90% SO_2 removal by the Unit 2 FGD scrubber. Today's limestone forced oxidation scrubbers are able to achieve significantly higher SO_2 removal; the Burns and McDonnell report used 98% SO_2 removal as the design basis for a new flue gas desulfurization unit. The ammonia-based scrubber data reviewed by Trimeric indicate that the technology can be designed to meet or exceed 98% SO_2 removal, which would translate to emissions of less than 0.12 lb SO_2 /MMBtu at A.B. Brown.

The supporting data for this conclusion are as follows:

- MET says it can guarantee 98% SO_2 removal.[11] The ammonia-based scrubber at DGC achieved greater than 93% SO_2 removal with a heavy residual/gaseous fuel containing 5-wt% sulfur, resulting in SO_2 outlet concentrations of approximately 750 mg/Nm^3 (or about 260 ppmv).[12] MET reports all of their installations were designed for 96% SO_2 removal or less; this removal level has been driven by market demand via regulatory requirements. MET has recently conducted pilot-scale testing that achieved greater than 98% SO_2 removal, but MET was unable to share the data with Trimeric at the time of this report.
- JET supplied test data summaries from four ammonia-based scrubbing units – two units were third generation EADS and two units were fourth generation EADS. The data indicate 98.5 to

[11] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[12] Evans, Amy P., Claudia Miller, Steve Pouliot. "Operational Experience of Commercial, Full Scale Ammonia-Based Wet FGD for Over a Decade." *www.met.net.* August 20, 2009. http://www.met.net/Data/Sites/35/assets/Information-Library/Technical%20Papers/Operational%20Experience%20of%20Commercial,%20Full%20Scale%20Ammonia-based%20Wet%20FGD%20for%20Over%20a%20Decade%20-%20August%202009%20-%20Presented%20at%20Coal-Gen%202009.pdf (accessed July 31, 2018).

>99.8% SO_2 removal for inlet SO_2 concentrations ranging from 650 to 4000 ppm SO_2, dry basis at 6% O_2. The corresponding outlet SO_2 concentrations ranged from < 7 ppm to 18 ppm.

Generation of a Saleable Ammonium Sulfate Fertilizer Product

For each short-ton of SO_2 scrubbed by the ammonia-based scrubber, 3.9 short-tons of ammonium sulfate fertilizer will be produced per reaction chemistry. An ammonia-based scrubber at A.B. Brown designed for 98% SO_2 removal for a 3.38% S coal and operating with an annual capacity of 52%, would generate approximately 150,000 short-tons/year of ammonium sulfate fertilizer. This production rate would require approximately 40,000 short-tons/year of anhydrous ammonia.

The purity specifications for fertilizer in the United States are regulated by the individual states; however, buyers may have more stringent specifications.[13] MET reports that production and sale of the fertilizer from DGC (marketed as Dak-Sul 45) allows DGC to recover some of the costs of scrubbing the boiler emissions. The plant produces 145,000 tons annually.[14]

The purity specifications for fertilizer include maximum concentrations allowable for various metals. According to MET and JET, meeting the metals specifications for fertilizer has not been a problem for any of their ammonia-based scrubbers.[15,16,17] Trimeric calculated the expected metals concentration in the fertilizer for the units at A.B. Brown based on the ash and metals concentration in the coal and the following assumptions: (1) 80% of the coal ash becomes fly ash, (2) fly ash and the non-volatile metals are removed with 99.6% efficiency by the particulate control device, (3) the volatile (Hg) and semi-volatile (Se, As) metals and halogens (Cl) are not removed upstream of the FGD (a worst-case assumption), (4) fly ash and its associated metals are removed with 80% efficiency across the FGD, and (5) the metals removed by the FGD are fully incorporated into the ammonium sulfate product (i.e., no purge of fly ash with the centrate). Trimeric calculated that all metals concentrations in the fertilizer produced at A.B. Brown should be lower than typical metals specifications for the fertilizer, an example of which was provided on a confidential basis by MET. Filtering of the fly ash from the centrate would result in even lower metals concentrations in the fertilizer.

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[13] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[14] Evans, Amy P., Claudia Miller, Steve Pouliot. "Operational Experience of Commercial, Full Scale Ammonia-Based Wet FGD for Over a Decade." *www.met.net.* August 20, 2009. http://www.met.net/Data/Sites/35/assets/Information-Library/Technical%20Papers/Operational%20Experience%20of%20Commercial,%20Full%20Scale%20Ammonia-based%20Wet%20FGD%20for%20Over%20a%20Decade%20-%20August%202009%20-%20Presented%20at%20Coal-Gen%202009.pdf (accessed July 31, 2018).

[15] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[16] Evans, Amy P., MET (Marsulex Environmental Technologies). "Advanced Ammonium Sulfate Wet FGD." July 26, 2012. http://www.mcilvainecompany.com/Universal_Power/Subscriber/PowerDescriptionLinks/Amy%20Evans%20-%20Marsulex%20Environmental%20Technologies%20-%207-26-12.pdf (accessed July 31, 2018).

[17] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.

The ammonium sulfate fertilizer produced by ammonia-based scrubbing at a coal-fired power plant would include approximately 0.6% ammonium chloride formed from the reaction of coal chloride with the scrubbing reagent. Ammonium chloride is a fertilizer enriched in nitrogen on mass basis, as compared to ammonium sulfate.[18] Both MET and JET indicated that incorporation of ammonium chloride into the ammonium sulfate fertilizer product was not a product quality issue.

Based on the information gathered by Trimeric, the ammonium sulfate produced by an ammonia-based scrubber at A.B. Brown should be a saleable product, as compared to the FGD solid waste from the dual alkali system, which is currently landfilled. A limestone forced oxidation scrubber would generate a gypsum byproduct, which could likewise be sold under favorable market conditions.

Elimination of ELG-Regulated Streams

One of the potential advantages of an ammonia-based scrubber over a limestone-based scrubber is that the ammonia-based process might be operated so as to not produce any wastewater streams subject to ELG. In a traditional limestone-based scrubber, water is purged from the scrubber to maintain the chloride concentration in the scrubbing slurry below the design limits for the scrubber materials of construction. This purged waste stream can create a need for a significant capital investment in wastewater treatment equipment in order to comply with the pending ELG rule.

In an ammonia-based scrubber, chlorides react with ammonia to form ammonium chloride, which is a fertilizer that is incorporated into the ammonium sulfate product. Using the A.B. Brown configuration data from Appendix A, both MET and JET determined than an ammonia-based scrubber should be able to operate without any wastewater discharge.[19,20] The only purge stream from the MET absorber would be from the centrate and the hydrocyclone overflow; MET sprays this stream onto the ammonium sulfate product, upstream of the dryer, resulting in recovery of more fertilizer product and reducing fugitive dust emissions within the production facility.[21,22] As the chloride concentration in the coal increases, the amount of purged centrate liquid increases in order to maintain chloride concentration in the scrubbing slurry. MET reported that the limitation on the quantity of this purge stream comes from the ability to dry the sprayed product; this limitation would be reached around 0.2 weight% Cl in the coal.[23] JET typically returns all of the centrate and hydrocyclone overflow streams back to the absorber.

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[18] *NUEweb.* 1999. http://nue.okstate.edu/N_Fertilizers/Ammonium_chloride.htm (accessed July 2018, 2018).

[19] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[20] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.

[21] Evans, Amy P., Claudia Miller, Steve Pouliot. "Operational Experience of Commercial, Full Scale Ammonia-Based Wet FGD for Over a Decade." *www.met.net.* August 20, 2009. http://www.met.net/Data/Sites/35/assets/Information-Library/Technical%20Papers/Operational%20Experience%20of%20Commercial,%20Full%20Scale%20Ammonia-based%20Wet%20FGD%20for%20Over%20a%20Decade%20-%20August%202009%20-%20Presented%20at%20Coal-Gen%202009.pdf (accessed July 31, 2018).

[22] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[23] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

JET offers a proprietary chlorine balancing system which allows for the further precipitation of ammonium chloride from the slurry. This system offers flexibility with respect to maintaining the composition of the slurry when firing high chloride coals.[24]

Discussion of Water Balance Streams

Water enters the process in the following streams:

- Flue gas: The flue gas entering the scrubber contains water vapor.
- Anhydrous ammonia: The anhydrous ammonia reagent is typically 99.6% pure; the balance of the reagent may or may not contain some water.
- Process water: Water is added to the scrubber to maintain water balance across the system (i.e., to make up for losses due to evaporation of slurry water into the flue gas). Process water is used for cleaning mist eliminators and other process internal equipment.

There are several water streams that are recycled internally within the ammonia-based scrubbing system:

- Hydrocyclone overflow: The hydrocyclone overflow stream is either returned to the reaction tank slurry or it is combined with the centrifuge waste stream for further processing in a filter press.
- Centrifuge waste water stream: The centrifuge waste stream consists of fly ash and water. This stream is either returned to the reaction tank slurry or sent through a filter press. The water removed by the filter press is either returned to the scrubber or sprayed onto the ammonium sulfate fertilizer product to recover more product and reduce dust formation from the product.

Water leaves the process with the following streams:

- Flue gas: As flue gas passes through the scrubber, water is evaporated from the slurry into the flue gas until the gas reaches its adiabatic saturation temperature.
- Water consumed by reaction: The reaction of one mole of SO_2 with two moles of NH_3 requires one mole of H_2O.
- Centrate waste: The centrate waste contains about 30-40% water after it has gone through a filter press – applicable only if a filter press is incorporated into the process design. The centrate liquid removed by the filter press can be sprayed onto the ammonium sulfate product as it enters the dryer.
- Ammonium sulfate product: The ammonium sulfate product is dried to < 1% moisture, leaving some small residual moisture in the product.
- Dryer exhaust: Water evaporated from the ammonium sulfate product is exhausted to atmosphere.

[24] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.

Analysis of Commercial Availability of Ammonia-based Scrubbers

Trimeric evaluated the commercial availability of ammonia-based scrubbers from a technical perspective. The evaluation methodology was modeled on metrics that the U.S. Department of Energy uses for assessing technology readiness levels. Namely, Trimeric evaluated whether the ammonia-based scrubbing technology has been commercially deployed in situations that approximate the scale, fidelity of process equipment, and application environment similar to the A. B. Brown Generating Station.

While the technology has been applied to various coal-based industrial sites in Europe and Asia and to a coal gasification unit in the United States, it has not been installed on a coal-fired electric generating station in the United States. Ammonia-based scrubbing technology is similar in many respects to limestone forced oxidation scrubbers which have seen widespread deployment in the United States.

Scale of Application

A.B. Brown consists of two coal-fired generating units, Units 1 and 2, each capable of generating 265 MW on a gross basis. Brown currently operates with separate scrubbers for Units 1 and 2. A replacement ammonia-based scrubber could likewise operate with two scrubbing trains. Both MET and JET claim commercial applications at the scale of the A.B. Brown Generating Units:

- MET's website lists an installation at Yanzhi Petrochemical Company Thermal Plant in China and Zaklady Azotowe Pulawy Heating and Power Plant in Poland. The Yanzhi scrubbers are two 100-MW units that commenced operation between the years 2010 and 2012. The installation at the Zaklady Azotowe Pulawy Heating and Power Plant consists of two 300-MW installations at industrial coal-fired boilers, one in 2012 and one in 2016.[25,26]
- JET's largest installation is at a coal gasification unit, which uses a single module scrubber to treat a gas stream flow rate of 2 MM Nm^3/hr. This gas rate is the equivalent of flue gas generated by approximately 500-MWe generating unit. JET's experience list includes four other plants with absorber modules in the range of 200 to 300 MW equivalent, very similar to the unit size at A.B. Brown.[27] While a single larger scrubbing unit could be installed to treat the combined gas from Units 1 and 2, two separate units provide more operational flexibility for turndown.

Process Equipment Fidelity

An ammonia-based scrubbing system is composed of equipment that is similar to equipment used in limestone-based scrubbing: namely an absorber tower (typically an open spray tower or a spray/tray type tower), a reaction vessel, oxidation air blowers, slurry recirculation pumps, and a hydrocyclone dewatering system. According to MET, the spray tower diameter for the ammonia-based scrubber is similar to a limestone-based scrubber; the reaction tank for the ammonia-based scrubber will be larger

[25] MET (Marsulex Environmental Technologies). 2018. http://www.met.net/wet-fgd-technologies-ammonium-sulfate.aspx (accessed July 31, 2018).

[26] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[27] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.

because the oxidation rate is slower. The recycle pumps will be of a similar size for the two systems, but the pumps for the ammonia-based scrubber will operate at a slightly lower flow rate because the reagent to gas ratio is lower for the ammonia-based scrubber. All wet scrubbers (i.e., dual alkali, ammonia, limestone-based scrubbers) that do not employ flue gas reheat require a wet stack design. For units where a new stack is required, JET offers a design with the stack directly on top of (i.e., integrated into) the absorber vessel.[28]

The ammonia reagent is more corrosive than the limestone reagent and must be accounted for in the choice of materials of construction for the process equipment. The materials for an ammonia-based scrubber are not unusual as compared to other wet FGD designs. MET's material selections are based on corrosion tests conducted over a range of chloride concentrations in ammonium sulfate solution. JET's designs include polymer materials for many of the scrubber internals, including the demister, spray nozzles, and pump internals. For the installation at A.B. Brown with the firing of 0.1 weight% Cl coal, MET anticipates that the scrubber slurry would contain approximately 66,000 ppm Cl. Both MET and JET indicated the use of glass-flake lined steel absorber vessels. Trimeric's discussions with FGD engineers at JET's installations in China revealed problems with the quality of application of the glass flake lining. These engineers recommended using higher grade alloys, if possible, to reduce maintenance during scheduled outages. The inlet and outlet ducts of the scrubber are very corrosive environments for both limestone-based and ammonia-based scrubbers; in either case, the use of a highly corrosion resistant alloy like C276 would be used.

The reagent handling system will be designed for ammonia rather than limestone. It will consist of an ammonia unloading facility, an ammonia storage tank, ammonia feed pumps (if feeding aqueous ammonia) or a control valve for feeding anhydrous ammonia.

The fertilizer processing equipment consists of equipment that is not typically found with a limestone-based scrubber, but the equipment is readily available: centrifuges, filter presses, dryers, and packaging machines. The equipment for dewatering of the solids requires a similar or smaller footprint than the solids handling equipment used in limestone-based scrubbers.

Application Environment

Ammonia-based scrubbers have been commercially installed in a wide range of industrial applications, including gas cleanup from coal-fired power plants, coal gasification units, oil refiners and other sulfur-containing streams. With respect to pulverized coal-fired power plant operations, the key application environmental factors to consider are coal type (including coal sulfur, chlorine, and trace metals concentrations),flue gas sulfuric acid content, flue gas temperature, and the variable nature of U.S. coal-fired power plant operations.

Both MET and JET have commercial installations of ammonia-based scrubbers at pulverized coal power generating facilities and at facilities firing coal with compositions similar to that fired at A.B. Brown:

[28] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.

- MET: MET reports that the 3.5% sulfur content of the A.B. Brown coal is within the range of sulfur content of the coals that MET has prepared designs. MET has prepared and constructed scrubbers to accommodate up to 4 – 5 weight% sulfur in the fuel. MET's installations in Poland operate on flue gas generated from pulverized coal. Some of MET's installations in China are at sites that more closely represent an electric utility application.
- JET: JET's test data were provided for coal-fired applications with SO_2 inlet concentrations ranging from 600 to 4000 ppm SO_2, dry basis, 6% O_2. For comparison, the flue gas at A.B. Brown would be expected to contain approximately 2600 ppm SO_2. JET reported that their installation experience includes coals with chloride contents around 0.1 weight%, similar to the coal chloride content at A.B. Brown.

Coal-fired plants firing high sulfur coals and equipped with an SCR can generate flue gases with significant concentrations of sulfuric acid. A.B. Brown is one such power plant; it uses a sorbent injection system to reduce sulfuric acid concentrations in the flue gas. However, even small amounts of sulfuric acid can react with ammonia in the scrubber to form ammonium sulfate particles that are not easily removed by a traditional scrubber design. Further investigation would be required to determine if additional particulate control technologies would need to be deployed with an ammonia-based scrubber at A.B. Brown to meet current particulate matter emission limits. Both MET and JET offer technologies that can be incorporated into the ammonia-based scrubber to reduce fine particulate matter that may form from the reaction of sulfuric acid in the flue gas with ammonia in the scrubber. The JET and MET technology offerings for fine particulate control are discussed in this report in the section "Effect on Other Air Emissions."

The design temperature for the A.B. Brown flue gas entering the FGD scrubber is 325°F. Both MET and JET indicated that this flue gas temperature will not pose any design issue for an ammonia-based scrubber.[29,30] According to JET, an ammonia-based scrubber using glass-flake lined steel as the material of construction can accommodate flue gas temperatures ranging from 130°C (266°F) to 170°C (338°F).[31] For higher flue gas temperatures, a water quench may be employed to cool the flue gas stream prior to entering the absorber.

Many of today's U.S. coal-fired power plants operate with unit load that varies with the demand for dispatch of the unit, and/or with extended periods where the unit is shut down in a reserve outage. Ammonia-based scrubbers are able to operate in a load-following mode. JET reports that the turndown ratio of their scrubber ranges from 30% to 110%,[32] which would enable the scrubber to operate at low unit loads. The ammonia-based scrubbing unit can circulate solvent ahead of the generating unit startup, so that the scrubbing unit is able to treat the first flue gas emerging from the unit.

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[29] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.
[30] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.
[31] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.
[32] Repp, David, Ke Zhang, Peter Lu, JET-Inc. "Ammonia-Based Desulfurization Technology." *Power-Gen International.* Las Vegas, NV, December 5-7, 2017.

Other Considerations

Trimeric evaluated other considerations for the deployment of the technology at A.B. Brown, including process availability/reliability/maintenance, ammonia and ammonium sulfate handling safety, effect on generating plant's water balance and byproducts, impact on ability to install carbon capture technologies, effect on other air emissions, and a preliminary economic analysis.

Process Availability, Reliability, Maintenance

Trimeric identified the following data for the availability, reliability, and maintenance of ammonia-based scrubbers:

- MET reports that the operational reliability of the ammonia-based scrubbers is equal to or greater than conventional wet FGD.[33]
- The site process engineers at the three JET installations visited by Trimeric indicated that the scrubber maintenance was conducted according to boiler maintenance schedule, which was anywhere from every six months to every two years. The site process engineers indicated that the absorbers were reliable between maintenance outages. The site process engineers indicated that maintenance repairs were focused on repairs to the glass flake lining of the vessel; they all recommended using higher grade alloys for construction.[34]
- JET designs for redundant trains for all moving parts (e.g., spare recirculation pumps and oxidation air blower). JET typically designs with one centralized fertilizer production facility for a site, but the facility includes a spare train.[35]
- Both MET and JET indicated that operation of the scrubber with ammonia reagent is less prone to maintenance issues associated with scaling as compared to operating with limestone reagent. Limestone-based scrubbers have a tendency to form a gypsum scale that is only moderately soluble in water (0.202 weight% at 20°C)[36]; great care with design of water washes and scrubber operating conditions is required to avoid scale formation. In contrast, the ammonium sulfate crystals that form in an ammonia-based scrubber are much more soluble in water (42.9 weight% at 20°C)[37]; a water wash is thus more effective in keeping mist eliminators and other internal equipment clean. In addition, MET operates the ammonia-scrubbing process in a sub-saturation mode on a periodic basis (frequency depends on unit load) in order to prevent crystals from

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[33] Evans, Amy P., Claudia Miller, Steve Pouliot. "Operational Experience of Commercial, Full Scale Ammonia-Based Wet FGD for Over a Decade." *www.met.net.* August 20, 2009. http://www.met.net/Data/Sites/35/assets/Information-Library/Technical%20Papers/Operational%20Experience%20of%20Commercial,%20Full%20Scale%20Ammonia-based%20Wet%20FGD%20for%20Over%20a%20Decade%20-%20August%202009%20-%20Presented%20at%20Coal-Gen%202009.pdf (accessed July 31, 2018).

[34] FGD Process Engineers at three JET installations in China. Personal Conversations. July 30 – August 3, 2018.

[35] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.

[36] In *CRC Handbook of Chemistry and Physics, 86th Edition*, by David R. (editor-in-chief) Lide, 8-113. Boca Raton, FL: Taylor & Francis Group, 2005.

[37] In *CRC Handbook of Chemistry and Physics, 86th Edition*, by David R. (editor-in-chief) Lide, 8-114. Boca Raton, FL: Taylor & Francis Group, 2005.

accumulating on the process internals. The operation in the sub-saturation mode does not affect the overall generation rate of ammonium sulfate.

Ammonia Handling Safety

The operation of an ammonia-based scrubber requires the storage of significant quantities of ammonia reagent on the power plant site. Based on JET's recommendation for storage of a five-day supply of ammonia, approximately 1,000 tons (2,000,000 lb) of ammonia would be stored on site. This value would trigger OSHA's Process Safety Management (PSM) standard, which is applicable to the storage of (1) more than 10,000 lb of anhydrous ammonia, or (2) more than 15,000 lb of >44% ammonia solutions by weight.[38] If for some reason storing anhydrous ammonia is not practical, then the use of aqueous ammonia is a potential alternative. JET reported that the economic case for ammonia-based scrubbing still holds when using a 29% ammonia reagent; the economics are compromised when the reagent concentration approaches 19%.[39]

JET reported that some of their facilities produce ammonia on site, while others have it delivered. JET has facilities that store as much or more ammonia as would be stored at A.B. Brown. JET reported having no safety issues associated with the storage of ammonia at any of its installations.[40]

Various regulations may apply to the safe storage and handling of anhydrous ammonia, including the American National Standards Institute (ANSI) for storage and handling of anhydrous ammonia (K61.1 – 1999), state regulations, and 29 CFR 1910.111, Storage and handling of anhydrous ammonia. The regulations address engineering design requirements for the construction, test and qualification of containers; location of storage containers; the design of appurtenances, piping, tubing, fittings, and hoses; safety relief devices; charging of containers; transfer of liquids; unloading operations, and electrical equipment and wiring.

The safety data sheet for anhydrous ammonia indicates the following Hazardous Materials Information System (HMIS) ratings: a flammability rating of 1 (materials must be moderately heated or exposed to high ambient temperatures before ignition will occur), a physical hazard rating of 2 (materials that are unstable and may undergo violent chemical changes at normal temperature and pressure with low risk for explosion.), a health rating of 3 (major injury likely unless prompt action is taken and medical treatment is given).[41]

Ammonium Sulfate Handling Safety

Ammonium sulfate is not a listed chemical in the OSHA PSM.[42] The safety data sheet for ammonium sulfate indicates a flammability Hazardous Materials Information System (HMIS) rating of 0 (material will not burn), a physical hazard HMIS rating of 0 (material is normally stable, even under fire conditions), a

[38] *Process Safety Management.* 2000. https://www.osha.gov/Publications/osha3132.html (accessed July 31, 2018).
[39] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.
[40] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.
[41] "Ammonia Safety Data Sheet." February 15, 2018. https://www.airgas.com/msds/001003.pdf (accessed July 31, 2018).
[42] *Process Safety Management.* 2000. https://www.osha.gov/Publications/osha3132.html (accessed July 31, 2018).

health HMIS rating of 1 (irritation or minor reversible injury possible). Ammonium sulfate may form a combustible dust in air during processing; best engineering practices for dust mitigation should be followed.[43] With respect to safety concerns, ammonium sulfate should not be confused with ammonium nitrate, which is also used as a fertilizer and is used along with fuel oil in explosive mixtures.

Effect on Generating Plant's Process Water Requirement

In comparison to a limestone or dual alkali-based scrubber, an ammonia-based scrubber should have a similar or lower process water requirement. All three scrubbing chemistries require process water for cleaning scrubber internals and for making up for water lost to evaporation into the flue gas and to the process chemistry. While limestone and dual-alkali scrubbers require a liquid purge stream (and the accompanying makeup water) to maintain chloride balance, ammonia-based scrubbers do not have this purge stream as they maintain water balance by incorporation of ammonium chloride into the fertilizer product.

Effect on Generating Plant's Byproducts

The operation of the ammonia-based scrubber would not affect the quality of the fly ash captured in the upstream particulate control devices, assuming that no additional controls (e.g., activated carbon injection, or increased sorbent rate for sulfuric acid control) are needed upstream of the FGD for mercury control (see later subsection "Mercury Emissions").

The ammonia-based scrubber should generate a saleable ammonium sulfate fertilizer, as compared to the current dual alkali system which generates a waste slurry; a limestone-based scrubber can generate a gypsum product that could be sold to wall board manufacturers.

Impact on Ability to Install Carbon Capture Technologies

Trimeric evaluated the effect of an ammonia-based scrubber on the ability to later install CO_2 capture technology downstream of the scrubber. With regard to controlling CO_2 emissions from A.B. Brown, the ammonia-based scrubber offers several potential advantages for carbon capture:

- No CO_2 is produced by the ammonia-based scrubbing reaction. In contrast, 0.68 ton of CO_2 is released for each ton of SO_2 that is scrubbed in a limestone-based scrubber.
- The ammonia-based scrubbing system can achieve low flue gas concentrations of SO_2 which is a contaminant for many CO_2 removal technologies. Many CO_2 removal technologies require an additional scrubber after an existing limestone FGD to achieve the required inlet SO_2 concentrations (typically less than 10 ppm, but can be 2 ppm or lower). Use of an ammonia-based scrubber designed for very high SO_2 removal may either eliminate or reduce the size of an additional SO_2 scrubber. JET provided data for one of its installations showing SO_2 concentrations averaging between 2 and 4 ppm over two different days.[44]

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[43] "Ammonium Sulfate Safety Data Sheet." December 28, 2014. https://beta-static.fishersci.com/content/dam/fishersci/en_US/documents/programs/education/regulatory-documents/sds/chemicals/chemicals-a/S25176A.pdf (accessed July 31, 2018).

[44] Repp, David (Sales Director, Jiangnan Environmental Technology). Email transmission. 07 August 2018.

- The ammonia-based scrubber is reported by JET to operate more energy efficiently than a limestone-based scrubber. Power consumption by the recirculation pumps is lower, since lower reagent to gas ratios are required.

Effect on Other Air Emissions

Trimeric evaluated the potential effect of the ammonia-based scrubber on non-SO_2 air emissions, including particulate matter, fine particulate matter, HCl, mercury, NO_X and ammonia. A significant fraction of many of these pollutants will have been removed by the upstream pollution control devices. For example, the ESP and fabric filters remove most of the particulate matter, the soda ash injection system removes most of the sulfuric acid and some HCl, some mercury is removed with the fly ash, and NOx is removed with the SCRs (but the SCRs also generate ammonia slip). Trimeric evaluated the fate of the pollutants that are in the flue gas as they are processed in the FGD system.

Particulate Matter, Including Fine Particulate Matter, Emissions

Trimeric assessed the possible effects of an ammonia-based scrubber on the particulate matter emissions. The particles in flue gas exhaust from fine particulate matter (defined as particles less than 10 microns [PM_{10}] and particles less than 2.5 microns [$PM_{2.5}$]) to significantly coarser particles. Particulate matter emissions (which includes fine and coarse particles) at A.B. Brown are limited to 0.03 lb/MMBtu. A.B. Brown has a Title V limit for sulfuric acid mist emissions, but otherwise does not have a limit for emissions of fine particles. However, when major modifications are made to a point source, the proposed emissions of that modified source are reviewed against the New Source Performance Standards to determine if the source modification will affect the local area's ability to comply with National Ambient Air Quality Standards for fine particulate matter (PM_{10} and $PM_{2.5}$).[45] Fine particulate matter is more difficult to remove from flue gas than coarse particulate matter and it is a more significant contributor to stack opacity.

Particulate matter in an ammonia-based scrubber exhaust gas could come from several sources, each of which will be discussed in turn: fly ash, scrubber carryover, sulfuric acid mist, ammonium sulfate, and ammonium chloride.

Fly ash (filterable particulate matter): The flue gas entering the FGD will contain particulate matter that was not removed by the upstream particulate control devices. According to MET, fly ash particulate matter is removed across the ammonia-based scrubber at the same rate it is removed across a limestone-based scrubber, about 70-80%.

Scrubber carryover: Fine droplets of scrubber slurry can be entrained in the flue gas exhaust. Mist eliminators reduce the concentration of scrubber carryover in the exhaust.

Sulfuric acid mist (condensable particulate matter): The scrubber inlet flue gas will also contain sulfuric acid (H_2SO_4), which is generated by SO_2 oxidizing in the boiler and across the SCR catalyst and then

[45] "Fact Sheet." https://www.epa.gov/sites/production/files/2015-12/documents/20121012fs.pdf (accessed July 31, 2018).

condensing with water vapor at lower flue gas temperatures. A.B. Brown operates an alkaline sorbent injection system to control sulfuric acid emissions upstream of the FGD and thereby achieve regulatory compliance for sulfuric acid emissions. In contrast to SO_2 which is entirely in the gas phase and is removed with very high efficiency across an FGD scrubber, sulfuric acid condenses into a fine mist. This fine sulfuric acid mist is not efficiently removed by a wet scrubber; typical removals range anywhere from 20 to 70% across a wet FGD system. The facility's Title V permit limits stack emissions to 0.008 lb H_2SO_4 /MMBtu for Unit 1 and to 0.010 lb H_2SO_4 /MMBtu for Unit 2.

Ammonium sulfate (fine particulate matter): Sulfuric acid entering the scrubber will react with ammonia reagent to form very fine ammonium sulfate particles. These fine particles are not efficiently removed by a traditional wet FGD (absent additional control measures) and exit with the exhaust gas. Based on A.B. Brown's current sulfuric acid emission rate of 0.008 lb/MMBtu[46] and assuming 50% H_2SO_4 removal across the scrubber, the scrubber inlet H_2SO_4 emissions would be 0.016 lb H_2SO_4 /MMBtu. Reaction of this sulfuric acid with ammonia could create up to 0.02 lb $(NH_4)_2SO_4$/MMBtu, which, absent additional controls, would be a significant portion of the allowable 0.03 lb/MMBtu particulate emissions.

An engineering study would be required to determine the appropriate measures to control the emissions of fine particulate matter from an ammonia-based scrubber at A.B. Brown. There are several possible solutions which could be used individually or in combination to achieve compliance with the particulate matter limit and to reduce stack opacity.

- The efficiency of the sulfuric acid control system upstream of the FGD could be improved to reduce the resulting formation of ammonium sulfate particles in the FGD exhaust gas.
- An advanced mist elimination system can be installed to remove particulate matter at increased efficiency. MET offers a proprietary design in partnership with a mist eliminator supplier with the potential of removing 30-40% of the submicron particles; the mist eliminator is located above the spray levels and below the first set of traditional mist eliminators. The advanced mist elimination system adds about 2" H_2O pressure drop to the system; this added pressure drop must be considered when determining if the existing induced draft fan for moving the flue gas through the scrubber would be sufficient.
- MET offers a single stage wet electrostatic precipitator (wet ESP). Addition of a wet ESP requires a wider diameter absorber to accommodate the lower required gas velocities (8-9 feet/second for wet ESP versus 12 feet/second for the absorber).[47] Wet ESPs are effective at removing sulfuric acid mist, fine particulate matter, and scrubber carryover. EPRI has reported performance data for wet ESPs ranging from 60-80% capture of fine particles and sulfuric acid mist with a single field wet ESP, up to 98.9% capture with multiple fields.[48] MET's DGC installation incorporated a wet ESP, as the inlet sulfuric acid concentration was higher than the

[46] Sulfuric Acid Mist (H_2SO_4) Emissions Test Report for A.B. Brown Generating Station Unit #2, Air Quality Services, Evansville, IN, August 14-17, 2017.
[47] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.
[48] *SO3 Mitigation Guide Update,* EPRI, Palo Alto, CA: 2004. 1004168.

design specification. A wet ESP is incorporated into MET's European installations to meet a European Union particulate matter emissions limit of 10 mg/Nm^3 at 6% O_2 (~0.008 lb/MMBtu); however, MET's European installations do not encounter high inlet sulfuric acid concentrations.

- JET offers an acoustic agglomeration technology that is incorporated into its 4th generation EADS technology. JET reports that the technology agglomerates submicron particles; however, at the time of this report, JET did not have particle size distribution data available to share. JET provided particulate matter emissions data from performance tests at four installations; the particulate matter emissions ranged from 0.002 to 0.011 lb/MMBtu, which are below the 0.03 lb/MMBtu regulatory limit for A.B. Brown. JET reported that it can meet the current particulate matter emissions limit for A.B. Brown with the current sulfuric acid concentrations at the FGD inlet, so long as the inlet particulate matter loading to the scrubber is less than 0.05 lb/MMBtu.[49]

The dryer exhaust would be a point source of particulate matter emissions within the ammonium sulfate fertilizer production facility; however, the exhaust gas flow rate from the dryer would be much smaller than the flue gas exhaust gas flow rate from the scrubber. Control of particulate matter emissions from ammonium sulfate manufacturing plants is achieved by installation of an emission control system, typically a venturi scrubber.[50]

HCl Emissions

The Mercury and Air Toxics Standard regulates HCl emissions from units such as A.B. Brown to 0.002 lb HCl/MMBtu; MATS alternatively allows for coal-fired units to demonstrate compliance with HCl emissions by showing that the wet-scrubbed unit has controlled SO_2 emissions to less than 0.2 lb SO_2/MMBtu. A.B. Brown fires a coal with a coal chloride concentration of about 0.1 weight%, which is equivalent to 0.075 lb HCl/MMBtu. The sorbent injection system at A.B. Brown may capture approximately half of the HCl,[51] reducing the FGD inlet concentrations to about 0.035 lb HCl/MMBtu. HCl entering flue gas desulfurization systems, whether ammonia-based or limestone-based, will be removed with high efficiency. JET did not have data on scrubber removal efficiencies of HCl, as China does not regulate HCl. MET's measurements of HCl emissions from European emissions shows HCl removed at levels of 99+%, with the caveat that the coal at these installations had a lower chloride content then the coal at A.B. Brown.[52] Assuming 98% HCl removal (same as the design SO_2 removal), the expected HCl emissions would be <0.001 lb/MMBtu, which is below the MATS regulatory limit of 0.002 lb/MMBtu. Alternatively, A.B. Brown could demonstrate compliance via its SO_2 emissions. At 98%

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[49] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.
[50] U.S. Environmental Protection Agency. Ammonium Sulfate Manufacture – Background Information for Proposed Emission Standards. EPA-450/3-79-034a. December 1979.
[51] Gray, Sterling M., Jim B. Jarvis, and Steven W. Kosler. "Combined Mercury and SO3 Removal Using SBS Injection." *Power.* July 1, 2014. https://www.powermag.com/combined-mercury-and-so3-removal-using-sbs-injection/?pagenum=4 (accessed July 31, 2018).
[52] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

SO_2 removal, the SO_2 emissions would be 0.12 lb/MMBtu, which is meets the 0.2 lb SO_2/MMBtu limit to forego direct HCl emissions measurements to demonstrate compliance.

Mercury Emissions

Under the Mercury and Air Toxics Standard, A.B. Brown Generating Station must meet a mercury emissions limit of 1.2 lb/TBtu. A.B. Brown currently meets this limit by adsorption of some of the gas-phase mercury to the fly ash, oxidation of mercury in the SCR and then its subsequent removal in the FGD scrubber, and the use of a mercury re-emissions additive to control FGD re-emissions.[53] Mercury re-emission is a phenomenon wherein scrubber mercury chemically transforms to a species that is not soluble in the scrubber liquor and is thus re-emitted to the stack gas.

Neither MET nor JET provided sufficient data for Trimeric to assess mercury removal across an ammonia-based scrubber; installed units in Europe and China have not had to comply with a mercury emissions limit. If re-emissions were an issue for ammonia chemistry, then strategies similar to those employed in limestone-based scrubbing, such as ORP control and/or the use of mercury re-emissions additive, could be tested for their effectiveness. If these strategies were not effective, then A.B. Brown may be able to achieve mercury compliance with one or more of the following approaches:

- Improved sulfuric acid controls, which would increase mercury removal by the fly ash, thus reducing the mercury load into the scrubber;
- Use of activated carbon injection to adsorb mercury and remove it in the particulate control devices. In this case, care would be needed in the selection of carbon type and injection rate to preserve the fly ash for beneficial reuse.

Nitrogen Oxide Emissions

Nitrogen oxides (NO_X) at A.B. Brown are controlled via low NO_X burners, low combustion air ratios, and an SCR. JET provided test data from four sites that show modest additional removal (5% – 25%) of NO_X by the ammonia-based scrubber. Little NO_X removal is expected because nitric oxide (NO) is not soluble in water, and nitric oxide does not react with ammonia at the operating temperature of the scrubber. Nitrogen dioxide (NO_2) is water soluble and would be partially removed by the scrubber, but little NO_2 would be present in the FGD inlet flue gas for a unit equipped with SCR.

Ammonia Emissions

A.B. Brown's Title V operating permit does not address ammonia emissions. Both MET and JET provided data for expected ammonia emissions from an ammonia-based scrubber:

- MET has a proprietary design to maintain ammonia slip to less than 10 ppmv, wet basis.[54] MET conveyed that the expected operating pH (of 5.2) and temperature at A.B. Brown are conducive to maintaining ammonia emissions below 10 ppm.

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[53] Verified (Public) Direct Testimony of Wayne D. Games, Vice President of Power Supply. Cause NO. 45052 (March 20, 2018).

[54] Evans, Amy P., Claudia Miller, Steve Pouliot. "Operational Experience of Commercial, Full Scale Ammonia-Based Wet FGD for Over a Decade." *www.met.net.* August 20, 2009.

- JET indicated a typical ammonia emissions guarantee for U.S. applications is less than 5 ppm.[55] Test report data supplied by JET indicated ammonia emission ranging from 0.3 to 7.0 ppm.

Economic Analysis

An economic analysis of ammonia-based scrubbing technology must consider the coal sulfur content, availability and delivered price for ammonia, the regional market place for ammonium sulfate, the ability to reuse and/or retrofit the existing FGD and other existing infrastructure (e.g., the induced draft fan), the new infrastructure required for receiving, handling, and storing ammonia reagent, the available transportation for reagents and products, the desired return-on-investment model, and other factors. Trimeric performed a preliminary analysis of each of these factors, as described below; a full economic assessment was beyond the scope of this report.

Coal Sulfur Content

The production rate of ammonium sulfate fertilizer is driven by size of the power plant (i.e., amount of coal combusted) and the coal sulfur content. MET has a rule of thumb that if the coal sulfur is 2% or greater (such as it is at AB Brown, which has 3.4% S), then the economics for an ammonia scrubber can be very favorable due to the high production rates of ammonium sulfate fertilizer.[56]

The economics of the ammonia-based scrubbing technology improve with higher sulfur coals and with higher SO_2 removal efficiency. Therefore, the ability to fire higher sulfur coals than what Vectren is currently firing could provide a further cost advantage to the unit. Higher sulfur coals are typically cheaper than lower sulfur coals, and coal feedstock typically contributes over 80% of the variable operating costs for a coal-fired generating unit.[57]

Availability and Delivered Price for Ammonia; Regional Market for Ammonium Sulfate

Another key to viable economics of an ammonia-based scrubber is the availability of ammonia at a competitive price. To date, most of the installations of MET's ammonia scrubbers are at sites that have ammonia readily available or produce it on site.[58] Not having ammonia source on site implies a longer payback period versus a limestone scrubber. Per MET, the amount of ammonium sulfate generated at

http://www.met.net/Data/Sites/35/assets/Information-Library/Technical%20Papers/Operational%20Experience%20of%20Commercial,%20Full%20Scale%20Ammonia-based%20Wet%20FGD%20for%20Over%20a%20Decade%20-%20August%202009%20-%20Presented%20at%20Coal-Gen%202009.pdf (accessed July 31, 2018).

[55] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.

[56] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[57] Connell, D. Opportunities for New Technology in Coal Mining and Beneficiation; In Proceedings of the National Coal Council Annual Spring Meeting 2018, Washington, DC, April 2018. Available: http://www.nationalcoalcouncil.org/page-Meeting-Presentations.html

[58] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

A.B. Brown is significant and favors the economics for application of the technology, even though ammonia is not produced on site.[59]

When operating at an annual capacity factor of 52%, the anhydrous ammonia required would be about 40,000 short tons per year. In comparison, an ammonia production facility is considered small scale when under 200,000 short tons per year, with some production plants as small as 30,000 tons/year. Ammonia production capacity in the US was 15 million tons/year in 2015.[60] Approximately 90% of US ammonia consumption was for fertilizer use.[61]

Natural gas feedstocks account for more than 95% of ammonia tonnage, and thus the price of ammonia and fertilizer is tied to natural gas prices.[62] Trimeric found a range in reported prices for anhydrous ammonia and ammonium sulfate.

- **Anhydrous ammonia.** MET recommended using an anhydrous ammonia cost of $370-375/ton to be reflective of what a power plant would pay for the reagent.[63] JET recommended an anhydrous ammonia cost of $300/ton.[64]
- **Ammonium sulfate.** MET indicated that the wholesale price for standard grade ammonium sulfate is $100-$120/ton, while the wholesale price for compacted ammonium sulfate ranges from $245-$280/ton. A power plant producing ammonium sulfate would receive a price less than these wholesale values.[65] JET indicated that a power plant might receive $135/ton of ammonium sulfate.[66]

Differences in assumptions for shipping distances (which were not specified) may play a significant part in the variation in prices. Trimeric is not an expert in ammonia or fertilizer markets and cannot validate the applicability of any of these reported values to A.B. Brown. A detailed economic analysis performed by experts with knowledge of local markets is recommended.

For the sake of understanding the impact of pricing on the potential product margin, Trimeric evaluated the cost and revenue streams for the ammonia-based scrubber for three different scenarios: (1) using

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[59] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[60] Brown, Trevor. "Small-scale ammonia production is the next big thing." *Ammonia Industry.* May 10, 2018. https://ammoniaindustry.com/small-scale-ammonia-production-is-the-next-big-thing/ (accessed July 31, 2018).

[61] Brown, Trevor. "2016 in preview: US ammonia capacity to increase by a third." *Ammonia Industry.* January 12, 2016. https://ammoniaindustry.com/2016-in-preview-us-ammonia-capacity-to-increase-by-a-third/ (accessed July 31, 2018).

[62] "Gas as fertilizer feedstock." *PetroWiki.* July 16, 2015. https://petrowiki.org/Gas_as_fertilizer_feedstock (accessed July 31, 2018).

[63] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[64] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.

[65] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[66] Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.

JET's suggested costs for ammonia and fertilizer, (2) using MET's suggested costs for ammonia and the standard fertilizer product, and (3) using MET's suggested data for ammonia and the compacted fertilizer product. These calculations were performed assuming 40,000 ton/year of ammonia use and 150,000 ton/year of ammonium sulfate production, based on 52% annual capacity factor for the two units. As shown in the table below, the annual margin between product and reagent costs could range from break-even (under the more conservative assumptions from MET) to as high as $27MM/year when making the compacted product.

Scenario #	Cost of NH_3 (\$/ton)	Price of AS (\$/ton)	Net annual difference in product revenue vs reagent cost (\$/yr): (price of AS x ton/yr of AS – cost of NH_3 x ton/yr of NH_3)
JET	300	135	\$8.25MM
MET Scenario #1 Standard Product	375	100	\$0MM
MET Scenario #2 Compacted Product	375	280	\$27MM

The type of final fertilizer product produced would be dependent on the contractual requirement with the off-taker. The plant would typically be designed to produce a single type of fertilizer product based on the product economics, such that the investment of equipment to make the standard crystals or the compacted product would only be made if the economics justified that product stream.

Trimeric asked JET about possible concerns with saturating the local fertilizer marker. JET reported that market saturation would not be an issue for the first several installations in the US market; the actual number of plants that would saturate the market is not known as it would depend on the technology's adoption rate. If the US market were to saturate, the next desirable markets are in Mexico and Canada, then South America. JET reported that total ammonium sulfate demand in North America is about 6 MM metric tons this year, and is expected to grow over the next four years.

Other operating costs

JET reported that non-reagent operating costs for an ammonia-based scrubber are below limestone scrubbing costs due to lower slurry recirculation rates resulting in lower power consumption.[67] MET also reported that the ammonia-based scrubber has lower circulation rates, but that the effect on overall power consumption is not significant enough to take into account in their economic analysis.[68]

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67 Repp, David (Sales Director, Jiangnan Environmental Technology). Personal Conversations. 3 and 18 July 2018.

68 Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

Capital costs

MET indicated that the initial capital cost is 30-40% more expensive than a limestone scrubber when the fertilizer plant is included.[69] JET indicated that the capital cost is on par with that of a limestone scrubber.[70]

Ability to Reuse Existing FGD Infrastructure

The existing dual alkali scrubber at A.B. Brown consists of several pieces of equipment that might be repurposed for an ammonia-based scrubber, including the induced draft fan, the absorber tower and reaction tank, the oxidation air blowers, the recirculation pumps, tanks, duct work, and chimney. This equipment would need to be in good condition or capable of being refurbished, and this equipment would need to be appropriately sized. An inspection conducted by Burns and McDonnell indicated that the lifetime of some of the existing FGD equipment may be very limited; however, this report appears to be based upon visual inspection of the external vessels, with no detailed metallographic analysis.[71] A more detailed structural inspection would be recommended to determine what existing equipment could be reused.

According to JET, the economics of the ammonia-based scrubber are viable, even if none of the existing FGD equipment is reused; JET prepared its economic analysis by assuming that the induced draft fan, chimney, and some connecting ductwork can be reused. The induced draft fan provides the motive force for conveying flue gas through the FGD scrubber. The pressure drop across the ammonia scrubber will be lower than a traditional scrubber, opening the possibility that the ID fan could be used in a scrubber retrofit. A detailed analysis would need to account for actual duct runs, pressure drop across scrubber, including any additional equipment such as advanced mist eliminators or wet ESPs that may be needed. If the induced draft fan and/or chimney could not be re-used, the payback period for the project would be lengthened.

New Infrastructure Required for Receiving, Handling, and Storing Ammonia Reagent

The ammonia reagent system for an ammonia-based scrubber will be larger than for ammonia system for the existing SCR, and will likely be a different reagent type. New infrastructure would be required, which would likely be provided by the ammonia-based scrubbing supplier.

Available transportation for reagents and products

The A.B. Brown Generating Station has rail and highway access for transport of anhydrous ammonia reagent and ammonium sulfate product.

Desired return-on-investment, contracting models, etc.

Trimeric did not complete a return-on-investment (ROI) analysis for the project, as this exercise was beyond the scope of this report. An ROI analysis would need to reconcile the expected life of a typical

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[69] Evans, Amy (Director of FGD Technology and Licensing, Marsulex Environmental Technology). Personal Conversations. 9, 12, and 19 July 2018.

[70] JET Brochure provided to K. Dombrowski on 31 July 2018.

[71] Verified (Public) Direct Testimony of Wayne D. Games, Vice President of Power Supply. Cause NO. 45052 (March 20, 2018).

new scrubber (which is typically about 30 years) to the expected remaining life for the balance of plant at A.B. Brown. The return on investment would need to be evaluated against project and contract risks, including the Engineering, Procurement, and Construction (EPC) contract and the contract for the offtake of the ammonium sulfate product.

While owning and operating a fertilizer production facility would be unusual for a coal-fired electric generating plant in the United States, this function can be outsourced under a long-term contract if the utility is unable or unwilling to take on the responsibility. Various business models may be possible, such as Build, Own, and Operate (BOO) or EPC and Operation.

Appendix A – Design Criteria Assumed for A.B. Brown

Parameter	AB Brown	Source of Data / Comments
Unit size	U1: 245 MW net, 265 MW gross U2: 245 MW net, 265 MW gross	Vectren testimony by Wayne D. Games
Flue gas at Scrubber Inlet	U1: 2,898,000 lb/hr U1: 922,000 acfm U2: 2,870,000 lb/hr U2: 913,000 acfm	Burns and McDonnell report (BMcD report)
Unit heat rate	U1: 11,576 Btu/kwh net U2: 11,007 Btu/kwh net	Vectren testimony
Load profile	Cycling; max ramp rate of 3 MWs/minute	Vectren testimony
Boiler type	Dry bottom, pulverized coal-fired boiler	Title V permit
Annual capacity factor	52% - 2017 actual	Vectren testimony
Air Heater Outlet Temperature	325°F	BMcD report
Coal type	Bituminous	Vectren testimony
Coal sulfur	3.38% S, as-received	Coal analysis by Standard Laboratories BMcD report: 3.75% S as received; 6.7 lb SO_2/MMBtu
Coal moisture	11.62% H_2O	Coal analysis by Standard Laboratories for Sunrise Coal, LLC
Coal chlorine	977 µg/g, dry; this is 0.0977 wt% Cl	Coal analysis by Standard Laboratories
Coal arsenic	4.6 µg/g, dry	Coal analysis by Standard Laboratories
Coal cadmium	0.49 µg/g, dry	Coal analysis by Standard Laboratories
Coal chromium	16 µg/g, dry	Coal analysis by Standard Laboratories
Coal lead	6.2 µg/g, dry	Coal analysis by Standard Laboratories
Coal mercury	0.077 µg/g, dry	Coal analysis by Standard Laboratories
Coal selenium	1.9 µg/g, dry	Coal analysis by Standard Laboratories
Coal ash aluminum oxide	19.84%	
Coal ash calcium oxide	1.82%	
Coal ash ferric oxide	21.28%	
Coal ash magnesium oxide	0.88%	

Parameter	AB Brown	Source of Data / Comments
Coal ash sodium oxide	0.76%	
Coal ash manganese dioxide	0.06%	
Coal HHV	11,486 Btu/lb as received coal	Coal analysis by Standard Laboratories
Existing SO_2 control	Dual alkali scrubber	Vectren testimony
Design SO_2 removal for new FGD	>=98% SO_2 removal	BMcD scrubber replacement analysis targeted >=98% SO_2 removal Title V permit for U2 specifies BACT with SO_2 controlled to at least 90.0%
SO_2 limit	0.855 lb SO_2/MMBtu on one hour average for U1 alone; 0.426 lb SO_2/MMBtu one hour average for U1/U2 simultaneously operating; 0.69 lb SO_2/MMBtu on thirty-day rolling average for U2 anytime it is operating, whether alone or with U1	From Title V permit, issued 11/28/2017
NO_X controls	Low excess air, low-NO_X burners, and SCRs for U1 and U2	Title V permit
NO_X limit	0.6 lb nitrogen oxides/MMBtu	Title V permit limit for U2
NH_3 limit	None specified	NH_3 is not addressed in Title V permit
HCl limit	None specified	No limit found in the Title V permit; it appears Vectren was able to get quarterly testing approved (rather than continuous testing that was initially specified in the permit). MATS does not require reported for units meeting SO_2 emissions < 0.2 lb/MMBtu
Hg controls	Organosulfide mercury re-emission additive for the FGD, plus co-benefit removal from SCR, particulate control devices, and FGD	Vectren testimony
Hg limit	< 1.2 lb/TBtu	MATS limit
PM Control	U1: Fabric filter U2: ESP	BMcD report
PM limit	0.03 lb PM/MMBtu	Title V permit limit specified for U2 emissions

Parameter	AB Brown	Source of Data / Comments
		No specification found for U1 other than to control with ESP with minimum collection efficiency of 99.6% when burning coal with maximum ash content of 10%, minimum sulfur content of 2.5% and minimum heat content of 11,000 Btu/lb
H_2SO_4 controls	Soda ash injection directly upstream of SCR	BMcD report
H_2SO_4 limit	Permit limit is H_2SO_4 emission limit of 0.008 lb/MMBtu for U1 and 0.010 lb/MMBtu for U2	Title V permit limit
Wastewater treatment	Physical/chemical system with organosulfides, coagulants, flocculants	Vectren testimony
Fate of FGD solids	Landfilled on site	Vectren testimony
Fate of fly ash	Sold for beneficial reuse in cement	Vectren testimony
Transit access	Rail access Highway access Near Ohio River	Vectren testimony