CANADA - BRITISH COLUMBIA OKANAGAN BASIN AGREEMENT

TASK 142

Review and Evaluation of Advanced Wastewater Treatment Methods

by
Associated Engineering Services Ltd.,
Stanley Associates Engineering Limited
Dayton & Knight Ltd.,
Vancouver, B.C.

N O T I C E

This report was prepared for the Okanagan Study Committee under the terms of the Canada-British Columbia Okanagan Basin Agreement. The information contained in this report is preliminary and subject to revision. The Study Committee does not necessarily concur with opinions expressed in the report

Office of the Study Director
Box 458, Penticton, B.C.

Published
January, 1973

SUMMARY

This report consists of a comprehensive literature review of advanced wastewater treatment methods with emphasis on the removal of the nutrients, nitrogen and phosphorus.

It has been extensively documented in the literature that the addition of nutrients to surface waters can cause excessive growths of algae and other aquatic vegetation. Such excessive and undesirable growth is referred to as "eutrophication". When these nutrient additions are the result of the activities of man the process is referred to as "cultural eutrophication".

Conventional wastewater treatment processes have not proven efficient in nutrient removal therefore during the past few years extensive research has been conducted on new techniques that remove a high percentage of nitrogen and phosphorus from wastewaters. In this report, these newly available techniques were evaluated with regard to classification, cost, ease of operation, and efficiency. In addition to nutrient removal techniques a series of advanced wastewater treatment methods that are employed for effluent polishing, nutrient removal and wastewater reclamation were also evaluated for their effectiveness in nutrient removal. Due to the current interest in physical-chemical wastewater treatment processes an appendix was added to the report describing several physical-chemical treatment plants being planned or under construction.

Nutrient removal processes were reviewed under the following headings:

Phosphorus Removal Processes
Nitrogen Removal Processes
Miscellaneous Processes

A synopsis of phosphorus removal processes A to F, nitrogen removal processes A to D and miscellaneous processes A to G follows.

PHOSPHORUS REMOVAL PROCESSES

(A) BIOLOGICAL

Phosphorus removal by means of modification to the conventional biological processes, activated sludge and trickling filters, has not been a predictable phenomenon. Therefore, it is not advisable to design on this basis. Maximum removals of 20 to 30 per cent are usually expected in a typically-operating activated sludge process. However, greater phosphorus reductions in both activated sludge and trickling filter plants are documented in the literature. When faced with the problem of upgrading existing conventional facilities to include additional phosphorus removal, process modifications to enhance phosphorus reduction should be considered because of the potential economy that may be achieved. Prior study of the wastewater characteristics and plant layout is essential, and pilot plant studies are desirable, before aerobic process modification for enhanced phosphorus removal can be successfully tested in existing conventional facilities.

(B) PRECIPITATION

Two points of application of chemicals, the primary clarifier or final effluent, are possible to promote phosphorus reduction by chemical precipitation. Chemical addition directly to aeration basins and trickling filters is considered to be a chemical-biological process and is discussed in the following section.

Chemical addition to the primary clarifier has been reported to provide the following advantanges:

1. Greatly enhances primary settling.

2. Produces BOD and suspended solids reductions as high as 60 per cent and 90 per cent, respectively, resulting in modest reduction in the size of the aeration tank or trickling filter.

3. Capital costs are lower.

The advantages of chemical addition to the final effluent is almost complete removal of phosphorus. Due to the incomplete hydrolysis of the complex phosphates, chemical addition to the primary clarifier can provide only moderate (60 - 80 per cent) total phosphorus removals.

Several different chemicals may be used for phosphorus precipitation. Aluminum salts, iron salts, and lime have all been tested in the laboratory, in pilot plants and in full-scale operations. All proved to

be effective in phosphorus removal. Lanthanum salts proved their superiority in laboratory studies and show a great potential for the removal of phosphorus but further pilot plant and full-scale testing is needed prior to adoption.

The choice of chemical, the dose, and the point of application should be based on careful evaluation of the wastewater characteristics, type of treatment facility, water quality criteria, economics, and sludge handling and disposal facilities.

(C) CHEMICAL-BIOLOGICAL

Chemical-biological, as defined here, includes the cases where chemicals are added to the aeration tank of an activated sludge plant or to the filter for a trickling filter plant. Chemicals may be added to the primary effluent, to a flash mix tank just prior to final sedimentation, to a recycled sludge or at any point in the aeration basin. In this process, chemical precipitation takes place in the aeration tank and the precipitated phosphorus is removed from the system through the waste activated sludge. The process is only capable of producing effluent with phosphorus concentration of 1 - 2 mg/l. The chemical-biological process has been reported to offer the following advantages:

1. Minimum capital cost through the utilization of both the aeration tank and the final clarifier.

2. Reduced chemical requirements - attributed to the chemical-biological interaction and the large floc surface area available for adsorption. In addition, the hydrolysis of the complex phosphates results in soluble orthophosphate being the only form in the aeration tank, which can be precipitated much more efficiently than the complex form.

3. Improved mixed liquor settling. This would also result in higher mixed liquor-volatile solids than may be maintained in the aeration tank, resulting in lower organic loadings.

(D) PHYSICAL-CHEMICAL

Physical-chemical processes, as defined here, include the cases where phosphorus removal is through chemical precipitation followed by filtration.

Compared to conventional biological treatment physical-chemical processes offer the following advantages:

1. Less sensitivity to shock loadings.

2. Not affected by toxicity.

3. Flexible in operation. Unit operations can be added for specific purposes, e.g. chemical precipitation for phosphorus reduction.

4. Requires only 25 per cent of the land area.

5. No secondary sludges, which are the most difficult to dewater, are produced.

The disadvantage of physical-chemical processes is the higher cost, particularly for smaller plants.

Because of the current interest in physical-chemical wastewater treatment processes an appendix has been added describing several physical-chemical plants that are either proposed, in the design stage, or under construction.

(E) ION EXCHANGE

This ion exchange process utilizes activated alumina columns to absorb phosphates from solutions. Regeneration of the columns is by acidification of the alumina with nitric acid.

Advantages claimed for alumina compared to chemical precipitation are:

1. Alumina is highly selective for phosphate, particularly polyphosphates.

2. No ions are added.

3. pH is not affected.

4. Little affected by wastewater variations.

5. Very low phosphorus residuals can be achieved.

Fouling of the exchange bed with solids and organic matter is a problem. Waste regenerant disposal requires more research.

(F) ELECTROCHEMICAL

Studies related to electrochemical treatment of wastewater are scarce. A Norwegian process mixes 20 per cent sea water by volume with the wastewater, resulting in a density separation with the sea water at the bottom (anode) of the cell. Current raises the cathode pH precipitating phosphorus and ammonia. Removals of 83 per cent phosphorus and 82 per cent ammonia are reported.

Another process uses sacrificial electrodes of iron or aluminum which are released by the current as ions into solution precipitating phosphorus and ammonia.

Electrochemical treatment of wastewater is still in the development stage and further research and testing is required before full-scale application.

A nitrate specific resin was recently developed to remove nitrate from feed solutions. It is regenerated by hydrochloric acid.

Ammonium ion exchange has a promising potential in freezing climates where ammonia stripping is not possible, and where low ammonia residuals are required. Nitrate specific resins require further development and testing.

(D) CHLORINATION OF AMMONIA

Ammonia can be oxidized to nitrogen gas by break point chlorination with either chlorine gas or sodium hypochlorite. Hypochlorite is more expensive than chlorine but is much safer to transport and handle. Break point chlorination will also disinfect the wastewater along with removing the ammonia. However, chlorination will add chloride ions which may be considered as pollutants. Sodium hypochlorite may cost twice as much as chlorine but associated costs are greatly reduced.

MISCELLANEOUS PROCESSES

A series of new processes and new uses for developed processes are now being employed for effluent polishing, nutrient removal and in wastewater reclamation. A discussion of their uses for nutrient removal follows:

(A) ACTIVATED CARBON

In this technique, wastewater is passed through a bed of granular or powdered activated carbon which has a high adsorption capacity for soluble organics found in water. Spent carbon must be regenerated for reuse to make the process economical. Reactivation of the carbon is accomplished by heating to temperatures of 1700^{o}F in a steam-air atmosphere to burn off adsorbed organics. Activated carbon adsorption is also discussed under physical-chemical processes and in the Appendix.

Further evaluation of the effects of biological activity in the columns is required since the carbon beds act as submerged anaerobic filters.

(B) ALGAE STRIPPING

Preblooming of algae is utilized in specially designed shallow ponds, on rotating discs, or in contact tanks for the activated algae process to convert nitrogen and phosphorus to algae cell tissue through photosynthesis. Natural or artificial light can be used.

The major disadvantages of algae preblooming and stripping in shallow ponds is the large land area required and unsuitability for colder climates. The rotating disc and activated algae processes require further research and development.

(C) ELECTRODIALYSIS

Electrodialysis, used basically for the demineralization of brackish waters, is a unit process which uses induced electric current to separate the components of an ionic solution. Separation of the ions is accomplished by membranes which permit only selected ions to pass through.

Research is now centered on making electrodialysis more generally effective for removal of both inorganic and organic contaminants, by converting nonionic organic molecules to ionic form. Further research is required to make this unit process attractive for treatment of wastewaters.

(D) OXIDATION

Chemical oxidation is being investigated as an alternative to carbon adsorption for removing organics. It is now considered possible to completely oxidize organic material to carbon dioxide, oxides of nitrogen and oxides of other elements. Several oxidation techniques now being studied include (1) the use of oxygen species such as ozone, hydrogen peroxide, and hydroxyl free radicals; (2) ultra-violet light-catylyzed chlorine oxidation; (3) use of nuclear radiation. Although these processes have been classified as technically feasible, they are not at this time economically competitive.

(E) REVERSE OSMOSIS

In this process, wastewater is forced through membranes (normally cellulose acetate) to remove both dissolved organics and inorganics from solution. Pilot plant studies indicate that suspended solids and soluble materials rejected by the membranes cause fouling and scaling problems. Other studies have shown that a portion of the nitrate ions will pass through the membranes. Further research is underway to develop longer-lived and cheaper membranes that can handle higher application rates. With proper pretreatment to remove organic and solid matter, reverse osmosis may become a very useful and economical method of nutrient removal.

(F) DISTILLATION

Distillation, a well-known process for producing pure water, has been researched as a possible method of advanced treatment. The process, at present, is expensive when compared with other methods. Pretreatment of raw wastewater by aeration or carbon is required to prevent rapid fouling of the heat transfer surfaces.

(G) LAND APPLICATION

The practice of the disposal and utilization of treated sewage and other wastes by application to land surfaces has recently gained in popularity. The disposal of wastewater by crop irrigation and irrigation of forest land is now an established practice in North America. Reclaimed treated wastewater is now being used for produce irrigation (spray and surface), irrigation of fodder, fibre, seed and processed food crops, landscape irrigation and recreational impoundment.

The disposal of sewage treated by conventional methods on land may be less expensive than the disposal into water for sewage treated by advanced treatment methods. Today's knowledge is insufficient to ascertain if the two methods of disposal achieve comparable goals in protection of the environment. When considering land irrigation in water-short areas such as the Okanagan Basin, the diversion of water at one location may detract an equivalent volume of water that could be used elsewhere. When comparing the cost/benefit of land application to alternative treatment and disposal methods, one must consider; the difficulty of altering the composition of the waste applied, the potential alteration of the soil composition, the cost of the wastewater delivered to the site.

TABLE OF CONTENTS

		Page
SUMMARY		i
TABLE OF CONTENTS		ix
LIST OF TABLES		x
LIST OF FIGURES		xi
GLOSSARY OF TERMS		xii
LIST OF ABBREVIATIONS		xvi
FOREWORD		xvii
I.	INTRODUCTION	1
II.	FORMS OF PHOSPHORUS & NITROGEN IN WASTEWATERS	4
III.	NUTRIENT REMOVAL PROCESSES	6
IV.	PHOSPHORUS REMOVAL PROCESSES	7
	(A) BIOLOGICAL	7
	(B) PRECIPITATION	15
	(C) CHEMICAL-BIOLOGICAL	26
	(D) PHYSICAL-CHEMICAL	36
	(E) ION EXCHANGE	43
	(F) ELECTROCHEMICAL	46
V.	NITROGEN REMOVAL PROCESSES	48
	(A) BIOLOGICAL DENITRIFICATION	48
	(B) AMMONIA STRIPPING	53
	(C) ION EXCHANGE	55
	(D) CHLORINATION OF AMMONIA	56
VI.	MISCELLANEOUS PROCESSES	57
	(A) ACTIVATED CARBON ADSORPTION	57
	(B) ALGAE STRIPPING	58
	(C) ELECTRODIALYSIS	60
	(D) OXIDATION	61
	(E) REVERSE OSMOSIS	61
	(F) DISTILLATION	61
	(G) LAND APPLICATION	62
VII.	DISCUSSION & CONCLUSIONS	65
	PHOSPHORUS REMOVAL	65
	NITROGEN REMOVAL	68
	MISCELLANEOUS PROCESSES	69
VIII.	ACKNOWLEDGEMENTS	70
IX.	LIST OF REFERENCES	71
X.	APPENDIX: PHYSICAL - CHEMICAL TREATMENT PLANTS IN PROGRESS	88

LIST OF TABLES

TABLE	TITLE	PAGE
1	Wastewater Treatment Processes	3
2	Phosphorus & BOD Removal for Lime Precipitation	23
3	Phosphorus & BOD Removal for Aluminum & Iron Precipitation	24
4	Effects of Aluminum on Sludges & Supernatent	27
5	Results of Screening for Mineral Supplement to Activated Sludge Process	30
6	Phosphorus & BOD Removal Through Chemical-Biological Treatment	30
7	Comparison of Chemical Precipitation & Activated Alumina for Phosphorus Removal	44
8	Comparison of Nutrient Removal Processes	66
9	Estimated Costs of Phosphorus Removal	67

LIST OF FIGURES

FIGURE	TITLE	PAGE
1	Nitrogen Cycle in Biological Oxidation Process	5
2	Various Lime Precipitation Schemes for Phosphorus Removal	25
3	Chemical-Biological Phosphorus Removal Process Scheme	25
4	Flow Diagram of Process Proposed by Eberhardt & Nesbitt	32
5	Three-Stage System for Nitrogen Removal	32
6	Schematic-Integrated, Biological-Chemical, Process Pilot Plant - Humenick & Kaufman	33
7	Flow Diagram of Single-Stage Lime Clarification and Activated Carbon Pilot Plant at Lebanon, Ohio (from Villiers 74)	39
8	Comparison of Operating Performance of Physical-Chemical Pilot Plant and Primary-Secondary Treatment at Lebanon, Ohio (from Villiers 74)	40
9	Potential Physical-Chemical Process for Removal of Organics, Nitrogen and Phosphorus from Raw Wastewater for a 10 MGD Plant (from Shuckrow et al, 75)	41
10	Physical-Chemical Treatment Pilot Plant (from Bishop et al, 76)	41

GLOSSARY OF TERMS

Activated Sludge Process	A biological wastewater treatment process in which a mixture of wastewater and activated sludge is agitated and aerated. The activated sludge is subsequently separated from the treated wastewater (mixed liquor) by sedimentation and wasted or returned to the process as needed.
Autotrophic Organisms	Bacteria which thrive by using inorganic materials for energy and growth.
Biochemical Oxygen Demand	A standard test used in assessing wastewater strength, requiring incubation for five days at 20°C.
Biological Oxidation	The process whereby living organisms in the presence of oxygen convert the organic matter contained in wastewater into a more stable or a mineral form.
Chemical Oxygen Demand	A measure of the oxygen-consuming capacity of inorganic and organic matter present in water or wastewater. It does not differentiate between stable and unstable organic matter and thus does not necessarily correlate with biochemical oxygen demand.
Clarification	Any process or combination of processes the primary purpose of which is to reduce the concentration of suspended matter in a liquid.
Coagulation	In water and wastewater treatment, the destabilization and initial aggregation of colloidal and finely divided suspended matter by the addition of a floc-forming chemical or by biological processes.
Coliform-Group Bacteria	A group of bacteria predominantly inhabiting the intestines of man or animal, but also occasionally found elsewhere. Important not only because they indicate pollutions but because their numbers in water can be determined by routine laboratory tests.
Demineralization	Reduction of the mineral content of water by a physical, chemical, or biological process; removal of salts.
Denitrification	Reduction of nitrate to nitrite, and further to elemental nitrogen.

Effluent	(1) A liquid which flows out of a containing space. (2) Wastewater or other liquid, partially or completely treated, or in its natural state, flowing out of a reservoir, basin, treatment plant, or industrial treatment plant, or part thereof.
Filtration	The process of passing a liquid through a filtering medium (which may consist of granular material, such as sand, magnetitie, or diatomaceous earth, finely woven cloth, unglazed porcelain, or specially prepared paper) for the removal of suspended or collodial matter.
Flocculation	In water and wastewater treatment, the agglomeration of colloidal and finely divided suspended matter after coagulation by gentle stirring by either mechanical or hydraulic means. In biological wastewater treatment where coagulation is not used, agglomeration may be accomplished biologically.
Heterotrophic Organisms	Bacteria that thrive only on organic materials for energy and growth.
Hydrolysis	(1) The reaction of a solute with water in aqueous solution. (2) A change in the chemical composition of matter produced by combination with water. Sometimes loosely applied in wastewater practice to the liquefaction of solid matter in a tank as a result of biochemical activity.
Hypertrophic	Waters of high nutrient content.
Influent	Water, wastewater, or other liquid flowing into a reservoir, basin, or treatment plant, or any unit thereof.
Kjeldahl Nitrogen	A standard water and wastewater analysis that includes ammonia and organic nitrogen, but does not include nitrate and nitrite nitrogen.
Mixed Liquor	A mixture of activated sludge and organic matter undergoing activated sludge treatment in the aeration tank.
Nitrate Nitrogen	The final form of nitrogen from the oxidation of organic nitrogen compounds.

Nitrification	(1) The conversion of nitrogenous matter into nitrates by bacteria. (2) The treatment of a material with nitric acid.
Phosphate	A salt or ester of phosphoric acid.
Phytotoxicity	Toxicity to plants.
Polyelectrolyte	Water-soluble high-molecular-weight polymers that contain groups capable of dissociation to give large highly charged ions. Acts to reduce stability of colloidal systems as an aid to coagulation in water and wastewater treatment.
Primary Treatment	(1) The first major (sometimes the only) treatment in a wastewater treatment works, usually sedimentation. (2) The removal of a substantial amount of suspended matter but little or no colloidal and dissolved matter.
Secondary Treatment	Reduction of oxygen demanding carbonaceous organic matter (BOD) in wastewaters by biological processes. Also produces significant reductions in total solids and bacteria.
Sedimentation	The process of subsidence and deposition of suspended matter carried by water, wastewater, or other liquids, by gravity. It is usually accomplished by reducing the velocity of the liquid below the point at which it can transport the suspended material. Also called settling.
Sludge Density Index	The reciprocal of the sludge volume index multiplied by 100.
Sludge Volume Index	The ratio of the volume in milliliters of sludge settled from a 1,000-ml sample in 30 min to the concentration of mixed liquor in milligrams per liter multiplied by 1,000.
Stoichiometric	Pertaining to or involving substances which are in the exact proportions required for a given reaction.
Suspended Solids	(1) Solids that either float on the surface of, or are in suspension in, water, wastewater, or other liquids, and which are largely removable by laboratory filtering. (2) The quantity of material removed from wastewater in a laboratory test, as prescribed in "Standard Methods for the Examination of Water and Wastewater" and referred to as nonfilterable residue.

Tertiary Treatment	Wastewater treatment beyond secondary, often employed to remove specific substances such as the nutrients phosphorus and nitrogen.
Total Organic Carbon	A rapid analysis technique used to estimate the degree of organic contamination of water and wastewater. Does not differentiate between stable and unstable organic matter and thus does not necessarily correlate with biochemical oxygen demand.
Trickling Filter	A filter consisting of an artificial bed of coarse material over which wastewater is distributed and through which it trickles to the underdrains, giving opportunity for the formation of zoogleal slimes which clarify and oxidize the wastewater.
Turbidity	A condition in water or wastewater caused by the presence of suspended matter, resulting in the scattering and absorption of light rays.
Tube Settling	Sedimentation within small inclined tubes to increase the efficiency of water and wastewater clarifiers.
Volatile Solids	The quantity of solids in water, wastewater, or other liquids, lost on ignition of the dry solids at 600°C.
Wastewater Reclamation	Processing of wastewater for reuse.

LIST OF ABBREVIATIONS

BOD	Biochemical oxygen demand
BV	Bed volume
°C	Degrees Centrigrade
Cap	(per) capita
COD	Chemical oxygen demand
cu m	Cubic meter
Do	Dissolved oxygen
°F	Degrees fahrenheit
gal	U.S. gallon
$gals/ft^2$	US gallons per square foot
gpm/ft^2	US gallons per minute per square foot
JTU	Jackson turbidity units
lb	pound
M	Molar (solution concentration)
MG	Million US gallons
MGD	Million US gallons per day
mg/l	Milligrams per liter
MLSS	Mixed liquor suspended solids
MLVS	Mixed liquor volatile solids
MLVSS	Mixed liquor volatile suspended solids
N	Nitrogen
N	Normal (solution concentration)
P	Phosphorus
PCT	Physical-chemical treatment
ppm	Parts per million
SDI	Sludge density index
SVI	Sludge volume index
TOC	Total organic carbon

FOREWORD

As outlined in the Report of the Special Group to the Study Committee, dated June 12, 1970, the B. C. Water Resources Service, Pollution Control Branch, was assigned the tasks associated with the Water Quality and Waste Treatment Programs of the Joint Canada-British Columbia Okanagan Basin Study Agreement. The Waste Treatment Program was assumed by the Municipal Division of the Pollution Control Branch.

A temporary report on Task 142, entitled "Review and Evaluation of Nutrient Removal Methods" was compiled on October 1, 1970, by D. Corrigan, P.Eng. of the Municipal Division, Pollution Control Branch. The consortium of Associated Engineering Services Limited, (AESL), Stanley Associates Engineering Limited, and Dayton & Knight Limited were assigned the task of updating and completing the final report in a letter of May 19, 1972 from Mr. W. N. Venables, P.Eng., Director of the Pollution Control Branch. By agreement between members of the consortium AESL was to complete the nutrient removal evaluation portion of Task 142 and Dayton & Knight the land application section. The material presented in the temporary report has been incorporated into this final report.

I. INTRODUCTION

In recent years increasing concern has been expressed both by the water resource management people and the general public regarding the discharge of nutrients to surface waters. This concern has been due mainly to the increasing problems of "eutrophication" of surface waters.

Eutrophication has been defined as the process of enrichment with nutrients (1). Eutrophication takes place when the aquatic life in a body of water becomes so fertilized with nutrients that the productivity of plant life in the water commences at a much faster rate than its decay. This results in an excessive growth of algae and rooted aquatic vegetation on the surface and bottom of streams, lakes and reservoirs. The excessive and undesirable growth of algae blooms has created nuisances, increased water treatment costs and in extreme cases destroyed the recreational value of water bodies.

Among the many nutrients that are essential for plant growth, nitrogen and phosphorus have been studied most intensively for their effects on eutrophication. However, there seems to be no general agreement among scientists and engineers whether the removal of nitrogen or phosphorus from wastewaters will control biostimulation in surface waters. Sawyer (2, 3) and Grundy (4) indicated several reasons why nitrogen control alone could be ineffective in most situations. Other researchers (5) have found that algae can store phosphorus when excess quantities are available and, therefore several investigators claim nitrogen can act as the limiting nutrient of plant growth under certain conditions. Until this controversy is resolved control of both nitrogen and phosphorus should be considered for effective control of eutrophication. There is no general agreement either on the threshold level of nutrients required to trigger nuisance algae blooms. Sawyer (6) reported from a study of Wisconsin Lakes that 0.30 mg/l of inorganic nitrogen and 0.005 mg/l phosphorus produced nuisance algae blooms. Sawyer never intended these figures to indicate threshold values although they have been widely quoted as such. Nitrogen (N) and phosphorus (P) are referred to in their elemental forms in this report unless specifically stated otherwise.

TABLE I

Wastewater Treatment Processes

After Eliassen & Tchobanoglous (11)

Classification	Description	Constituents Removed
Biological	Conventional secondary treatment (trickling filter and activated sludge)	Suspended solids, organic matter, bacteria, etc.
	Aerobic process modifications	Conventional treatment plus nutrients
	Anaerobic denitrification	Nitrate nitrogen
	Algae harvesting	Nitrate nitrogen and phosphorus
Chemical	Ammonia stripping	Ammonia nitrogen
	Ion exchange	Nitrates and phosphates
	Electrodialysis	Salts
	Chemical precipitation	Suspended solids and phosphates
Physical	Activated carbon adsorption	Organic compounds and suspended solids
	Sorption (Alumina Column ion exchange)	Phosphates
	Sedimentation	Suspended solids
	Filtration	Suspended solids
	Reverse osmosis	Salts
	Distillation	Salts
	Foam separation	Detergents
	Land application	Suspended and organic and inorganic matter

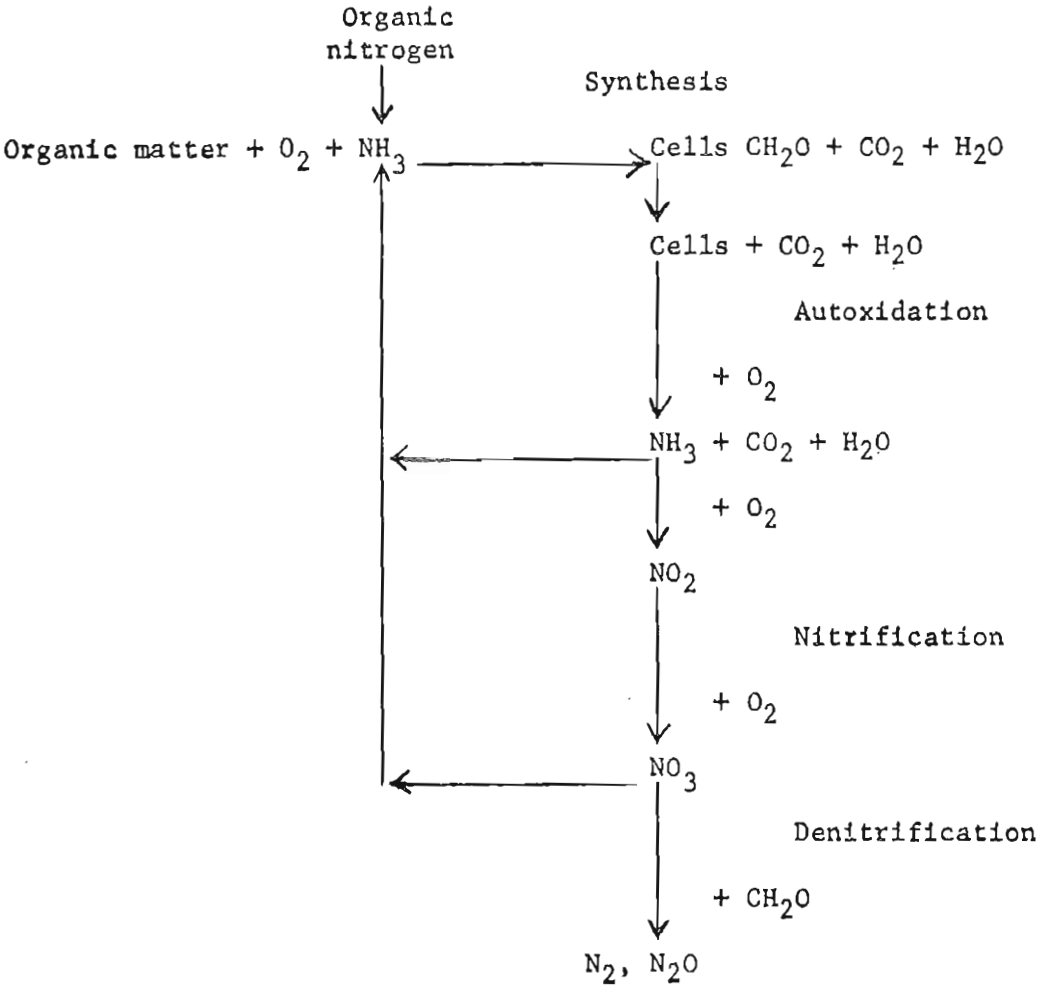


FIGURE 1 - NITROGEN CYCLE IN BIOLOGICAL OXIDATION PROCESS AFTER ECKENFELDER (85)

IV. PHOSPHORUS REMOVAL PROCESSES

(A) BIOLOGICAL

GENERAL

The metabolism of organic matter by the microorganisms in an aerobic biological wastewater treatment system requires several essential elements. Among these essential elements are nitrogen and phosphorus. The heterotrophic bacteria, responsible for the wastewater treatment in an aerobic biological system, oxidize a fraction of the organic matter present in the waste to carbon dioxide and water and derive their energy through the process. The remaining fraction of the organic matter is synthesized into cell material. Cell synthesis is responsible for any nitrogen and phosphorus removals which may occur in a conventional biological wastewater treatment process.

Of the several biological treatment processes currently available, only activated sludge has been reported to provide any consistent nutrient removal. This may be attributed to the large sludge build-up and wastage encountered in an activated sludge plant.

PHOSPHORUS REMOVAL IN AN ACTIVATED SLUDGE PROCESS

As previously mentioned, the biological removal of phosphorus in an activated sludge process is accomplished through assimilation into cell material. In a typically operating plant, the volatile mass of activated sludge has been reported to normally contain between 2 - 3 per cent phosphorus (15, 16, 17) resulting in an average phosphorus removal of 20 - 30 per cent by the activated sludge process alone.

The normal low efficiency of an activated sludge process to remove phosphorus from domestic wastewaters may be explained by examining the stoichiometrical relationship between Carbon:Nitrogen:Phosphorus (C:N:P) for the domestic waste and the cell mass. Stumm and Morgan (18) reported a mean stoichiometrical relationship for domestic wastewater as C:N:P = 70:17:1 and for bacterial sludge as C:N:P = 106:16:1. These data indicate that, stoichimetrically, there is not enough organic carbon available in domestic waste to produce enough

2. The normal total phosphorus content of activated sludge is 2-3 per cent of the volatile solids.

3. The maximum phosphorus removal in a typically operating activated sludge process treating domestic waste would range between 20-30 per cent.

However, in contrast to the preceding, phosphorus removal in some activated sludge plants has been reported to exceed 90 per cent. One such highly publicized activated sludge plant noted for high phosphorus removal is the Rilling plant at San Antonio, Texas. The Rilling treatment plant is one of three activated sludge plants, (including the west plant and the east plant), in San Antonio located at the same site and treating the same wastes. While the west plant averaged 35% and the east plant 60% Ibid (15). The Rilling plant was surveyed by Vacker, et al (24), and the authors listed the following operating parameters as the ones coinciding with the period of optimum phosphorus removals:

Mixed liquor dissolved oxygen $\geq$ 1.5 - 2.0 mg/l
Mixed liquor suspended solids (MLSS) = 1000 mg/l
BOD Loading = 0.50 lb BOD/lb MLSS - day
Sludge Volume Index (SVI) = 150 mg/l
Effluent BOD = 10 - 30 mg/l
Effluent suspended solids = 5 - 15 mg/l
Effluent NO_3 - N = 1 mg/l

It was concluded that the rate of mixed liquor aeration and the organic loading are the two principle parameters for effective phosphorus removal.

Based on the encouraging results obtained at San Antonio, the Federal Water Pollution Control administration (currently the Environmental Protection Agency) initiated a survey program whereby 13 additional activated sludge plants were monitored for 1 - 2 weeks in order to arrive at the optimum operating conditions for phosphorus removal by activated sludge. One of these surveyed plants reported to have high phosphorus removals is the Back River plant, Baltimore, Maryland. Scalf, et al, (25) in a plant investigation conducted April 3 - 15, 1967, reported phosphorus removal efficiency exceeding

Except for the Rilling Road plant at San Antonio and the Back River plant at Baltimore, the results of the FWPCA surveys of activated sludge plants generally showed very little phosphorus removal, Ibid (20, 22) and (29, 30, 31).

The mechanism of the high phosphorus removal, as encountered at the Rilling plant and the Back River plant, by activated sludge beyond that needed for cell synthesis has been described by two different hypotheses:

1. The occurrence of luxury biological uptake and biologically enhanced precipitation of phosphorous; and

2. Metal precipitation of phosphorus depending on the mineral content of wastewater.

The theory of "luxury uptake" was first introduced by Levin and Shapiro (32). In a bench scale and pilot plant study, the authors concluded that phosphorus uptake by the sludge could occur in the absence of cell growth. The phosphorus uptake in excess of that needed for cell synthesis was then referred to by the authors as "luxury uptake". Dissolved oxygen, rate of aeration, pH, and the phosphorus uptake. In a later experiment, Shapiro, et al, (33) demonstrated the release of orthophosphate under anoxic conditions. The authors stated that stripping of phosphorus from the return sludge would enhance phosphorus uptake and consequent removal in the aeration tank.

The theory of "luxury uptake" was supported by other investigators. It was stated Ibid (21) that in the declining growth and bioflocculation phase, where conventional activated sludge operates, and in the presence of 2 mg/1 of dissolved oxygen "luxury metabolic uptake" of phosphorus may be as high as 6.5 - 7.2 mg P/100 mg solids. The authors listed several operating parameters under which phosphorus uptake will be maximized. Spiegel (34) summarizing the results of laboratory studies conducted by the firm of Ryckman, Edgerley, Tomlinson, and Associates reported 80 percent total phosphorus removal under certain dissolved oxygen exceeding 1.9 mg/1 and acid stripping of phosphorus from return sludge at a pH of 5.0 Wells (35) in a batch study stated that, for the same organic removals, some sludges take up phosphorus at a rate of 65 mg/1/hr while

calcium incorporated biologically into activated sludge. The authors related the degree of calcium phosphate precipitation to the pH, which in turn is controlled by the CO_2 production in the aeration basin which is influenced by the hydraulic regime of the aeration basin. Plug flow conditions were reported to produce the highest phosphorus removals. The high CO_2 production at the head of the aeration basin in a plug flow regime results in a drop of the pH to a point where Ca^{++} ions will be released and the complex phosphate will be hydrolyzed to orthophosphate. However, as the flow proceeds along the aeration tank, CO_2 production will decrease due to the decrease in the substrate available for oxidation. At some point in the aeration tank, CO_2 production will decrease to a level that results in a rise of the pH to a value which causes calcium phosphate precipitation. In a completely mixed regime this segregation of reactions will not occur. Completely mixed activated sludge also does not allow enough residence time for the release of Ca^{++} ions and phosphate hydrolysis.

The high phosphorus removals at the Rilling plant was attributed to the hydraulic regime of the aeration basins where plug flow decreased from highest at Rilling to lowest at the west plant, Ibid (16, 17).

The chemical precipitation theory was supported by Ferguson, et al, (38) who stated that low magnesium and low carbonate concentrations encourage higher removals by calcium phosphate precipitation. The presence of calcium phosphate seed particles was also observed to accelerate the calcium removal of phosphorus in sterile wastewater free of biological activity.

Tests to validate the calcium phosphate precipitation theory also produced erratic results. Connell (39) reported that operating a segment of Hyperion, California plant according to the guidelines outlined by the theory has greatly increased the efficiency of phosphorus removals. However studies at Texas City, Texas where attempts were made to deliberately force calcium

(B) PRECIPITATION

Chemical precipitation appears to be the most widely accepted method available for phosphorus removal. Chemical precipitation, as defined here, includes the cases where chemicals are added either to the raw waste or to the final effluent. Chemical addition to the aeration tank is classified as chemical-biological and will be discussed in the next section.

Chemical addition to the primary clarifier has been reported to provide the following advantages:

1. Can be used with both trickling filtration and activated sludge.

2. Greatly enhances primary settling.

3. Produces BOD and suspended solids reductions as high as 60 percent and 90 percent, respectively, resulting in modest reduction in the size of the aeration tank. However, due to the incomplete hydrolysis of the complex phosphates, the process can only provide moderate (60-80 percent) total phosphorus removals. The addition of chemicals to the final effluent will produce an almost complete removal of the residual phosphorus, however, capital costs will be higher.

The most widely used chemicals include: iron salts (ferric chloride, ferric sulfate, ferrous chloride and ferrous sulfate), aluminum salts (alum and sodium aluminate), and lime. Removal of phosphorus utilizing iron or aluminum salts has been considered as a combination of chemical precipitation as well as absorption. It was reported Ibid (13) that chemical precipitation of phosphorus utilizing iron salts is through the formation of $FePO_4$ which is contained within the hydroxide floc which acts as an efficient absorbent for organic phosphorus compounds and other inorganic complex phosphates. The author stated that for efficient phosphorus removal, the stoichiometrical requirements of 1.88 mg/l Fe per mg/l P must be supplemented with at least 10 mg/l Fe for hydroxide formation. Stumm (40) on the other hand, states that the interaction of aluminum and iron with orthophosphate results in the formation of insoluble metal phosphates.

Precipitation of condensed phosphates with aluminum and iron salts was found to be strongly dependent on pH and the reactant concentration. At a molar ratio of 2:1 cation-to-phosphorus equivalence, maximum removals of phosphorus were observed at pH levels close to 4 and 6 with Fe^{+3} and Al^{+3}, respectively. At this ratio of the reactants, pyrophosphate was reduced from 18 mg/l to a residual of 0.9 and 0.06 mg/l while tripolyphosphate was reduced from 21.6 mg/l to 3.8 and 0.65 mg/l, with Al^{+3} and Fe^{+3}, respectively However, little or no phosphorus was removed at pH levels $\pm$ 1 unit from those for maximum removals. At a 1:1 cation-to-phosphorus ratio, neither Al^{+3} nor Fe^{+3} could effect any removal of tripolyphosphate at several pH levels examined.

Hannah (43) reported on two plant scale investigations where ferrous chloride was added in the primary clarifier. At Grayling, Michigan, a dose of 15-30 mg/l ferrous chloride, 30-50 mg/l sodium hydroxide, and 0.3-0.5 mg/l polymer produced 72 percent total phosphorus removal. In another study at Mentor, Ohio, where waste pickle liquor was used as a source of ferrous chloride, a dose of 43 mg/l as Fe, 66 mg/l of lime and 0.4 mg/l polymer produced 83.5 percent removal of total phosphorus. In the Nassau County Ibid (34) demonstration project, an alum dose of 200 mg/l at pH of 5.5-6.5 reduced phosphorus from 9 mg/l to 1.34 mg/l in the clarifier effluent. Operating costs were estimated at $0.04/1000 gal. not including disposal of alum sludge.

Culp (44) in pilot plant studies reported that a dose of 100-200 mg/l of alum applied to the activated sludge plant effluent will produce effluents with residual phosphorus of less than 0.3 mg/l at a cost of $63-117/million. gallons for plant capacity ranges from 2.5-200 MGD. All quantities referred to are in U. S. Gallons.

Lime precipitation of phosphorus occurs through the formation of hydroxyapatite and calcium carbonate. When lime is added to wastewater it reacts with the bicarbonate alkalinity to form calcium carbonate. Calcium ions also react with the orthophosphate to precipitate hydroxyapatite ($Ca_5(OH)(PO_4)_3$) The reaction proceeds as follows (45):

in the second stage with the addition of 6-12 mg/l of Fe^{+3}. Results of treatment Ibid (43) utilizing single and two-stage systems at Washington, D. C. and Lebanon, Ohio, where lime as CaO at a dose of 350-400 mg/l (pH 11.8-12) and 250 mg/l (pH = 9.5) produced a residual phosphorus content after multi-media filtration of 0.40 mg/l and less than 0.1 mg/l or 96 percent and greater than 89 percent removals, respectively. Cost of the single stage lime treatment was reported at 6.09¢/1000 gallons for 1 MGD plant without lime recovery.

Lime application to raw wastewaters was investigated in the laboratory (46) where lime addition to a pH of 11 resulted in total phosphorus removals of 80-90 percent while soluble orthophosphate was reduced by 97 percent. BOD removals of 50-70 percent and nitrogen and coliform removals of 25 percent and 99.9 percent were also achieved. Sludge production was reported as 1 percent of the volume of the raw waste treated.

In a study of an existing 1.6 mgd conventional activated sludge plant, Black and Lewandowski (47) showed that lime addition to the raw sewage influent increased the primary clarifier BOD, suspended solids, and total phosphorus removal efficiencies from 38, 57 and 25 to 72, 79 and 82 percent respectively. Other benefits noted were increased hydraulic and organic capacities in both primary and secondary processes.

Lime application to industrial wastes was illustrated in a laboratory and pilot plant study on the wastes from the Hercules, Inc., Harbor Beach plant where wheat flour is used to produce edible and industrial starches and glutin (48). Lime doses of 1340 mg/l to produce a pH of 9.5 followed by sedimentation resulted in the reduction of total phosphorus (all in the PO_4 form) from 300 mg/l to 5.6 mg/l, suspended solids from 3740 mg/l to 193 mg/l while BOD reduction averaged 27 percent.

Commercially available phosphorus precipitation processes include the Dorr-Oliver phosphate extraction process (PEP), the Eimco process and the Dow process. In the PEP process, lime is added to the primary clarifier to remove a major portion of the phosphorus and thereafter utilizing the activated sludge culture for removing a major portion of that remaining (49). The unique

Lanthanum was also found effective in precipitating condensed inorganic phosphates. For an initial pyrophosphate concentration of 18 mg/1 P, minimum phosphorus residuals of 0.05 mg/1 P (at pH 5.6) and 0.002 mg 1 P (at pH 8-9) were obtained with lanthanum-to-pyrophosphate equivalence ratio of 1:1 and 2:1, respectively. Using the same molar ratios and initial tripolyphosphate concentrations of 21.6 mg/1 P, residuals of 0.18 mg/1 P (at pH 6) and 0.007 mg/1 P (pH of 9) were obtained, respectively.

Comparison of the results of phosphorus removals using lanthanum and aluminum indicates the clear superiority of lanthanum for the precipitation of phosphorus. For example, at an initial orthophosphate concentration of 12 mg/1 and with precipitant-to-phosphorus molar ratios of 0.5:1, 1:1, and 2:1 phosphorus residuals of 6.8, 3.5, and 0.09 mg/1 P, 4.8, 0.01, <0.01 mg/1 were obtained using aluminum and lanthanum, respectively. The superiority of lanthanum to aluminum is especially pronounced in the precipitation of condensed phosphates. For example, at a 1:1 cation-to-phosphorus equivalence ratio, lanthanum produced good removals of tripolyphosphate over a broad range with a minimum residual of 0.18 mg/1 P at pH 6, while no tripolyphosphates removals were obtained with aluminum at several pH levels examined. Also at 2:1 equivalence ratio, no condensed phosphates removal was observed with aluminum at pH levels $\pm$1 unit from the optiumum pH of 5 while lanthanum produced residuals of less than 0.1 mg/1 P at pH range of 6-10 and less than 1.0 mg/1 P in the 4-10.5 pH range. This indicates the broad effective pH range for lanthanum as compared to aluminum.

Chemical precipitation of phosphorus from digester supernatant was recently investigated by Dearborn Chemical Division, W. R. Grace & Company, Chicago (54). In the first of two processes investigated, chemicals (soluble magnesium salts) were added to precipitate orthophosphates. Ultimate pH for precipitation was reported at pH-9-9.5.Ammonium hydroxide or sodium hydroxide were recommended to raise the pH. Orthophosphate may be precipitated as $Mg\ NH_4PO_4.6H_2O$, $Mg(PO_4).4H_2O$, or $Ca_3(PO_4)$. For hard waters, the authors recommended only pH adjustment to precipitate the phosphorus.

TABLE 2 - Phosphorus and BOD Removal for Lime Precipitation after Nesbitt (56)

Ref. No.		Process Scheme*	Size of Test	Coagulant		pH	Phosphorus Data		BOD Removal (%)
				Type	Dosage (mg/l)		Effluent ($mgPO_4/l$)	Removal (%)	
(109)		2	0.77 mgd	CaO	545	11.0	5.2	79	94
(109)	(110)	2 + filt.	0.77 mgd	CaO	545	11.0	0.4	98	--
(104)		2	--	$Ca(OH)_2$	280	--	1.5	93	--
(106)		2	jar	$Ca(OH)_2$	330	--	3.1	91	63†
(111)	(110)	1	jar	$Ca(OH)_2$	300	11.4	1.8	93	71
(112)	(110)	2	10 gpm	$Ca(OH)_2$ and alum	300	--	2.3	92	83
(113)		3	jar	$Ca(OH)_2$	200 20	9.5-10	5‡	--	70‡
(46)		1 + act.sl.	lab.	lime	--	<11.0	0.5-4.2	88-96	87-93
(46)		1 + Ox.PD.	lab.	lime	--	<11.0	0.2-0.3	98-99	--
(46)		1 + act.sl.	lab.	lime	--	9.5	4.0	90	92
(114) (115)		2 + filt.	7 mgd	lime	150 200	--	2.4	93	--

* Number refers to Figure 2.

† Refers to additional removal obtained by lime precipitation.

‡ Includes only mixing, coagulation, and settling.

NOTE: MGD x 3,785 = cu m/day

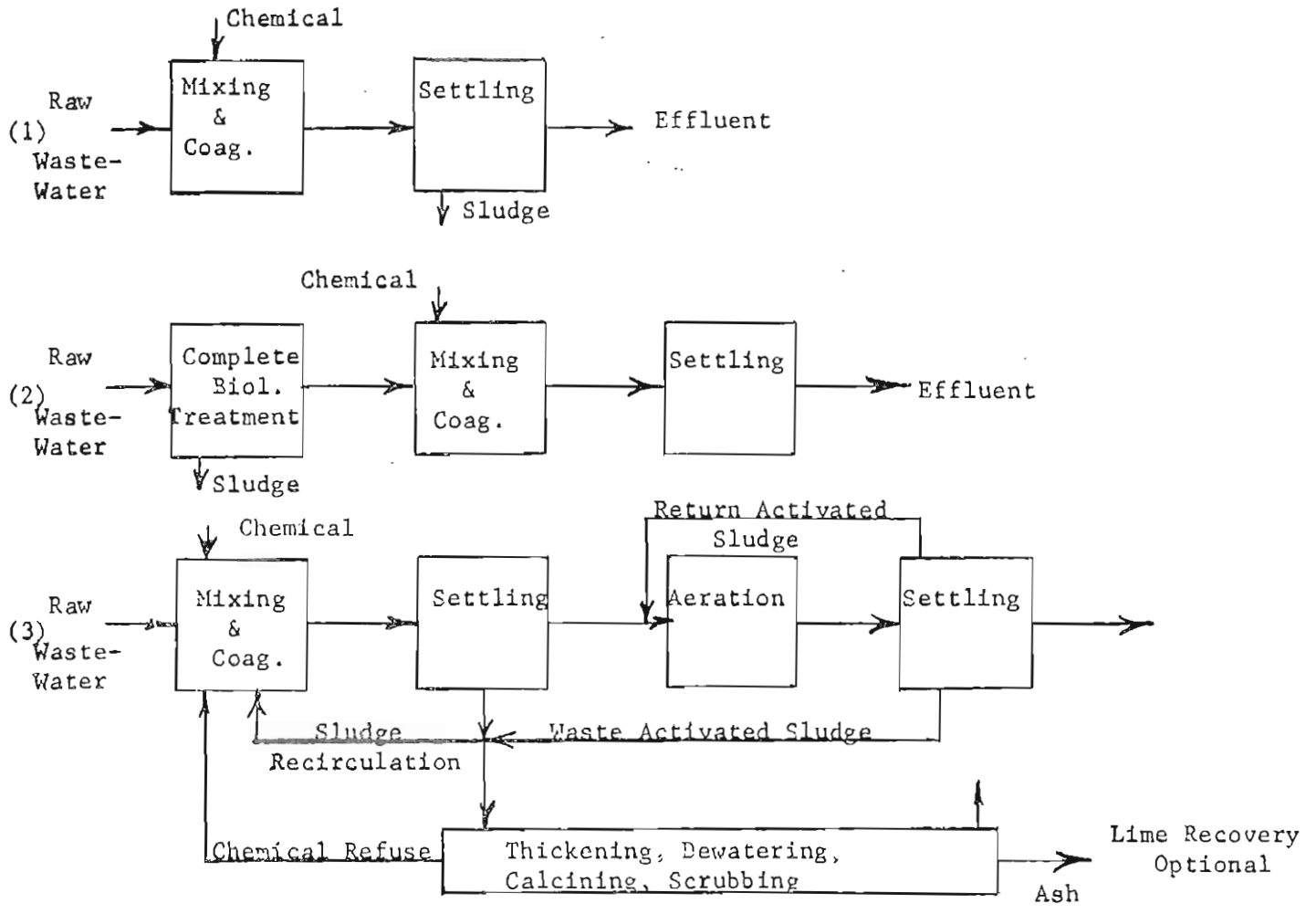


FIGURE 2: VARIOUS LIME PRECIPITATION SCHEMES
FOR PHOSPHORUS REMOVAL AFTER NESBITT (56)

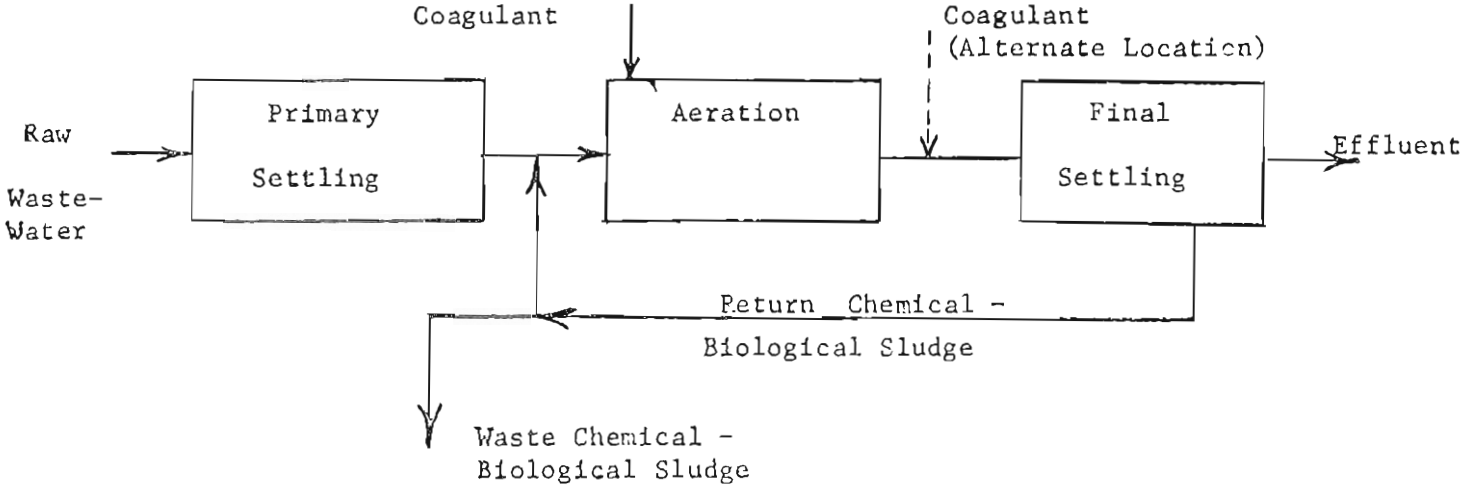


FIGURE 3: CHEMICAL-BIOLGICAL PHOSPHORUS REMOVAL PROCESS SCHEME
AFTER NESBITT (56)

TABLE 4

Effect of Aluminum on Sludges and Supernatant

After Brenner (57)

A. HIGH-RATE MIXED LIQUOR CHARACTERISTICS

	MLSS mg/l	MLVSS mg/l	% VOLATILE	SDI	ORGANIC LOAD lb COD/day/ lb MLVSS
BEFORE Al^{+++}	1,450	900	62	0.44	2.6
AFTER Al^{+++}	3,385	1,740	51	1.12	1.6

B. PER CENT PHOSPHORUS IN SLUDGES - TOTAL SOLIDS BASIS

	PRIMARY	WASTE ACTIVATED	MIXED PRIMARY PLUS W. ACTIVATED	DIGESTED
BEFORE Al^{+++}	1.1	2.1	1.6	2.2
AFTER Al^{+++}	1.1	6.2	4.5	5.2

C. TOTAL PHOSPHORUS IN SUPERNATANT - mg/l

BEFORE Al^{+++}	170
AFTER Al^{+++}	60

Studies at Pomona, California (58) indicated total phosphate removals of 85 per cent and 90 per cent at AL:P ratios of 1.5:1 and 2:1, respectively. Sodium aluminate was used as the coagulant. A plant scale study Ibid (57) at the Xenia, Ohio, Little Miami Plant utilizing sodium aluminate applied to the head of the aeration tank produced 90 per cent phosphorus removal at a dose of AL:P of 1.5:1 to 1.8:1 by weight. Barth and Ettinger (59) in a 12-day pilot plant study where sodium aluminate was added to the aeration tank reported an average total phosphorus residual and per cent removal of 1.53 mg/1 and 94.6 per cent, respectively. The average molar ratio of AL:P over this period was 1.26. The addition of aluminate was also reported to decrease the Sludge Volume Index (SVI) from 200 to 77.

Results of mineral additions to the aeration basin are summarized in Table 5. A summary of the performance of the chemical-biological processes is shown in Table 6.

Eberhardt and Nesbitt (60), in bench scale studies utilizing synthetic waste and a combined high rate activated sludge with chemical treatment, reported that for a pH of 5.5 and an alum dose of 261 mg/1 (Al:P molar ratio of 1.75:1) the total phosphorus removal exceeded 90 per cent. Total BOD_5 and filtered COD removals were reported to exceed 93 per cent. Sludge production was high but the sludge settleability improved as indicated by a Sludge Volume Index (SVI) of 22-25 as compared to 220 for the control. Upon repeating their investigation utilizing domestic waste, the authors discovered that additions of the chemicals to the aeration basin resulted in poor flocculation as well as clarification and recommended that chemicals be applied in the effluent line of the aeration basin. Employment of this system with combined aeration, mixing-flocculation and clarification theoretical detention time of only 4.16 hours, and an alum dose of 335 mg/1 (Al:P molar ratio of 2.44:1) at a pH 6 produced phosphorus, BOD_5, and suspended solids residuals and removals, respectively, of 1.6 mg/1 P and 95 per cent, 20 mg/1 BOD_5 and 92.3 per cent, 18 mg/1 suspended solids and 85.4 per cent. A flow diagram and the design parameters of the recommended process are shown in Figure 4.

One of the unique systems developed for nutrient removal is the three stage system developed at the advanced waste treatment research laboratory, Cincinnati, Ohio (61, 62). As shown in Figure 5, the system consists of three separate biological systems, each having its own separate sludge recycle. The first system is a high rate activated sludge for carbon oxidation along with chemical addition for phosphorus precipitation. The second stage is to provide nitrification that is followed by denitrification in the third stage for nitrogen removal. The wastewater flows in series through the three stages. Sodium aluminate is added to the aeration tank of the high rate activated sludge and the phosphorus is removed with the waste sludge. From pilot plant studies it was reported that an overall removal of COD, suspended solids, nitrogen, and total phosphorus at 86 per cent, 95 per cent, 91 per cent, and 88 per cent, respectively. Sodium aluminate of 1.5:1 on a mass input basis was reported. Chemical cost estimate for the aluminate was reported at $0.04/1000 gal. for 10 mg/1 phosphorus content.

Another unique chemical-biological process is a two-stage integrated system recently reported by Humenick and Kaufman (63). The first-stage is an aerobic biological process for the removal of the organic matter with its own sludge recirculation system. The second stage is a chemical precipitation stage for phosphorus removal. A flow diagram of the process is shown in Figure 6. Chemicals were applied into the conduit between the first stage clarifier and the flocculator. The unique feature of this process is the recirculation of the chemical sludge from the second stage clarifier to the first stage aerator in an amount approximately equal to the organic sludge. This aided in maintaining a high level of volatile solids in the aerator (>4000 mg/1) and at the same time made possible an increase in the organic loadings. Results of an eight months pilot plant study using sewage and sewage plus skimmed milk indicated that phosphorus removal exceeded 95 per cent with an effluent total phosphate of 0.27-0.4 mg/1. Flocculation detention as little as 16 minutes was reported. Both lime and alum were effective in providing high phosphorus removals. Lime dosage was 280 mg/1 producing a pH of 10.7-11 in the flocculator. Alum dosage was 200 mg/1 (AL:P molar ratio of 1.7:1) and HCl was used to maintain a constant pH of 5.7 in the flocculator. The process was also reported to provide BOD_5, COD, and suspended solids removals

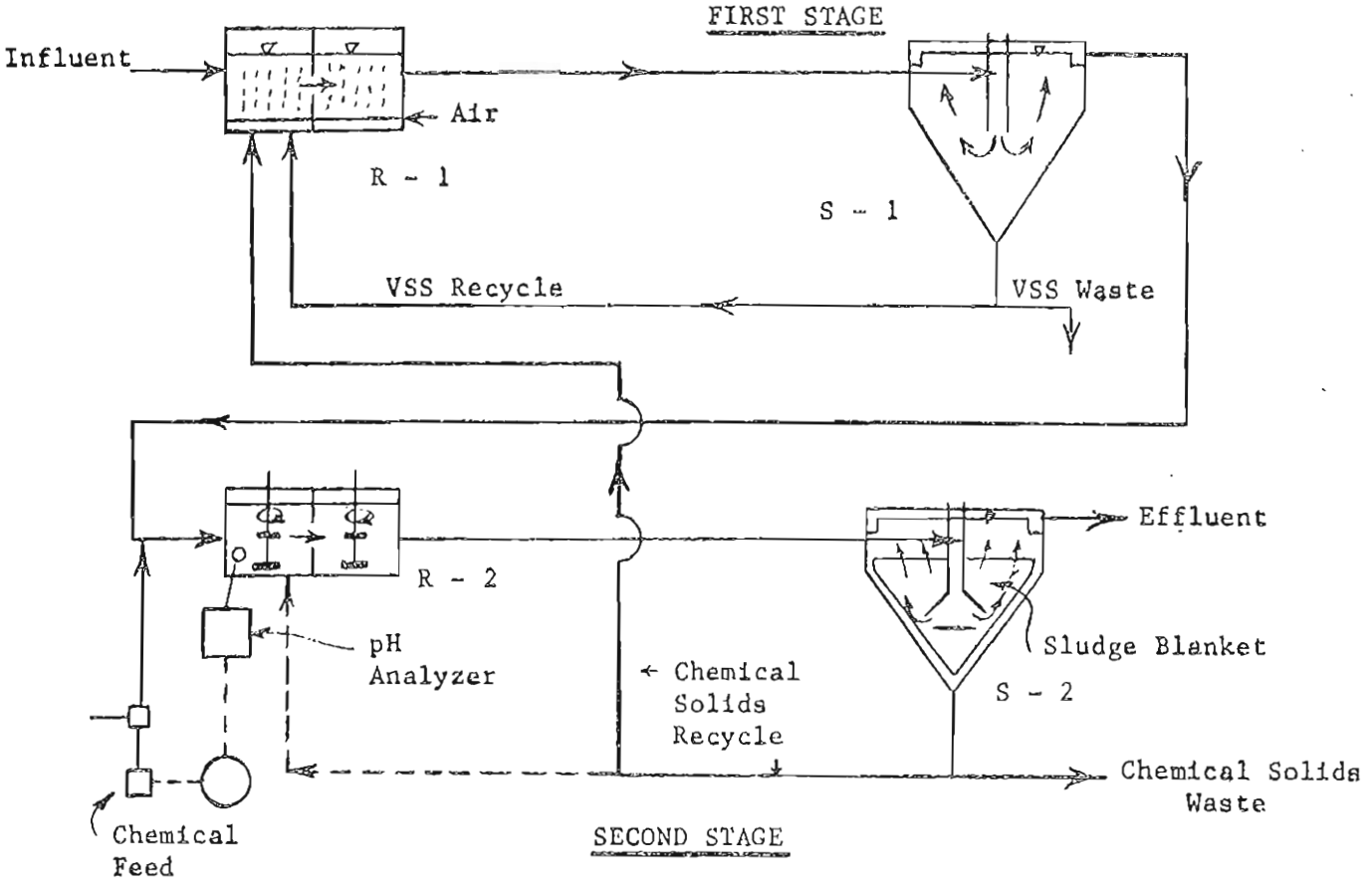


FIGURE 6: SCHEMATIC-INTEGRATED, BIOLOGICAL-CHEMICAL, PROCESS-PILOT PLANT
AFTER HUMENICK & KAUFMAN (63)

Grigoropoulos, et al, (65) added sodium aluminate ($Na_2O.AlO_3$-$3H_2O$) and alum (Al_2^{+3})(SO_4)$_3$- $18H_2O$) directly to the aeration tank in 145 liter/day activated sludge pilot plants at the Rolla, Missouri, southeast treatment plant. A sodium aluminate Al:P ratio of 1.3 and an alum Al:P ratio of 1.9 were optimum dosages. Phosphorus reductions averaged 84 per cent for both precipitants, from an influent concentration of 10.5 mg/l P to 1.7 mg/l in the effluent. Aluminum precipitated phosphorus concentrated in the anaerobic digesters was not released during the digestion process. Toxic effects from aluminum on the digestion process were not observed.

Studies on the application of chemicals to trickling filters are scarce. Barth, et al, (66) reported that application of sodium aluminate directly to the filter at Fairborn, Ohio, averaged 64 per cent phosphorus removal compared to 17 per cent removal for the undosed filter. Low removal was attributed to insufficient mixing, reduced residence time, short circuiting, and the absence of moving biological flocs.

Jebens and Boyle (67) concluded that phosphorus removals obtained during a four month experimental design period for a synthetic media trickling filter pilot plant, located at the Nine Springs Madison, Wisconsin, sewage treatment plant, were not related to the operational parameters of hydraulic load, depth, recirculation, or waste strength; however, consistently greater removals of phosphorus than could be attributed to biological removal were measured. This bonus-removal of phosphorus was attributed to a chemical precipitation of phosphorus with cations present in the hard water wastewater. Slime samples from the pilot filters were found to contain crystalline aluminum phosphate as demonstrated by x-ray diffraction. Preserved slime samples released calcium and phosphorus in molar ratios compatible with an apatite precipitate. Release of phosphorus from nonpreserved samples of filter slime suggested that precipitates of ferric iron phosphate were present.

From the previous discussion, one may conclude:

1. Chemical-biological processes appear to be more attractive than pure chemical precipitation when operating conventional biological plants.

must be sufficient to satisfy the waste "alum demand" before soluble phosphorus can be effectively removed. Cost for 1 MGD plant was estimated at $264,000 for capital and 12¢ per 1000 gallons for operation costs.

Weber, et al, (71) in a pilot plant investigation demonstrated the application of "physicochemical" treatment as a complete system. The system consisted of chemical coagulation-precipitation-dual media filtration and carbon absorption. Results consistently showed TOC and BOD_5 removals of 95-97 per cent at an alum dose of 170 mg/l despite the variation in wastewater strength and composition. Phosphorus removals of 90 per cent and nitrate of about 95 per cent were reported. For full scale operation, the authors recommended expanded bed columns and filtration, if needed, to follow the carbon absorption. Cost estimates were reported at $0.16/1000 gallons including amortization and capital cost. Conventional biological treatment was estimated at $0.11/ 1000 gallons. However, if tertiary treatment were to be added to the biological treatment to produce effluent comparable to that produced by the physicochemical, the total cost was estimated to be $0.26/1000 gallons.

Rizzo and Schade (72) reported on a polymer/carbon process which was demonstrated at the Cuyohoga County Waste Treatment Plant in Rocky River, Ohio. In this study, approximately 0.3 mg/l of anionic polymer was introduced to the raw sewage influent. The polymer was introduced to increase the removal of suspended solids in the existing primary clarifiers to a level which could be handled by granular activated carbon beds. Chemically clarified effluent was then applied to four pilot-scale, carbon absorption columns at a feed rate of 4 gpm/ft^2 and a contact time of 33 minutes. Results indicated that 93 percent BOD and suspended solid removal can be readily achieved with this process. Based on this study, it was concluded that activated carbon adsorption in place of conventional secondary treatment can treat the wastes to levels beyond that possible with only secondary treatment. A full scale, 10 MGD polymer/carbon process plant is now being installed and projected operating costs, including clarification, is 3 cents/1000 gal. of water treated.

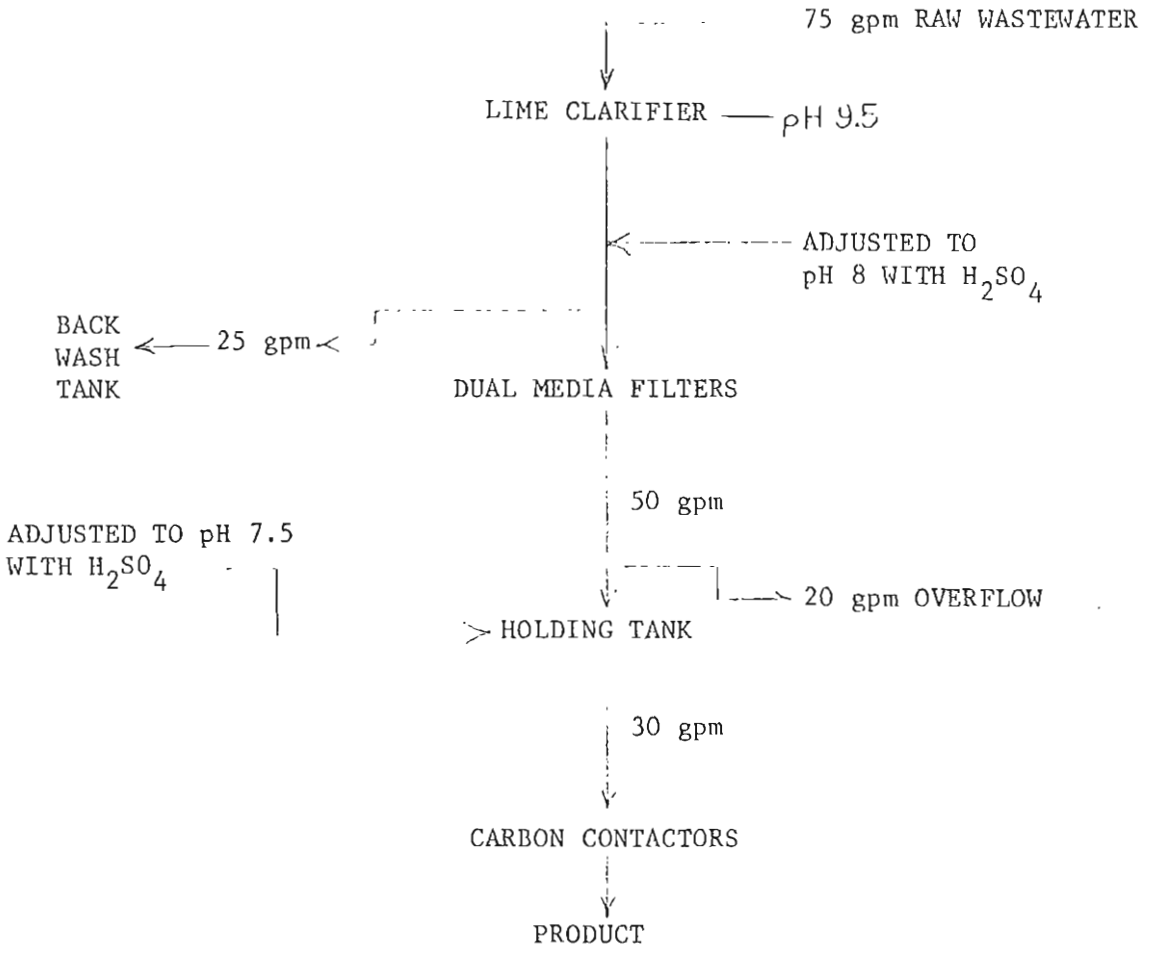


FIGURE 7 - FLOW DIAGRAM OF SINGLE-STAGE LIME CLARIFICATION AND ACTIVATED CARBON PILOT PLANT AT LEBANON, OHIO, FROM VILLIERS (74).

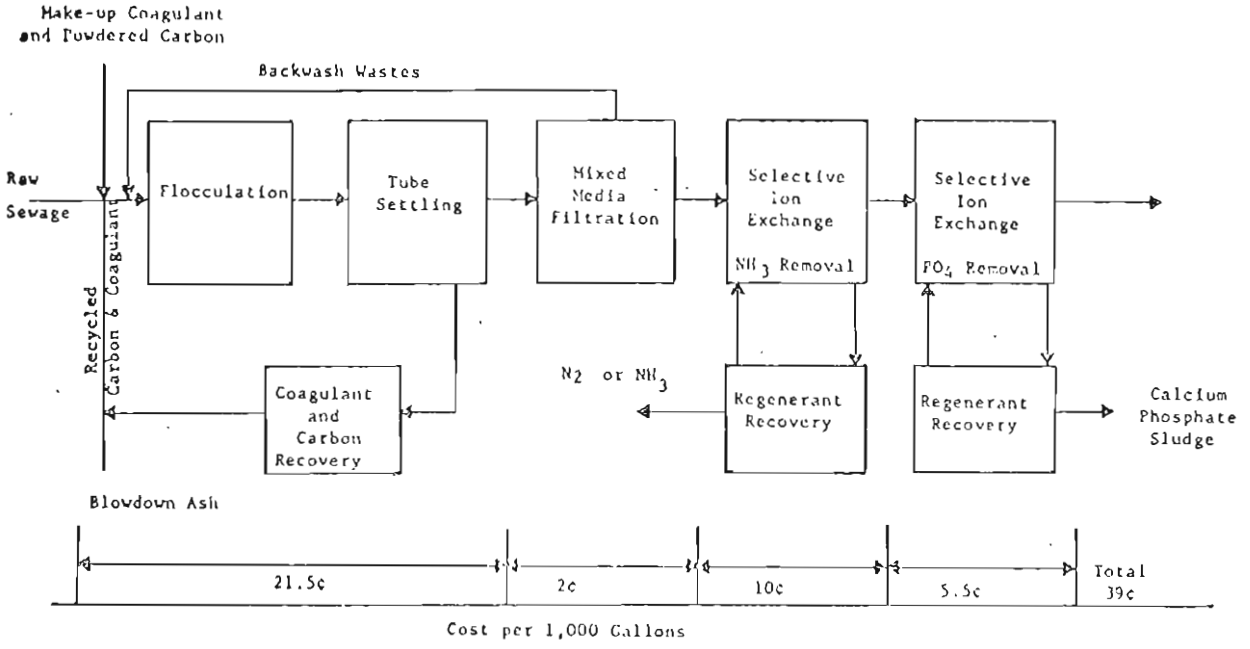


FIGURE 9 - POTENTIAL PHYSICAL-CHEMICAL PROCESS FOR REMOVAL OF ORGANICS, NITROGEN AND PHOSPHORUS FROM RAW WASTEWATER. COSTS FOR A 10 MGD PLANT, FROM SHUCKROW, ET AL, (75).

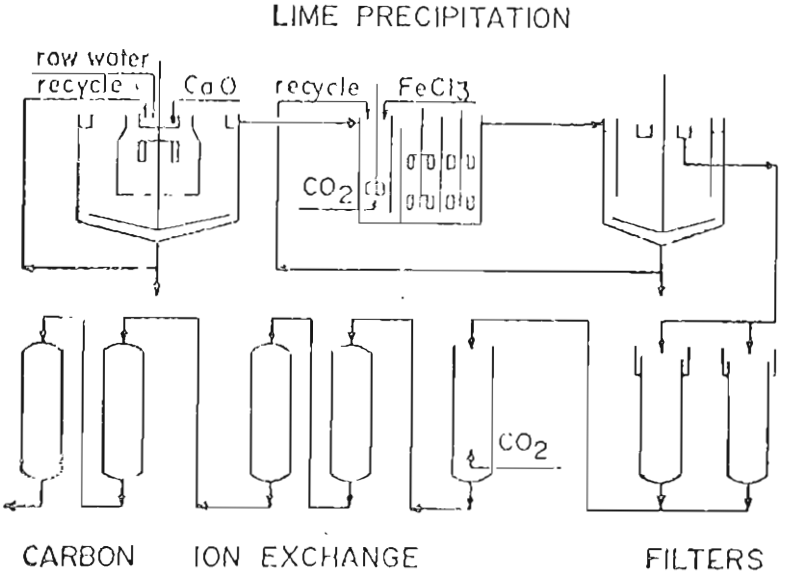


FIGURE 10 - PHYSICAL-CHEMICAL TREATMENT PILOT PLANT, FROM BISHOP ET AL (76).

From the previous discussion one may conclude that the physical-chemical systems appear to be an attractive approach to wastewater treatment. Compared to conventional biological treatment, the process offers:

1. Less sensitivity to shock loadings.
2. Not effected by toxicity.
3. Flexible in operation.
4. Requires only 25 per cent of the land area.
5. No secondary sludges produced.

Because of the current interest in physical-chemical wastewater treatment an appendix has been added describing several physical-chemical plants that are either proposed, in the design stage, or under construction.

(E) ION EXCHANGE (referred to in Table 1 as absorption)

The utilization of ion exchange for phosphorus removal was first investigated on an extensive level by Yee (77) working at the Oak Ridge National Laboratory. Yee tested three different types (A, B, and C) of a commerically available activated alumina (type A is designated F-1 and types B and C as F-20 and H-51 by the manufacturer, Aluminum Company of America) using two solutions (5 mg/1 and 25 mg/1 as PO_4) of each of the following: sodium orthophosphate, tetra-sodium pyrophosphate, penta-sodium tripolyphosphate, and sodium hexametaphosphate. Based on the results obtained, it was concluded that Type A alumina is the most desirable to use. Breakthrough curves for Type A indicated that orthophosphate removals of over 99 per cent with effluent concentrations of <0.05 mg/1 and <0.25 mg/1 could be acieved with 3000 and 1000 bed volumes (BV) for the 5 mg/1 and 25 mg/1, respectively. It was also noted that alumina treats polyphosphate better than orthophosphate. Regeneration of Type A alumina using sodium hydroxide followed by reacidifying with nitric acid produced a total of 12 BV of regenerant waste. The author concluded that for an initial orthophosphate concentration of 1 mg/1, a total of 20,000 BV can be processed with greater than 99 per cent phosphorus removal, making the process very attractive as a final polishing step. Cost estimates were reported at $39/million gallons and $64/MG for a feed containing 14 mg/1 and 23 mg/1 orthophosphate, respectively. These estimates assume an 8 per cent loss of aluminum for each regeneration cycle, when in fact, cycles after the second amounted to only 5 per cent loss. Comparison of the costs of this process with chemical precipitation is shown in Table 7.

Advantages of alumina columns over chemical precipitation were listed as follows by Convery (78):

1. Alumina is highly selective for phosphate and removes polyphosphate even better than orthophosphate.

2. In contrast to alum, iron or calcium salts, no extraneous ions are added.

3. Treatment with alumina does not effect the pH.

4. Variation in feed water composition and quality have little or no effect on removal efficiency.

5. Extremely low phosphorus residuals, in the order of 0.02 mg/l, could be achieved.

Laboratory work at Batelle - Northwest (79) extended the work of Yee and demonstrated that 95 per cent to better than 99 per cent phosphorus removals could be obtained from synthetic wastes containing 10--30 mg/l orthophosphate producing a residual phosphorus content of 0.03 mg/l. Column flow rates were reported at less than 10 column volumes/hour. Similar removal efficiencies were obtained with up to 500 column volumes of Richland trickling filter effluent containing 25--35 mg/l PO_4. Regeneration of the alumina columns was accomplished with 8 column volumes of 2 M NaOH. This regenerant solution was then treated with lime, precipitating the phosphorus as hydroxyapatite and the carbonate as calcite. Thus, a very small volume of solid waste is produced and practically no liquid waste. Alumina losses were put at 0.1 per cent per elution. Estimated cost, including filtration, for a 10 MGD plant was reported between 5-6¢/1000 gallons for effluent containing 3-4 mg/l phosphorus.

Elliassen and Wyckoff (80) in laboratory studies utilizing filtered activated sludge effluent and a commercially available anion exchanger (Duolite A-120D, product of Diamond Alkali Co., Redwood City, California) reported 97 per cent phosphorus removal, or a residual phosphorus of less than 0.2 mg/l in the effluent when treating up to 200 BV prior to regeneration.

Recently, Dynatech Corporation conducted laboratory studies on the electrochemical method to remove phosphates from wastewaters (83). The process utilizes sacrificial electrodes (aluminum or iron) and operates on the assumption that phosphate removal results from either a chemical precipitation or physical absorption or both. The electrode metal is at first dissolved by the flow of the current which reacts with the anions in the solution and precipitates as a floc. Results indicated that complete removal of phosphates occurred when using 300 coulombs/liter charge for normal phosphate concentration with both types of electrodes. Aluminum consumption averaged 0.7 mass units per single mass unit of PO_4 removed for complete phosphate removal. This mass ratio was about 2.0 for iron. Treatment cost (excluding labor and filtration) was estimated at 2.5¢ per 1000 gallons and 8¢ for 1000 gallons for iron and aluminum electrodes, respectively. Tests on raw sewage revealed the possiblity for utilizing the hydrogen generated for flotation.

Miller and Knipe (84) reported that in the electrochemical oxidation of municipal wastes the major cost factor is anode replacement and electrical power. Based on the type of anode used, costs varied from $0.90 to $2.40/ 1000 gallons.

From the preceding discussion, one may conclude that electrochemical treatment is still in the development stage and further research and testing would have to be conducted before full scale application.

require a minimum residence time of about 12 hours and over 24 hours at 17°C and 7°C, respectively.

In addition to sludge retention time, several other factors have been reported to influence nitrification in activated sludge plants. Johnson and Schroepfer (87) reported that a highly nitrified effluent would be obtained providing that the organic loading (lb BOD/lb MLVSS-day) of the aeration unit would be less than 0.30. Downing (88) Limited the dissolved oxygen in the aeration tank to a minimum of 1 mg/l for effective nitrification and listed the pH and the temperature as important environmental factors affecting the growth of the Nitrosomonas.

Biological denitrification is the process where nitrate is reduced to nitrogen gas. The denitrifiers are heterotrophic organisms utilizing organic sources of carbon for energy and growth. These include species of pseudomonas, Archromobacter, Bacillus and Micrococcus.

Since the denitrifiers require organic carbon for their metabolic activities and because in a typical activated sludge plant effluent most of the available carbon has already been oxidized, an external source of carbon has usually been added to the denitrification process. Methanol has received the widest application as a supplementary source of carbon.

Methanol requirements for effective denitrification have been reported by many investigators. McCarty, et al, (89) and St. Amant and McCarty (90) reported that total methanol requirements would consist of:

1. that needed for the reduction of nitrate to nitrogen gas calculated as 1.9 mg/l methanol per mg/l NO_3 - N reduced according to the following reaction:

$$NO_3^- + \frac{5}{6} CH_3OH \longrightarrow \frac{1}{2} N_2 + \frac{5}{6} CO_2 + \frac{7}{6} H_2O + OH^-$$

2. that consumed by the presence of oxygen, calculated at 0.67 mg/l of methanol per mg/l dissolved oxygen present according to the following reaction:

$$O_2 + \frac{2}{3} CH_3OH \longrightarrow \frac{2}{3} CO_2 + \frac{4}{3} H_2O$$

3. that needed to satisfy the requirements for bacterial growth estimated at 30 per cent in addition to the stoichiometrical requirements of 1. and 2. above. The authors presented the following relationship for estimating the total methanol requirements: $C_m = 2.47\ N_o + 1.53\ N_1 + 0.87\ D_o$

Another recent detailed study (93) of the process of nitrification-denitrification was conducted by ENVIROGENICS, a division of Aerojet-General Corporation, El Monte, California. The investigation was carried out in a laboratory scale unit consisting of an activated bed where the waste is continuously recirculated over a dense mass of microorganisms.

Results indicated that nitrification was complete at an organic loading up to 1.1 g COD/day/g MLVS which is higher than the loading of 0.30 lb BOD/lb MLVS-day reported by Johnson and Schroepfer. Dissolved oxygen utilization in the nitrification unit was typical of the endogenous respiration of bacteria. Both the rate of nitrification and the form of nitrogen present were influenced by the residence time. A residence time of 71 minutes resulted in 95 per cent nitrification. The rate of denitrification was reported to double for a 10°C rise in temperature. Downing had reported a double in the growth rate of the Nitrosomonas for a 7°C rise in temperature while studies at the Gulf South Research Institute reported that temperatures between 5 - 30°C had no appreciable effect on the denitrification process as long as adequate amounts of methanol are added.

Dissolved oxygen level in the nitrified effluent appeared to have an influence on the denitrification process. The authors reported a residence time of 400 minutes above which dissolved oxygen was reported to have no effect on the denitrification process and other studies Ibid (92) showed that dissolved oxygen did not affect biological denitrification. The authors concluded that the energy derived from the oxidation of the residual COD entering the denitrification unit is sufficient to account for only 12 per cent of the $N O_3$ - N reduction and, therefore, the bacteria must be utilizing stored reserves as the principle energy source. Denitrification efficiency was reported to be 90 per cent at a residence time of 8 hours while the overall efficiency of the nitrification-denitrification process was reported to range betwen 70-90 per cent of the total Kjeldhal nitrogen in the feed.

denitrification of the sedimentation supernatant, it was found that 90 percent of the nitrogen in the recycled mixture was removed.

From the preceding discussion, one may conclude:

1. Nitrification-denitrification is a reliable process for nitrogen removal. It has been tested by many workers under a variety of operating conditions and proved to achieve a high and consistent removal at an acceptable cost.

2. The columnar reactor appears to be more efficient than the suspended growth reactor and holds a promising potential for a wider application.

3. Methanol appears to be the most economical and the most practical source of carbon for the denitrification process. Total methanol requirements may be predicted by using the relationship developed by McCarty and his Co-Workers. Optimum methanol: NO_3 - N ratio appears to range between 2:1 to 3:1.

4. Sludge age seems to be the pertinent factor controlling the degree of nitrification. Sludge age of 2-3 days appears adequate.

5. Biological-denitrification will be best suited at locations where cold-freezing weather may prevail for a long period of time.

(B) AMMONIA STRIPPING

In raw domestic wastewaters, about 90 per cent of the nitrogen present is in the form of ammonia or urea with the remainder in the form of complex organic compounds such as proteins and amino acids. Most of these organic compounds will break down to form ammonia. Provided that nitrification has not set in during the treatment process, nitrogen (ammonia) can be stripped off.

Ammonia stripping operates on the principle of converting the ammonium ions to ammonia gas and then stripping off the ammonia gas by contacting the waste with ammonia-free air. Ammonium ions in wastewater exist in equilibrium with ammonia and hydrogen ions as follows:

$$NH_4^+ \rightleftarrows NH_3 + H^+$$

From the preceding discussion, one may conclude that although ammonia stripping will be limited to climates where freezing does not occur. In addition, the scale problem has yet to be solved.

(C) ION EXCHANGE

Information relative to the use of ion exchange for the removal of ammonium and nitrate ions from wastewater is scarce. Pilot plant studies Ibid (98) at Lake Tahoe making use of a commercial resin (Duolite C25, product of diamond Alkali) showed that 400 bed volumes could be treated prior to breakthrough to 1 mg/l ammonia-nitrogen. Influent ammonia-nitrogen was reported at 12-28 mg/l. Regeneration was with salt solution which was estimated at 0.5 per cent of the flow treated.

Recently, Battelle-Northwest Laboratory reported the development of a selective ion exchange process utilizing a natural zeolite, clinoptilolite, which was reported to be selective for ammonium ions in the presence of sodium, magnesium, and calcium ions (100, 101). Clinoptilolite occurs naturally in several extensive deposits in the western United States. The process basically concentrates the ammonia in a small volume of regenerant which can be recovered by air stripping or electrolyte treatment to remove the ammonia-nitrogen. Pilot plant application to clarified secondary effluent containing 16 mg/l ammonia nitrogen resulted in an average of 97 per cent ammonia removal at a flow rate of 6 gal/ft^2/min for a total of 70,000 gallons per day. Two-500 gallon clinoptilolite columns were used. An average of 93 per cent ammonia removal was also obtained in 330-gallon clinoptilolite columns at a flow rate of 8.4 gal/ft^2/min with a filtered secondary effluent having an initial ammonia-nitrogen content of 15 mg/l. Laboratory studies showed that organic fouling reduced the available exchange capacity by about 25 per cent during two upflow runs with no pre-treatment of secondary effluent. Cost estimates for 95 per cent ammonia removal were reported to be 10-14¢/1000 gallons in the 10-300 MGD plant range.

Nitrate specific ion exchange resin was developed by TYCO Laboratories, Inc., which incorporated selected primary Amines in Polystyrene (102). The best selectivity of nitrate ion over chloride ion ranged from 7.5-14 with

VI. MISCELLANEOUS PROCESSES

A series of new processes and new uses for developed processes are now being employed for effluent polishing, nutrient removal and in wastewater reclamation. A discussion of their uses for nutrient removal follows:

(A) ACTIVATED CARBON ADSORPTION

In this technique, wastewater is passed through a bed of granular or powdered activated carbon which has a high adsorption capacity for soluble organics found in water, (122, 123). Further references to activated carbon are found in the physical-chemical treatment section in the text and the Appendix.

Slechta and Culp Ibid (98) reported on the operation of the first full-scale granular carbon adsorption system (7.5 MGD) at South Lake Tahoe. Effluent from the conventional activated sludge process received chemical precipitation and filtration prior to activated carbon treatment. Over 80 per cent of the organics found in the secondary effluent was removed.

At Pomona, California, extensive work has been carried out utilizing a 200 gpm carbon treatment system consisting of four granular activated carbon columns operating in series. Parkhurst et al (124) report that the carbon contactors removed all the suspended solids and up to 78 per cent of the dissolved BOD in the secondary effluent. Further studies showed that by providing a supplemental organic feed (methanol) prior to carbon treatment, biological flora within the carbon columns will contribute significantly to the removal of organic matter and nitrates from the wastewater. From these studies it has been estimated that a four-stage granular activated carbon adsorption column, complete with regeneration, would cost $0.08/1000 gal for a 10 MGD plant (includes capital and operating costs).

Activated carbon, which is very porous with a large surface area per unit volume, is used primarily for removal of biodegradable organics, color and residual BOD (carbon nutrients). In order for this method of treatment to be economical, spent carbon must be regenerated for reuse. Presently the only practical method of reactivation of exhausted carbon is by thermal reactivation.

Yount and Crossman (128) indicated in a Florida study that growing organisms in hypertropic ponds and harvesting them reduces the productivity of those waters.

Shindala and Stewart (129) reported that the optimum chemical dosage for coagulation of municipal wastewaters in stabilization ponds was 75 to 100 mg/l of alum. Alum was the best coagulant of three studied. The others were ferric chloride ($FeCl_3$) and ferric sulphate ($Fe_2(SO4)_3$). Effluent concentrations were 2.5 mg/l BOD, 22.0 mg/l COD, 1.5 mg/l PO_4 and 3.5 mg/l Total N. Further research, with the addition of sludge recycle, was recommended.

Humenik and Hanna (130) operated a continuous laboratory scale system that indicated the existence of a symbiotic relationship between algae and bacteria for the removal of nutrients from wastewater. Supplemental aeration was not required and the process re-established after an upset. Settling was accomplished by an algae-bacterial floc, with good settling characteristics and a clear supernatant. The dominant algae was chlorella.

Torpey, et al, (131) used rotating aluminum disks illuminated by cool white fluorescent light to produce luxuriant growths of algae. Nutrient removal would be by algae stripping. This was followed by multi-media filtration and carbon adsorption. Flow varied from 7.5 to 9 gpm. The studies were conducted at the Jamaica water pollution control center in New York City.

McCriff and McKinney (132) examined an "activated algae" system on a laboratory scale at the University of Kansas using domestic sewage as a substrate. The study utilized a two-unit process approach that could be used to simulate the dark-light cycle experienced by biomass undergoing mixing in a large-scale mixing tank. Removals of 97 percent BOD, 87 percent COD, 92 percent nitrogen and 74 percent phosphorus were indicated. Operating parameters for larger scale application are being studied at the University of Kansas and the University of Mississippi.

(D) OXIDATION

Chemical oxidation is being investigated as an alternative to carbon adsorption for removing organics Ibid (126). It is now considered possible to completely oxidize organic material to carbon dioxide, oxides of nitrogen and oxides of other elements. Several oxidation techniques now being studied include (1) the use of oxygen species such as ozone, hydrogen peroxide, and hydroxyl free radicals; (2) ultra-violet light-catylyzed chlorine oxidation; (3) use of nuclear radiation. Although these processes have been classified as technically feasible, they are not at this time economically competitive.

(E) REVERSE OSMOSIS

In this process, wastewater is forced through membranes (normally cellulose acetate) to remove both dissolved organics and inorganics from solution. Pilot plant studies at Pomona, Ibid (126) indicate that suspended solids and soluble materials rejected by the membranes cause fouling and scaling problems. Other studies have shown that a portion of the nitrate ions will pass through the membranes. Based on these studies, it is estimated that reverse osmosis will cost from $0.25 to $1.00 per 1000 gal for a 10 MGD plant. Further research is underway to develop longer-lived and cheaper membranes that can handle higher application rates. With proper pretreatment to remove organic and solid matter, reverse osmosis may become a very useful and economical method of nutrient removal.

(F) DISTILLATION

Distillation, a well-known process for producing pure water, has been researched as a possible method of advanced treatment (135). The process, at the present, is very expensive when compared with other methods. Rapid organic fouling of the heat transfer surfaces require pretreatment of the wastewater by aeration or carbon methods. Present cost for distillation of sea water is estimated at $1.00 per 1000 gal treated and this cost estimate is also considered to be applicable to wastewater treatment (136).

Tilstra et al (144) investigated the use of a peat soil as a means of nutrient removal from secondary effluent at Detroit Lakes, Minn. Well drained soil conditions (aerobic) resulted in 95 to 99 percent removal of phosphorus. Nitrogen removal occurred with saturated conditions (anaerobic) but phosphorus removals decreased. The preferable system would be drainage for phosphorus removal. Nitrogen would have to be harvested in crops which could severely limit the hydraulic loading.

Lance (145) reviewed nitrogen removal by soil mechanisms. Nitrogen may be removed from a soil in gaseous form by volatilization of ammonia or by denitrification. Volatilization of ammonia is not important except in streams or channels during travel to a disposal area. Denitrification by bacterial action, as in anaerobic columns, occurs when the soil is saturated and anaerobic conditions exist. Additional research is required to determine if denitrification can be sustained and if an additional carbon source is necessary. Large quantities of ammonium ion can be absorbed by clays but the immobilization is not permanent. Soil organic matter and microbial cell tissue, which is converted to soil organic matter as the microbes die, may also immobilize nitrogen in large quantities. Further study is needed on how to utilize this capacity on a long term basis. Removal of nitrogen in plant tissue is effective but is unsuitable for large urban areas because it requires large tracts of land. At a rate of 300 pound/acre-year of nitrogen 160 acres would be required for 1 MGD. It may be attractive for small to medium sized communities because of cheaper land costs and the economic return from the crop harvested.

DeVries (146) indicated that renovation of primary effluent with fine sand was close to 100 percent with respect to BOD and phosphorus. An Ottawa sand filter resulted in only partial renovation. Nitrate removals were low. When the soil filters were operated at near freezing temperatures, clogging occurred. The clogging reversed after temperatures were increased. This indicated that irrigation of frozen soils with effluents would not be advisable.

Kardos & Sopper (147) have successfully operated a year round irrigation system at Pennsylvania State University and note that while at sub-zero temperatures soil in grassy cropland areas has frozen shut, soil in forested areas has remained porous and receptive to effluent even in the coldest winter.

VII. DISCUSSION & CONCLUSIONS

The extensive research in the literature clearly indicates that the technology is currently available to provide effective nutrient removal from wastewaters at reasonable cost. A variety of processes have been extensively investigated and proved, through field testing, to achieve high efficiencies in removing both nitrogen and phosphorus from wastewater. The choice for process selection by the design engineer depends on numerous considerations, among which are the type of nutrient to be removed, the desired efficiency, the disposal of produced residues, the water quality criteria for receiving streams, and the economic feasibility.

PHOSPHORUS REMOVAL

The currently available methods for phosphorus removal include biological, some type of chemical precipitation, and ion exchange. To date, biological removal by activated sludge through "luxury uptake" based on modification of aeration system operating parameters to maximize phosphorus uptake has not proven to be a predictable phenomenon and, therefore, design for phosphorus removal on this basis should not be attempted.

Some type of chemical precipitation appears to be the most reliable and economic method currently available for phosphate removal. A variety of chemicals, (iron salts, aluminum salts, and lime) have been extensively tested and proved to be equally effective in producing effluents with very low (less than 0.1 mg/1) phosphorus residuals at a modest cost. In addition to the precipitation of phosphorus, chemical precipitation provides a modest reduction in BOD and a high suspended solids reduction. Lanthanum proved to be far superior to aluminum for the precipitation of phosphorus and shows a great potential for full scale application.

Chemicals may be added to raw sewage, to the aeration tank, or to the final effluent as a tertiary process. Direct chemical application to the aeration basin appears to be the most economical, but leaves phosphorus residuals of 1-2 mg/1. All chemicals and points of application have been fully investigated and field tested. The choice of chemical, chemical dose, and point of

TABLE 9 - Estimated Cost of Phosphorus Removal
After Nesbitt (56)

Ref. No.	Precipitant	Process Scheme	Plant Size (mgd)	Treatment Cost (¢/1,000gal)
(24) (108)	biological	act. sl.	pilot	<1
(107)	biological	act. sl + acid strip.	10	4
(56)	bio-chem.	Figure 3	10	<5
(56)	cation	Figure 2, scheme 2	10	<4
(56)	cation	Figure 2, scheme 2 + filtration	10	<8
(113)	lime	Figure 2, scheme 3 w/o lime recovery	1	0‡ 2+*
(108) (115)	lime	Figure 2, scheme 2 + filtration	4-7.5	<9
(114)	lime	Figure 2, scheme 1 + act. sl.	10	0.3‡
(68)	fil. alum	Figure 2, scheme 2 + filtration + lakes	3	15
(108) (119)	liquid alum	Figure 2, scheme 2 + filtration	2.5-4	<9
(81)	ion exchange		1 and 10	6†

*Chemical costs. Authors estimate these costs would be balanced by reductions in power and sludge handling due to 50-percent reduction in organic load on biological treatment units.

†Does not include cost of waste regenerant disposal.

‡ Includes savings because of reduction in secondary unit size and sludge handling costs.

Note: Mgd x 3,785 = cu m/day; gal x 3.785 = liter

to be best suited to locations where freezing weather prevails over a long period and where consistently high removals need to be maintained.

A comparison of nutrient removal processes is presented in Table 8, and cost estimates for phosphorus removal are summarized in Table 9.

MISCELLANEOUS PROCESSES

Carbon adsorption, both granular and powdered, is an efficient unit operation for removal of soluble organic materials from pretreated wastewaters. The effects of biological activity in the carbon columns or beds has still to be fully evaluated.

Algae preblooming in ponds is potentially very useful where land is available and the climate is suitable. The activated algae and rotating biological disks processes require further research and development.

Removal of all inorganics from wastewater has not received widespread attention so far, but it will become more important when the need for reclaimed wastewater increases. Electrodialysis appears to be the most practical, with reverse osmosis and distillation becoming more competitive with further research. The various forms of oxidation are not economically competitive with established processes at this time.

Land application may afford an economical approach towards the reduction of phosphorus in the sewage effluent from small and medium sized communities and some organic industrial wastewaters.

Reduction of other nutrients such as nitrogen has been successfully achieved on a pilot scale by land application, but the practical application of such a process to full scale, long term conditions is not yet proven.

A careful assessment of the following factors; wastewater discharge management, economics, cation exchange capacity, nitrogen reduction, land drainage, land stability, and climate must be made before land disposal of effluent for nutrient removal is attempted.

IX. LIST OF REFERENCES

1. Sawyer, C. N. , "Basic Concepts of Eutrophication," Journal Water Pollution Control Federation, 38, 5, 737 (May, 1966).

2. Sawyer, C. N., "The Need for Nutrient Control," Journal Water Pollution Control Federation, 40, 3, 363 (March 6, 1968).

3. Sawyer, C. N., "ABC's of Cultural Eutrophication and its Control," Water and Sewer Works, 118, 9, 278 (September, 1971) and 10, 322 (October, 1971).

4. Grundy, Richard D., "Strategies for Control of Man Made Eutrophication," Environmental Science and Technology, 5, 12, 1185 (December, 1971).

5. Rodhe, W., "Environmental Requirements of Fresh Water Plankton Algae, "Symbolae Botanicae Upsaliensis, 10, 1 (1948).

6. Sawyer, C. N., "Fertilization of Lakes by Agricultural & Urban Drainage," Journal New England Water Works Association, 61, 109 (1947).

7. Schmidt, F. L., and McKinney, R. E., "Phosphate Removal by Lime Biological Scheme," Journal Water Pollution Control Federation, 41, 7, 1259 (July, 1969).

8. Advanced Waste Treatment Research, Federal Water Pollution Control Administration Summary Report, "Advanced Waste Treatment July, 1974 - July, 1967, FWPCA Publication No. WP-20-AWTR-19 (1968).

9. Summary Report, "The Advanced Waste Treatment Research Program, United States Public Health Service - January, 1962 - June, 1964 P.H.S. Publication No. 999-WP-24 (1965).

10. Eliassen R. and Tchobanoglous, G., "Chemical Processing of Wastewater for Nutrient Removal," Journal Water Pollution Control Federation, 40, 5, Part 2, R171 (May, 1968).

20. Scalf, M. R., et al., "Phosphate Removal by Activated Sludge-Amenability Studies at Mansfield, Ohio," Federal Water Pollution Control Administration, Robert S. Kerr Water Research Center (November, 1968).

21. Connell, C. H., Vacker, D., and Wells, N. W., "Parameters of Phosphate Removal by Activated Sludge" 7th Industrial Water & Waste Conference, University of Texas (June 1-2, 1967).

22. Myers, L. H., et al., "Phosphate Removal by Activated Sludge-Amenability Studies at Smithfield, North Carolina," Federal Water Pollution Control Administration. Robert S. Kerr Water Research Center (November, 1968).

23. Sekikawa, K. S., Nishikawa, M., Okazaki, Kato, K. "Release of Soluble Phosphate in the Activated Sludge Processes" 3rd International Conference on Water Pollution Research, Munich, Germany, (September 1966) cited after Menar and Jenkins (16).

24. Vacker, D., Connell, C. H., and Wells, W. N., "Phosphate Removal through Municipal Wastewater Treatment at San Antoino, Texas," Journal Water Pollution Control Federation, 39, 5, 750 (May, 1967).

25. Scalf, M. R. Pfeffer, F. M., and Lively, D., "Phosphate Removal at Baltimore, Maryland," Proc. American Society Civil Engineers, 95, SA 5, p. 817 (October, 1969).

26. Milbury, William F, McCauley, Donald, Hawthorne, Charles H., "Operation of Conventional Activated Sludge for Maximum Phosphorus Removal," Journal Water Pollution Control Federation, 43, 9, 1890 (September, 1971).

27. _____, "Phosphate Study at Baltimore Back River Waste Water Treatment Plant," By the City of Baltimore, Environmental Protection Agency, Report No. 17010 DFV 09/70 (September, 1970).

28. Witherow, J. L. "Phosphate Removal by Activated Sludge," Federal Water Pollution Control Administration, Robert S. Kerr Water Research Center (May, 1969).

36. Borchardt, J. A. and Azad, H. A., "Biological Extraction of Nutrients," Journal Water Pollution Control Federation, 40, 10, 1739 (October, 1968).

37. Mulbarger, M. C., Shifflett, O. G., Murphy, M. C., and Huffman, D. D., "A Full Scale Evaluation of "Luxury Uptake" For Phosphorus Removal," Journal Water Pollution Control Federation, 43, 8, 1617 (August, 1971).

38. Ferguson, J. F., Stumm, W., and Jenkins, D., "Calcium Phosphate Precipitation in Waste Water Treatment Processes," 3rd. Joint Meeting, American Institute of Chemical Engineers and Institute Mexicano De Ingenieros Quimicos, Denver, Colorado (August 30-September 2, 1970) cited after (27).

39. Connell, C. H., "Biological Phosphorus Removals" Current status, Advanced Waste Water Treatment, Federal Water Quality Administration (July, 1970).

40. Stumm, W., Discussion in "Advances in Water Pollution Control Research" Proc. 1st. International Conference Water Pollution Research, Pergman Press, London, Vol. 2, p. 216 (1964).

41. Convery, J. J., "Phosphate Removal By Tertiary Treatment With Lime and Alum" Symposiumon Nutrient Removal and Advanced Waste Treatment, Tampa, Florida (1968).

42. Recht, H. L. and Ghassemi, M., "Kinetics and Mechanism of Precipitation and Nature of the Precipitate Obtained in Phosphate Removal From Waste Water Using Aluminum (111) and Iron (111) Salts" Federal Water Quality Administration, Report No. 17010 EKI 04/70, Cincinnati, Ohio (April, 1970).

51. Wukasch, R. F., "The Dow Process for Phosphate Removal," Federal Water Pollution Control Adminstration, Phosphorus Removal Symposium, Chicago, Ilinois (June, 1968).

52. Thomas, E. A., "Phosphate Removal by Recirculating Iron Sludge," Journal Water Pollution Control Federation, 44, 2, 176 (February, 1972).

53. Recht, H. L., and Ghassemi, M., "Phosphate Removal from Waste Waters Using Lanthanum Precipitation," Federal Water Quality Administration, Report No. 17010 EFX/70, Cincinnati, Ohio (April, 1970).

54. Dunseth, M. G., et al., "Ultimate Disposal of Phosphate from Waste Water by Recovery as Fertilizer," Federal Water Quality Administration, Report No. 17010ESJ/70, Cincinnati, Ohio (January, 1970).

55. Eberhardt, W. A. and Nesbitt, J. B., "Chemical Precipitation of Phosphorus in a High-Rate Activated Sludge System," Journal Water Pollution Control Federation, 40, 7, 1239 (July, 1968).

56. Nesbitt, J. B. "Phosphorus Removal - The State of the Art" Journal Water Pollution Control Federation, 41, 5, 701 (May, 1969).

57. Brenner, R. C., "Combined Biological - Chemical Treatment for Control of Phosphorus," Symposium on Advanced Waste Treatment, Dallas, Texas (January 12-16, 1971).

58. Barth, E. F., "Phosphate Removals by Mineral Addition," Symposium on Nutrient Removal and Advanced Waste Treatment, Tampa, Florida (November, 1968).

59. Barth, E. F., and Ettinger, M. B., "Mineral Controlled Phosphorus Removal in Activated Sludge Process," Journal Water Pollution Control Federation, 39, 8, 1367 (August, 1967).

60. Eberhardt, W. A., and Nesbitt, J. B., "Chemical Precipitation of Phosphate Within a High Rate Biooxidation System I," Proc. of 22nd. Purdue Industrial Waste Conference, Purdue University (1967).

69. Bell, G. R., Libby, D. R., and Lordi, D. T., "Phosphorus Removal Using Chemical Coagulation and a Continuous Counter Current Filtration," Federal Water Quality Administration, Report No. 17010 EDO 06/70, Cincinnati, Ohio, (June, 1970).

70. Libby, D. V., Bell G. R., and Wirsig, O. A., "Chemical-Physical Treatment of Municipal Wastewater Using Continuous Counter-Current Filtration," Journal Water Pollution Control Federation, 44, 4, 574 (April, 1972).

71. Weber, W. J., Jr., Hopkins, C. B., and Bloom, R., Jr., "Physicochemical Treatment of Waste Water," Journal Water Pollution Control Federation, 42, 1, 83 (January, 1970).

72. Rizzo, J. L., and Schade, R. E., "Secondary Treatment with Granular Activated Carbon," Water and Sewage Works, 118, R62, (Reference, 1971).

73. Villiers, R.V., Berg, E.L., Brenner, C.A., and Masse, A.N., 'Municipal Wastewater Treatment by Physical and Chemical Methods," Water and Sewage Works, 118, R62, (Reference, 1971).

74. Villiers, Roland V., "Single-Stage Process Checks Out", Water and Wastes Engineering, 32 (January, 1972).

75. Shuckrow, A. J., Dawson, G. W., and Olesen, D. E., "Treatment of Raw and Combined Sewage," Water and Sewage Works, 118, 4, 104 (April, 1971).

76. Bishop, Doloff F., O'Farrell, Thomas P., and Stamberg, John B., "Physical-Chemical Treatment of Wastewater," Journal Water Pollution Control Federation, 44, 3, 361 (March, 1972).

77. Lee, W. C., "Selective Removal of Mixed Phosphate by Activated Alumina," Journal American Water Works Association, 58, 2, 239 (February, 1966).

78. Convery, J. J., "Alternative Methods for Phosphate Removal" Symposium on Nutrient Removal and Advanced Waste Treatment, Tampa, Florida (November, 1968).

79. Ames, L. L., and Dean, R. B., "Phosphorus Removal from Effluents in Alumina Columns," Journal Water Pollution Control Federation, 42, 5, R161 (May, 1970).

90. St. Amant, P. P. and McCarty, P. L., "Treatment of High Nitrate Waters," Journal American Water Works Association, 61, 12, 659 (December, 1969).

91. English, J. N., "Nitrate Removal in Granular Activated Carbon and Sand Columns," Internal Report of the Advanced Waste Treatment, Research Laboratory, Federal Water Quality Administration, Pomona Water Reclamation Plant, Pomona, California (February 1969) cited after Smith.

92. _____, "Methanol Requirements and Temperature Effects in Waste Water Denitrification," Gulf South Research Institute for the Environmental Protection Agency, Report No. 17010 DHT 09/70, Cincinnati, Ohio (September, 1970).

93. Mechalas, B. J., Allen, P. M. III, and Matyskiela, W. W., "A Study of Nitrification and Denitrification," ENVIROGENICS, For the Federal Water Quality Administration, Report No. 17010 DRD 07/70, Cincinnati, Ohio (July, 1970).

94. Smith, J. M. Masse, A. N., Feige, W. A. and Kamphake, L. J., "Nitrogen Removal From Municipal Waste Water by Columnar Denitrification," Environmental Science and Technology, 6, 3, 260 (March, 1972).

95. Tamblyn, T. A., and Sword, B. R., "The Anaerobic Filter for the Denitrification of Agricultural Subsurface Drainage," 24th Purdue Industrial Waste Conference, Purdue University (May, 1969).

96. Seidel, D. F., and Crites, R. W., "Evaluation of Anaerobic Denitrification Process," Proc. American Society of Civil Engineers, 96 SA 2, 267 (April, 1970).

97. Mulbarger, M. C., "Modification of the Activated Sludge Process for Nitrification and Denitrification," 43rd. Conference Water Pollution Control Federation, Dallas (October, 1969).

98. Slechta, A. F., and Culp, G. L., "Water Reclamation Studies at the South Tahoe Public Utility District," Journal Water Pollution Control Federation, 39, 5, 787 (May, 1967).

99. Farrell, J. B., "Ammonia Nitrogen Removal by Stripping with Air," Symposium on Advanced Waste Treatment, Dallas, Texas (January 12-14, 1971).

109. Owen, R., "Removal of Phosphorus from Sewage Plant Effluent With Lime," Sewage and Industrial Wastes, 25, 5, 548 (May, 1953).

110. Eberhardt, W. A. and Nesbitt, J. B., "Chemical Precipitation of Phosphorus in a High-Rate Activated Sludge System," Journal Water Pollution Control Federation, 40, 7, 1239 (July, 1968).

111. Rand, M. C., and Nemerow, N. L., "Removal of Algae Nutrients From Domestic Waste Water," Report No. 9, Department of Civil Engineering, Syracuse University Research Institute (1965).

112. Garland, C. F., and Shell, G. L., "Integrated Chemical-Biological Waste Water Treatment," AWTRA-FWPCA, U. S. Department of Interior, Washington, D. C., (1966).

113. Albertson, O. E., and Sherwood, R. T., "Phosphate Extration Process," Journal Water Pollution Control Federation, 41, 8, 1467 (August, 1969).

114. Schmidt, L. A., and McKinney, R. E., "Optimization of Phosphorus Removal With Lime Treatment," Paper Presented, University of Kansas, Sanitary Engineering Conference.

115. Culp, R. L., Paper Presented at a FWPCA - Sponsored Workshop on Phosphorus Removal, Chicago, Illinois (1968).

116. Neil, J. H., "Problems and Control of Unnatural Fertilization of Lake Waters," Proc. 12th. Purdue Industrial Waste Conference, Purdue University, (1958).

117. Lea, W. L., Rohlich, G. A., and Katz, W. J., "Removal of Phosphates From Treated Sewage," Sewage Industrial Wastes, 26, 3, 261 (March, 1954).

118. Bennet, G. E., Eliassen, R., and McCarty, P. L., "Reclamation of Reusable Water From Sewage," Technology Report 58, Department of Civil Engineering, Standford University (1965).

119. Priday, W., Moyer, H. E., and Culp, R. L., "The Most Complete Waste Water Treatment Plant in the World," American City, 79, 123 (1964).

130. Humenik, Frank J., and Hanna, George P. Jr. "Algae-Bacterial Symbiosis for Removal and Conservation of Wastewater Nutrients," Journal Water Pollution Control Federation, 43, 4, 580 (April, 1971).

131. Torpey, Wilbur N., Heukelekian, H., Kaplovsky, A. Joel, and Epstein, R., "Rotating Disks with Biological Growths Prepare Wastewater for Disposal or Reuse, "Journal Water Pollution Control Federation, 43, 11, 2181 (November, 1971).

132. McGriff, E. Corbin, and McKinney, Ross E., "Activated Algae: A Nutrient Removal Process," Water and Sewage Works, 108, 11, 377 (November, 1971).

133. Smith, J. O., and Eisenman, J. L., "Electrodialysis in Advanced Waste Treatment," Federal Water Pollution Control Administration, Publication No. WP-20-AWTR-18 (1966).

134. Brunner, C. A. "Pilot-Plant Experiences in Demineralization of Secondary Effluent Using Electrodialysis," Journal Water Pollution Control Federation, 39, 10, Part 2, R1 (October, 1967).

135. Neale, J. H., "Advanced Waste Treatment by Distillation," U. S. Public Health Service, Publication No. 999-WP-9 (1964).

136. Gerster, J. A., "Cost of Purifying Municipal Wastes by Distillation," U. S. Public Health Service, Publication No. 999-WP-6 (1963).

137. Evans, David R. and Wilson, Jerry C. "Capital and Operating Costs - AWT," Journal Water Pollution Control Federation, 44, 1, 1 (January, 1972).

138. Atkinson, A. L., and Jones, P. H., "Reduction of Nitrogen from an Existing Activated Sludge Plant - A Case Study", 4th Canadian Symposium on Water Pollution Research, McMaster University (February, 1969).

139. Foster, H. B. Jr., and Jopling, W. F., "Rationale of Standards for Use of Reclaimed Water," Journal of the Sanitary Engineering Division, Proc. of the A.S.C.E., 95, SA3, 503 (June, 1969).

149. Bouwer H., "Symposium on Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland, August 21-24, 1972".

150. Parizek R. H., "Symposium on Recycling Treated Municipal Wastewater and Sludge through Forest and Cropland, August 21-24, 1972"

X. APPENDIX

PHYSICAL-CHEMICAL TREATMENT PLANTS

IN PROGRESS

X. APPENDIX

PHYSICAL-CHEMICAL TREATMENT PLANTS IN PROGRESS

A.1 General

The basic design parameters used in the design of carbon treatment plants may vary in practice over only a relatively narrow range. Determination of the values of these parameters for a particular wastewater must be accomplished by testing.

Table A-1 summarizes the design parameters from some of the new carbon plants being designed as well as from older plants. Many of the figures are drawn from preliminary engineering reports and must therefore be regarded as tentative and subject to change. The ranges over which some of these parameters vary are:

Design Parameters

Carbon Requirements: (tertiary plants)	250–350 lbs of Carbon per MG
(secondary plants)	500–1800 lbs of Carbon per MG
Hydraulic Loading	2–10 gpm/sq ft
Contact Time (empty bed)	15–40 minutes
Backwash Rate	15–20 gpm/sq ft
Vessel Configuration	One and two stage

A.2 Physical Chemical Treatment Plants Being Built

Most design engineers considering the application of carbon as part of a physical-chemical treatment scheme cite its main attraction to be its ability to produce an effluent very low in dissolved organics. This ability makes it rather easy to meet treatment objectives of 85% BOD removal or more, either through upgrading an existing biological plant or through building an entirely new PCT plant. Table A-2 is a list of some of those plants which are incorporating physical-chemical treatment. Some of the plants cited above are worthy of further comment.

Rocky River, Ohio(1)

Originally a primary treatment plant, effluent quality standards intended to protect Lake Erie demanded an improved treatment performance by the Rocky River plant. The treatment objective was set at BOD_5=15 mg/l. Restrictive land area forbade the construction of a conventional biological secondary plant, so a PCT plant was designed. The primary facility will be converted into part of the PCT plant, so the influent to the PCT plant will be raw wastewater. The treatment sequence is planned to be: 1. gross solids removal; 2. chemical clarification via ferric chloride and polymer; 3. downflow carbon adsorption; 4. chlorination. No filtration step is provided prior to the carbon treatment, a notable point.

The design (average) flow is 10 MGD, projected for 1980. The peak flow is projected as 20 MGD. Average raw wastewater characteristics (1967) include: suspended solids: 140 mg/l; BOD_5: 110 mg/l; COD:240 mg/l; total phosphorus: 21 mg/l. The $FeCl_3$ feeder capacity is planned to be 30 mg/l Fe.

The 8 single-stage carbon columns are pressurized downflow systems. One column can be backwashed using the effluent volume from the other 7 columns.

TABLE A-1 (Continued)

DESIGN SPECIFICATIONS OF SOME PCT PLANTS

(B) Tertiary Plants, upgrading biological plants

	Colorado Springs, Colorado	Pomona, California	South Lake Tahoe, California
Carbon Requirements	250 lbs/MG	350 lbs/MG	250 lbs/MG
Plant Size	3 MGD	0.3 MGD	7.5 MGD
Hydraulic Loading	5 gpm/ sq ft	7 gpm/ sq ft	6.2 gpm/sq ft
Contact Time	30 minutes	40 minutes	17 minutes
Bed Depth	20 ft	38 ft	14 ft
Contactor Size	20 ft dia x 20 ft	6 ft dia x 16 ft	12 ft dia x 14 ft
Carbon Size	8 x 30 mesh	12 x 40 mesh	8 x 30 mesh
Carbon Inventory	250,000 lbs	—	500,000 lbs
Backwash Rate	20 gpm/sq ft	12 gpm/sq ft	N/A
Surface Wash	—	—	N/A
Air Scour	—	—	N/A
Vessel Type	pressure-downflow	pressure-downflow	pressure-upflow
Regeneration Rate	75 lbs/hr	110/hr	250 lbs/hr
Furnace*	30 ID 6	30 ID 6	54 ID 6
Corrosion Protection	—	coal tar epoxy	coal tar epoxy
After Burner	yes	yes	available
Wet Scrubber	—	yes	yes

*30 ID 6 means 30" inner diameter and a 6-hearth furnace

Owosso, Michigan(2)

A new plant is being built to accommodate several adjacent towns in the Owosso area. The existing primary plant must be upgraded as well as expanded, particularly in the area of phosphorus and nitrogen removal. The treatment objectives now will require a BOD_5 of 7 mg/l during low river stages, and 85% removal of phosphorus in order to safeguard the Shiawassee River. The proposed treatment sequence is: 1. gross solids removal; 2. chemical clarification via lime and alum; 3. pressurized deep bed filtration; 4. upflow carbon adsorption; 5. breakpoint chlorination of ammonia (projected); 6. removal of excess chlorine and an organic polishing in downflow carbon columns.

The design (average) flow is 6 MGD, with a projected peak flow of 12 MGD. Average raw wastewater characteristics include: suspended solids: 180 mg/l; BOD_5: 90 mg/l; COD: 300 mg/l.

The carbon columns will include 6 parallel trains of 2-stage contactors, and will be pressurized upflow systems.

Garland, Texas(3)

The expansion of the Duck Creek plant in Garland (suburban Dallas) will incorporate PCT largely because of the influx of industrial wastes into the municipal waste stream. The treatment sequence will feature: 1. gross solids removal; 2. filtration; 3. gravity expanded bed upflow carbon adsorption; 4. chlorination. Initially, the existing trickling filter plant will be operated in parallel with the PCT plant.

The PCT design flow will initially be 22.5 MGD. The total plant (including trickling filter) will be 30 MGD. This is an example of a modular approach to plant design and construction. Ultimately the plant capacity (entirely PCT) will go up to 90 MGD. Average raw wastewater characteristics include: suspended solids: 230 mg/l; BOD_5: 260 mg/l; COD: 540 mg/l; filtered COD: 240 mg/l.

The carbon contactors will be 10 rectangular concrete-walled single-stage beds operating upflow under gravity. The projected carbon requirement here is 1800 lbs/MG, a conservative figure which presumes little or no biological treatment on the carbon.

Niagara Falls, New York(4)

Maintaining the quality of the Niagara River, which discharges into Lake Ontario, was the main reason for construction of a PCT plant at Niagara Falls. The high industrial waste load at Niagara Falls would not be readily amenable to biological treatment. The process sequence includes: 1. gross solids removal; 2. chemical clarification; 3. sedimentation; 4. gravity downflow carbon adsorption; 5. chlorination.

The design (average) flow will be 60 MGD. Raw wastewater characteristics include: suspended solids: 280 mg/l; BOD_5: 50 mg/l; COD: 150 mg/l.

The carbon portion of the plant will be comprised of 32 single-stage gravity downflow contactors.

treatment and then discharged into the Channel. The stricter effluent quality standards imposed required that an improved treatment system also be installed. The variations in flow due to the combined collection system mitigated against the construction of a biological plant. A PCT plant including activated carbon has been operational since December 1970. The pretreatment steps consist of a variety of processes intended to remove oil from the waste stream, and included flocculation and air flotation.

The design flow is 4.2 MGD and is uniform due to the preceding impoundment basin. The plant is expected to reduce 250 mg/l of COD to no more than 30 mg/l, and suspended solids to virtually nil. The hydraulic loading is 1.7 gpm/sq ft with a contact time of 1 hour. The concrete gravity contactors are 12 x 12 x 26 ft deep, each containing 13 ft of carbon. There are 12 parallel single-stage contactors. Backwashing is once per day.