Staged Turbulent Air Reactor (STAR^{TM}) Beneficiation Process – Commercial Update

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ABSTRACT

The positive economic and technical benefits of utilizing fly ash as a replacement for cement in concrete have been well established. Further, it is well known that ever increasing environmental regulations on coal-fired plants has led to the development of several types of fly ash beneficiation processes in order to make a product suitable for utilization.

The SEFA Group, a long time leader in the fly ash utilization industry, has developed a new, unique, and proprietary thermal beneficiation technology. The STAR^{TM} – Staged Turbulent Air Reactor – process has been successfully demonstrated on a commercial scale at the South Carolina Electric and Gas McMeekin Station and most recently at NRG's Morgantown Station.

The STAR^{TM} technology offers many new advantages and opportunities not formerly available with other beneficiation processes. Further, STAR^{TM} has demonstrated the ability to provide a range of products that can be applied across a wide variety of new markets not previously open to by-product fly ash or other beneficiation processes.

This paper will discuss various aspects of the technology, operating experience, test results and product characterizations.

INTRODUCTION

The SEFA Group has been operating thermal beneficiation plants since 1999 and over that time has processed nearly 5 million tons (4.5 million metric tons) of fly ash. In 2006-07, SEFA developed a new thermal beneficiation process – Staged Turbulent Air Reactor (STAR) – and began commercial operations in February 2008. The STAR Plant is specifically designed and operated to reduce the heterogeneity of fly ash by lowering or eliminating the amount of unburned carbon and other contaminants, including unburned organics from alternative fuels.

The STAR Plant operates at temperatures that are high enough to burn off residual organics comingled in the fly ash, including coal char particles. The STAR Plant can also be operated to reduce some types of agglomerates, improving particle size distribution, as well as to blend various coal fly ashes in order to reduce variations in ash chemistry or to optimize the performance of coal ash for particular ash utilization opportunities/markets.

Recently, The SEFA Group has tested the use of reclaimed fly ash, from ponds and landfills, as raw feed material to the STAR Process.

COMMERCIAL STAR PLANT EXPERIENCE

The first STAR Plant was built at SCE&G's McMeekin Station, which is located near the Administrative Offices of The SEFA Group, in Lexington, South Carolina. This facility was designed with a maximum heat input of 35 MM Btu/hr (equivalent to approximately 10.25 MW), and is permitted to process upwards of 140,000 tons (127,000 metric tons) per year. Actual throughput is dependent upon available LOI of feed material. Figure 1 below shows the relationship of material throughput of the STAR at varying raw feed LOIs and design heat inputs.

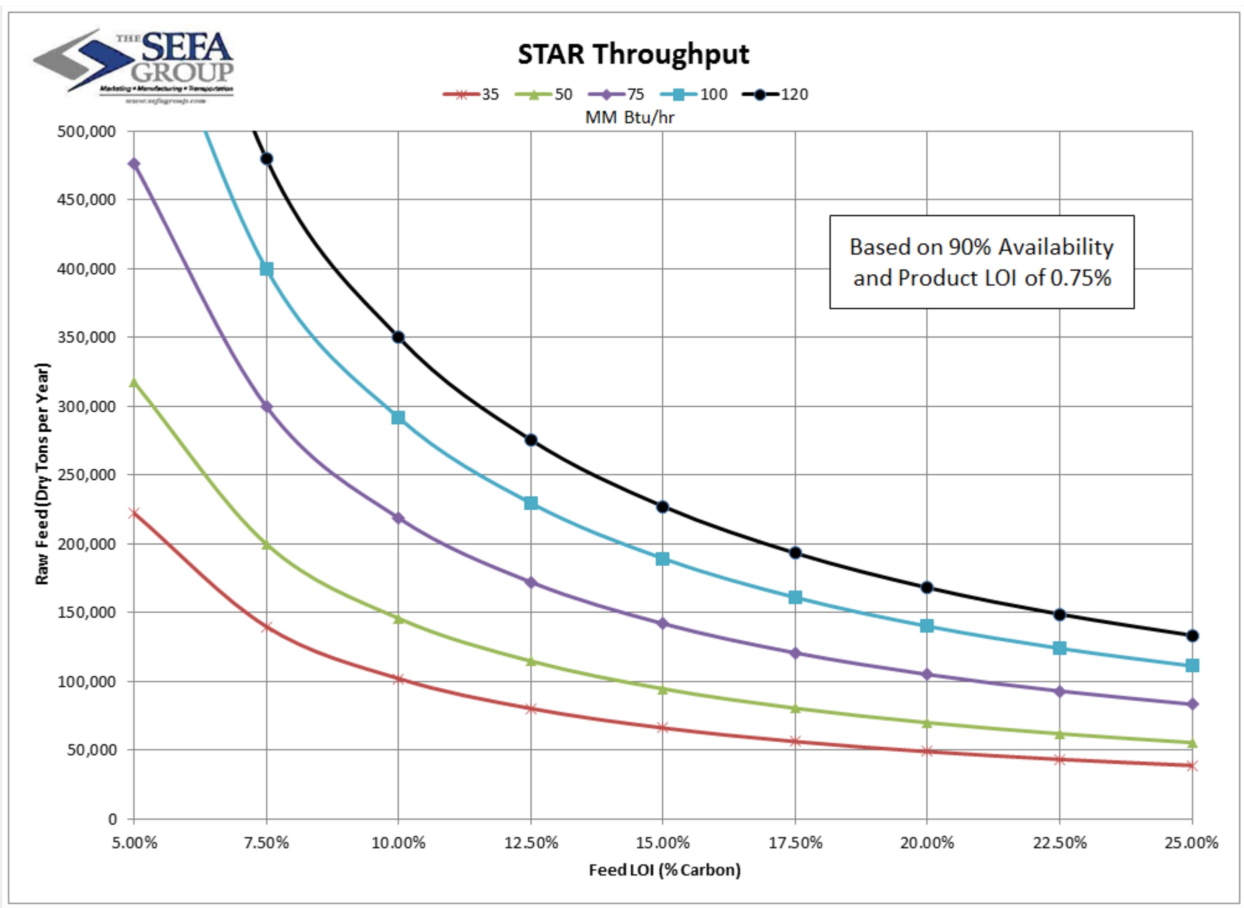

Figure 1 – STAR Throughput based on Raw Feed LOI

To date the McMeekin STAR has processed nearly 400,000 tons (363,000 metric tons) of high LOI fly ash originating from more than sixteen (16) different facilities with feed

LOIs ranging from 5 to 25%. The final product is of premium quality with typical LOIs at or below 1.0%.

The McMeekin facility is wholly owned and operated by The SEFA Group, and is permitted as a stand-alone facility. As such, the plant includes a wet scrubber for control of sulfur emissions, and a Continuous Emissions Monitoring System (CEMS) to confirm environmental compliance. Annual RATA testing is conducted to ensure compliance with all other critical air pollutants – Carbon Monoxide (CO), Nitrogen Oxides (NOx), Volatile Organic Compounds (VOC) and Particulate Matter (PM and PM_{10}).

Lessons learned from the McMeekin “first-of-a-kind” STAR Plant were incorporated into the design of the next generation STAR facility, referred to as STAR II.

The STAR II facility is owned by NRG, and is designed to process 100% of all fly ash generated at their Morgantown and Chalk Point facilities. The STAR Plant was designed with a maximum heat input of 120 MM Btu/hr, (35 MW) and has a nominal processing capacity of 360,000 tons (326,587 metric tons) per year. The facility includes a concrete storage dome capable of holding more than 30,000 tons (27,211 metric tons) of finished product.

While the Morgantown STAR plant is owned by NRG, it was also permitted as a stand-alone facility, and can operate independently of the host utility. Similarly to the McMeekin STAR, the STAR II facility includes a wet scrubber for control of Sulfur Oxide (SO_X) emissions, as well as a CEMS is included to ensure compliance with all criteria pollutants and permit restrictions.

Figure 2 – Morgantown STAR II Facility

STAR PRODUCT QUALITY

During typical commercial operation, the STAR Plant processes bituminous coal fly ash. However, some sub-bituminous coal fly ash and various blends of bituminous and sub-bituminous coal fly ashes have been processed. Raw feed fly ashes from 16 different coal-fired power plants have been processed through the McMeekin STAR Plant. As of the writing of this paper, the loss on ignition (LOI) of the raw feed fly ashes processed through the STAR Plant have ranged from slightly over 24% LOI to slightly over 5% LOI. Hourly samples of raw feed and STAR-processed fly ashes are collected and tested for LOI.

Commercial operation removes all ammonia – through chemical decomposition into nitrogen and water vapor – and can also reduce other contaminants. Obviously, STAR processing lowers the amount of residual unburned carbon, reducing the LOI to be under the maximum LOI limit of all relevant specifications. Typical STAR-processed fly ash is slightly below 1% LOI. However, STAR Plant operating conditions can be adjusted to change/control the LOI of the finished product to meet the expectations of the marketplace.

A major objective for processing fly ash using STAR is to increase the quality and, therefore, the value of fly ash that is currently used in the commercial marketplace – for example, as pozzolan in concrete. The STAR Plant is easily able to accomplish this objective by removing and/or treating unburned carbon found in residual coal char particles.[1] The STAR process, therefore, decreases the heterogeneity of coal fly ash by increasing the polar nature of STAR fly ash.[2] Further to this effect, STAR Plant operation can be varied to create an oxidizing treatment of any remaining carbon to either partially or completely de-activate it so as to match the expected adsorptive characteristics/requirements of various manufacturing processes, such as air-entraining admixture (AEA) dosage rates in concrete production.[3]

Current commercial STAR Plant operation processes Class F coal fly ash; however, during R&D activities, Class C (sub-bituminous) coal fly ash and blends of Class F and Class C fly ashes were successfully processed.[4] STAR Plant operation can be varied to either reduce or remove all carbon from any of the fly ashes processed to date.[5]

The STAR Plant can produce two streams of fly ash, each of which has slightly different chemical and physical characteristics. One stream can be processed in such a way as to perform some size classification of the fly ash, tailoring it to the expectations and/or requirements of particular markets, especially high-value mineral filler markets.[6] This product stream will also reduce or remove many contaminants (e.g., mercury), further enhancing its value in certain consumer products and some manufacturing processes – especially high-temperature processes.[7] If it is not desirable to segregate this material it is comingled with the normal product stream and captured in the filter fabric baghouse.

The main product stream captures higher concentrations of these contaminants. The STAR-processed fly ash from this stream is used in products, such as concrete, that do not restrict the presence of these contaminants and which will serve to reduce their potential toxicity and/or sequester them, as in the case of mercury, for example, through entombment in the cementitious paste matrix of concrete products.[8]

In summary, improved commercial performance and certain unique characteristics of STAR fly ash result from tailored STAR-processing, which can be controlled to:

- Reduce unburned carbon content in fly ash in order to meet relevant product specifications that require low loss on ignition;
- Eliminate all unburned carbon in fly ash, allowing the contaminant-free mineral matter to be used as higher-value mineral admixtures in paints, plastics, etc.;
- Sequester a portion of the residual unburned carbon char in fly ash by treating it to increase polarity, thereby optimizing concrete AEA dosage rates or reducing the heterogeneity of fly ash for use as high-value mineral admixtures;
- Increase the fineness of the mineral matter and improve its strength-producing character in concrete;
- Size-classify the mineral matter;
- Manage certain trace elements, such as mercury, selenium, etc., in order to either remove them from product material or to concentrate them in a different product stream for sequestration.

RECLAIMED ASH AS STAR RAW FEED

Recently The SEFA Group has conducted testing at its McMeekin STAR facility to process material reclaimed from existing ash ponds and landfills. The material tested contained up to 30% moisture and varied in LOI from approximately 8% to 19% (dry basis). The objectives of this testing were to confirm that the STAR could transform this material into a suitable pozzolan for use in Ready-Mix Concrete and to determine if the process could remain self-sustaining.

Due to the operational flexibility of the STAR process, the reclaimed material can be successfully fed into the unit with no major modifications required to the standard plant design. Tests were conducted by blending certain percentages of reclaimed material with normal dry feed, as well as with 100% reclaimed material as feed. The majority of testing was conducted by first screening the material at the location where it was reclaimed (or “mined”). In no test cases was any of the material first dried prior to introduction into the STAR.

Table 1 illustrates the results from ASTM C-618 testing for four (4) STAR Plant samples processing reclaimed ash. The first sample was a blend of 25% reclaimed pond ash material with 75% typical dry feed ash, the second and third represent samples that are 100% reclaimed pond ash material, and the fourth is 100% reclaimed material from an ash landfill (i.e., structural fill). In all cases the Strength Activity Index met or exceeded ASTM requirements, and closely approximated STAR product under normal commercial operations.

Table 1: Reclaimed Ash ASTM C-618 Test Results

Chemical Analysis	25% Reclaimed Pond Ash	100% Reclaimed Pond Ash	100% Reclaimed Pond Ash	100% Reclaimed Landfill Ash
Silicon Dioxide (SiO2)	52.79	51.99	51.33	53.36
Aluminum Oxide (Al2O3)	27.48	27.52	27.57	26.84
Iron Oxide (Fe2O3)	9.53	11.45	10.72	11.01
Sum of Silicon, Aluminum, Iron (SiO_2, Al_2O_3 & Fe_2O_3)	89.81	90.96	89.62	91.21
Calcium Oxide (CaO)	2.18	1.66	1.98	1.86
Magnesium Oxide (MgO)	1.37	1.17	1.24	1.17
Sodium Oxide (Na2O)	0.54	0.48	0.52	0.54
Potassium Oxide (K2O)	2.43	2.59	2.58	2.31
Titanium Dioxide (TiO2)	1.43	1.38	1.40	1.41
Manganese Dioxide (MnO2)	0.03	0.03	0.03	0.03
Phosphorus Pentoxide (P2O5)	0.32	0.36	0.36	0.27
Strontium Oxide (SrO)	0.14	0.14	0.15	0.14
Barium Oxide (BaO)	0.12	0.14	0.15	0.14
Sulfur Trioxide (SO3)	0.20	0.12	0.22	0.21
Loss on Ignition	1.44	0.98	1.75	0.72
Moisture Content	0.06	0.05	0.06	0.03
Physical Analysis				
Fineness (% Retained on #325 Sieve)	19.27	30.03	19.73	22.17
Specific Gravity	2.27	2.34	2.32	2.30
	Strength Activity Index (SAI)			
At 7 Days:	75	76	78	81
At 28 Days:	83	81	81	83
Water Requirements (% Test H_2O/Control H_2O)	97	96	96	96
Autoclave Expansion (%)	-0.03	0.02	-0.01	0.02

CONCRETE MIX RESULTS

As shown in Table 2, six laboratory concrete mixes were designed to incorporate six different fly ashes at 25% of total cementitious material:

1) STAR-Processed dry fly ash for a control mix
2) STAR-Processed Blend of dry fly ash (75%) and Reclaimed Ash (25%)
3) 100% STAR-Processed Reclaimed Ash (Morning Run)
4) 100% STAR-Processed Reclaimed Ash (Afternoon Run)
5) By-Product Fly Ash – Source A
6) By-Product Fly Ash – Source B

Both the plastic and hardened characteristics of the concretes containing STAR-Processed Reclaimed Ash were as good as or better than the STAR-Processed Control (i.e., dry fly ash) concrete and the compressive strengths for the concretes containing STAR-Processed Ashes were higher than the concretes made with the by-product fly ashes.

Table 2: Laboratory Concrete Mix Test Results

Cubic Yard Mix Proportions (lbs)	**Mix 1 Control**	**Mix 2 Blend**	**Mix 3 100%**	**Mix 4 100%**	**Mix 5 Plant A**	**Mix 6 Plant B**
Type I Cement	420	420	420	420	420	420
Fly Ash	140	140	140	140	140	140
Loss on Ignition, %	0.9	1.7	1.2	1.9	3.5	2.6
Total Cementitious Material	560	560	560	560	560	560
% SCM	25%	25%	25%	25%	25%	25%
#57 Stone	1850	1850	1850	1850	1850	1850
Natural Sand	1258	1258	1258	1258	1258	1258
City Water, gallons	32.2	32.3	31.5	32.2	32.1	33.0
w/cm Ratio	0.48	0.48	0.47	0.48	0.48	0.49
Water Reducer (oz/cwt)	3.00	3.00	3.00	3.00	3.00	3.00
Air Entrainer (oz/cwt)	0.36	0.36	0.36	0.52	1.60	2.20
Trial Batch Results						
Slump (inches)	4.75	4.75	4.50	4.75	4.75	5.00
Air %	4.4	4.4	4.5	4.4	4.5	5.2
Unit Weight (pcf)	147.5	148.0	147.4	147.6	147.6	146.4
Relative Yield %	98.83%	98.54%	98.77%	98.74%	98.77%	99.71%
Concrete Temp (°F)	56	56	59	60	62	64
Air Temp (°F)	58	59	50	60	60	60
Compressive Strength Results (psi)						
7-day Average	**3540**	**3670**	**3660**	**3530**	**3930**	**2960**
28-day Average	**4650**	**4930**	**4730**	**4820**	**4800**	**3530**
7-28 Gain	1110	1260	1070	1290	870	570

Table 2a: Laboratory Concrete Mix Test Results (metric)

Cubic Meter Mix Proportions (kg)	Mix 1 Control	Mix 2 Blend	Mix 3 100%	Mix 4 100%	Mix 5 Plant A	Mix 6 Plant B
Type I Cement	249	249	249	249	249	249
Fly Ash	83	83	83	83	83	83
Loss on Ignition, %	0.9	1.7	1.2	1.9	3.5	2.6
Total Cementitious Material	332	332	332	332	332	332
% SCM	25%	25%	25%	25%	25%	25%
#57 Stone	1098	1098	1098	1098	1098	1098
Natural Sand	746	746	746	746	746	746
City Water, liters	121.7	122.2	119.1	122.0	121.6	124.9
w/cm Ratio	0.48	0.48	0.47	0.48	0.48	0.49
Water Reducer (ml)	496.8	496.8	496.8	496.8	496.8	496.8
Air Entrainer (ml)	59.6	59.6	59.6	86.1	265.0	364.3
Trial Batch Results						
Slump (cm)	12.1	12.1	11.4	12.1	12.1	12.7
Air %	4.4	4.4	4.5	4.4	4.5	5.2
Unit Weight (kg/m3)	2362	2370	2360	2365	2364	2346
Relative Yield %	98.83%	98.54%	98.77%	98.74%	98.77%	99.71%
Concrete Temp (°C)	13	13	15	16	17	18
Air Temp (°C)	14	15	10	16	16	16
Compressive Strength Results (MPa)						
7-day Average	24.41	25.30	25.23	24.34	27.10	20.41
28-day Average	32.06	33.99	32.61	33.23	33.09	24.34
7-28 Gain	7.65	8.69	7.38	8.89	6.00	3.93

EXCESS HEAT

As a by-product of commercial STAR Plant operation, a significant amount of excess heat is available for a variety of uses, both internal to the process as well as to outside energy consumers. In general, upwards of 75% of the heat input to the STAR must be removed from the flue gas and finished product to enable product capture in the STAR Plant's filter fabric baghouse.

Current commercial STAR operation at both facilities dissipates the excess heat to atmosphere using fin fan cooling towers. However, there are a number of potential beneficial uses for this waste heat. If a STAR Plant is located adjacent to a power plant, the most obvious beneficial use would be to transfer it into the power plant's boiler loop by directly preheating condensate or feedwater. Heat transferred into these power plant streams reduces the amount of extraction steam required in the steam turbines, thereby increasing net generation. For that matter, the STAR Plant itself could utilize this waste heat to generate electricity for the facility's own energy consumption or return this power to the local grid.

An alternate use would be to generate process steam from the STAR waste heat. In this scenario, the STAR facility could be located adjacent to any energy consumer who is burning a fuel to generate steam for their process (e.g., chemical industry, food industry, etc.). Of course, uses for STAR waste heat are not limited to water and/or steam cycles, heat could be transferred into a variety of thermal fluids for use in a number of different processes (e.g., drying, building heat, etc.)

AIR EMISSIONS

As mentioned earlier, the McMeekin STAR Plant is adjacent to a power plant, McMeekin Station. However, the STAR Plant is designated as a separate source with its own air operating permit. The Morgantown STAR II facility is also a stand-alone facility, but because it is owned by NRG it is regulated under the Morgantown Generating Station's permit. Since future STAR Plants can also be designed as stand-alone facilities or co-located at power plants, there are a variety of permitting options, depending on the specific situation of the actual site.

The primary reaction during STAR-processing is the conversion of residual carbon char into carbon dioxide (CO2). Emissions CO2 are directly proportional to the amount of carbon burned out of the feed ash; therefore, CO2 emissions will be 3.67 times the mass of carbon burned (approximately 0.126 Ton CO2 per MM Btu Heat Input).

However, it is important to note that since the primary use of STAR fly ash is as a partial replacement of cement in concrete, there is actually a net reduction in CO2 emissions due to the operation of the STAR Plant. For example, according to the US Environmental Protection Agency, the "Net Recycling Emissions" from the use of fly ash is a *negative* 0.87 metric tons of CO2 equivalent per short ton of fly ash.[9] Assuming the STAR Plant has a 50-ton (45.36 metric tons) per hour feed rate of 8% LOI fly ash, the CO2 emission rate would be 14.67 tons (13.31 metric tons) per hour. The production rate of STAR fly ash would be at least 46 tons (41.73 metric tons) per hour.

Therefore, in this example, the STAR Plant would generate14.67 tons (13.31 metric tons) of CO2 per hour while also producing enough STAR fly ash to reduce CO2 emissions by 44.11 tons (40 metric tons) per hour. Consequently, there is a net *reduction* of 29.44 tons (26.69 metric tons) per hour in CO2 emissions (this would represent a new reduction of 250,000 tons of CO2 per year for a 120 MM Btu/hr plant).

Uncontrolled sulfur dioxide (SO2) emissions are also directly proportional to the mass of sulfur that volatizes during STAR-processing. Therefore, since the amount of residual sulfur in feed fly ash varies by source of the coal ash, the amount of SO2 emissions will vary accordingly. Regardless, commercial STAR Plant infrastructure includes a small, flue gas desulfurization scrubber to reduce SO2 emissions below the maximum limit of the STAR Plant's air operating permit. Controlled emissions below 10 lb/hr (40 TPY) have been achieved.

Due to the operational flexibility of the STAR Plant, other criteria pollutants, such as carbon monoxide (CO) and nitrogen oxides (NOx) can be effectively controlled by manipulating the operating conditions of the process. Emission factors for CO and NOx are typically expressed in terms of pounds per million British Thermal Units (lb/MM Btu). The STAR process has demonstrated uncontrolled emissions below 0.10 lb/MM Btu for CO and 0.05 lb/MM Btu for NOx. Lower values are possible using proprietary operating techniques.

The product of the STAR Plant is a fine particulate matter; therefore, a high-efficiency dust collector serves as both the "product capture device" as well as the "particulate control device." Particulate matter emissions are below 0.025 lb/SCF; therefore, a 100 MM Btu/hr STAR Plant would have particulate emissions less than 5 lb/hr. Also, since commercial STAR plant operation includes wet-scrubbing, particulate emission can be cut further – by more than a factor of 10.

SUMMARY

The SEFA Group developed a thermal beneficiation process for fly ash – Staged Turbulent Air Reactor. The first facility located at SCE&G's McMeekin Station began commercial operations in 2008, and the second, or STAR II facility located at NRG's Morgantown Generating Station in Southern Maryland began commercial operations in September of 2012. Various aspects of STAR Plant operating experience, emission data, and STAR fly ash product characterizations, including recent test results processing material reclaimed from ash ponds and landfills were discussed in this paper.

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