City of Huntsville, Arkansas

Supplemental Report:

Feasibility of Treatment Alternatives for Total Dissolved Solids and Chloride

October 21, 2013

GBMc & Associates
Strategic Environmental Services

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Prepared for:

City of Huntsville, Arkansas
P.O. Box 430
Huntsville, AR 72740

Prepared by:

GBM[c] & Associates
219 Brown Lane
Bryant, AR 72022

10/21/13

October 21, 2013

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1.0 INTRODUCTION

The City of Huntsville has conducted additional review of the feasibility of treatment alternatives pursuant to Commission Minute Order No. 13-23 regarding the removal of dissolved solids (minerals) from the effluent of its current waste water treatment system. The scope of the review included emerging technologies that have not been proved beyond the laboratory or pilot scale levels. However, only technologies demonstrated to perform at the full scale flow and loading of the City of Huntsville's wastewater treatment facility were considered for further cost evaluation.

This report summarizes three treatment options identified by the review. The three technologies determined to be capable of removal of minerals at discharged flows and concentrations are: reverse osmosis (RO), electrodialysis (ED), and capacitive deionization technology (CDT). Reverse osmosis and a particular implementation of electrodialysis, electrodialysis reversal (EDR) are the most commonly used technologies for removal of TDS at the concentrations present in the City of Huntsville's effluent. CDT is a newer, up-and-coming technology that has not yet been widely adopted.

For each of the three treatment technologies further evaluated, an estimate of the capital construction cost plus annual operation/maintenance cost was developed using published reports and/or engineering estimation resources.

2.0 REVERSE OSMOSIS

For the reverse osmosis treatment, a treatment train consisting of: twenty-four hour emergency storage followed by ultrafiltration, eight hour storage, carbon filtration, twenty-four hour storage, reverse osmosis, forty hour reject storage, brine concentration, and finally brine crystallization was analyzed.

The emergency storage is required to prevent the release of partially treated effluent in the event of a failure in the system. Intermediate storage allows for equipment maintenance, filter and membrane replacement, and routine scheduled treatment interruptions.

Reverse osmosis utilizes a membrane to filter solutes from solution. Organics, oil and grease, and other particulates must be removed to reduce membrane fouling. To that end, ultrafiltration and carbon filtration are used to prolong membrane life. This also reduces loss of membrane function from chemical attack, which is the result of reactions from chemicals used in cleaning and regenerating a fouled membrane.

In the reverse osmosis step, enough pressure is applied to the untreated water to overcome osmotic pressure and force the water through a membrane. The membrane prevents the passage of solutes, resulting in water with greatly reduced TDS loads. Reverse osmosis membranes are sensitive to scaling and fouling. They can be regenerated to a large degree by cleaning, but as mentioned previously, cleaning chemicals are a source of chemical attack that reduces membrane life. These membranes are also susceptible to creep, performing less efficiently over time as the membrane is slowly deformed by the pressures applied to the system.

In the final steps, the concentrated brine reject solution from reverse osmosis is sent to an evaporator to reduce the volume of water in the reject solution through a vapor-compression process. That process prepares the now extremely concentrated reject for the crystallization step where the brine is heated and swirled in a vortex where some brine evaporates, leading to the formation of crystals. A small stream carries these to a filter press where final dewatering to 20% moisture content results in a filter cake that can then be disposed of.

2.1 Capital Cost Estimate

The total capital cost for reverse osmosis treatment is estimated to be $30.8 million. This includes $13.7 million for pretreatment and RO treatment, $1.25 million for storage tanks, and $15.8 million for the evaporative crystallization system. These costs include permitting, engineering, and site and structural work. These costs were developed using information from GE Power and Water's technical papers and "Perry's Chemical Engineering Handbook" and prices were adjusted using Implicit Price Deflator data from the Federal Reserve Bank of St. Louis.

2.2 Operation/Maintenance Costs

The total annual operating cost associated with reverse osmosis treatment is estimated to be $4.59 million. This includes $250,000 per year for costs associated with filtration, $1.97 million per year for costs involving the reverse osmosis treatment step, $824,000 per year for costs associated with the evaporative crystallization step, and $1.54 million per year for equipment replacement. Included in calculating these costs were: energy usage, labor, maintenance equipment, and disposal of solid salts generated. These costs were likewise developed using information from GE Power and Water's technical papers and "Perry's Chemical Engineering Handbook" and prices were adjusted using Implicit Price Deflator data from the Federal Reserve Bank of St. Louis.

3.0 ELECTRODIALYSIS

For the electrodialysis treatment, a treatment train similar to reverse osmosis is required: twenty-four hour emergency storage, followed by ultrafiltration, eight hour storage, carbon filtration, twenty-four hour storage, electrodialysis, forty hour reject storage, brine concentration, and finally brine crystallization.

The storage components of the treatment train are required for the same reasons discussed for reverse osmosis: to ensure safety in the event of system failure and to allow components to be taken offline for maintenance, cleaning, membrane replacement, etc.

Since electrodialysis is a membrane-based technology, it too requires pretreatment using filtration, for the same reasons as reverse osmosis. One of the main advantages of electrodialysis reversal (EDR) is that due to the nature of the technology, EDR membranes are much less susceptible to fouling and scaling.

Electrodialysis reversal is another membrane-based separation technology that acts on ionic species. With this technology, the feed water is run through a chamber with an electrical potential created by charged electrodes. The chamber is divided into cells by alternatingly charged ion-exchange membranes. Each membrane is highly selective, passing only cations or only anions. Cations are passed to an adjacent cell through the first membrane they encounter as they travel toward the cathode, while anions are passed through to an opposite cell adjacent to that which the feed water originally entered by the first membrane they encounter on their way toward the anode. Each specie, however, is blocked from entering subsequent cells by either an anion-exchange or cation-exchange membrane, respectively. These cells concentrate ions, reducing the TDS of the water fed into the initial cell. In the reversal stage of the process, the polarity of the electrode is reversed, and the diluate cells become concentrate cells. This helps regenerate the membranes, leading a large reduction in scaling and fouling. This also prolongs membrane life by reducing cleaning requirements.

The final steps are the same as for reverse osmosis: the concentrated brine reject solution from electrodialysis is sent to an evaporator to reduce the volume of water in the reject solution through a vapor-compression process. That process prepares the now extremely concentrated reject for the crystallization step where the brine is heated and swirled in a vortex where some brine evaporates, leading to the formation of crystals. A small stream carries these to a filter press where final dewatering to 20% moisture content results in a filter cake that can then be disposed of.

3.1 Capital Cost Estimate

The total capital cost for electrodialysis treatment is estimated to be $22 million. This includes $4.88 million for pretreatment and ED treatment, $1.25 million for storage tanks, and $15.8 million for the evaporative crystallization system. These costs include permitting, engineering, and site and structural work. These costs were developed using information from GE Power and Water's technical papers and "Perry's Chemical Engineering Handbook" and prices were adjusted using Implicit Price Deflator data from the Federal Reserve Bank of St. Louis.

3.2 Operation/Maintenance Costs

The total annual operating cost associated with electrodialysis treatment is estimated to be $2.89 million. This includes $250,000 per year for costs associated with filtration, $268,000 per year for costs involving the electrodialysis treatment step, $824,000 per year for costs associated with the evaporative crystallization step, and $1.54 million per year for equipment replacement. Included in calculating these costs were: energy usage, labor, maintenance equipment, and disposal of solid salts generated. These costs were developed using information from GE Power and Water's technical papers and "Perry's Chemical Engineering Handbook" and prices were adjusted using Implicit Price Deflator data from the Federal Reserve Bank of St. Louis.

4.0 CAPACITIVE DEIONIZATION TECHNOLOGY

Like the previous two technologies, capacitive deionization technology begins with a treatment train that uses twenty-four hour emergency storage, followed by ultrafiltration, eight hour storage, carbon filtration, and twenty-four hour storage. This is followed by the capacitive deionization step and then continues with forty hour reject storage, brine concentration, and finally brine crystallization.

The storage used with this technology serves the same functions discussed in the previous two treatment technologies.

With this technology, feed water is run through carbon-aerogel electrodes, a foam material consisting of countless pores. Organics and other suspended solids must be removed for the system to work properly. The filtration pretreatment steps effectively prepare the water for CDT treatment.

Capacitive deionization technology consists of passing water through carbon-aerogel electrodes, which are kept at a potential difference of about one volt. Ionic species in the water are induced to move toward their respective electrodes, and adsorb to their surfaces. The electrodes are made of a special air-filled foam that exhibits ideal properties for this application due to their high electrical conductivity, high specific surface area, and controllable pore-size distribution. Adsorbed ions are desorbed from the surface of the electrodes by eliminating the charge on the electrodes between treatment cycles. The ions are then flushed from the system in what becomes the reject water. When the treatment cycle begins again, the electrodes' polarity is reversed, further regenerating their capacity and reducing or eliminating scaling. The major drawback is that large volumes of reject water are generated when flushing previously adsorbed ions from the highly porous electrodes.

As with the previous two treatment systems, the concentrated brine reject solution from capacitive deionization is sent to an evaporator to reduce the volume of water in the reject solution through a vapor-compression process. That process prepares the now extremely concentrated reject for the crystallization step where the brine is heated and swirled in a vortex where some brine evaporates, leading to the formation of crystals. A small stream carries these to a filter press where final dewatering to 20% moisture content results in a filter cake that can then be then disposed of.

4.1 Capital Cost Estimate

The total capital cost for capacitive deionization technology treatment is estimated to be $58.5 million. This includes $25.6 million for pretreatment and CDT treatment, $1.25 million for storage tanks, and $31.7 million for the evaporative crystallization system. These costs include permitting, engineering, and site and structural work. These costs were developed using information published in the U.S. Department of the Interior Bureau of Reclamation's "Reclamation: Managing Water in the West" journal and prices were adjusted using Implicit Price Deflator data from the Federal Reserve Bank of St. Louis.

4.2 Operation/Maintenance Costs

The total annual operating cost associated with capacitive deionization technology treatment is estimated to be $4.42 million. This includes $250,000 per year for costs associated with filtration, $983,000 per year for costs involving the capacitive deionization technology treatment step, $1.65 million per year for costs associated with the evaporative crystallization step, and $1.54 million per year for equipment replacement. Included in calculating these costs were: energy usage, labor, maintenance equipment, and disposal of solid salts generated. These costs were developed using information published in the U.S. Department of the Interior Bureau of Reclamation's "Reclamation: Managing Water in the West" journal and prices were adjusted using Implicit Price Deflator data from the Federal Reserve Bank of St. Louis.

5.0 SUMMARY & CONCLUSION

A supplemental review of treatment alternatives for dissolved minerals removal from water and wastewater was undertaken at the request of the Arkansas Pollution Control and Ecology Commission. This review identified a number of articles describing treatment methods (Appendix B). However, only technologies demonstrated to perform at the full scale flow and loading of the City of Huntsville's wastewater treatment facility were considered for evaluation. Consideration of experimental or academic technologies not yet proven would be speculative and contrary to accepted engineering practices.

The costs associated with the three technologies reviewed are summarized in Table 1 below. Each of the treatment technologies reviewed are technically viable options for reducing TDS, however, the estimated costs for each technology are not feasible for the City.

These costs would jeopardize the continued operation of the Butterball Facility, the largest employer in Madison County. The consequence of the loss of the Butterball Facility would likely prove to be disastrous for the City of Huntsville, Madison County and the surrounding northwest Arkansas community. This region relies heavily on the economic impact of the Butterball facility. The facility employs almost 700 citizens and provides them an annual payroll of more than $22,000,000. It also acts as a critical client/customer to a number of local businesses and pays more than $138,000 in local property taxes.

Table 1. Associated costs for each of the three treatment technologies reviewed.

Treatment Technology	Capital Cost (Million $)	Annual O/M Cost (Million $)
Reverse Osmosis	30.1	4.6
Electrodialysis	22.0	2.9
CDT	58.5	4.4

6.0 SOURCES

Apte Sagar. S., Apte Shruti S., Kore, V. S., Kore, S. V. “Chloride Removal from Wastewater by Biosorption with the Plant Biomass”. Universal Journal of Environmental Research and Technology Volume 1, Issue 4: 416-422. (2011). 7 Oct 2013.

Desalination.com. GWA, 2013. Web. 7 Oct 2013.

“DOWEX Ion Exchange Resins: Water Conditioning Manual.” Dow Water Solutions. n.d. Web. 7 Oct 2013.

Drewes, J.E., Xu, Pei, Wang, Gary. "Multibeneficial use of produced water through high-pressure treatment and capacitive deionization technology." Reclamation: Managing Water in the West. Program Report No. 133 (2009). Print.

“Evaporation & Reverse Osmosis Reject: Using Evaporation to Dewater Reverse Osmosis Reject Waste Streams.” ENCON Evaporators. n.d. Web. 7 Oct 2013.

Federal Reserve Bank of St. Louis. *FRED Economic Data*. Web. 7 Oct 2013.

Jacobson, Kyle S., Drew David M., He Zhen. “Efficient salt removal in a continuously operated upflow microbial desalination cell with an air cathode”. Bioresource Technology, Volume 102, Issue 1, Pages 376-380. (2011). Print.

Kameda, T., Miyano, Y., Yoshioka, T., Uchida M., Okuwaki, A. “New Treatment Methods for Waste Water Containing Chloride Ion Using Magnesium–Aluminum Oxide” Chemistry Letters 2000, Chemical Society of Japan. 1136-1137. (2000). Web. 7 Oct 2013.

“Multi Stage Flash Desalination Plant System.” Weir Power and Industrial. n.d. Web. 7 Oct 2013.

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Nkwonta, O.I., Ochieng, G.M. “Total Dissolved Solids Removal in Wastewater Using Roughing Filters”. Chemical Sciences Journal, Volume 2010: 1-6. (2010). Web.

Perry, Robert H. and Green, Don W. *Perry’s Chemical Engineering Handbook*. 7th ed. New York: McGraw Hill, 1997. Print.

Pelckmans, Jan-Tiest, Püntener Alois. “Reduction of the Salt Freight in Tannery Effluent”. TFL Leather Technology Ltd. Web. 7 Oct 2013.

“Power Purge Deioinization Systems High Efficiency DI.” Remco Engineering. n.d. Web. 7 Oct 2013.

Water Treatment Solutions. Lenntech, 2013. Web. 7 Oct 2013.

Yu, J.T., Lue, S.J. “Desalination of high NaCl wastewater using electrodialysis”. Department of Chemical and Materials Engineering, Chang Gung University. Web. 7 Oct 2013.

Appendix A

Cost Calculations

1.0 REVERSE OSMOSIS CALCULATIONS (PERRY'S CHEMICAL ENGINEERING HANDBOOK)

Reverse Osmosis and Pretreatment Costs

FROM PERRY'S P.22-52			Implicit Price Deflator			
6 MGD 38 g/l 45% conversion 6 train system			1996	83.159	1995	92.103
NEED 1.25 MGD, 3.4 g/l 95% conversion			2006	103.231	2012Q4	114.46
assume 1 train system, 35% of cost	1996	0.35	inflation adj			
	base	adj	2006	2012Q4		
ITEM	$000	$000	$000			
UF+ Carbon filter			3000			
Membranes+housings installed	3600	$1,260	$1,564.12	$2,152.86		
process equip	13700	$4,795	$5,952.36	$8,192.83		
site work	500	$175	$217.24	$299.01		
structural	1850	$648	$803.79	$1,106.33		
permitting	25	$9	$10.86	$14.95		
Engr	3341	$1,169	$1,451.59	$1,997.97		
TOT CAP		$8,056	**$13,000**	**$13,764**		
OPERATING						
elec	1976.875	$692	$858.91	$1,182.20		
consum+chem	187	$65	$81.25	$111.83		
Maint	482	$169	$209.42	$288.24		
labor	265	$93	$115.14	$158.47		
membrane repl	390	$137	$169.45	$233.23		
TOT OP		$1,155	**$1,434**	**$1,974**		

Reject Treatment

RO REJECT TREATMENT				
Per Bill Heinz, VP GE Treatment 425-828-2400x1330				
Trt train consists of (2) 250 GPM Brine Concentrator, then (1) 20 GPM Crystallizer				
includes solids conveyor		0.6	Butterball assume half capacity, 60% of cost	
	2006			2012Q4
CAPITAL	$ (000)			
Brine Conc.	$9,100	$5,460		$6,053.91
Crystallizer	$4,900	$2,940		$3,259.80
Installation	$9,800	$5,880		$6,519.60
TOTAL	$23,800	$14,280		$15,833

Total RO Costs

CAPITAL	TOTAL ($000)
UF+Carbon+RO	$13,764
Storage tanks	$1,250
Evaporative crystallization system	$15,833
TOTAL CAPITAL	**$30,847**
ANNUAL OPERATING	TOTAL ($000)
Filtration	$250
RO	$1,974
CRYSTALLIZATION	$824
EQUIP REPLACEMENT	$1,542
TOTAL OPERATING	**$4,590**

2.0 ELECTRODIALYSIS CALCULATIONS (PERRY'S CHEMICAL ENGINEERING HANDBOOK)

ED Step Operating Costs (in 1993 dollars)
1 MGD = 3823.036 m^3/day
Basis: 1000 m^3 product water

$66	Membrane-replacement cost (assuming seven-year life)
32	Plant power
16	Filters and pretreatment chemicals
11	Labor
8	Maintenance
133	Total

Convert ED step per 1000 m^3 to annual operating costs (1993 Dollars)

$$1\ MGD * \frac{3785.184\ \frac{m^3}{day}}{1\ MGD} * \frac{\$133}{1000\ m^3} * \frac{365\ days}{1\ year} = \$183751.76$$

Covert ED step Operating Costs in 1993 dollars to 2013 dollars

$$\$183751.76 \div \frac{\$79.28}{\$115.51} = \$267724.08$$

Convert UF + Carbon Filter Capital Costs from 2006 dollars to 2013 dollars

$$\$3000000 \div \frac{\$103.23}{\$115.51} = \$3356834$$

ED Capital Costs from Perry's: given typical plant at 4700 m^3/day built in 1993 capital costs were $1210000 these costs scale by the 0.7 power. Covert to 1 MGD (3785.184 m^3/day).

$$\$1210000 * \left(\frac{3785.184\ m^3/day}{4700\ m^3/day}\right)^{0.7} = \$1039866.93$$

Covert ED Capital Costs from 1993 to 2013 dollars

$$\$\mathbf{1039866.93} \div \frac{\$\mathbf{79.28}}{\$\mathbf{115.51}} = \$\mathbf{1515059}$$

According to literature, the reject from ED is similar to RO, so use same process separate water and salts. Pretreatment uses the same process as the other technologies.

Total ED Costs

CAPITAL	**TOTAL ($000)**
UF+Carbon+Electrodialysis	$4,871
Storage tanks	$1,250
Evaporative crystallization system	$15,833
TOTAL CAPITAL	**$21,954**
ANNUAL OPERATING	TOTAL ($000)
Filtration	$250
RO	$268
CRYSTALLIZATION	$824
EQUIP REPLACEMENT	$1,542
TOTAL OPERATING	**$2,884**

3.0 Capacitive Deionization Technology Calculations (Reclamation: Managing Water in the West. Program Report No. 133)

Basis

Plant life		20 years
Interest rate		10%
Capacity	Product	1.0 MGD
Capital	Including initial module cost plus supporting equipment	$1000/module
Module replacement	10 year module lifetime	$770/module
Energy cost	Purchased from off-site	$0.06/kwh

Annual Costs Given

Initial Capital ($ per year)	Replace modules ($ per year)	Labor ($ per year)	Energy ($ per year)	Total costs ($ per year)	Total costs ($ per 1000 gallons product)
2612044	868406	38400	76650	3595500	

Convert UF + Carbon Filter Capital Costs from 2006 dollars to 2013 dollars

$$\$3000000 \div \frac{\$103.23}{\$115.51} = \$3356834$$

CDT step Capital Costs Series Present Worth (P/A, *i*, n)

$$P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]$$

$$P = \$2612044\left[\frac{(1+0.1)^{20} - 1}{0.1(1+0.1)^{20}}\right] = \$\ 22{,}237{,}803.03$$

Reject Treatment

Reject flow at 33% water recovery. Reject 0.667 MGD
Using same process as RO to treat reject, scale up processes.
Determine number of 250 gpm brine concentrators needed

$$\frac{666667 gal}{day} * \frac{1\ day}{24\ hr} * \frac{1\ hr}{60\ min} * \frac{1\ concentrator}{250\ gpm} = 1.85$$

Double RO reject capital and operating costs

Total CDT Costs

CAPITAL	TOTAL ($000)
UF+Carbon+RO	$25,595
Storage tanks	$1,250
Evaporative crystallization system	$31,667
TOTAL CAPITAL	**$58,511**
ANNUAL OPERATING	TOTAL ($000)
Filtration	$250
CDT	$983
CRYSTALLIZATION	$1,648
EQUIP REPLACEMENT	$1,542
TOTAL OPERATING	**$4,424**

Appendix B

City of Huntsville Research Information

City of Huntsville Research Information

Desalination System Targets Fracking Wastewater
http://www.treehugger.com/clean-technology/new-low-cost-desalination-system-targets-fracking-wastewater.html

Different Applied Methods - to Reduce Salt Freight in Tannery Effluent
http://www.tfl.com/web/files/reductionsaltfreighttanneryeffluent.pdf

Desalination of high NaCl wastewater using electro dialysis
http://research.cgu.edu.tw/ezfiles/14/1014/img/651/98-B-32.pdf

Efficient Salt removal in a continuously operated upflow microbial desalination cell with an air cathode
https://pantherfile.uwm.edu/zhenhe/www/papers/Efficient%20salt%20removal%20in%20a%20continuously%20operated%20UMDC.pdf

Chloride Removal from Wastewater by Biosorption with the Plant Biomass
http://www.environmentaljournal.org/1-4/ujert-1-4-4.pdf

New Treatment Methods for Waste Water Containing Chloride Ion Using Magnesium-Aluminum Oxide
http://ir.library.tohoku.ac.jp/re/bitstream/10097/51573/1/29_1136.pdf

Dealkalization By Anion Exchange
http://www.resintech.com/Uploads/resintech/Documents/TDS/Dealkalization%20by%20Anion%20Exchange.pdf

Deionization Systems High Efficiency DI - http://www.remco.com/di.htm
Reverse Osmosis and Utlrafiltration Systems - http://www.remco.com/di.htm

Helpful Document -
http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0885/0901b80380885879.pdf?filepath=liquidseps/pdfs/noreg/177-01766.pdf&fromPage=GetDoc

ECON MVC Evaporator - http://www.evaporator.com/reverse-osmosis-reject

Continuous microfiltration pretreatment to reverse osmosis
http://www.sciencedirect.com/science/article/pii/S001191640100248X

MCDI System – Desalination of a thermal power plant wastewater by membrane capacitive deionization
http://www.sciencedirect.com/science/article/pii/S0011916406004279

TDS Removal using Roughing Filters
http://astonjournals.com/manuscripts/Vol2010/CSJ-6_Vol2010.pdf

Removal of TDS and BOD via Adsorption
http://www.ipcbee.com/vol41/034-ICEBB2012-R034.pdf

Extraction by electodialysis study on TDS removal
http://www.lenntech.com/abstracts/2717/study-on-tds-removal-from-polymer-flooding-wastewater-in-crude-oil-extraction.html

Solar-heated hollow fiber membrane distillation system
http://www.lenntech.com/abstracts/78/feasibility-research-of-potable-water-production-via-solar-heated-hollow-fiber-membrane-distillation.html

www.lenntech.com has an excellent database of scholarly articles related to this research
www.desalination.com is another related website that could be useful