Chemically Enhanced Wastewater Treatment: An Alternative & Complement to Biological Wastewater Treatment

The addition of metal salts and polymers in the wastewater treatment process can produce treatment benefits without incurring a significant increase in capital cost.

INGEMAR KARLSSON &
SHAWN P. MORRISSEY

Two types of chemically enhanced wastewater treatment (CEWT) processes — chemically enhanced primary treatment (CEPT) and direct precipitation — which add metal salts and polymers at the beginning of the treatment process provide the means to supplant or augment biological wastewater treatment. The primary difference between these CEWT processes is the amount of chemicals added to the system.

CEPT has been used since the early 1980s in southern California and Canada (see Figure 1 and Table 1). It is usually accomplished by requiring minimal additional construction to conventional primary treatment plants. Therefore, little capital cost is required to convert a primary treatment plant to a chemically enhanced primary treatment plant.

The treatment consists of adding metal salts (such as ferric chloride or aluminum sulfate) and/or cationic polymers and an anionic polymer to the waste stream to enhance settling. The metal salts, which are used as a coagulating agent, need rapid mixing in order to optimize the coagulation process. At concentrations of 20 to 30 mg/l, they should be added as far upstream of the sedimentation tanks as possible

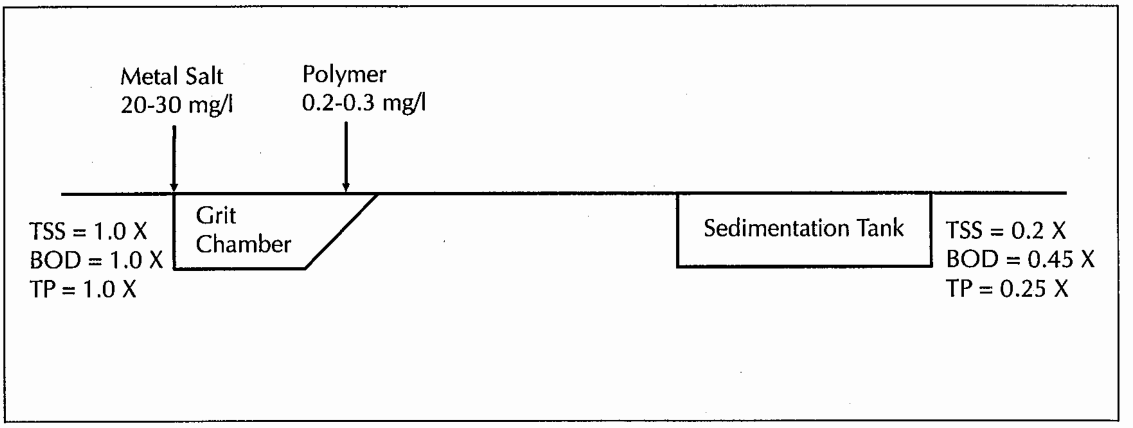


FIGURE 1. Schematic of the CEPT process.

to allow enough mixing time for the coagulation process to occur. The anionic polymer (0.2 to 0.3 mg/l) needs rapid mixing initially to dilute the polymer, then gentle mixing to promote flocculation and the formation of large settleable flocs. It should be added ahead of the sedimentation tanks. CEPT has typically achieved 80 percent total suspended solids (TSS), 50 to 60 percent biochemcial oxygen demand (BOD) and 75 percent total phosphorus (TP) removal.[1]

Direct precipitation is being used in Norway and Sweden in plants designed to optimize the chemical treatment process for phosphorus removal (see Figure 2 and Table 2). The treatment consists of approximately 150 mg/l of a metal salt. The difference between it and CEPT is that in the direct precipitation process, phosphorus removal is a primary objective; hence, the use of the large concentration of metal salts. Direct precipitation consistently achieves 90 percent TSS, 85 percent BOD and 90 percent phosphorus removal.[2]

The Effect of CEWT on Subsequent Treatment Processes

Carbon Removal. For very sensitive receiving waters, the quantity of organic matter in the effluent from wastewater treatment plants has to be very low. This requires that the chemical

TABLE 1
Summary of Treatment Efficiency & Chemical Addition for Various Advanced Primary Treatment Plants

Location	Performance					Chemical Addition		
	Flow (mgd)	BOD (mg/l) Influent	BOD (mg/l) Effluent	TSS (mg/l) Influent	TSS (mg/l) Effluent	Type	Concentration (ppm)	Duration
Pt. Loma San Diego	191	276	119	305	60	$FeCl_3$ Anionic Polymer	35 0.26	Continuous
Orange County Plant 1	60	263	162	229	81	$FeCl_3$ Anionic Polymer	20 0.25	8 hrs (Peak Flow)
Orange County Plant 2	184	248	134	232	71	$FeCl_3$ Anionic Polymer	30 0.14	12 hrs (Peak Flow)
JWPCP Los Angeles County	380	365	210	475	105	Anionic Polymer	0.15	Continuous
Hyperion Los Angeles	370	300	145	270	45	$FeCl_3$ Anionic Polymer	20 0.25	Continuous
Sarnia Ontario, Canada	10	98	49	124	25	$FeCl_3$ Anionic Polymer	17 0.3	Continuous

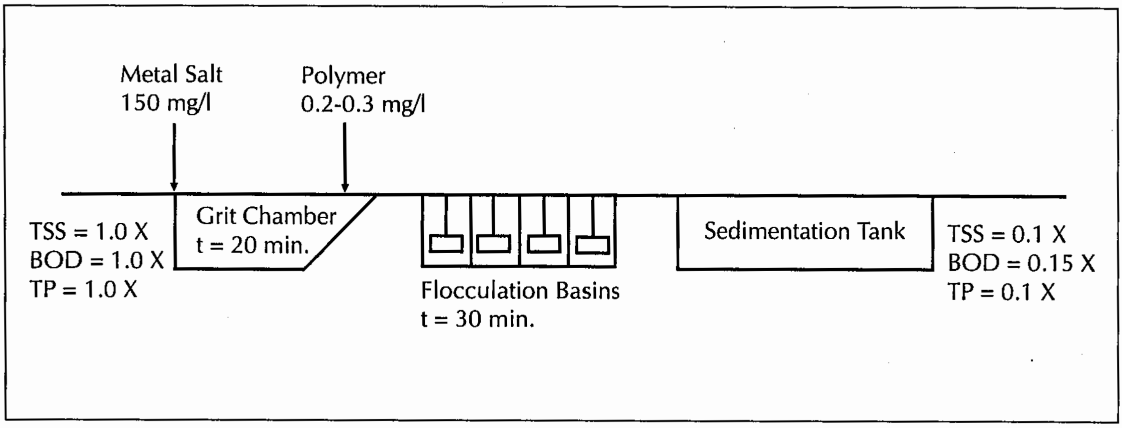


FIGURE 2. Schematic of the direct precipitation wastewater treatment process.

precipitation step be supplemented with a biological step.

In some cases, with direct precipitation alone, it is possible to reach BOD reductions comparable to those obtained from a conventional biological treatment plant at lower costs and by using less space. In addition, the phosphorous reduction will be 70 percent higher. Direct precipitation can also be used for unloading an overloaded conventional biological plant.

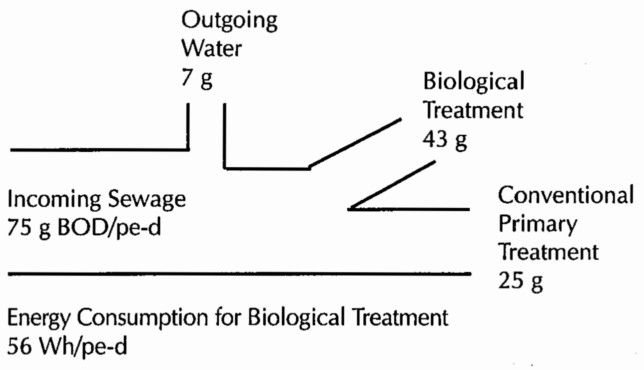
Consider the economic aspects of CEPT. Figure 3 shows how organic material is distributed in a conventional biological treatment plant. Of an incoming amount of 75 grams of BOD per person per day (g BOD/pe-d), 30 percent is separated in the primary clarifier, 60 percent in the biostage and the remaining 10 percent goes into the receiving water. The 60 percent converts into 43 grams biodegraded in the biostage. To biodegrade 1 kilogram of BOD requires about 1.3 kWh. (A conventional activated sludge biological treatment plant utilizes large amounts of electrical energy to produce and disperse into the aeration basin the oxygen necessary to reduce the BOD.) Power consumption is then about 20 kWh per person per year for a conventional biological treatment plant.

With CEPT, 60 percent of the organic substance is separated in the primary clarifiers and 30 percent, or 23 grams of BOD, goes to the biological stage (see Figure 4). Only 11 kWh per person per year is required — a 45 percent reduction in the energy demand of a conventional system.

Nitrification. Scandinavia and the United States now have new regulations limiting the discharge of nitrogen into receiving waters. The force of these regulations creates a problem for wastewater treatment plants because most have insufficient biological volumes and reten-

TABLE 2
Summary of Treatment Efficiency & Chemical Addition for Direct Precipitation Plants in Norway

Location	Performance							Chemical Addition		
	Flow (mgd)	P_{tot} (mg/l) Influent	Effluent	BOD (mg/l) Influent	Effluent	TSS (mg/l) Influent	Effluent	Type	Concentration (ppm)	T_{mix} (min)
Average of 23 Plants From Norway		5.5	0.5	216	42	172	27	Lime/$FeCl_3$ Anionic Polymer	100-200 0-0.2	20 30
Oslo	62	2.9	0.14	140	30	120	10	$FeCl_3$ Anionic Polymer	150 0.2	15 30



Note: The term person equivalent (pe) is often used to express the loading to a treatment plant in terms of a particular pollutant. This term takes into account all industrial, commercial and residential loadings and equates it to the number of people in the community. Therefore, a community that has a large industrial component would have a large concentration in terms of g pe-d than a strictly residential community.

FIGURE 3. The separation of organic matter in conventional biological treatment.

tion times to achieve the required nitrification and denitrification. CEWT techniques can be applied to this problem with very favorable results.

To remove nitrogen biologically, two separate stages are necessary — an aerobic and an anoxic stage. An anoxic stage differs from an anaerobic stage in that oxygen, bound as a nitrate, is present. In the aerobic stage, ammonia in the wastewater is oxidized to nitrite and then to nitrate in a process referred to as nitrification, while in the anoxic stage the nitrate is reduced to a gaseous form in a process referred to as denitrification.

With a trickling filter nitrifiers start to grow when most of the organic matter is consumed and the number of fast-growing heterotrophic bacteria (organisms that use organic carbon for the formation of cell tissue) start to decrease. Large volumes and surface areas are necessary if the BOD/N ratio is high. The lower the BOD/N ratio, the smaller the surface area in the trickling filter required to achieve nitrification.[3]

For an activated sludge process, sludge age is one of the most important parameters for nitrification. In order to build up a nitrifying system, it is necessary to increase the sludge age enough so that slow-growing autotrophic bacteria (organisms that derive cell carbon from carbon dioxide) are not washed out of the biological system. During winter, with low water temperatures (often below 10°C), it is necessary to further increase the sludge age.

An increased removal of organic matter (BOD) and suspended solids (up to 100 percent) over the primary system can be expected when CEPT is used. This situation will in fact double the sludge age, if the same aeration tank volume and sludge concentration is used as illustrated by the following design equation for completely mixed activated sludge with recycle:

$$SA = BOD/(F/M * X)$$

where:

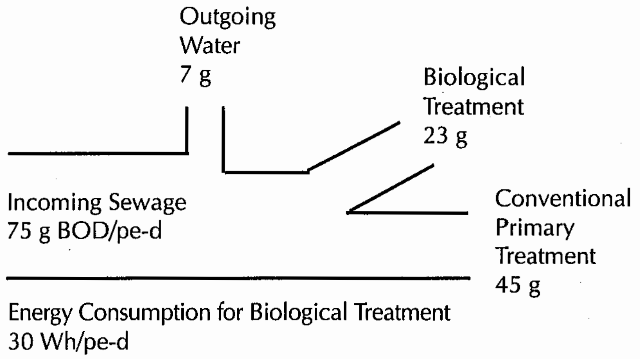


FIGURE 4. The separation of organic matter using CEPT followed by biological treatment.

SA = Sludge age (days)
BOD = influent BOD concentration (mg/l)
F/M = Food-to-microorganism ratio (1/day)
X = Solids concentration in aeration tank (mg/l)

In addition, the organic matter is mainly in a dissolved, readily denitrifiable form that will further increase the sludge age based on changes in kinetic parameters. The use of CEPT thus enables nitrification without requiring aeration tank expansion.

Denitrification. In the second stage of nitrogen removal (denitrification) the nitrate produced in the first stage (nitrification) is reduced to a gaseous form of nitrogen and is released to the atmosphere. Generally, the gaseous form is nitrogen gas (N_2) but it can also be nitrous or nitric oxide. This transformation can be accomplished by a wide variety of microorganisms, which under anoxic conditions use nitrate as their electron acceptor in place of oxygen. These bacteria are classified as facultative heterotrophic bacteria, due to their ability to utilize either oxygen or nitrate in their oxidation of organic matter.

Nitrogen removal treatment processes can be classified as post-denitrification and pre-denitrification. These processes are differentiated by the point at which denitrification occurs. In post-denitrification, the wastewater is first nitrified aerobically, then passed to the anoxic zone. Because the denitrifying bacteria require a carbon source for growth, water that has already received primary, and some secondary, treatment may be too depleted in carbon, in which case a carbon source such as methanol or hydrolyzed sludge must be added to the anoxic zone.

In pre-denitrification, the wastewater flows first through the anoxic zone, where denitrifiers can take advantage of the highest possible carbon concentration. The water then passes to an aerobic zone, and nitrified water produced at that point is then recirculated to the anoxic zone for denitrification.

One important factor influencing the predenitrification process is the BOD/N ratio. Opposite to the nitrification process, a high ratio is favorable. CEPT decreases the BOD/N ratio; however, the remaining fraction of organic substances shows the highest oxidation rate since they are highly soluble. This fraction corresponds to the soluble content of BOD and will have the same level as water without chemical treatment.

TABLE 3
Typical Wastewater Composition

TSS	200 mg/l	80 g pe-d
BOD	200 mg/l	80 g pe-d
SBOD*	50 mg/l	20 g pe-d
COD**	450 mg/l	180 g pe-d
TP	7 mg/l	2.8 g pe-d
N	35 mg/l	14 g pe-d

Notes: * SBOD = Soluble BOD
** COD = Chemical Oxygen Demand

If the readily denitrifiable organic matter in the wastewater is too low to fulfill the nitrogen removal demands, it is possible to use the precipitated CEPT sludge that has a volume less than one percent of the wastewater being treated (containing about 75 percent of the organic matter in the wastewater). Thus, there is a good possibility that this sludge can be treated in a separate optimized process and that it can be hydrolyzed into an easily degradable form. The denitrification process can be accelerated and additional volume can be saved. The use of CEPT to accelerate the nitrification and for hydrolysis of the sludge to accelerate the denitrification process has been developed and implemented commercially.[4] The hydrolysis process can be performed in different ways, the most interesting being biological anaerobic fermentation and thermal hydrolysis.

Sludge & Energy Production for Carbon Removal

A typical wastewater has the composition as shown in Table 3. Sludge production has been calculated for different wastewater treatment processes. The suspended solids, including some of the BOD plus the contribution from the coagulant, removed from the primary settling tanks constitutes the primary sludge. In the

TABLE 4
Comparison of Various Treatment Processes

	CEPT	DP*	CPT**+AS***	CEPT+AS	DP+AS
BOD Removed	60%	75%	90%	90%	90%
TSS Removed	80%	90%	90%	90%	90%
TP Removed	75%	90%	20%	75%	90%
Retention Time	2 hrs	4 hrs	12 hrs	7 hrs	9 hrs
Energy Produced	120 Wh/pe-d	150 Wh/pe-d	180 Wh/pe-d	180 Wh/pe-d	180 Wh/pe-d
Energy Consumed	0	0	51 Wh/pe-d	35 Wh/pe-d	29 Wh/pe-d
Net Energy	120 Wh/pe-d	150 Wh/pe-d	129 Wh/pe-d	145 Wh/pe-d	151 Wh/pe-d
Digested Sludge	46 g/pe-d	73 g/pe-d	51 g/pe-d	55 g/pe-d	77 g/pe-d

Notes: * DP = Direct Precipitation
** CPT = Conventional Primary Treatment
*** AS = Activated Sludge Secondary Treatment

biological step, the conversion of organic matter, mostly soluble BOD, into removable form constitutes the secondary sludge. Sludge digestion produces gas equivalent to 2.5 Wh per gram of BOD.

For all examples, the "typical" wastewater characteristics are as shown in Table 3 with references made to person equivalence. Sludge production is calculated assuming a 50 percent reduction in BOD during digestion.

Table 4 summarizes parameters of the various conventional and CEWT treatment processes — removal percentages, retention times, energy produced and consumed, and disgested sludge quantities. Figures 5 through 9 illustrate these key parameters. In

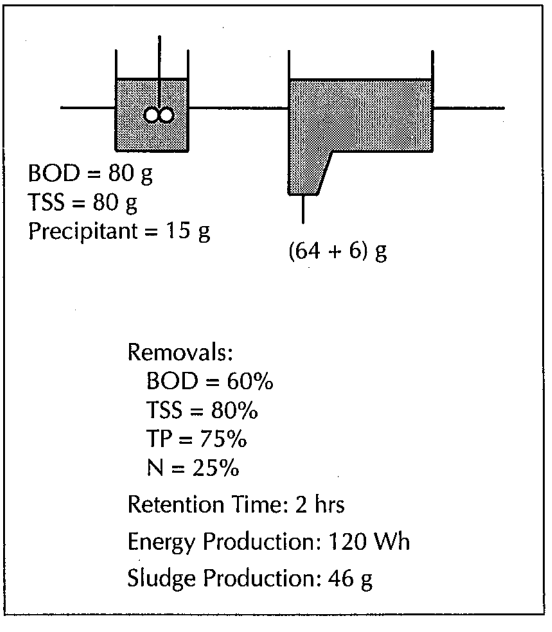


FIGURE 5. CEPT sludge and energy production.

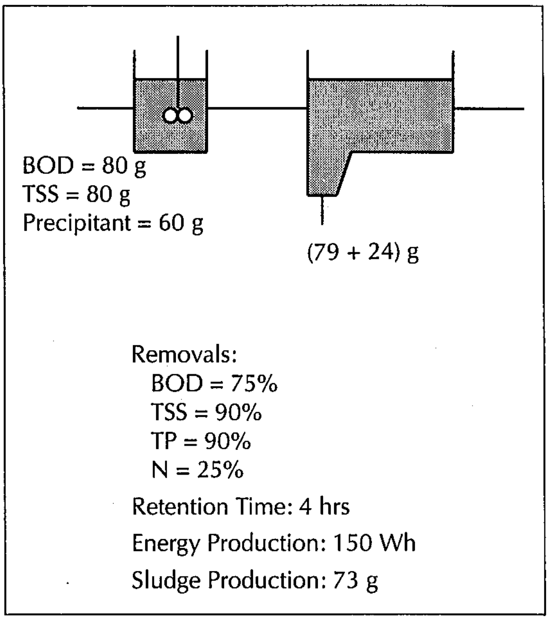


FIGURE 6. Direct precipitation sludge and energy production.

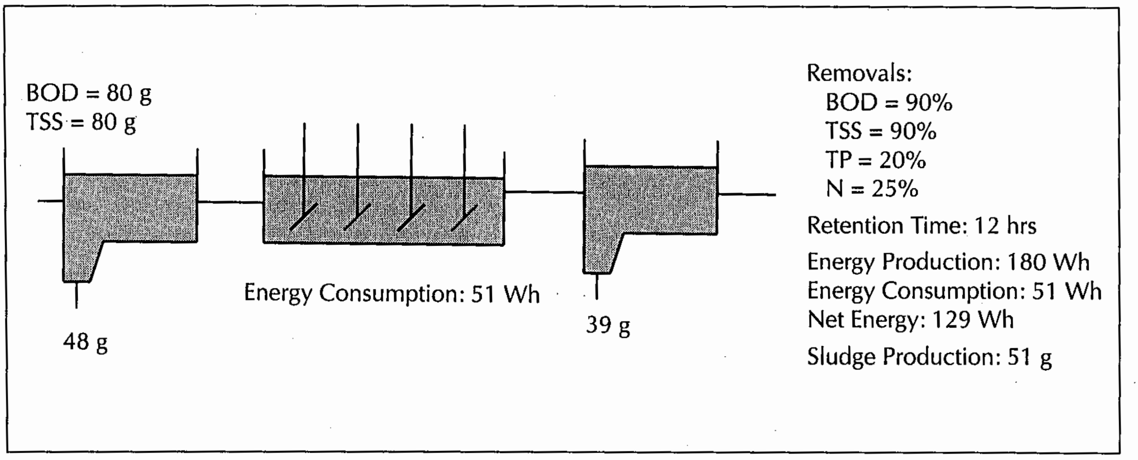


FIGURE 7. Conventional primary treatment followed by an activated sludge process (sludge and energy production/consumption).

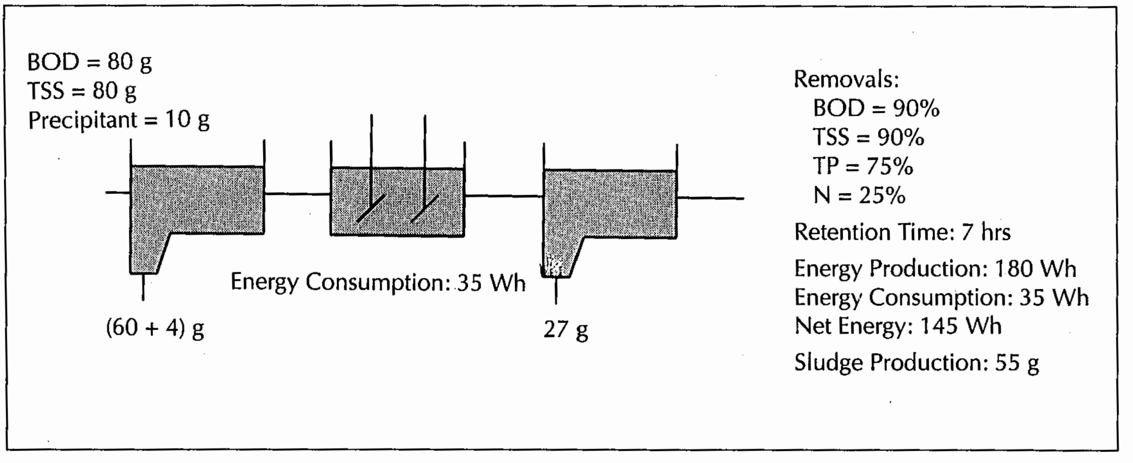


FIGURE 8. CEPT followed by an activated sludge process (sludge and energy production/consumption).

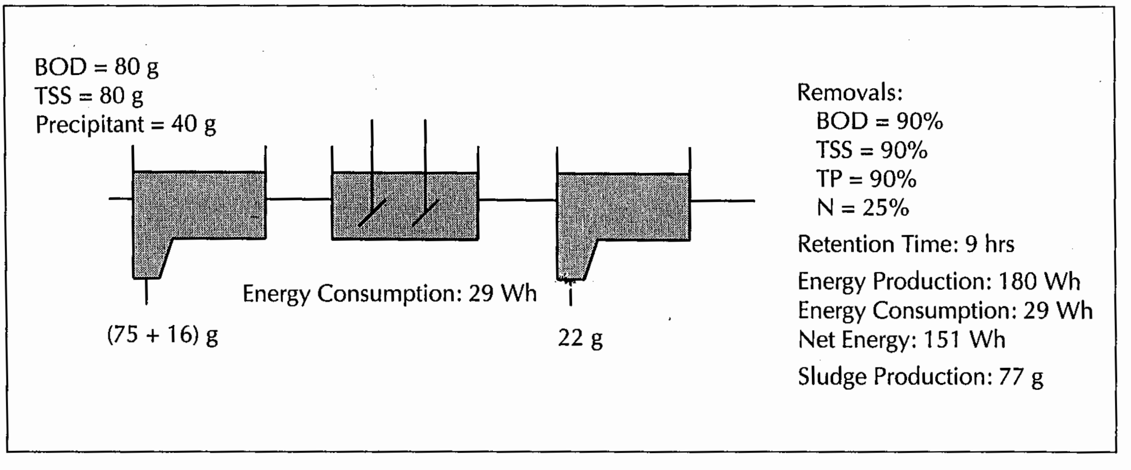


FIGURE 9. Direct precipitation followed by an activated sludge process (sludge and energy production/consumption).

TABLE 5
Characteristics of MWRA Wastewater

Parameter	Influent (mg/l)	Primary Effluent (mg/l)	CEPT Effluent (mg/l)
BOD	171	120	60
SBOD	50	50	50
COD	360	250	120
NH_4-N	10	10	10
NO_3-N	2	2	2
TKN*	19	17	16
Total N	21	19	18
TP	3.5	3.0	1.5

Note: * TKN = Total Kinetic (Non-Inert) Nitrogen

all of these illustrations, typical wastewater having the composition shown in Table 3 is being treated.

To produce one metric ton of a typical chemical used in wastewater treatment requires approximately 200 kWh of energy. This includes all energy requirements (such as for raw material production, heating, transportation of raw material and transportation of the final product to the customer). Therefore, the energy cost associated with chemical usage for CEPT is 3 Wh/pe-d, for direct precipitation is 12 Wh/pe-d, for CEPT and activated sludge treatment is 2 Wh/pe-d and for direct precipitation and activated sludge treatment is 8 Wh/pe-d.

Possible Implementation: The Boston Harbor Project

CEWT may be appropriate for incorporation into the Boston Harbor Project. A main component of the project is the construction of the new Deer Island wastewater treatment plant. The facility is designed to treat an average flow of 480 mgd and a maximum flow of 1,270 mgd. The present plan calls for four primary treatment batteries as well as four secondary treatment batteries. In 1991, the Massachusetts Water Resources Authority (MWRA) contracted with the Massachusetts Institute of Technology (MIT) to evaluate the applicability

TABLE 6
Distribution of Organic Matter in COD Units in MWRA Wastewater

Parameter	Influent		Primary Effluent		CEPT Effluent	
	(mg/l)	(%)	(mg/l)	(%)	(mg/l)	(%)
VFA	36	10	36	14	36	30
Soluble Matter	36	10	36	14	36	30
Colloidal Matter	72	20	72	29	12	10
Suspended Matter	180	50	70	29	0	0
Inert Matter	36	10	36	14	36	30
Total	360	100	250	100	120	100

TABLE 7
Denitrification Capacity and Rate for MWRA Wastewater

	Maximum Removal of Total N (mg/l)	Denitrification Rate (g N/kg VSS-h)	Volume Required for Dentrification	Volume Required for Nitrification
Influent	24	0.7	1.0	1.0
Primary Effluent	20	0.88	0.8	0.7
CEPT Effluent	13	1.4	0.5	0.3

Note: VSS-h = Volatile Suspended Solids per Hour

of the CEPT process for the new plant. That work confirmed the benefits of CEPT as outlined below.[5] The MWRA is currently evaluating CEPT in a 2-mgd pilot facility on Deer Island.

Based on the characteristics of the wastewater that would be treated at Deer Island, the removal efficiencies of different parameters were calculated for both CEPT and conventional primary treatment (see Table 5).

Currently, the MWRA has no requirements for nitrogen removal. However, if nutrient removal may be required in the future, it would be important to determine how the MWRA may react since there are critical space limitations on Deer Island.

The organic matter in wastewater can be divided into five different groups (see Table 6). The fractionation of these groups is important in biological processes because they affect sludge production and biological activity in different ways. For biological nitrogen removal, the volatile fatty acids (VFA) have the highest denitrification rate. The soluble part without VFA is slower. The colloidal and suspended fractions are even slower because they must be hydrolyzed into a more easily degradable form first. As seen in Table 6, CEPT effluent has a higher percentage of easily degradable organic matter.

Assuming 6 mg of COD is needed to remove 1 mg of nitrogen, and that 100 percent of the VFA, 100 percent of the soluble matter, 50 percent of the colloidal matter and 20 percent of the suspended matter will be utilized, and that the denitrification rate (grams of Nitrogen per kilogram of volatile suspended solids per hour) for VFA is 3, for soluble matter is 1.5, for colloidal matter is 0.5 and for suspended solids is 0.3, the denitrification rate and volumes (compared to no treatment) for nitrification and denitrification were determined for CEPT and conventional primary treatment effluents.

The CEPT process requires a much smaller volume than the conventional primary treatment process (see Table 7), although only 13 mg/l of the total nitrogen (18 mg/l) for CEPT effluent can be removed without the addition of an additional carbon source. Hence, any volume freed by CEPT during the secondary treatment process could be used for additional nutrient removal if needed at Deer Island.

ACKNOWLEDGMENT — *This article is an adaptation of Ingemar Karlsson's presentation at the eighth annual Boston Harbor/Massachusetts Bay Symposium, "Harbor Cleanups: Social Costs and Engineering Alternatives," sponsored by the Massachusetts Bay Marine Studies Consortium and held on March 31, 1993.*

NOTE — *Kemira Kemi AB has developed the use of CEPT to accelerate nitrification and for hydrolysis of the sludge to accelerate the denitrification process, calling the technology HYPRO.*

INGEMAR KARLSSON *is a Chemical Engineer and a Biochemical Technology Engineer from Stockholm, Sweden. He works for Kemira Kemi AB and is involved in international research projects within Europe. At Kemira, he is*

involved in the research and development of chemical treatment systems and processes. The results of his research work have been widely published and presented. He has also been involved in the development and marketing of water treatment facilities and systems for municipalities as well as for the pulp and paper industries, and in research on single cell production.

SHAWN P. MORRISSEY *received his B.S. in geological engineering from the Colorado School of Mines in 1984 and his M.S. from the Massachusetts Institute of Technology (MIT) in 1990. Before attending MIT, he worked for the Union Oil Company of California as a programmer/analyst. He is currently working as a Research Engineer at MIT and is involved with the implementation of chemically enhanced wastewater treatment.*

REFERENCES

1. Morrissey, S.P., *Chemically Enhanced Wastewater Treatment,* Massachusetts Institute of Technology, Cambridge, Mass., Masters Thesis, 1990.

2. Odegaard, H., "Appropriate Technology for Wastewater Treatment in Coastal Areas," *Water Science Technology,* Vol. 21, No. 1, 1988, pp. 1-17.

3. Parker, D.S., *et al.,* "Process Design Manual for Nitrogen Control," EPA 625/1-75-007, USEPA, Washington, DC, 1975.

4. Karlsson, I., Goransson, J., & Rindel, K., "Use of Internal Carbon From Sludge Hydrolysis in Biological Wastewater Treatment," in *Chemical Water and Wastewater Treatment,* H.H. Hahn & R. Klute, eds., Springer-Verlag Berlin Heideburg, 1992 pp. 329-339.

5. Harleman, D.R.F., Wolman, L.M.G., & Curll, D.B., III, *Boston Harbor Cleanup Plan Can Be Improved,* Pioneer Institute Better Government Competition, 1992 Winners.