Energy usage comparison between activated sludge treatment and rotating biological contactor treatment of municipal wastewater

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Abstract

Attached growth wastewater treatment processes have long been recognized as more energy efficient than suspended growth processes. The rotating biological contactor (RBC) attached growth process has been promoted as being nearly twice as efficient as the most common suspended growth process - activated sludge (AS). However, there is very little, recent information in the literature confirming this assertion through actual field data. This paper presents field data from two similar municipal wastewater treatment plants, with the exception of the secondary treatment process, which in one case is AS and the other is an air-driven (no longer made) RBC.

Both plants are located near Grand Rapids, Michigan, have similar discharge permit limits, treat similar flows and are well operated. The information from these plants was supplemented by data from a third plant a mechanically-driven (as is the case for all currently manufactured RBCs) RBC facility in Grosse Ile, Michigan, and published information.

The results of this study show that the air driven RBC process is an approximately 30% more energy efficient process than AS and the mechanically driven RBC is more than 50% more efficient. In addition, the labor requirements of the RBC facilities were found to be significantly less than for AS, primarily because of the need for additional process monitoring and management for the AS process.

Keywords: Energy, wastewater treatment, rotating biological contactor, RBC, activated sludge, AS,

INTRODUCTION

Background

Water and wastewater systems are estimated to consume over 4% of the United States' electrical energy.[1] Wastewater treatment alone is estimated to consume 1.5% of the nation's electrical power[2], or approximately 60 tWh (terawatt hours) per year.

In municipal wastewater treatment, the largest proportion of energy is used in biological treatment, generally in the range of 30% to 60% of plant usage. Using a mid-range percentage of 40%, secondary treatment in the United States consumes approximately 24 tWh per year of electrical energy, or over 2.7 gW of generating capacity, which is the equivalent output of over 5 average size coal fired power plants.

A 2008 estimate of coal fired power plant construction cost was found to be approximately $3,500 per kW.[3] Thus, the current value of the capital needed to supply power for wastewater treatment in the United States is approximately $9.45 billion. Based on this information, energy efficiency in the biological portion of the wastewater treatment process can result in valuable avoided cost savings for the country, as well as reduced energy costs for the plant owner.

Further, the cost of energy is likely to increase more rapidly than inflation because of 1) the expected future difficulties in finding and recovering new energy sources, 2) the high cost of alternative energy sources, 3) the difficulties in siting new power plants, and 4) the expected future higher cost of meeting air emission standards at power plants. For this reason, the energy efficiency of the alternative biological processes becomes more important with time to designers and owners in selecting a treatment process.

Alternative Biological Treatment Processes

Biological treatment can be accomplished by growing microorganisms on a fixed media (attached growth process), or in suspension in the wastewater (suspended growth process), or by a process combining these two approaches.

Attached Growth Processes

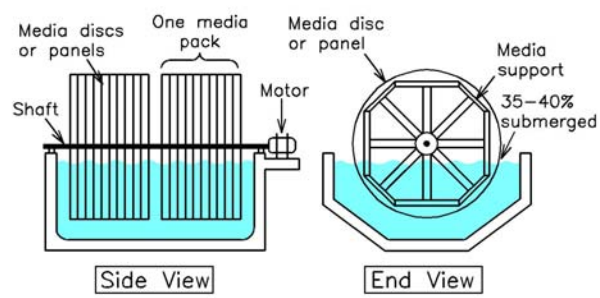
The earliest and most common attached growth process is the trickling filter process. It uses a bed of either rock or synthetic media over which the wastewater is distributed. The wastewater flowing downward through the media provides the nutrients for the growth of microorganisms that attach to the media. The microorganisms metabolize the organic pollutants in the wastewater, removing them from the wastewater, creating cell mass.

A later attached growth process development was the rotating biological contactor (RBC) developed in Germany in the 1960s. RBCs are an attached growth, aerobic, biological wastewater treatment system. Physically, they consist of a plurality of parallel, deformed discs mounted perpendicularly on a shaft that is slowly rotated in a tank through which the wastewater to be treated is passed. The shaft is mounted just above the water level in the tank, submerging approximately 40% of the media.

The shafts are rotated through the water using one of two methods of propulsion. The first, most common, is the use of an electrical motor, operating through a drive system. This is the only currently available system of propulsion.

A proprietary air-drive system was once also available. This system consisted of a blower that bubbled air into the RBC tank below the RBC and off center. The perimeter of the discs contained cups that captured the rising air bubbles. The captured air caused increased buoyancy on one side of the discs, with the result that the discs rotated.

A schematic drawing of a mechanically-driven RBC follows.



Simplified Schematic of Rotating Biological Contractor

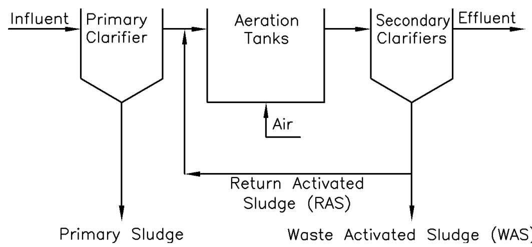
Municipal scale RBCs typically are mounted in concrete tanks as shown in the following photo:

During the treatment process, microbes that remove the organic material in the wastewater (by using the organic material as a food source) attach themselves to the disc surfaces. They grow in a thin biofilm, whose thickness is controlled by the shearing force of the discs being rotated through the water. By rotating out of the water into the atmosphere, the microorganisms, growing on the disc, are provided oxygen. The surplus microorganisms that are sheared off the discs are carried with the wastewater to clarifiers where they are separated from the treated wastewater.

RBCs were originally promoted as a simple, operator-friendly process, requiring even lower energy than the oxidation tower or trickling filter process.

Suspended Growth Process

By contrast, the most common suspended growth system is the activated sludge process (AS). In this process the wastewater is introduced to a vessel that has air bubbled into it. The rising air bubbles provide mixing to suspend microorganisms and oxygen for their respiration. The resulting mixture of microorganisms and wastewater are sent to a clarifier where the microorganisms are settled out and returned to the aeration vessel to increase the concentration of microorganisms. Once the desired concentration of microorganisms is reached surplus microorganisms are wasted from the system. A schematic of the process follows:



Simplified Schematic of Activated Sludge Process

Suspended growth processes generally allow more operator intervention and process flexibility than attached growth processes. This flexibility comes with a cost of process monitoring and control. Suspended growth processes are also generally acknowledged to require more energy than attached growth processes.

Biological Treatment Power Consumption Studies

The Electrical Power Research Institute (EPRI) has studied power usage for trickling filter wastewater treatment plants and activated sludge wastewater treatment plants. They found that trickling filter plants consume approximately 70% of the electricity consumed by activated sludge plants. [4]

Membrane reactor plants (an increasingly popular variation of the activated sludge process that uses membranes to separate the microorganisms from the wastewater rather than clarifiers) have been found to consume 150% to 300% of the electricity of a conventional activated sludge plant[5].

EPRI found that median energy usage for activated sludge plants is 1,322 kWh per million gallons treated and 955 kWh per million gallons treated for trickling filter plants. (Science Applications International Corp. did a study for the State of Wisconsin that found 1 to 5 mgd activated sludge plants use approximately 2,500 kWh per million gallons, with 54.6%, or over 1,300 kWh per million gallons, consumed in the activated sludge process.[6])

The previously cited Science Applications International Wisconsin study also found that, in contrast with the average plant surveyed, the most energy efficient quartile of activated sludge plants in the 1 to 5 mgd range could be expected to require 1510 kWh per million gallons treated.[7] So a reasonable approximation of the energy consumption of the biological treatment portion of a well operated activated sludge plant would be expected to be approximately 800 kWh per million gallons treated.

A prior study of twenty-two RBC plants reported in 1986[8] found that mechanically-driven 12 foot diameter by 25 foot long shafts used 2 kW per shaft on average and that air-driven units (no longer available) of the same size used approximately 5 kW per shaft. Although, no information was given as to the amount of hydraulic or organic load being treated.

Common design practice has been to size the typical, nominally 12 foot diameter by 25 foot long RBC shafts to treat approximately 150,000 gpd per shaft for mechanical drive units and 200,000 gpd per shaft for air driven units of domestic wastewater following primary clarification. Using this information, mechanically-driven RBCs would be expected to require 336 kWh per million gallons treated and air-driven RBCs 490 kWh per million gallons treated.

A 2004 study[9], evaluated the effect of organic loading on efficiency of RBCs and concluded that an effluent BOD of less than or equal to 25 mg/l could be achieved with a BOD loading of 0.0043 pounds of BOD per square foot per day. With a domestic wastewater containing 250 mg/l of BOD and 30% of that removed in primary clarification, this would translate to an hydraulic loading of close to 300,000 gpd per shaft.

Commonly, the peak day influent BOD loading is found to be approximately 2.5 times the average. Therefore, the design loading based on this study would be 0.0017 pounds of BOD per square foot per day, or 120,000 gallons per day per shaft having 100,000 square feet of surface area, using the previously assumed 250 mg/l BOD influent wastewater.

Benchmarking

Both the Austrian Association for Water and Waste and the German energy manual, MURL, use 23 kWh/yr – pe (population equivalent) as benchmarks for domestic wastewater treatment.

At 23 kWh per year per pe and assuming 70 gallons per day per pe, the Austrian/German benchmark is 38 kW/mgd of capacity. Assuming that the Wisconsin study finding of approximately 55% of AS plant power is required for the AS process, the AS process benchmark could be as low as 21 kWh/mgd of capacity.

In a Swedish study[10], Swedish wastewater plants were found to use 42 kWh/yr – pe and extrapolating from the data in this study a well operated, larger Swedish wastewater plant uses approximately 27 kW/mgd for the AS portion of the process. This higher usage than the benchmark in Germany and Austria was attributed to the fact that the Austrians and Germans have carried out benchmarking programs for many years and that Swedish wastewater is more dilute (approximately 175 mg/1 BOD versus 290 mg/1 in Austria). It also highlights the aggressive nature of the Austrian/German benchmarking goals.

The Austrian benchmarking program has been reported to result in a 30% reduction in energy usage, indicating that on a per capita basis the Austrian plants were more efficient than the Swedish plants even before undertaking benchmarking.

The Science Applications' Wisconsin study also suggested a best practices benchmark for plants of 1 to 5 mgd of capacity of 1,650 kWh per million gallons. Using the reports 54.6% of energy consumed in the activated sludge process, an approximation of a benchmark for the activated sludge process at 900 kWh per million gallons could be made.

STUDY OBJECTIVES AND METHODOLOGY

Objectives

The primary objective of this paper is to field verify energy consumption at two similarly located and sized wastewater treatment plants meeting similar discharge criteria. One of these plants is using the activated sludge process and the other the RBC process. This data will be used to support or refine the previously reported energy consumption of RBCs and activated sludge plants relative to the quantity of wastewater and organic load treated.

There are also purportedly other differences between the two processes, relating to sludge production and labor. A secondary objective of this study is to obtain information on these issues.

Methodology

Two wastewater treatment plants with similar discharge permits, similar design capacities, treating similar wastewater, located in the same geographic area were chosen to make this comparison.

The study methodology used was to gather basic information regarding the plants:

1. Plant description.
2. NPDES effluent permit limits.
3. Monthly average flow and load data.
4. Monthly average load data to secondary treatment.
5. Monthly average secondary effluent data.
6. Monthly plant electrical usage.
7. Monthly plant natural gas usage.
8. Quantity and quality of sludge produced.
9. Motor running time information, if available.
10. Identify non-motor electrical and natural gas loads.
11. Identify secondary process staffing needs.
12. Identify laboratory analyses for process control and monitoring.

After assembling and evaluating the above information, on-site observations and plant staff interviews were conducted with the following objectives.

1. Determine how to estimate secondary energy usage.
2. Determine how to estimate other plant systems energy usage.
3. Interview staff regarding energy conservation measures recently implemented or planned.
4. Spot check electrical consumption with an amprobe.

The final phase of this study was data analysis:

1. Compile flow, load, electrical usage, estimated secondary treatment electrical usage, and natural gas usage for both plants by month.
2. If appropriate, evaluate statistical correlation of flow and load to energy usage by plant.

3. If appropriate, evaluate correlation of energy usage and seasonality by plant.
4. Additional observations regarding plant operations related to secondary process selection.

RESULTS AND DISCUSSION

Allendale, Michigan WWTP (Air Driven RBCs)

The Allendale WWTP has a design capacity of 1.6 mgd. It is treating primarily domestic wastewater, with the largest customer being Grand Valley State University. It is required to meet secondary treatment limits. The plant must produce an effluent containing less than 25 mg/l of CBOD, less than 30 mg/l of TSS and less than 1 mg/l of phosphorus on a monthly average basis.

The average daily flow during 2010 was 1 mgd, with monthly averages ranging from 0.75 mgd to 1.5 mgd, with the highest flows occurring when the University was in session.

The influent wastewater is screened and degritted prior to settling in four primary clarifiers, each with a surface area of approximately 672 square feet. The average design overflow rate is approximately 600 gpd per square foot. The design primary effluent/secondary influent BOD is 175 mg/1, while the actual 2010 data averaged approximately 125 mg/1. The plant design influent wastewater BOD concentration was 250 mg/l and the 2010 influent sewage BOD averaged approximately 261 mg/l.

Secondary treatment is provided by eight, air-driven, rotating biological contactors. The contactors are operated in pairs, in series, and each shaft is approximately 24 feet long and 12 feet in diameter.

The first stage shafts have approximately 100,000 square feet of media surface area and the second stage shafts have a media surface of approximately 150,000 square feet. Design loadings are 0.0023 pounds BOD per day per square foot, a first stage loading of 0.0058 pounds of BOD per day per square foot, and an hydraulic loading of 1.6 gpd per square foot.

Two, 55 foot diameter secondary clarifiers follow the RBCs, providing a surface overflow rate of approximately 340 gpd per square foot at design average flow. The secondary effluent is chlorinated, and then dechlorinated in a two million gallon pond, providing approximately 30 hours of detention, before discharging to the Grand River.

The plant also has a parallel, partially aerated lagoon system to treat a segregated industrial waste.

Excess biosolids are disposed of in a sludge lagoon.

The Allendale WWTP is operated to maximize treatment and all eight RBCs are operated year round. This requires the operation of two, 25 horsepower blowers. The secondary effluent BOD averaged 12 mg/1 during 2010.

The plant consumed approximately 100,000 cubic feet of natural gas per month (ranging from approximately 5,000 to nearly 300,000 cubic feet per month) during the year and 68,800 kWh per month of electrical energy (ranging from approximately 62,000 to 81,000 kWh per month), or 2,260 kWh per million gallons treated. This data was obtained from plant meter readings and for the electrical power the plant power factor is equal to 0.94.

The relatively high amount of natural gas used is a reflection of the fact that the plant does not have anaerobic digesters with digester gas recovery. The plant is in the process of adding anaerobic digestion and natural gas consumption is anticipated to decline dramatically once this process is implemented. The high overall kilowatt usage is because of the partially aerated lagoons used to treat a segregated industrial waste (cheese plant) and the fact that the plant was operated to maximize effluent quality by operating all RBCs.

The RBCs consumed approximately 173,000 kWh during the year, based on amp draw readings of the blower motors and a nominal power factor correction for the motors of 80.5%. Since the RBCs were run as if the plant was treating its design load, the power consumption for the RBCs would have been 510 kWh per million gallons, or 350 kWh per 1,000 pounds of BOD applied. This energy consumption confirms the previous literature value of 500 kWh per million gallons treated for air-driven RBCs.

The nameplate horsepower associated with the secondary treatment process at Allendale is just over 75 horsepower (50 horsepower of firm capacity), or 47 horsepower per million gallons per day of treatment capacity.

Statistical analyses of the correlation of plant power consumption to influent flow, load, or temperature is not appropriate, since the plant is operated throughout the year to maximize treatment with all RBC shafts online, all of the time.

Grosse Ile Township, Michigan WWTP (Mechanically Driven RBCs)

Electric motor driven RBCs consume approximately 300 kWh per million gallons treated according to the literature, or 2 kW per shaft. As part of this study we had amp draw readings taken at the Grosse Ile WWTP, which revealed a typical power consumption of 2 kW per shaft (with 10 shafts treating 2.25 mgd) or well under 300 kWh per million gallons treated. This confirms the previously reported literature value.

The Grosse Ile plant treats a very dilute wastewater and thus the organic loadings are so low as to make comparison of energy usage to organic load meaningless for the purposes of this study. However, if the influent wastewater contained 250 mg/l of BOD, as a typical domestic wastewater would, and primary clarification reduced this by 30%, the design loading to the RBCs would be 0.0033 pounds of BOD per day per square foot of media surface area. Using the design charts in the Walker Process EnviroDisc brochure[11], this loading may be expected to produce an effluent meeting "secondary treatment" levels.

Lowell, Michigan WWTP (Extended Aeration Activated Sludge)

The Lowell WWTP has a design capacity of 1.42 mgd average daily flow. It treats primarily domestic wastewater. The plant must meet secondary treatment limits - monthly effluent limits of 25 mg/1 CBOD, 30 mg/1 of TSS, and total phosphorus of 1 mg/1.

The average annual flow rate for 2010 was 1.2 mgd, with a monthly range of 1.1 to 1.5 mgd.

The raw wastewater is screened and degritted prior to being treated in the activated sludge system, consisting of a pair of oxidation ditches, with each ditch having a capacity of approximately 720,000 gallons. The oxidation ditches are aerated and mixed using two, 40 horsepower, brush style aerators in each basin. Return activated sludge pumping is accomplished using two Archimedes screw pumps with 10 horsepower motors.

The oxidation ditches are followed by two, 50 foot diameter final clarifiers, with an approximately 360 gallon per day per square foot overflow rate at design flow. The effluent is disinfected before discharging to the Flat River at its confluence with the Grand River.

The Lowell WWTP is operated to minimize energy usage to some extent. The oxidation ditches do not have dissolved oxygen control, but the operator has found, through experience, that operating the aerators at less than full immersion and operating the second aerator in each ditch for 30 minutes on and 30 minutes off will produce the desired results.

The design secondary process influent BOD is 217 mg/1, while the actual 2010 average BOD was nearly 200 mg/1.

The plant consumed approximately 27,000 cubic feet of natural gas per month during the year(ranging from approximately 400 to 83,000 cubic feet per month). The plant electrical consumption averaged 57,700 kWh per month (ranging from approximately 52,000 to 69,000 kWh per month) or 1,553 kWh per million gallons treated. This data was obtained from plant meter readings. In the case of electrical power, the plant power factor is equal to 0.68.

The activated sludge system consumed approximately 390,000 kWh during the year, based on amp draw readings of the aeration rotor and RAS motors and a nameplate power factor correction for the motors of 87.5%.

Since the plant was operated to minimize power consumption, and influent flows and loads were at design levels for extended periods, and effluent limits were met, the power consumption for the activated sludge system per million gallons was 750 kWh per million gallons of design capacity, and just over 545 kWh per 1,000 pounds of BOD removed.

These are relatively low numbers compared to average reported values in other studies. It is believed that this finding is because of the efficiency of the brush aerators, when compared to the more commonly used coarse bubble diffusion system used in activated sludge plants of this size and the operator's attention to minimizing power consumption.

From a design perspective, the Lowell plant has just over 180 nameplate horsepower (130 horsepower of firm capacity) associated with its secondary treatment process, or 125 nameplate horsepower per mgd of capacity.

With regard to anticipated future energy saving projects affecting the plant, Lowell is considering sending its biosolids to a community digester that will also use agricultural and manufacturing waste to generate electricity and heat.

Statistical correlation of plant power consumption to influent flow, organic load, or temperature was not attempted since power usage in the most energy intensive process, AS, did not vary throughout the year.

Plant Labor Related to Secondary Process

Secondary treatment processes require daily observation, routine maintenance, and process control testing and adjustment. This issue was studied by the United States Environmental Protection Agency and the results were published by the Office of Research and Development in "Treatability Manual – EPA-600/8-80-042d". In this study, it was estimated that a plant treating approximately 2.5 mgd using an RBC process would use less than one-half the labor required by a conventional activated sludge plant using mechanical aeration and approximately one fifth for plants treating 25 mgd.

Based on the field evaluations of the plants in this study, a better estimate of the difference in labor hours between an approximately 1 mgd activated sludge plant and a similarly sized RBC can be made.

This was done by interviewing the plant operators.

The Allendale and Grosse Ile plants employ RBCs and the plant staffs daily inspect the rotating biological contactor equipment. This consists of an approximately 15 minute visual inspection, or 65 hours per year. No separate laboratory analyses are conducted for process control at either facility. However, process monitoring requires laboratory testing for influent and effluent BOD. This is estimated to require 250 hours per year. Routine maintenance consists of motor and gearbox maintenance. Annual routine labor requirements for maintenance of the RBC portion of these plants are estimated by the plant superintendents to be on the order of 55 to 70 hours per year. Therefore, the estimated annual routine labor associated with the RBC process is 370 hours per year.

The Lowell activated sludge plant staff daily inspects its aeration and return sludge equipment, including flow metering. This is an approximately 10 minute inspection, or approximately 43 hours per year. Process control sampling and analysis consists of every other day testing of BOD (influent and effluent), SVI, DO (mixed liquor), pH, MLSS, MLVSS, RAS SS and RAS VSS. This testing and the process control analysis are estimated to require approximately 8 to 10 hours per week, or up to 520 hours per year. Annual routine maintenance of the activated sludge process equipment is estimated to be 18 hours per year. Therefore, the estimated annual routine labor associated with the activated sludge process is approximately 580 hours per year.

The RBC process requires significantly less process sampling and analysis than the activated sludge process. This is the primary reason for RBC plants requiring less labor. For the plants in this study, operating in the range of 1 to 2.25 mgd, the annual savings in labor is estimated to be on the order of 200 hours per year.

Solids Generated

None of the plants in this study had sufficiently accurate means of measuring waste sludge volumes and concentrations to allow meaningful conclusions to be drawn. However, the literature frequently cites sludge yields for trickling filters that are approximately 10% less than those for activated sludge.

Also, it is well known in the industry that attached growth sloughings settle more readily than AS mixed liquor solids. This is reflected in the higher allowable final clarifier loading rates for attached growth processes in the Ten State Standards[12] (1,200 gpd per square foot (48.9 m3/m2-d) for attached growth (attached growth) processes and 800 to 1,200 gpd per square foot (32.6 to 48.9 m3/m2-d) for activated sludge processes, depending on process variation).

CONCLUSIONS

Power usage by attached growth plants has frequently been reported to be significantly less than suspended growth plants. The RBC variation of the attached growth process has been reported to require approximately 50% of the energy of the activated sludge process.

There are several ways to look at the power issue, supplemented by the field investigations conducted for this study, to assess the validity of this assumption and to quantify the difference in energy consumption.

The first approach is to simply look at the firm, connected power as a representation of the actual power that is needed to operate the process at design flows and loads. This overlooks actual power usage patterns and is too simplistic to be other than an indicator.

The second approach is to look at actual power usage in operating plants. This approach is useful after adjustment for site specific information, such as operator preferences, flow and load variability, and process control capability. However, this information, after adjustment, can provide useful data that considers the actual process power usage in a real-life situation where flows and loads change throughout the day and from day to day.

Literature data gathered from operating facilities is also valuable in supplementing the data gathered from a limited number of plants, as in this case. It is also valuable in providing a check on the data obtained in this study.

Benchmarking studies have found that average actual usage is often significantly higher than might be achieved with optimized energy control. This information provides a floor for energy consumption by process. However, it does not consider such things as process reliability, the risk of non-attainment of effluent limits, or safety factor.

The following table summarizes the findings in each of these ways of viewing the power usage question.

Table 1
Secondary Treatment Process Power

kW per mgd[1] (kW/m3-d)				
Process	Firm, Connected Power	Measured Power	Literature Power	Benchmark Power
RBC-Air[2]	32 (0.008)	22 (0.006)	25 (0.007)	n/a
AS[3]	92 (0.024)	31 (0.008)	54[5] (0.014)	21 – 38[5]
RBC Mech[4]	20 (0.005)	11 (0.003)	13 (0.003)	n/a

[1] Design capacity
[2] Allendale, Michigan
[3] Lowell, Michigan – extended aeration
[4] Grosse Ile, Michigan
[5] Conventional activated sludge

From this information, it can be clearly seen that RBCs can use significantly less power than the activated sludge process.

There is an important caveat to these findings, though, and that is that at less than design flows and loads AS plants are generally more able to reduce power to a point at which the process is mixing limited. Also, the AS process can be controlled by mixed liquor dissolved oxygen, allowing energy consumption to be reduced during periods of low loading. RBCs do not offer this flexibility, except to accommodate lower loadings that are expected to last for long periods of time by removing shafts from service. All this being said, even the most aggressive benchmarking, which takes advantage of these process control possibilities for the AS process does not result in a reduction that approaches the energy consumption of RBCs.

Based on these findings, a reasonable approximation of the energy usage of RBC treatment is one half of AS treatment. With the biological portion of the wastewater treatment process requiring an estimated 24 tWh of electrical energy per year in the United States, the potential for very large energy savings through the increased use of RBCs is evident.

The labor required to operate an RBC plant in the 1 to 2 mgd range is also significantly less than for AS. In the plants in this study, the AS plant required approximately 580 hours per year and the RBC plants required approximately 370 hours per year.

While excess biosolids are generally acknowledged in the industry to be approximately 10% less for RBCs than for AS, the data generated at the plants in this study were not sufficiently accurate to allow calculation.

SI to Metric Unit Conversion Factors:

1 ft = 0.3048 m
1 ft^2 = 0.0929 m^2
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 million gallons = 3,785 m^3
1 lb/ft^2 = 48.87 g/m^2
1 HP = 0.748 kW

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