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Economic Feasibility Of Sludge Treatment By Nitro-Hydrolysis With Product Recovery And Recycle

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I am submitting herewith a thesis written by Shinu George Simon entitled "Economic Feasibility Of Sludge Treatment By Nitro-Hydrolysis With Product Recovery And Recycle." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Chemical Engineering.

Dr. Paul R. Bienkowski, Major Professor

We have read this thesis and recommend its acceptance:

Dr. Robert M. Counce, Dr. Frederick E. Weber

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

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Dr. Paul R. Bienkowski

Major Professor

We have read this thesis
and recommend its acceptance

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ECONOMIC FEASABILITY STUDY OF SLUDGE TREATMENT
BY NITRO-HYDROLYSIS WITH PRODUCT RECOVERY AND
RECYCLE

A THESIS PRESENTED FOR THE
MASTER OF SCIENCE DEGREE
THE UNIVERSITY OF TENNESSEE,KNOXVILLE

SHINU GEORGE SIMON
December 2002

DEDICATION

This thesis is dedicated to my parents , my lovely niece Ginger Geneva Simon and the rest of the family, for always believing in me, inspiring me, and encouraging me to reach higher in order to achieve my goals.

ACKNOWLEDGEMENTS

I wish to thank all those who helped me in completing my Master of Science degree in Chemical Engineering. I thank my advisor, Dr. Paul R. Bienkowski for his guidance and his valuable suggestions. I also thank my other committee members including Dr. Robert M. Counce and Dr. Frederick E. Weber. I would also like to thank other faculty members of the Department of Chemical Engineering for their support and guidance throughout my stay at the University of Tennessee, Knoxville.

I thank God, for giving me the wisdom and strength .I thank my family and friends, whose suggestions and encouragement made this work possible.

ABSTRACT

Activated sludge treatment facilities generate a waste stream consisting of 0.25-4% sludge, which must be disposed of as a solid waste. Conventional methods such as landfills, land farming, wet air oxidation, and incineration. The main disadvantages of such disposal methods have been the high cost of operation and aesthetic objections.

The purpose of the research was to investigate the economic and technical feasibility of utilizing a nitro-hydrolysis process as a means of sludge disposal. The nitro-hydrolysis process is based on the nitric acid hydrolysis of sludge. A generalized reaction can be written as



The hydrolysis gives a variety of carboxylic acids, mainly acetic and formic acid. The product stream contains no solid wastes. The products could either be recovered and sold commercially or recycled back to the treatment plant.

The Knoxville Utilities Board generates 65 tons of sludge, dry basis, per day. The sludge is disposed via land farms 70 miles away, difficulties in getting new land farms sites and the high cost of transportation, led KUB to consider to look for an alternate means of disposal. In this thesis, the feasibility to use nitro-hydrolysis process as an alternative disposal means, was investigated. A nitro hydrolysis process plant was designed, using a 20% solids concentration KUB sludge. The economic feasibility for both product recovery and product recycle was studied and compared to land farming and incineration

A sensitivity analysis for the process with product recovery was accomplished. The process economics depend significantly on the yield, energy, price of raw materials, capital, and inlet sludge concentration.

Due to its high viscosity, large solid lump compositions and fouling properties, running the process effectively could be challenging at high inlet solid

concentration, if not unfeasible. The economics and design of the process was done on the assumption that the process could be run, without any major difficulties.

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LIST OF SYMBOLS USED

A	[ft ²]	Area
a	[-]	Stoichiometric coefficient for sludge
b	[-]	Stoichiometric coefficient for nitric acid
b/a	[-]	Ratio of Stoichiometric coefficients
C	[lb.mol/ft ³]	Concentration
D	[ft]	Diameter
d ₀	[ft]	Hole size
d _s	[ft]	Triangular spacing between holes
F	[lb.mol/min]	Molar flow rate
H	[ft]	Height
k	[ft ³ /ft ³ ·lb.mol·min]	Reaction rate constant
K	[ft/sec]	Velocity
L	[ft ³ /hr]	Volumetric flow rate
M	[lb/hr]	Mass flow rate
N	[-]	Number of theoretical trays
V	[ft ³]	Volume
V _d	[ft/hr]	Flooding velocity
V _v	[ft ³ /hr]	Volumetric flow rate
V ₀	[ft ³ /min]	Volumetric flow rate
V _{max}	[ft/sec]	Maximum velocity
x	[-]	Conversion
Z _t	[ft]	Tray spacing
Θ _b	[-]	Ratio of molar rates
ρ	Lb/ft ³	Density
Σ	[-]	Efficiency
σ	[dyne/cm]	Surface Tension
τ	[min]	Residence time

CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION

Sludge is the name that generally describes a muddy or slushy mass deposit or sediment as: (a) the precipitated solid matter produced by water and sewage treatment processes (2), (b) mud from a drill hole in boring (5), (c) the muddy sediment in a steam boiler, (e) the precipitated or settled matter from industrial processes (34). In this thesis, the term sludge refers to the residual material removed from wastewater treatment facilities.

Biosolids are nutrient rich organic materials derived from wastewater solids (sewage sludge and domestic septage), which can also be beneficially recycled(2). The EPA defines sewage sludge as “*a solid, semi solid or liquid residue generated during the treatment of domestic sewage in a treatment works*” they include solids or scum that are removed in either the primary, secondary or advanced wastewater treatment processes. Materials such as the ash generated by the firing of the sewage, grit and screenings are not considered as sewage sludge. Domestic septage is defined by the EPA as “*a liquid or solid material removed from a septic tank, cesspool, portable toilet or any similar system*”. This excludes grease –trap pumpings and commercial or industrial waste.

Physically sludge is primarily composed of water and suspended solids between 0.25% and 4 % by weight; it is in principle just excess biosolids however it may also get mixed with materials such as dirt, CaCO_3 , metals & inerts that can make up to 8-9% of the composition(27).Chemically Sludge is composed of 85-95% water, 0.25-4 % organic matter ,1-4 %Nitrogen, 1-3 % Phosphorous ,0-0.25% Metals,0-0.25% Inerts ,0-5% CaCO_3 and 0-4% Dirt (28).

As mentioned earlier sludge is formed during wastewater treatment. Wastewater is a combination of the liquid- or water carried wastes removed from residential, institutional, commercial and industrial establishments, together with ground water, surface water and storm water, as may be

present (27). Wastewater may contain certain undesirable components, including organic, inorganic and toxic substances. The main group of organic solids in wastewater are proteins, carbohydrates, fats and oils (28).

In its untreated form; wastewater cannot be disposed of for several reasons. First, the biological decomposition of the organic materials in wastewater consumes oxygen and thus reduces the quantity available for the aquatic life in the receiving waters (2). The decomposition also produces large quantities of malodorous gases (5). Secondly, the numerous pathogenic or disease-causing micro-organisms in untreated wastewater are health hazards to human beings (4). Third, its toxic compounds, especially heavy metals, can be dangerous to both plants and animals, and finally the presence of phosphates and nitrogen may lead to uncontrolled growth of aquatic life (28). It is therefore necessary to reduce the organic components, nitrogen and phosphorous, toxic compounds, as well as to destroy the pathogenic or disease-causing micro-organisms from wastewater before its disposal.

A modern wastewater treatment plant usually employs three stages of wastewater treatment, i.e. mechanical, biological, and an additional (third) stage for the elimination of nitrogen and phosphorous. The biological and the third stage, generate sludge. The most commonly used technique for the disposal of wastewater is the activated sludge process (10). The organic material is either converted to heat, water and carbon dioxide or incorporated into the biomass, excess biomass must be produced for the process to operate efficiently and the excess biomass generates a sludge stream, which is disposed of as a solid waste. The local Utilities board, Knoxville Utility Board, for example generates 65 000 pounds of dry sludge per day via the activated sludge process(11).

Generally, the selection of the best disposal route for the sludge from a particular treatment plant starts by identifying the most secure, financially and environmentally acceptable final destination for the sludge, which would in turn dictate the type of treatment required (2). This reverse sequence of selection procedures rarely occurs in practice and, indeed, sludge disposal has often

been done on an adhoc basis, with each wastewater treatment plant management determining a local disposal solution. Currently, the sludge disposal outlets, which exist, are land farming (4), Incineration (5) landfill (6) and Wet Air Oxidation (5). These Disposal techniques will be discussed in detail in chapter 2.

KUB for example disposes its sludge via land farming. Land farming is becoming increasingly difficult due to various economic and social reasons (mainly aesthetic reasons)(43). The non-availability of disposal land at nearby locations means that the sludge has to be currently transported 70 miles. Every year more sludge will be generated per day, due to the population growth, Industrialization, etc. With the ever-increasing distance from disposal sites, the credit associated with transporting and land filling the sludge will increase. Such means of disposal might soon become uneconomical. Further more news reports such as the death of a man in Greenland, New Hampshire (Reuters, November 1995)(42), caused by the excessive inhalation of a nitrogen based polymer (used to remove water from sludge) and lime, while land farming sludge makes it difficult to market the idea to the public.

In the recent past, the application of sludge on agricultural land has met a lot of set backs due to the presence of heavy metals in the sludge (Reuters, April 1999)(42). A study by the EPA (1998)(43) showed that the average content of heavy metals in municipal sludge is higher than the average for most farming soils. This implies that uncontrolled addition of sludge to agricultural land may increase the concentration of heavy metals in the farmlands (24). This could have an effect on the crop production due to uptake and lead to the transfer of heavy metals to human beings through plants and animals (4). To regulate the use of sludge on agricultural, the EPA has introduced limit concentrations, in either the soil or sludge, and the frequency of application (EPA Rule 503) (4).

The limitations facing land fill and land application lead to the expectation that the role of incineration will increase in the future (24). Sludge incineration enjoys a combination of several advantages that are not found in other

treatment alternatives, including a large reduction of sludge volume to a small-stabilized ash and thermal destruction of toxic organic constituents. (26). Further, the calorific value of dry sludge corresponds to that of brown coal, and therefore through incineration this energy content may be recovered (29) if the water content is sufficiently reduced. The main disadvantage of this process is the prohibitive costs of installing and running incinerators (25) and additional air pollution problems caused by the incineration process (4).

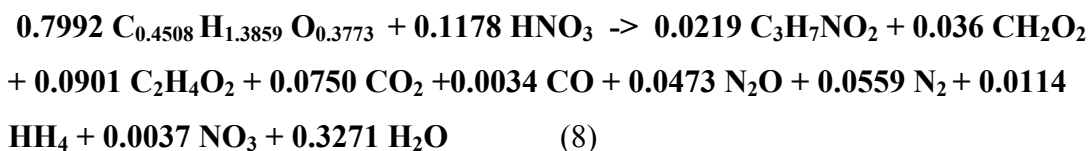
Currently industries such as DuPont and Tennessee Eastman use the Incineration of sludge, as an onsite disposal technique(11). The water content of these sludges is such that additional fuel will be consumed to ensure complete combustion of the sludge. The development of a more energy efficient, environmentally and economically favorable process to dispose such sludge will also be helpful to them.

The purpose of this research is to investigate the economic and technical feasibility of utilizing the nitro-hydrolysis process to produce marketable products from the excess sludge produced by biological wastewater treatment plants. An economical and environmentally feasible process would be beneficial, for both the public and the various companies generating sludge. Such a process not only effectively treats sludge but also reduces the cost and energy requirements compared to other processes. Products generated from the nitro-hydrolysis process could be marketed, generating additional income to the company.

The nitro-hydrolysis process is based on the nitric acid hydrolysis of sludge. DuPont (8) discovered the process in an attempt to increase the filterability of sludge. They found out that by using a mild hydrolysis of sludge by an acid (nitric acid), in a plug flow reactor they were able to pump and filter the sludge more easily. The water during nitro-hydrolysis reduced the viscosity of the sludge Further studies into this process by Dupont and Perkins et al (11) led them to deduce that at higher temperatures (180 °C), the sludge can be converted into a variety of carboxylic acids (mainly acetic, formic and propionic). The sludge was almost completely converted into a liquid stream, reducing the solid wastes by 96%of the volume. Although other

acids could also be used for the hydrolysis process, Nitric acid was so chosen because Dupont was better equipped to handle nitrate emissions.

The reaction step was determined in laboratory studies with Industrial sludge. The chemical stoichiometry of the reaction was given as :

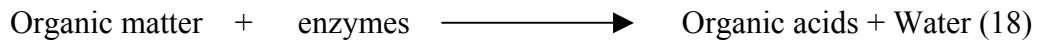


A more generalized reaction can be written as



In literature several other hydrolysis methods have been suggested and used in wastewater plants to improve the performance of the plant. Other hydrolysis methods used are biological(18), alkaline(31) and thermal (32).

Biological hydrolysis of sludge have been used by Andreasen et al (18), in order to reduce the nutrient emission (nitrogen and phosphorous) wastewater plants. They found that by the pre-treatment in the form of primary sedimentation or chemical precipitation in wastewater plants, resulted in a removal of organic components which were essential to the biological removal of nitrogen and phosphorous. To rectify this problem, they introduced an additional carbon source to ensure a complete and efficient biological removal of nutrients. This was done by the biological hydrolysis of primary or activated sludge, which resulted in the formation of easily degradable organic substances, primarily lower fatty acids (18). The hydrolysis of raw wastewater sludge was carried out at temperatures around 20°C in a hydrolysis tank having a residence time of 3 days. The hydrolysate typically consisted of approximately, 90% volatile fatty acids, 50-60% of these being acetic acid (18). A generalized chemical equation for biological hydrolysis is



Chiu Y.S et al (31) have also suggested that alkaline hydrolysis by of sludge using sodium hydroxide, alone or coupled with other treatment methods such as ultrasonic treatment when used as pretreatment for waste activated sludge resulted in an improved efficiency of the subsequent anaerobic biotransformation of the organic matter .A generalized equation can be written as

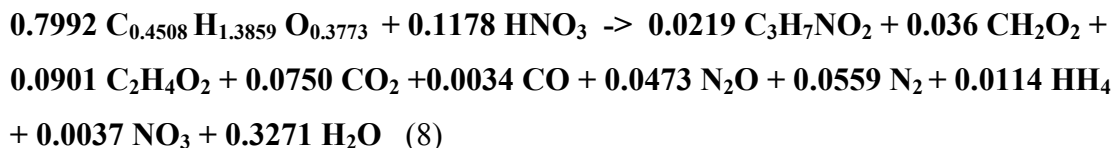
$$\text{Organic Matter} + \text{NaOH} \longrightarrow \text{Organic Acids} + \text{Sodium Salts} + \text{water} \quad (31)$$

So far, the hydrolysis of sludge has only been used to improve the performance of wastewater plants, not as an alternative means of disposal of sludge. Nitro hydrolysis of sludge, results in the complete elimination of solids. Which could be more economical than disposals via land fills. An important by product of the hydrolysis process is acetic acid and formic acid.

This thesis will focus on the design and economic feasibility of a facility to utilize nitro hydrolysis to convert the sludge into marketable products such as acetic and formic acid. This method of disposal will be compared to standard disposal methods such as incineration and land farming.

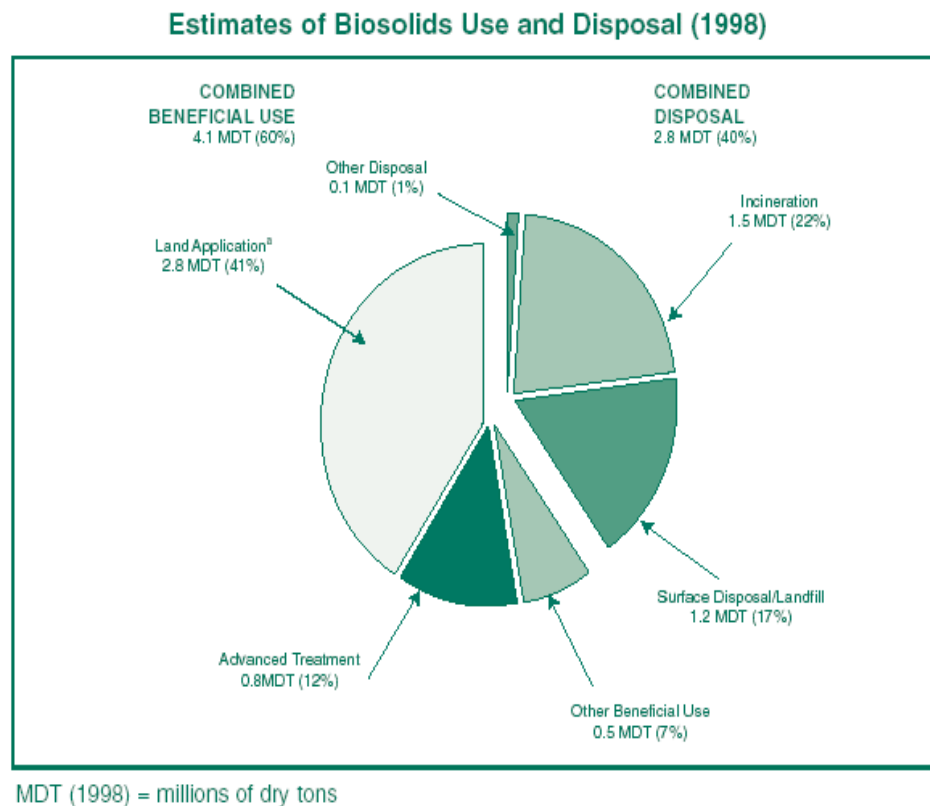
1.2 PROCESS DESIGN BASIS

In the initial design of this process several constraints were given on which to base the entire plant design. These constraints include the flow rate and composition of sludge, and conversion rates. The wet sludge feed was set at 65 000 pounds on a dry basis, the influent sludge will have a 4% concentration of solids. The flow of nitric acid was calculated according to the reaction stoichiometry with dry sludge. Using sludge as the basis, the reactor system effluent flow rates were calculated from the balanced stoichiometry



1.3 ECONOMIC POTENTIAL

The Figure I and Table I below shows the amount of biosolids generated in the US in 1998(24). A total of 6.9 million tons of dry biosolids were produced. Out of which 60% were beneficially used as land applications etc. While 40 % of the biosolids were disposed of by landfills, incineration or other means. If Nitro-hydrolysis is an economically viable process, and assuming 20% of the sludge is used by a nitro-hydrolysis process to produce Acetic acid, an additional revenue of \$ 440 million will be generated per year (basis price of Acetic acid Jan 1 2002 (\$ 0.455/lb)(44)). The Acetic acid market in the US was \$3.3 billion. Production of Acetic acid by this means, will not adversely affect the market



Source (24)

FIGURE 1 ESTIMATE OF BIOSOILDS USE AND DISPOSAL IN THE US

TABLE 1 ESTIMATES OF BIOSOLIDS GENERATION FOR USE OR DISPOSAL IN THE US (1998)

Estimate (millions)	Beneficial Use				Disposal				
	Land Application ^a	Advanced Treatment ^b	Other Beneficial Use	Total	Surface Disposal/ Landfill	Inciner- ation	Other	Total	Total
1998 Dry Tons	2.8	0.8	0.5	4.1	1.2	1.5	0.1	2.8	6.9
Percent of Total	41%	12%	7%	60%	17%	22%	1%	40%	100%

CHAPTER 2

WASTEWATER TREATMENT AND DISPOSAL

2.1 WASTEWATER TREATMENT

Wastewater treatment is a multi-stage process to renovate wastewater before it re-enters a body of water, is applied to the land or is reused. The goal is to reduce or remove organic matter, solids, nutrients, disease-causing organisms and other pollutants from wastewater. Each receiving body of water has limits to the amount of pollutants it can receive without degradation.

The various methods for wastewater treatment are:

Activated sludge: The most common option, it uses microorganisms in the treatment process to breakdown organic material with aeration and agitation, then allows any remaining solids to settle down. Bacteria containing “activated sludge “ is continuously recirculated back to the aeration basin to increase the rate of organic decomposition. (5). The activated sludge process is described in detail in section 2.2

Trickling filters: These are beds of coarse media (often stones or plastic) 3-10 feet deep. Wastewater is sprayed into the air (aeration), and then allowed to trickle through the media. Microorganisms attached to and growing on the media, breakdown organic material in the wastewater. Trickling filters drain at the bottom: the wastewater is collected and then undergoes sedimentation. (2).

Lagoons: These are slow, cheap and relatively inefficient, but can be used for various types of wastewater. They rely on the interaction of sunlight, algae, microorganisms and oxygen. Algae grow within the lagoons and utilize sunlight to produce oxygen, which in turn is used by microorganisms in the lagoon to break down organic material in the wastewater. Wastewater solids settle in the lagoon. (10)

Among the various wastewater treatment options the activated sludge process is used the most, (example KUB), while part of the biosolids is recycled back

to the sludge process, the rest of the sludge is transported to landfill sites for disposal. KUB generates about 65, 000 pounds of sludge (dry basis) everyday (11). Trickling filters and lagoons as a treatment option in communities with a population of less than 1000 people (10). The activated sludge process produces almost exclusively all the excess sludge in the US(24). Trickling beds and lagoons have a significantly lower excess sludge compared to the activated sludge process(10).

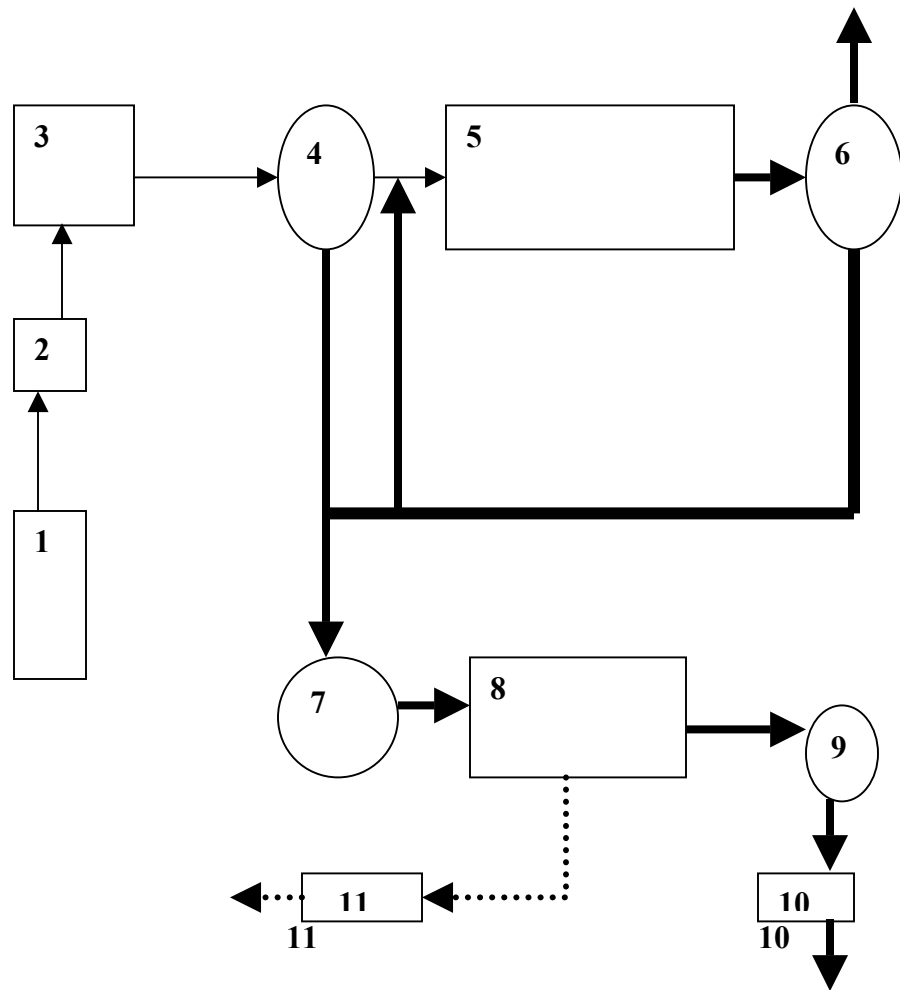
2.2 ACTIVATED SLUDGE PROCESS

In 1914, E.Arden and W.T.Lockett discovered the activated sludge process (10) in England. They noted aeration of sewage led to formation of flocculent suspended particles. They discovered that the time to remove organic contaminants was reduced from days to hours when these flocculent particles were held in the system (10). They referred to the suspended particles, more specifically the resulting sludge from the settling to collect the particles, as being “activated” and so was born the activated sludge process.

Activated sludge consists of a mixed community of microorganisms that metabolize and transform organic and inorganic substances into environmentally acceptable forms. The typical microbiology of activated sludge consists of approximately 95% bacteria and 5% higher organisms (protozoa, rotifers, and higher forms of invertebrates). Normally the activated sludge process is strictly aerobic. In simple terms, the activated sludge process consists of a reactor called the aeration tank, primary settling tanks, final settling tanks, solids recycle from the settler to the aeration tank.

Description of an Activated sludge process

The Wastewater is first stored in large tanks (stream # 1) as seen in Figure 2, from these tanks they are fed into the screening and grit units (stream # 2). Which removes large objects that could block pumps and clog pipes and channels; this step can also be used for grinding waste to reduce particle size. Heavy inorganic particles such as sand, gravel, and cinders are removed in this step (10). The next step in the activated sludge process is the Primary treatment, which will



1 Storage tank	7 Gravity thickener
2 Screening and Grit Units	8 Anaerobic Digester
3 Pre-aeration Tanks	9 Secondary Thickener
4 Primary clarifier	10 Dewatering Process
5 Aeration chamber	11 Methane Tank
6 Secondary Clarifier	

FIGURE 2 **BLOCK DIAGRAM OF AN ACTIVATED SLUDGE PROCESS**

remove over 75% of the total suspended solids in the wastewater(3).The wastewater flows from the grit cambers to the pre-aeration tanks(stream# 3). The main purpose of the pre aeration tank is to remove scum and grease, so as not to hinder the secondary treatment (27). After aeration, by a series of bubble diffusers, the wastewater passes through a “quiescent settling zones “to allow scum and greased to rise to the surface. A mechanical skimmer removes the scum (5). The pre-aeration is not intended to provide solids treatment or their removal, however a sludge mechanism is included to clean the bottom of the tank of any heavy solids as they accumulate (10). Wastewater is then pumped by a series of pumps into the primary clarifier (stream # 4),it uses gravity settling to remove particles from water(5).

Sedimentation takes place in the primary clarifiers. Particulates suspended in wastewater can range in size from 10^{-1} to 10^{-7} mm in diameter (27). Turbidity or cloudiness in water is caused by those particles larger than 10^{-4} mm, while particles smaller than 10^{-4} mm contribute to the water’s color and taste (10). Wastewater is detained long enough for the larger particles to settle to the bottom before the clarified water leaves the tank over a weir at the outlet end. Particles that have settled to the bottom of the tank are removed manually or by mechanical scrapers on the site pending their treatment or removal (3). The clarified wastewater then flows into an aeration chamber (stream point #5).

The aeration chamber is a suspended – growth reactor containing microbial aggregates, or *flocs*, of microorganism termed the activated sludge(10). The aeration chamber normally provides 6 to 24 hours retention time for the wastewater. The contents of the aeration tank are referred to as mixed liquor, and the solids are called mixed liquor suspended solids (MLSS)(2). The latter includes inert material as well as living and dead microbial cells. In the aeration tank, microorganisms are kept in suspension by mechanical mixers or diffused air, and the concentration in the tank is maintained by the continuous return of the biological floc from a secondary settling tank to the aeration tank(29). Treating sewage biologically means to remove

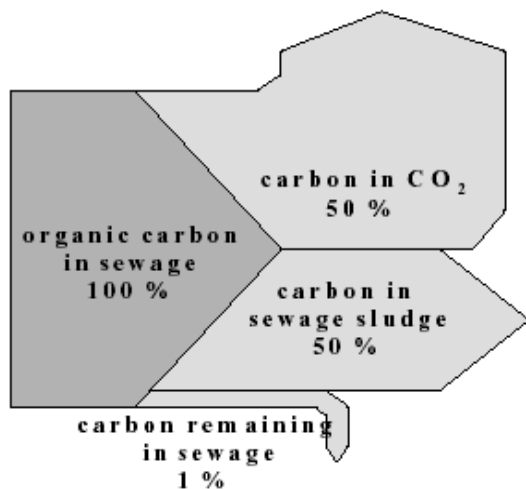


FIGURE 3 THE CARBON BALANCE

dissolved and suspended organic pollutants and to some degree minerals from water . During the aerobic process, the polluting products removed are either transformed into biomass, known as sewage sludge, or burnt biologically to carbon dioxide (CO₂)(5). The result of this degradation process is about 50 % of the energy content in form of new biomass and 50 % energy in form of heat (10). The Figure 3 gives a pictorial representation of the carbon balance. The biomass created is partly recycled and partly removed.

The generalized equation can be given as

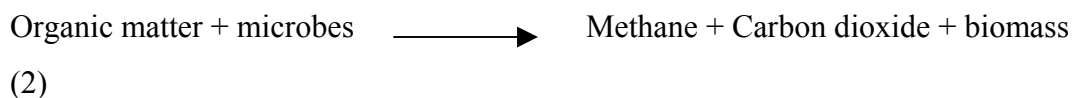


Ideally this biomass could serve as feed to the nitro-hydrolysis process, instead the biomass or sludge that is removed from the aerobic process is further treated to remove nutrients and grit and other solids removed in the primary stage are added to it .The sludge produced flows into the secondary clarifier (stream point #6). Constructed similarly to the primary clarifiers they provide longer detention and lower overflow rates. When the sludge settles to the bottom of the tank, it is still active and is able to remove more BOD from the wastewater (2). By recycling part of the activated sludge back to the aeration chamber on a continuous

basis (stream # 5), it helps maintain the microorganism concentration in the aeration chamber (27). The cleaner water at the top of the settling chamber overflows through openings at the top of the chamber to the chlorination tank.

Sludge from the secondary clarifier is passed on to through to the gravity thickener(stream point # 10), the purpose of which is to thicken the primary sludge from 1% to about 8% solids (10). From the Gravity thicker the sludge and the scum removed in the primary clarifier (stream point #7) are sent into the anaerobic digesters (primary and secondary digesters)(stream point # 8)(5). Under anaerobic conditions large compounds of biomass are stepwise degraded to sugar and fatty acids and further to methane (CH₄) and carbon dioxide (CO₂)(27). This process is only to a very little degree exothermal and subsequently very little bacteria mass is formed. Under degradation of biomass about 7% of its COD is transformed into new bacteria mass and over 90 % into methane (2).The methane is usually vented of (stream # 11)and is either burnt or used as a secondary burning fuel(5). The heat production is very small (1 to 2 %, depending on the type of substance (10) and is seen to be negligible. Carbon is the main energy content of organic compounds. Through the digestion process there is a reduction in odors and pathogenic (harmful) bacteria levels, as well as a reduction of the overall sludge volume (5) ,and nutrient levels. During digestion process, the sludge mixed. Complex organic materials break down into simpler compounds, and then acid-forming organisms convert these organic compounds into volatile organic acids. These acids are changed into methane and carbon dioxide by other bacteria. Depending on the volatility of the solids, this solids reduction can range from 30-40%(5).

The generalized chemical equation can be written as



The sludge leaves the digester as a dark black liquid containing about 2% solids and 98% water (27) it is concentrated further via a secondary thickener

(stream point # 9).The sludge is then conditioned, with lime ,ferric chloride or certain polymers to aid the final dewatering process(stream # 10)

2.3 USE AND DISPOSAL OF SLUDGE

Sludge be it industrial or municipal, is usually disposed of by the four main methods, Incineration, Landfill ,wet air oxidation & Land farming. Prior to 1992 sludge could be dumped into the ocean .However in 1988 a bill was passed in the U.S Congress banning the ocean dumping of sludge (24), effective from 1992.The alternatives suggested where incineration or land filling of sludge (Reuters 1992)(42). As Environmental objections intensified, the EPA adopted the idea of disposing of the sludge by spreading it as a “fertilizer” on agricultural land. (Reuters 1993)(42). The commonly used methods of disposal are Incineration, Land farming, land filling & Wet air Oxidation. Each one of these methods are discussed in detail

2.3.1 INCINERATION

The limitations facing landfill, land farming, and the ban on sea disposal lead to the expectation that the role of incineration will increase. Sludge incineration enjoys a combination of several advantages that are not found in other treatment alternatives(25),including a large reduction of sludge volume to a small stabilized ash, and thermal destruction of toxic organic constituents(24).In large urban areas where vast quantities of wastewater sludge is produced, lack of readily available disposal space and the need to minimize odor generation from landfill and the aesthetic objections of the nearby population makes incineration an attractive sludge disposal technique. There have been considerable improvements to the technology of incineration. Techniques are now available to control gaseous emissions (29)

Incineration is the process of direct burning of wastes in enclosed unit at high temperatures (800 C) devices in the presence of excess air (oxygen)

liberating heat energy, inert gases and ash (26). Approximately 20% of the biosolids presently generated by large industrial and municipal wastewater treatment facilities are incinerated (24).

The generalized chemical equation can be given as



Incinerator systems generally consist of an incinerator (furnace) and one or more air pollution control devices (APCDs). The most commonly used incinerators are multiple-hearth, fluidized-bed, and electric infrared incinerators. Frequently industrial sludge is incinerated in steam boilers. However the EPA is placing new restrictions on this process from 2005 onwards. Starting in 2005, steam boilers which burn waste will be treated as incinerators by the EPA.

Most APCDs are used to either remove small particles and their adhering metals in the exhaust gas or to further decompose organics (26). Examples of metal removing APCDs are wet scrubbers, dry and wet electrostatic precipitators, and fabric filters (24). Afterburners, another type of APCD, are used to burn organics in exhaust gases more completely (26).

Auxiliary fuel is often used to boost the BTU value of the sludge. Any additives to biosolids that are fired in a biosolids incinerator, such as natural gas, fuel, grit, screenings, wood chips, coal, dewatering chemicals, and municipal solid waste is considered auxiliary fuel. However according to Part 503 of the EPA rules, if the municipal solid waste accounts for more than 30 percent (by dry weight) of the mixture of biosolids and auxiliary fuel, it will not be considered as an auxiliary fuel.

Sludge can be incinerated either alone (mono-incineration) or with other materials (co-combustion) (29). In co-combustion the sludge is usually burned with municipal solid wastes or with coal (27).

With 70-80% moisture content, the net heating value of sludge is not sufficient for auto-thermal combustion, and supplementary fuel may be necessary (29). This problem can be resolved by drying the sludge before it is fed into

the incinerator though during drying of sludge passes through a sticky phase(35), which complicates the sludge feeding mechanism into the incinerator. After incineration, up to 50 wt% of the input dry mass of sewage sludge remains as ash and most of the toxic heavy metals in sludge are retained, this complicates ash disposal (24). The nitrogen, chlorine, sulfur, etc present in the sludge are usually released as gaseous pollutants in various forms during combustion, this necessitates extensive flue gas cleaning.

Although it is an energy intensive process, its advantages are it is hygienic, low land requirements, relatively noiseless and odorless, reduces the cost of waste transportation(24). The disadvantages of incineration are it's high capital and O&M costs, in addition to particulates, SO_x and NO_x emissions, heavy metal, chlorinated compounds are a cause of concern, which requires elaborate pollution control equipment (26).

The evaluation of the economics of this means of disposal can be taken into consideration .The following variables must be considered,the amount of energy required to heat the sludge , the capital recovery of the plant and maintenance costs. The incineration credit will depend significantly on the concentration of the influent sludge. As the concentration of the sludge increases , the amount of heat that will be required to heat the sludge will decrease due to the decreasing amount of water. At a certain concentration the sludge will provide the heat required for incineration.Sludge gives an average 8000 BTU per pound on a dry basis (5).At lower concentrations , more heat energy will be required to heat the water up to 1500 F.

Incinerators are commonly equipped with one or more post combustion APCDs (4) to remove various pollutants prior to release from the stack (e.g., particulate matter, heavy metals, acid gases and organic contaminants Various APCDs include:

Electrostatic Precipitator: The electrostatic precipitator is generally used to collect and control particulate matter that evolves during incineration (26), by introducing a strong electrical field in the flue gas stream, this in turn, charges the

particles entrained in the combustion gases(24). Large collection plates receive an opposite charge to attract and collect the particles.

Fabric Filters: Fabric filters are also particulate matter control devices, which remove dioxins associated with particles and any vapors that adsorb to the particles (25). Six to eight inch diameter bags, made from woven fiberglass material, are usually arranged in series. An induction fan forces the combustion gases through the tightly woven fabric. The porosity of the bag allows the bags to act as a filter media and to retain a broad range of particles sizes (i.e. less than one micrometer in diameter)(24).

Dry Scrubbers: Dry scrubbers also called spray dryer adsorption (26); remove both acid gas and particulate matter from the post incineration gasses although they have little effect on dioxin emissions. Hot combustion gases enter a scrubber reactor vessel. Atomized hydrated lime slurry is injected into the reactor at a controlled velocity. The slurry rapidly mixes with the combustion gases within the reactor (25). The water in the hydrated lime slurry quickly evaporates; the heat of evaporation causes the combustion gas to rapidly decrease. The neutralizing capacity of hydrated lime reduces the combustion gas content of acid gas constituents by greater than 70 percent. A dry product, consisting of particulate matter and hydrated lime settles to the bottom of the reactor vessel. The dry scrubber is usually used in combination with the electrostatic precipitator (24).

Dry Sorbent Injection: Dry sorbent injection is used to reduce acid gas emissions (24). It involves the injection of dry hydrated lime or soda ash either directly into the combustion chamber or into the flue duct of the post –combustion gases. The reagent reacts and neutralizes the acid gas constituents (26).

Wet Scrubber: Wet scrubbers are designed for acid gas removal (24). They also help in the reduction of emission of dioxins in both vapor and particulate forms. Wet scrubbers devices consist of two stage scrubbers (25). The first stage removes the removes hydrogen chloride and the second stage removes sulfur

dioxide. Water is used to remove the HCl and caustic or hydrated lime is added to remove SO₂ from the combustion gases.

2.3.2 LANDFILL

Landfills are engineered areas where waste is placed into land (5). The aim, while engineering a land fill is to avoid any hydraulic connection between the wastes and the surrounding environment particularly groundwater (24). While selecting a landfill it is crucial that a proper natural hydro geological setting be selected, which must be so selected to minimize the possibility of wastes escaping to groundwater beneath the landfill, the geology of the land must be known so that in the event of a leak it should be possible to predict the direction the waste will travel, in order for wells to be dug at such points and the escaped wastes be pumped out. Even though sludge is not considered a hazardous waste, the presence of heavy metals etc in the sludge, could make them be grouped as a hazardous waste. They could also be considered so, if there is sufficient evidence to believe that the gradual accumulation of these heavy metals could lead to toxic levels in the landfill. The main parts of a properly engineered landfill are

Bottom liner: It is usually one or more layers of clay or a synthetic flexible membrane (or a combination of these)(24). The liner effectively prevents the wastes from migrating into the environment. There are usually three types of liners: clay, plastic (e.g. high density polyethylene (HDPE)) and composite(27).

Leachate collection system: collects leachate that seeps to the bottom of the landfill via a system of pipes. The bottom of a landfill is sloped: pipes laid along the bottom capture contaminated water and other fluid (leachate) as they accumulate (5). If the leachate collection system fails, liquids will accumulate in the land fill, building up an additional liquid pressure, further stressing the bottom liners(24).

Cover or cap: The cover is an umbrella over the landfill to keep water out (to prevent leachate formation)(5). It generally consists of several sloped layers: clay or membrane liner (to prevent rain from intruding), overlain by a very permeable layer

of sandy or gravelly soil (to promote rain runoff), overlain by topsoil in which vegetation can root (to stabilize the underlying layers of the cover)(24).

Methane collection system: A series of pipes are usually embedded with the landfill to collect landfill gas which is approximately 50% methane, 49% carbon dioxide with traces of oxygen and nitrogen(27). Landfill gas is produced as a byproduct of the anaerobic breakdown of the waste by microorganisms in the landfill. In some landfills the gas is vented or burned(5).

2.3.3 LAND APPLICATION OF BIOSOLIDS

Land application is the application of biosolids to land to either condition the soil or to fertilize the crops or other vegetation grown in the soil(5). According to the EPA nearly half of the biosolids produced in the United States is currently being used beneficially to improve soils. Biosolids can either be applied to land in bulk or sold or given away in bags or other containers for land application(24).

Biosolids are generally land applied using one of several techniques. The biosolids may be sprayed or spread on the soil surface(5). They also may be tilled (incorporated) into the soil after being surface applied or injected directly below the surface for producing row crops or other vegetation(4).

Biosolids in a liquid state can be applied using tractors, tank wagons, irrigation systems, or special application vehicles. Dewatered biosolids are typically applied to land using equipment similar to that used for applying limestone, animal manures or commercial fertilizers. Both liquid and dewatered biosolids are applied to land with or without subsequent incorporation into the soil. The Table 2 below gives the management practices that should be followed for the surface disposal of biosolids as specified by the EPA

2.3.4 WET AIR OXIDATION

It involves the wet oxidization of untreated sludge at an elevated temperature and pressure. Untreated sludge is ground and is ground and mixed with a

TABLE 2 MANAGEMENT PRACTICES FOR THE SURFACE DISPOSAL SITES

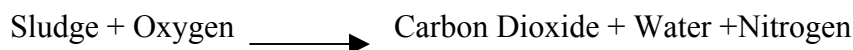
<p>Biosolids placed on a disposal unit must not harm threatened or endangered species</p> <p>The active biosolids unit must not restrict base flood flow</p> <p>The active biosolids unit must be located in a geologically stable area:</p> <ul style="list-style-type: none"> — must not be located in an unstable area — must not be located in a fault area with displacement in Holocene time (unless allowed by the permitting authority) — if located in a seismic impact zone, must be able to withstand certain ground movements <p>The active biosolids unit cannot be located in wetlands (unless allowed in a permit)</p> <p>Runoff must be collected from the surface disposal site with a system capability to handle a 25-year, 24-hour storm event</p> <p>Only where there is a liner, must leachate be collected and must the owner/operator maintain and operate a leachate collection system</p> <p>Only where there is a cover, must there be limits on concentrations of methane gas in air in any structure on the site and in air at the property line of the surface disposal site</p> <p>The owner/operator cannot grow crops on site (unless allowed by the permitting authority)</p> <p>The owner/operator cannot graze animals on site (unless allowed by the permitting authority)</p> <p>The owner/operator must restrict public access</p> <p>The biosolids placed in the active biosolids unit must not contaminate an aquifer</p>

Source

(24)

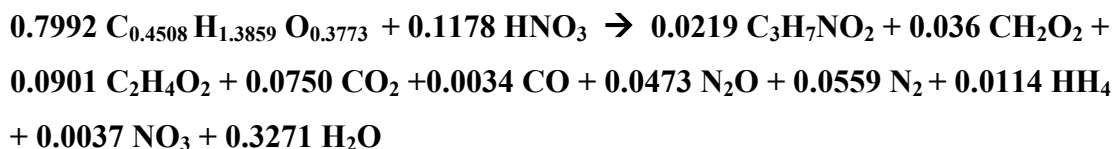
specified amount of air. The mixture is pumped through a series of heat exchangers and then enters a reactor, which is pressurized to keep the water in the liquid phase (5). At the reactor operation temperature of 350-600 °F Gases, liquid and ash leave the reactor. Wet air oxidation has been implemented in a limited number of installation, many if those implemented have been subsequently been taken out of service because of corrosion, high energy costs and excessive maintenance and odor problems(5)

The chemical reaction is similar to that of an incinerator



2.4 NITRO-HYDROLYSIS

Nitro-hydrolysis or chemolysis, is an acid- catalyzed hydrolysis of biosolids, the heavy organic waste is converted to short-chained acids, CO, CO₂, NO_x gases, and water. These NO_x gases are further converted to N₂, N₂O, NO₃⁻ (aq) and NH₄⁺ (aq). The decomposition of fats during the process will result in valuable products such as formic and acetic acids. The chemical stoichiometry of the reaction for industrial sludge is given below



A more generalized reaction can be written as



Carboxylic acids (mainly acetic, formic and propionic) are the organic materials produced in the process. Other acids have been researched for the sludge

destruction, but nitric acid is the most promising because it blends into the chemistry of the waste treatment process (16).

Bench scale batch experiments conducted with a 4.1% biosolids stream obtained from KUB, by Larry Perkins et al demonstrated that the treatment with dilute nitric acid at 180 ° C at 200 psia , the nitric acid initiates a hydrolysis reaction that converts 40-80% of the biosolids to biodegradable substances suitable for recycle (18). The reaction was first order with respect to the reactants and second order overall (18). A carbon balance showed that nearly 50% of the available carbon in the sludge will be converted into acetic and formic acids. The nitro-hydrolysis results in an almost complete reduction in solids sludge composition (16).

3.1 PROCESS DESCRIPTION

The facility for the treatment of biosolids by nitro-hydrolysis can be built adjacent to an existing activated sludge process plant. The only modifications to the existing activated sludge plant will be that the biosolids that are removed from the secondary thickener, and used for landfill or other disposal techniques will instead be re-directed and serve as the feed for the nitro-hydrolysis facility. The biosolids produced by the activated sludge process are usually 0.25-4% by weight concentration, these biosolids will have to be concentrated to 20 % by weight concentration before being used as feed for the nitro-hydrolysis process. This can be achieved by concentrating the concentrating the sludge further by a thickener. A thickener with the use of coagulants such as ferric chloride and lime and a residence time of 24 hours, although rudimentary, will give sludge of 20 % concentration, the use of much faster techniques such as centrifugation(34), drying(32) and filter presses(35) may be ill advised because , filter aids(2-4% by weight)(35) have to be added, in these dewatering operations. The presence of such elements in the sludge stream, further complicates the reaction process, as well as they scale and foul, in pipe and tube heat exchangers(35)

70% nitric acid, which will be stored in large atmospheric pressure storage tank, the capacity of the storage tank will be such as to store the amount of nitric acid that will be used in the process for 30 days (24 hour runs). See block diagram in Figure 4 The atmospheric pressure tank which is the most economical tank for liquid storage, will be constructed out of 316 stainless steel, with an internal vent system will be utilized to compensate for any changes in the ambient pressure and temperature. 316 stainless steel was chosen as the construction material because it corrosive resistant and economical compared to other materials

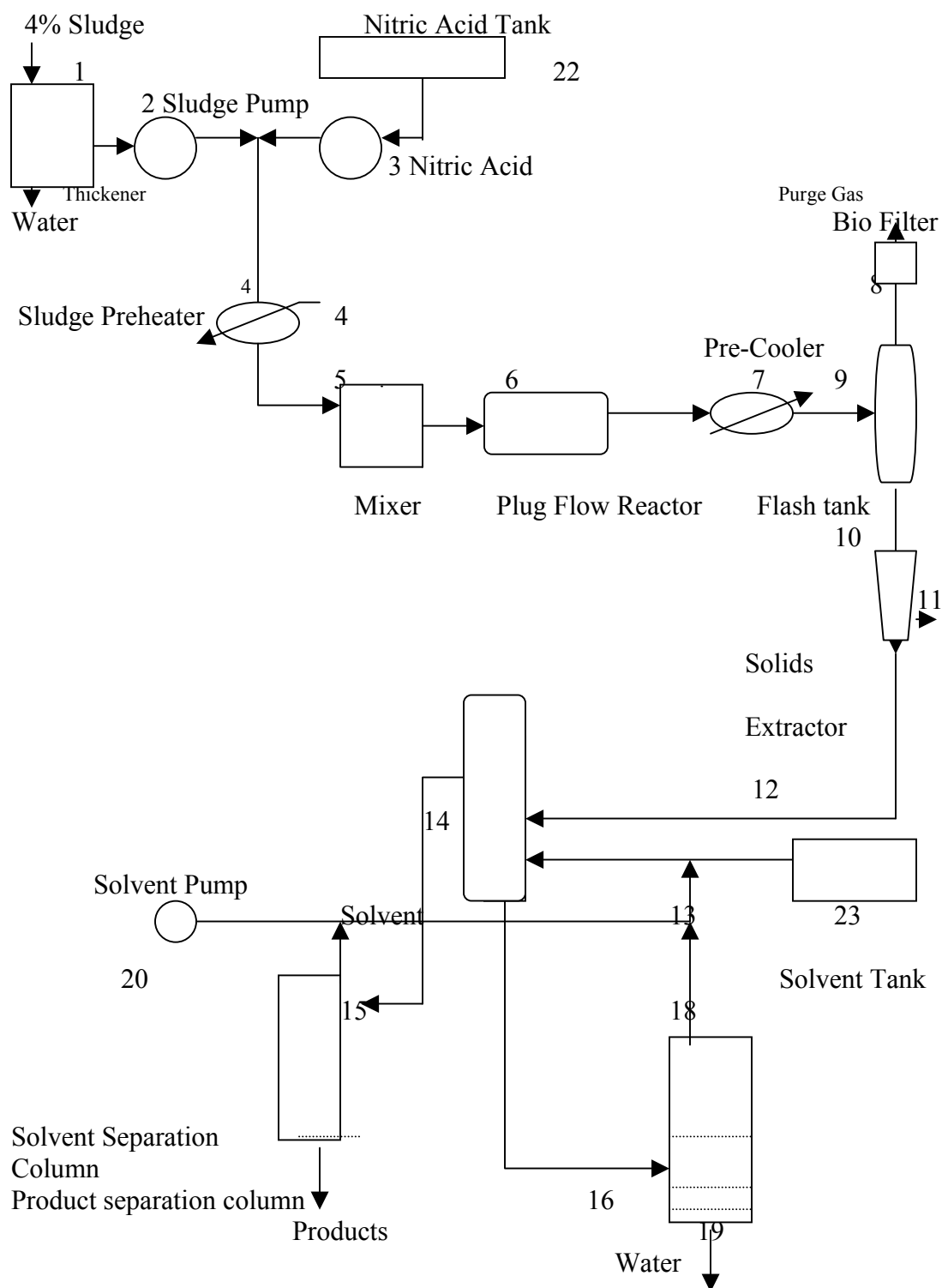


FIGURE 4 BLOCK DIAGRAM OF THE NITRO HYDROLYSIS PROCESS WITH PRODUCT RECOVERY

For the efficient running of the downstream plug flow reactor both the biosolids and nitric acid stream will be pressurized, to avoid a vapor phase. The biosolids stream will be pressurized by a centrifugal pump (stream # 1) , made from cast steel a discharge pressure of 200 psia, the centrifugal pump was so chosen because it could handle liquids with large suspended solids, since the biosolids are non- corrosive, cast steel which is also economical will be used for the centrifugal pump .

The nitric acid will be pressurized by a positive displacement pump(stream # 2) at 200 psia, since it is critical that the amount of nitric acid flowing into the reactor be correctly regulated.The positive displacement pumps flow has the above quality.A positive displacement pump with a flexible liner made out of stainless steel was chosen because of the corrosive nature of the 70% nitric acid. Excess nitric acid would result in unconverted nitrates in the reactor effluent.

The biosolids and the 70% nitric acid will be mixed in a mixer, and fed into a shell and tube heat exchanger, which will heat the feed to 180 °C before it goes to the plug flow reactor (stream #5). The shell of the shell and tube heat exchanger will be made of carbon steel because water is not corrosive. But the tubes of the shell and tube heat exchanger will be made of stainless steel due to the corrosive action of the 70% nitric acid .In order to prevent fouling and possible plugging of the tubes, the tube side velocity has to be carefully selected.

Earlier studies on nitro hydrolysis by Dupont and by Perkins et al(11) have shown that a plug flow reactor with a residence time of 5 minutes will result in a desirable conversion of the biosolids into biodegradable products. Therefore, in this study only a plug flow reactor made of stainless steel will be used,

The effluent from the reactor contains unreacted biosolids, liquids and gases (point 6).A flash tank (stream # 7) made of cast steel will be used to separate the gases from the solids and liquids. The gases will be passed through a biofilter (stream # 8) consisting of stainless steel and diatomaceous will be treated to remove

nitrous oxide and to keep the carbon monoxide concentrations under the limits covered by Title V of the Clean Air Act(12).

There are several possible alternatives for removing the solids from the liquids. The amount of solids left in the stream after the reactor is nominal compared to the amount of liquid. So they can be recycled back into the wastewater system, sometimes in municipal wastewater treatment plants dirt, etc may account for about 0-4% of the sludge concentration, recycling the dirt back to the wastewater plant is not advisable. Dirt and other non-reactable components could accumulate over a period of time causing the pipes to foul. In order to avoid this, the dirt and other non-reactable components have to be removed or allowed to build up to half of allowed solids and then purged. Since the solids are easy to filter, they will be removed within the process before the liquid separation. In this design, a multimedia screen filter will be utilized (stream # 10). This is the best option because of the low-maintenance design, stainless steel construction and exceptional efficiency (11). Over a period of time the heavy metals concentration could rise to levels where it will be deemed a hazardous waste, if such a situation does arise the effluent will have to be treated as a hazardous waste and disposed of as per the EPA guide lines. The disposal of Heavy metals is given in appendix III. In this particular case we assume that heavy metals concentrations will not be a problem, hence the sludge could be disposed of as a non hazardous waste

Multistage distillation has been by far the most widely used separation technique for liquid mixtures. Technically, distillation is the most mature and energy intensive separation process (14). The process was designed using a distillation and liquid -liquid extraction as a means to separate the various liquids, over other separation techniques such as, membrane separation, adsorption and desublimation, since design and operation procedures are well established.

Utilizing distillation and extraction separation techniques both the formic and acetic acid can be separated. The process was designed wherein liquid-

liquid extraction (stream #12) is used to remove the acetic and formic acid from water with a compatible organic solvent, ethyl ether. Ethyl ether was selected over solvents such as benzene, chloroform, ethyl acetate, furfural, diethyl ether and vinyl acetate. Selection of the right solvent depends on several factors. One is whether the solvent can be easily distilled from the organic acids (21).

. Another consideration is the health and environmental risks of toxic solvents. An important solvent property is the equilibrium distribution coefficient, K_o (21). Finally, some solvents might prove to be more economically favorable. Ethyl ether was chosen as the solvent for the liquid- liquid extraction based on the ease of recovery of the products. The range of distribution coefficients for ethers (K_o) is between 0.63-0.14 (11). Also there is sufficient difference in liquid densities, 63 lb/ft³ for the raffinate and 45.5 lb/ft³ for the extract, for efficient phase separation (11).

After the extractor, the acids would need to be distilled from the solvent (point14), which would be recycled back to the extractor (stream #15). The solvent will be pumped back to the stream using a centrifugal pump (stream # 13). Additional solvent will be supplemented from the storage tank (stream # 23). The final separation step would be to split the binary mixture of acetic and formic acid into pure components (stream # 17). It will be feasible to separate acetic acid and formic acid by distillation since the boiling points differ by 17⁰C

A second alternative to consider, besides product recovery would be to recover no products, and simply recycle the effluent from the reactor back to the wastewater treatment facility.

The figure 5 below gives a block diagram of the process. The initial steps of the process are similar to that of the nitro hydrolysis process with product recovery. A flash tank (stream #9) would separate the gases from the liquids and a biofilter to remove the hazardous gases (stream # 8). Solids that are not destroyed such as dirt, ash, metals etc could be filtered while the liquid stream (stream #12) is recycled back to the wastewater facility .

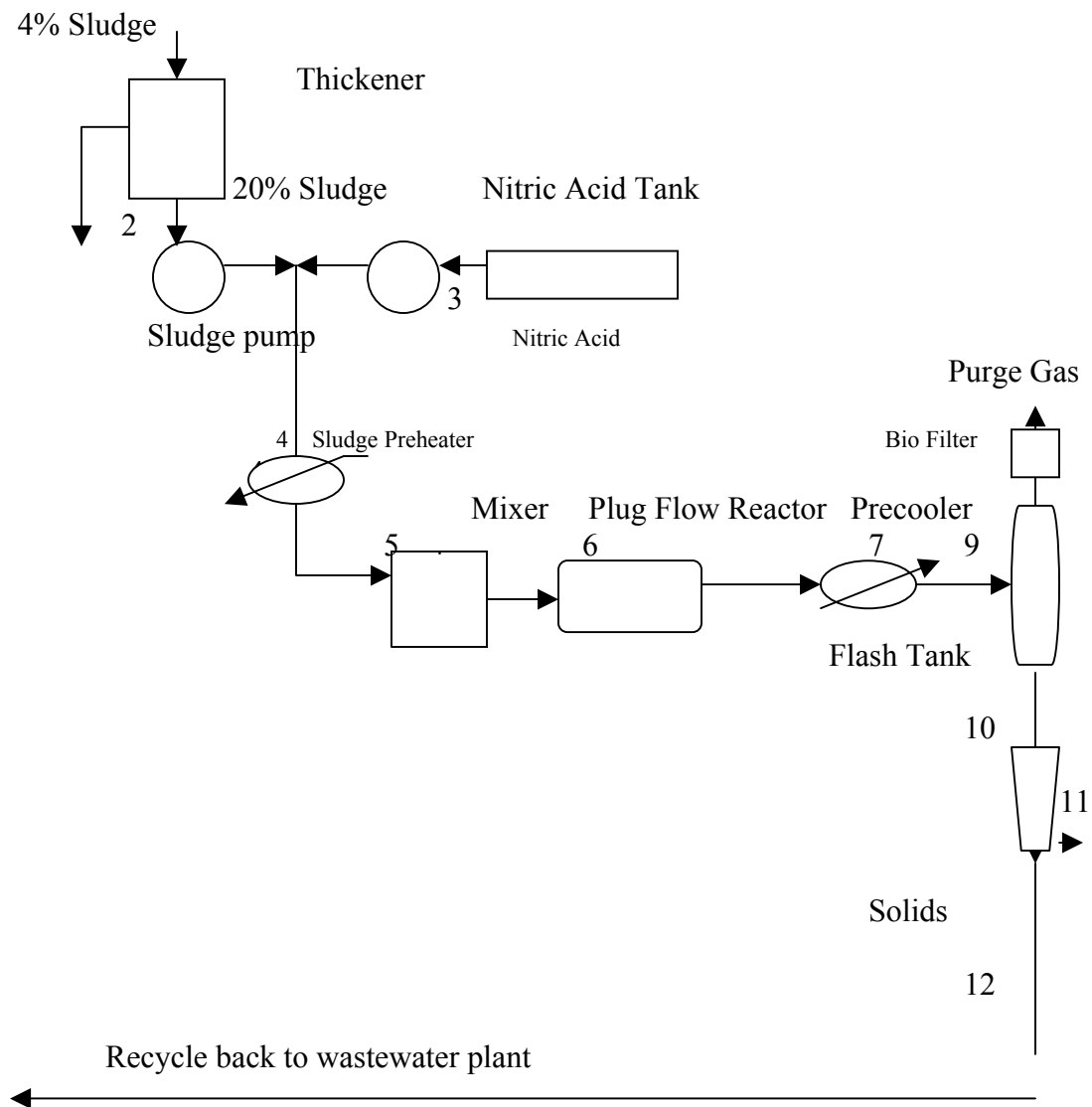


FIGURE 5 BLOCK DIAGRAM OF THE NITRO HYDROLYSIS PROCESS WITH PRODUCT RECYCLE

3.2 MATERIAL BALANCES

The material balances were done by hand calculations. Data for the design were taken from the Perry's chemical engineering hand book, supplementary data were taken from Douglas, "Conceptual Design of chemical process"(23), Gael D. Ulrich" A guide to chemical engineers process design and economics"(7) .In order to verify the design, HYSYS was used to cross check the flow rates in and out of the reactors and columns.

The Table 3 the gives the material balance for the nitro-hydrolysis process with product recovery. The numbers shown on Table 5 corresponds to source #'s in the Figure 6.

3.3 EQUIPMENT SPECIFICATIONS

The table 4 below gives the plant specifications; the design for each equipment is given in detail in the appendix of the thesis. Data and design equations for the design were taken from the Perry's chemical engineering hand book(39), supplementary design equations were taken from Douglas, "Conceptual Design of chemical process"(23), & Gael D. Ulrich" A guide to chemical engineers process design and economics"(7).

3.4 CAPITAL AND OPERATING EXPENCES

The table 6below gives the capital and operating cost of the process, The price of the equipments were calculated from graphs in literature (18,19,15).The operating expenses were calculated using an excel spread sheet and verified by hand calculations. The basis for these calculations were taken from Peters and Timmerhaus "Plant Design and Economics for Chemical Engineers" (37) and from Blank and Tarquin "Engineering Economy"(20).

**TABLE 3 MATERIAL BALANCE FOR NITRO-HYDROLYSIS WITH
PRODUCT RECOVERY**

Stream properties	Units	1	2	3	4	5	6	7	8	9	10	11	12
comp flow	lb/hr												
Sludge		3200	3200	0	3200	3200	6800	320	0		320	320	0
Water		80000	1280	2667	15467	12867	12867	17753	3		17750	0	177150
Nitric acid			0	6224	6224	6199	6199	62	1		61	0	61
Acetic acid			0	0	0	0	0	2144	1		2145	0	2145
Formic acid			0	0	0	0	0	656	12		646	0	646
C3H7NO2			0	0	0	0	0	774	0		774	774	0
Carbon oxides			0	0	0	0	0	1384	1300		48	0	48
oxides of Nitrogen			0	0	0	0	0	1621	1586		35	0	35
Diethyl Ether			0	0	0	0	0	0	0		0	0	0
Total flow	lb/hr		16000	8891	24891	24891	24891	24891	2900		21991	1094	20897

TABLE 3 CONT'D

Stream properties	Units	12	13	14	15	16	17	18	19	22	23
comp flow	lb/hr										
Sludge		0	0	0	0	0	0	0	0	0	0
Water		177150	0	17394	0	17394	365	356	0	356	0
Nitric acid		61	0	61	0	61	0	0	0	0	0
Acetic acid		2145	0	4	0	4	2141	0	2141	0	30
Formic acid		646	0	0	0	0	646	0	646	0	0
C3H7NO2		0	0	0	0	0	0	0	0	0	0
Carbon oxides		48	0	0	0	0	0	0	0	0	0
oxides of Nitrogen		35	0	35	0	35	0	0	0	0	0
Diethyl Ether		0	64337	1230	1230	0	63107	63106	1	0	1230
Total flow	lb/hr	20897	25856	187240	1230	17494	66250	78918	2788	356	1230

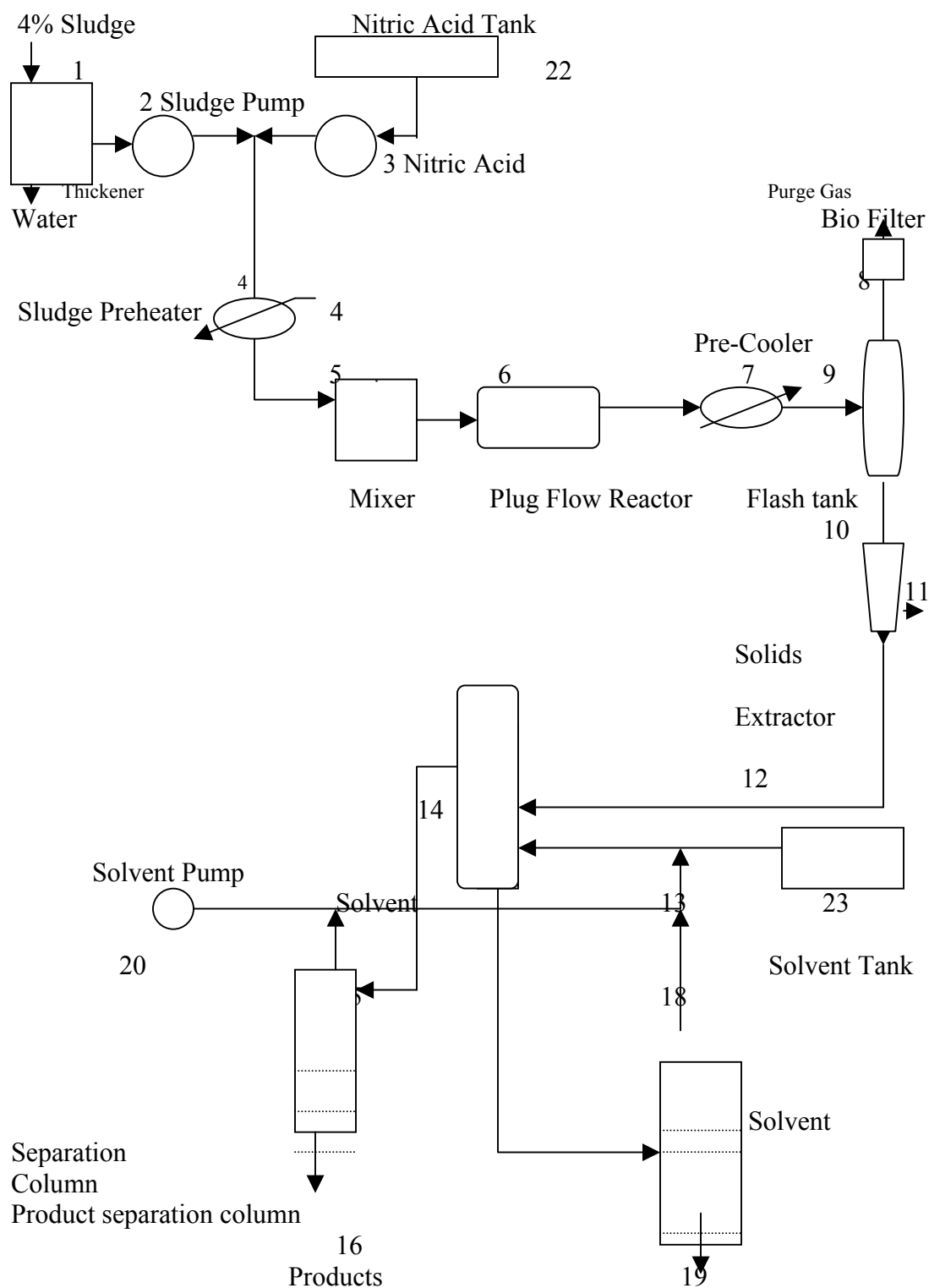


FIGURE 6 SOURCE POINTS FOR THE MATERIAL BALANCE FOR NITRO-HYDROLYSIS WITH PRODUCT RECOVERY

TABLE 4 PLANT SPECIFICATION

Nitric acid storage tank		Solvent storage tank	
Volume (gal)	2,325,000	Volume (gal)	44,900
30 day supply basis operation 24 hrs/day		30 day supply basis operation 24 hrs/day	
Cone roof vertical fabrication		Cone roof vertical fabrication	
Material spec	SS	Material spec	SS
Sludge pump		Solvent pump	
Type	Centrifugal	Type	Centrifugal
Energy required (Btu/hr)	75,050	Energy required (Btu/hr)	1.12E+05
Efficiency	70%	Efficiency	70%
Discharge	200	Discharge	100
Material Spec	CS	Material Spec	CS
Size (hp)	30	Size (hp)	50
Nitric acid pump		Biofilter	
Type	Flexible	Amount N2O removed (lb/yr)	36,470,243
Energy required (Btu/hr)	22,850	Material	SS
Efficiency	60%	L/L Extractor (Sieve Tray Tower)	
Discharge	200		
Material Spec	SS		
Size (hp)	10		
Effluent Cooler		Flash Tank	
Outlet Temp (F)	130	Pressure (psia)	
Heat tx to water (Btu/hr)	5.498E+07	Temperature	
Heat Transfer Coeff (Btu/hr*ft*ft)	200	Weight Fraction – Formic Acid in Lqd	
Area Required (ft*ft)	1671	Vapor Density	
T water in (F)	118	Liquid Density	
T product in (F)	356	K (ft/s)	
T water out (F)	129	Vmax (ft/s)	
Material Spec	CS/SS	Vapor Flow Rate (ft*ft*ft/hr)	
		Cross Sect Area	
		Diameter (ft)	
		Final D (10% higher)	
		H (ft)	
		Material Spec	

TABLE 5 CAPITAL AND OPERATING EXPENCES

<u>CAPITAL AND OPERATING EXPENCES</u>							
Capital Expenses				Operating Expenses			
Onsite Costs				Annual Utility Costs			
Nitric Acid Pump		\$ 48,000.00		Electricity Costs			
Sludge Pump		\$ 80,000.00		Sludge Pump		\$ 8,000.00	
Nitric Acid storage tank		\$ 300,000.00		Nitric Acid pump		\$ 6,880.00	
Feed Pre-Heater		\$ 17,600.00		Solvent Recycle Pump		\$ 4,587.00	
Screen		\$ 30,000.00		Total Electricity Costs		\$ 19,467.00	
PFR		\$ 25,580.00					
Effluent Cooler		\$ 16,500.00		Steam Costs			
Solids Filter		\$ 34,850.00		Heat Exchangers		\$ 54,247.00	
Flash Tank		\$ 57,600.00		Product Separation Distillation Col		\$368,578.00	
Solvent Recycle Pump		\$ 16,000.00		Solvent Recovery Reboiler		\$112,464.40	
Solvent Storage Tank		\$ 280,000.00		Total Steam Costs		\$535,289.40	
BioFilter		\$ 135,000.00					
Extractor		\$ 320,823.00		Cooling Water Costs			
Product Separation Col		\$ 475,000.00		Product Separation Condenser		\$ 10,207.08	
Solvent Recovery Col		\$ 570,000.00		Solvent Recovery Condenser		\$ 284.64	
Thickener		\$ 50,000.00		Total CW cost		\$ 10,491.72	
Mixer		\$ 112,000.00					
Total		\$ 2,568,953.00		Total Utility Cost		\$545,781.12	
Piping (10% of FCI)		\$ 256,895.30		<i>Other Operating Costs</i>			
Instru/ Controls (5% of FCI)		\$ 128,447.65		Solids Filtering (Landfill)		\$102,689.80	
Electrical Equipment (4% of FCI)		\$ 115,602.89		Biofilter		\$ 75,000.00	
	Total onsite cost	\$ 3,069,898.84					

TABLE 5 CONT'D

Total Capital Investment Costs		Total Production Costs	
Direct Costs		Direct Production Costs	
Onsite Costs	\$ 3,069,898.84	Raw materials	\$12,427,130.00
Offsite Costs (45%)	\$ 1,381,454.48	Utilities	\$ 545,781.12
Total Direct	\$ 4,451,353.31		
		Maintenance & Repairs (4%)	\$ 267,081.20
<u>Indirect Costs</u>		Operating Supplies (15% of	\$ 4,006.22
		Operating Labour	\$ 1,945,936.67
Owner's Cost (5% of Direct)	\$ 222,567.67	Supervision, clerical (30 % of OpL)	\$ 583,781.00
Contingency (20%)	\$ 890,270.66		
Total Indirect Costs	\$ 1,112,838.33	Total direct product costs	\$15,773,716.21
		Fixed Charges	
Fixed Capital	\$ 5,564,191.64	Local taxes (2.5% of FCI)	\$ 139,104.79
(Total Direct and Working Capital	\$ 1,500,000.00	Insurance (0.7% of FCI)	\$ 389,493.41
Startup Costs	\$ 556,419.16	Interest (3.5% of TCI)	\$ 266,721.38
		Total Fixed Charges	\$ 795,319.58
Total Capital	\$ 7,620,610.80	Plant Overhead (60% of	\$ 1,680,483.05
		Manufacturing Cost	\$19,044,838.42
<u>Annual Raw Material Costs</u>		<u>General Expenses</u>	
Nitric Acid	\$ 7,535,389.00	Administrative costs (15% of	\$ 469,833.75
Di-Ethyl Ether	\$ 4,891,741.00	Distribution costs (10% of	\$ 1,566,112.50
Total	\$ 12,427,130.00	R & D Costs (5% of TPC)	\$ 783,056.25
		Total Product Cost	\$21,080,784.67

CHAPTER 4 RESULTS AND DISSCUSSIONS

4.1 RESULTS AND DISSCUSSIONS

The conversion of sludge to biodegradable and valuable products using nitro-hydrolysis is a potentially viable process; the process gives a 1% rate of return on capital invested. In calculating the economic potential, the Minimum attractive rate of return (MARR) was selected as 8 %.The project life was assumed to be 15 years, with no salvage value after the project life. The material costs of Nitric, Acetic acid Formic acid and the solvent, were the price of such materials on Jan 1, 2002(45).

The economic potential of the process were estimated using equations given by Leland Blank and Antony Tarquin(20). Savings in comparisons to land filling sludge were also calculated. The credit associated with transporting and to landfill sludge was taken to be \$0.18/lb at 20% sludge. These credits were determined from landfill cost and transportation cost. The Table 6 below gives the economic basis on which the economic analysis was calculated. Table 7 give the prices of raw materials on which the economic analysis was made

The annual savings was calculated by subtracting the expences and capital recovery from the sum of the product sales and the land fill credit.The landfill credit could be considered a profit because the money allocated by the company into landfill disposal was not used. The landfill credit was calculated taking into account the transportation cost (rent of the trucks + diesel + labor + maintenance) and the cost of the lands. KUB rents 10 trucks, each of which makes only one trip of 140 miles a day to the landfill sites.

Table 8 give the economic analysis for the process with product recovery.The capital return for the investment was calculated to be a 1 %.The capital return on investment was calculated as the percentage ratio between the annual savings for the process to the total investment. The return on investment was calculated on an economic basis based on the current prices of equipment and the prices of the product, and raw materials as on January 1 2002.

TABLE 6 ECONOMIC BASIS

Economic Basis		
M&S (4 th Qtr 2001)	1004.5	
CEI (Dec 2001 general)	315	
CEI base year mid-1982	405	
Cooling Water Cost (\$/1000 gal)	\$0.015	
Steam Cost (\$/1000 #)	\$4.50	
Electricity Cost (\$/KWh)	\$0.046	
Project Life	15	Yrs
Corporate Tax Rate	40%	
Deprecation Life	9	Yrs
Salvage Value	\$0.00	
Project MARR	8%	

TABLE 7 MATERIAL COSTS

Material Costs		
Nitric Acid	0.1075	\$/lb
Acetic Acid	0.455	\$/lb
Formic Acid	0.42	\$/lb
Diethyl Ether	0.46	\$/lb

**TABLE 8 ECONOMIC ANALYSIS FOR NITROHYDROLYSIS WITH
PRODUCT RECOVERY**

ECONOMIC ANALYSIS	
GROSS SALES OF PRODUCT	\$ 9,819,325.00
TOTAL PRODUCT COST	\$ 21,080,784.67
CREDIT FOR FORGOING SLUDGE FARMING	\$ 10,676,250.00
ANNUAL SAVINGS	\$ 261,524.86
RATE OF RETURN	1%

To understand the effect of certain variables on the return of capital, a sensitivity analysis was done with each of the variables. The general procedure to follow while calculating a thorough sensitivity analysis is to first determine which parameters of interest might vary the most likely estimated value. Once the parameters have been selected, the probable range and increment of variation for each parameter must be selected. The sensitivity analysis is calculated by changing each parameter over the selected range. An important assumption in the sensitivity analysis is that only the selected variable changes, while all other variables remain constant. In reality, this might not be the case, with several parameters changing simultaneously. Nevertheless, the sensitivity analysis will give investors and project designers a better picture on the factors affecting the economics of the project.

The rate of return will depend on the capital, energy, raw material costs, product costs, yield and the credit for sludge. Another very important factor for the process will be the inlet sludge concentration. To get a better picture of the economics, variations of these parameters with the rate of return on capital was plotted graphically using excel. The calculations were done using an excel spreadsheet and verified using hand calculations.

The first parameter that will be considered will be the cost of solvent; the solvent will be used to extract the product acetic acid and formic acid from the reacted product stream. In calculating the economic potential of the process, the cost of the solvent Diethyl Ether on January 1 2002 was used. Even though the price of the solvent has not changed dramatically over the last 5 years. The price of the solvent could change, if the nitro-hydrolysis process were to be implemented by other wastewater treatment plants, with approximately 7000 wastewater plants in the US, a sudden increase in demand for the solvent, with existing production rates will fuel the price for the solvent. Figure 7 gives a graphical representation of the sensitivity analysis.

On the other hand, if a cheaper process to manufacture the solvent was introduced, the price of the solvent in the market could plummet downwards. As seen from the figure above, an increase of 30% in the price of the solvent, will decrease the rate of return to -17%, from its original 1% using January 1 2002 prices. However, a decrease of 30 % will result in a 17% rate of return.

Another important parameter in the design of this process was the yield. A yield conversion of 90% was assumed, even though a conversion of 96%(5) was reported by DuPont.

The yield of the process depends on factors like, quality of the sludge, residence time of the reactants in the plug flow reactor, reaction conditions and the quality and concentration of the nitric acid. As can be seen from the Figure 8 below, a change in the yield will greatly affect the rate of return. A 4% decrease from the designed yield will lower the rate of return to -4%. At the same time an increase of 3%, will increase the rate of return to 4%. It is therefore very important to maintain the yield of the process at its designed conversion rate.

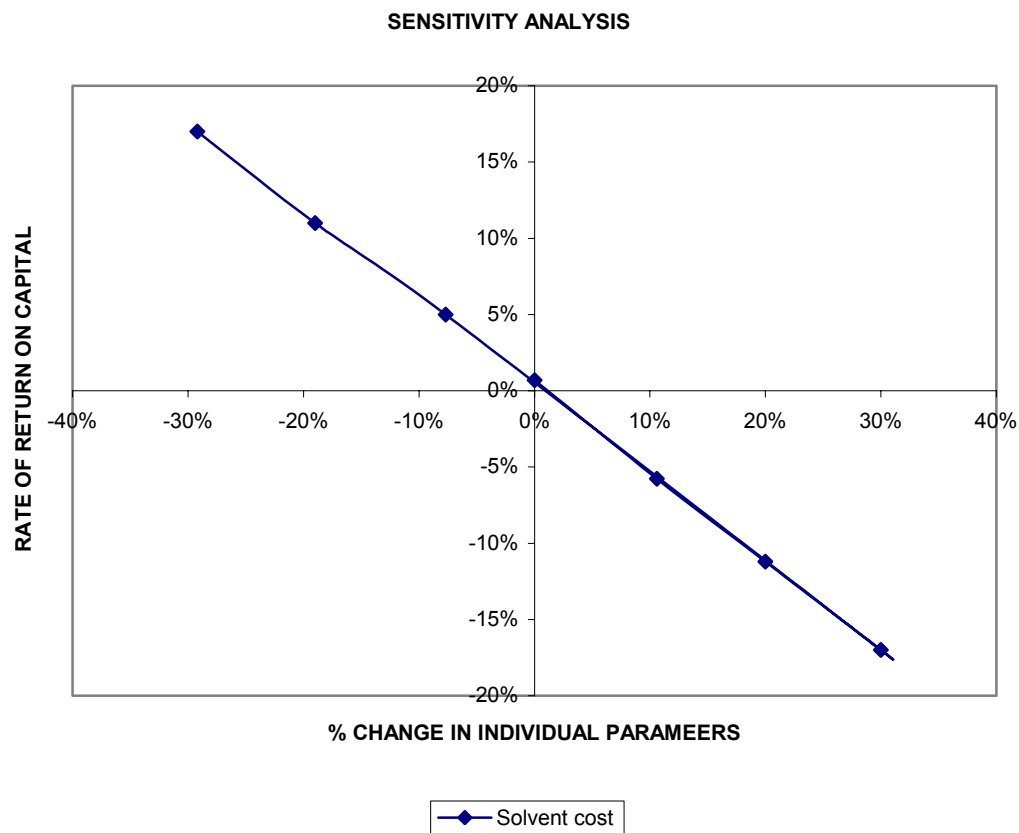


FIGURE 7 SENSITIVITY ANALYSIS FOR SOLVENT

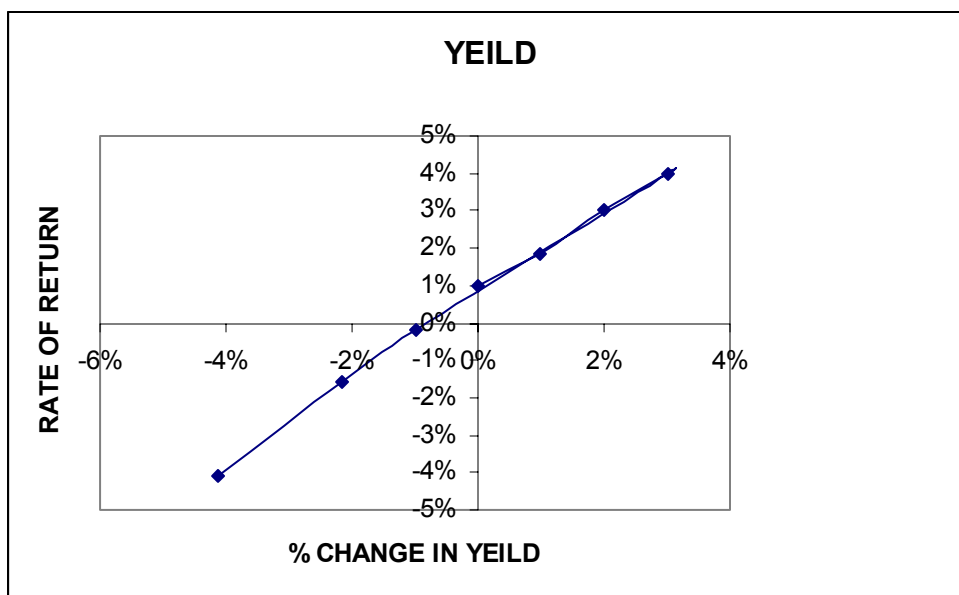


FIGURE 8 SENSITIVITY ANALYSIS FOR YEILD

The other factors that were considered important to the rate of return were the capital invested, the price of the raw material nitric acid, energy costs and the sludge credit. The capital invested depends on the price of the equipment installed, the installation costs etc. In order to calculate the cost of the equipment direct quotes from vendors as well as estimates from graphs (20,18,8) was used. These estimates have an accuracy of 20%.

The Figure 9 below shows the sensitivity of the rate of return to changes in the capital invested. 20 % increase in the capital invested will see the rate of return decrease to -40% while a 20% decrease would result in a 40% rate of return.

The price of key raw material nitric acid is also crucial. A sudden increase in demand in nitric acid, with existing production rates ,would cause the price of nitric acid in the market to increase .An increase of 30 % in the price would result in the rate of return on capital diminish to-12 %, on the other hand a decrease of 30% would see the rate of return rise up to 17%.

Nitro-hydrolysis is an energy dependent process. The cost of energy plays a crucial role in the finances of the process. The cost of energy includes the steam costs, heating & cooling costs and electricity costs.

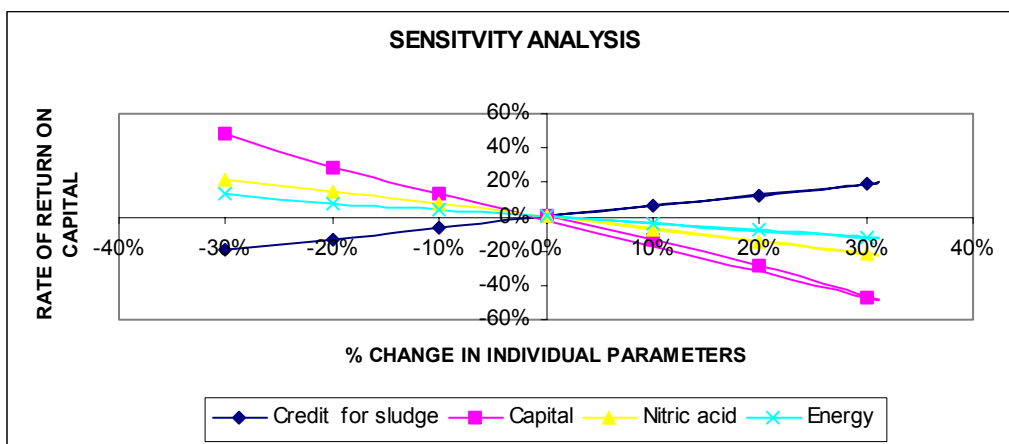


FIGURE 9 SENSITIVITY ANALYSIS FOR SOLVENT

With the increasing costs of energy, an increase in the energy cost can always be expected. A 30% increase in the energy cost will see the rate of return drop to -18% .An unlikely 20% fall in the cost of energy gives a 18% rate of return.

KUB disposes it's sludge through landfills. A certain amount of the production costs of the process is allocated for this purpose. Using the nitro-hydrolysis process such means of disposal can be eliminated. As a result capital allocated by the company for the disposal of sludge can be considered a saving or a credit, the money could be re invested or shown as a profit. The figure above shows the dependence of the rate of return on the capital on . 20% increase will see the rate of return increase to 14% while a drop of 20% will see the rate of return to -14%.

4.2 SLUDGE CONCENTRATION

The concentration of the influent sludge is a very critical factor in the process as well as in the process economics. The influent sludge stream was 20% by weight solids for this process, using such a concentration a handsome rate of return of 1% can be achieved .KUB produces 4% sludge (solids) from it's activated sludge process. While designing this process, a clarifier was used to thicken the sludge: this involves adding a large quantities of alum and ferric chloride to coagulant the sludge the sludge with an appropriate residence time. This method of thickening might not be the appropriate means of concentrating the sludge. In order to concentrate the sludge, it would be critical to know the dewatering characteristics.

Sludge dewatering is a difficult process in water and wastewater sludge treatment, as commonly achieved through filtration as well as consolidation practice. The sludge systems markedly differ from conventional particulate systems (such as kaolin or CaCO_3 (40) with distinguishing features: highly porous, fractal-like floc interior structure(41), the high resistance to dewatering(34) and a large amount of bound water(32)

The moisture in sludge can be as high as 99%(32) Historically, water in sludge has been defined as either bound water or bulk water. Water in sludge appears in four forms (32). (1) Free water: water that is not attached to sludge solids and that can be separated by simple gravitational settling (2) Interstitial water: water that is trapped within the floc structure and travels with the flocs, or perhaps water trapped within the cell. This water can be released when the floc is broken up or the cell is destroyed. Some interstitial water might be removed by mechanical dewatering devices such as centrifuges. (3) Vicinal Water: Water that is associated with the solid particles. This water is held on particle surface by virtue of the molecular structure of the water molecules and cannot be removed by centrifugation or other mechanical means.(4)Water of hydration: water that is chemically bound to the particle and can be released only by thermo chemical destruction of the particles.

Sludge concentration is an energy intensive process. Before sludge concentration, the digested sludge is usually conditioned to generate flocs that are easy to filter (5). Chemical conditioning using polythelectrolytes, Fe(III), Fe(II),lime or Al(III),is the most common method(3).The chemicals act as either coagulants by reducing the zeta potential of the solid particles or flocculants through the bridging effect to form proper sized flocs(34).Thermal conditioning by simple heating or wet oxidation can also be used(35) .An effective method that can be used in cold regions in winter is freezing/thawing(34). During the freezing period, the ice crystals formed will push the contaminants, in this case the sludge particles, out of the lattices to form solid bricks. The sludge should be fully frozen (34). The thawing and quick removal of water result in a dewatered sludge of more than 20% solid content (35). The thawed sludge should not be agitated in order to keep its filterability.

There are several alternatives of mechanical dewatering of sludge. They are vacuum filters, belt filter presses, centrifuges, and membrane filter presses. Vacuum filters are among the earliest mechanical devices employed. Although many of its installations are being replaced by more efficient belt filters, the use of vacuum filters is popular when applied with percoat filtration (35). Another

configuration is the rotary belt vacuum filter (34). The difference between a belt vacuum filter and a rotary drum vacuum filter is that the filter medium is wrapped around the surface of the drum rather than fixed to the drum (36). This gives the advantages of continuous belt washing and more efficient cake discharge.

In a belt filter press, the conditioned sludge is first drained under gravity before being sandwiched between two endless filtering belts. The pressure from the tensioned belts squeezes the water out of the sludge with a continuous cake discharged at about 15-25% solid content. Plate and frame filter presses can also be used if the volume of the sludge to be treated is not high. The rotary press is a recent development. Sludge is pumped into a peripheral channel that has walls made of rotating filter elements. As the mechanism rotates, compression is created and liquid is forced through the filter elements. A cake is formed in the interior channel and then extruded.

Centrifugal dewatering uses the centrifugal forces developed by spinning a bowl or basket to separate the sludge solids from the liquids. Disc, basket, and solid bowl centrifuges are all used for sludge dewatering with the latter being the most common. The current generation of centrifuges can achieve solid contents of 25-35%.

Mechanical filter presses are modified filter presses with the introduction on inflatable membrane systems, automatic cloth washing, controlled filling techniques, dual –speed plate separation and automatic discharge. Thermal drying of sludge is necessary when the required final product water content is low as in fertilizer production, when the heating value of the sludge needs to be improved for efficient incineration, or in the case of reduction of transportation cost in disposal such as land filling. Thermal drying can also help inactivate indigenous viruses.

Even with technical advances over the last century, sludge dewatering technology continues to be improved. No simple method exists for selecting the best dewatering process for a wastewater treatment plant. The

dewatering process chosen will be a function of sludge disposal and capacity, along with the plants' operation and maintenance.

Sludge can be concentrated up to a maximum of 20-40% (37), before large lumps of solids begin to appear. Mechanical dewatering process will concentrate the sludge to concentrations as high as 40-45%, using a high concentration looks economically feasible but it may lead to other problems in the running of the process, namely the transportation of the sludge, pump efficiency etc. Reduction in the sludge concentration will ease this problem but it will be offset by an increase in production cost, because larger separation, reaction columns and pumps have to be used. Larry et al(11) have shown using a 4% stream only third of the theoretical amount of acetic acid was produced. Concentration of 20-25% although practical are not be economically feasible. At such high concentration incineration of the waste becomes cost effective and might prove to be a more practical investment

The Figure 10below shows the rate of return on capital with changes in the concentration of sludge unlike the other sensitivity analysis, all other parameters affecting the process were also varied, and the process was essentially redesigned. As the graph shows using sludge concentration as low as 15% below the design concentration reduced the rate of return to -22 % .Increasing the Sludge concentration to 40% will give a 60% rate of return, but although economically feasible there will be operational difficulties. Therefore operation between ranges of 20-25% sludge concentration is the only operational and economically viable concentration

4.3 ECONOMIC ANALYSIS FOR NITRO-HYDROLYSIS WITHOUT PRODUCT RECOVERY

The economics of the nitro-hydrolysis process using 25% sludge concentration but with no product recovery was also studied. In this process, all the solids were converted into organic acids. The liquid stream which contained no solids was then recycled back to the wastewater plant.

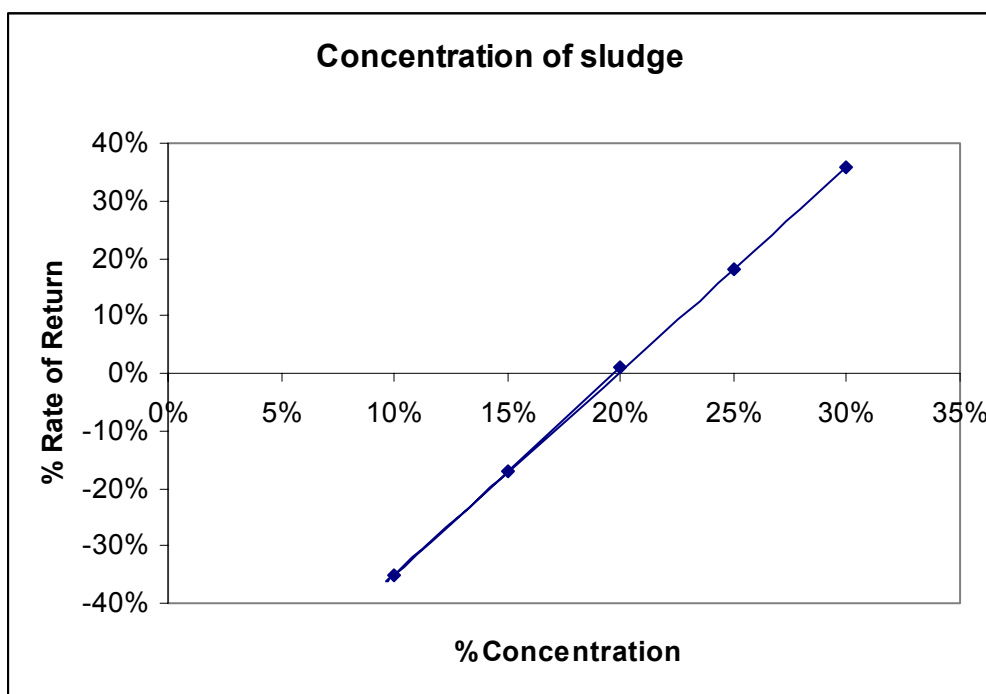


FIGURE 10 SENSITIVITY ANALYSIS FOR CONCENTRATION

The plant would be much smaller compared to a plant with product recovery. The capital invested and Total product cost was considerably smaller, due to the fact that equipments such as distillation columns, solvent pumps, solvent storage tanks and solvents will not be required. The Table 9 below shows the economic analysis for the process.

The only source of income for the process was the landfill credit. An economic study into the process showed that the process did manage to make a profit, but it has -13% return on capital invested. Such a process would be non viable and will only be practical, if nitro-hydrolysis was used solely as a sludge disposal means but not as another source of income.

4.4 INCINERATION AS MEANS OF DISPOSAL

The energy requirements to incinerate the sludge at a solid concentration of 12.5% was also reviewed. It was calculated that 0.24 trillion BTU's/yr will be required to incinerate. If the sludge was incinerated at 4% solid concentration, 0.53 trillion BTU/year will be required as energy costs only.

**TABLE 9 ECONOMIC ANALYSIS FOR NITROHYDROLYSIS WITH
PRODUCT RECLYLE**

ECONOMIC ANALYSIS		
GROSS SALES OF PRODUCT	\$	0
TOTAL PRODUCT COST	\$	12,776,305
CREDIT FOR FORGOING SLUDGE FARMING	\$	10,676,250
ANNUAL SAVINGS	\$	1,693,248
RATE OF RETURN		-13%

This does not take into account the capital and operating expenses required for the incinerators (fluidized bed reactor) and thickeners .A rough estimate of the capital and operating costs (29) shows that approximately 19 million dollars will have to be invested to treat sludge at 12.5% solid concentration. Using a 4% feed the capital and operating costs will be approximately 30 million dollars. The only source of income will be the landfill credits, which would only account for a fraction of the cost of operating the incineration process.

4.5 COST COMPARISONS

Tables 10, 11, 12 gives a breakdown of the economics of the disposal methods .Even though land farming is a cheaper option, the nitro-hydrolysis method with product recovery, is the more economically viable method, it becomes more feasibleIf it replaces land farming, and the land farming credits is added to the nitro-hydrolysis process as a savings. Incineration is still an expensive method of incineration, the only possible income generated is the sale of the ash, in doing this analysis the sale of the ash was not considered.The nitro hydrolysis process with product recovery although economically unviable, is cheaper than incineration

TABLE 10 DISPOSAL CREDITS FOR NITROHYDROLYSIS WITH PRODUCT RECOVERY

CREDIT FOR LAND FARMING	\$10,678,250
GROSS SALE OF PRODUCT	\$ 9,819,325
TOTAL PRODUCT COST	\$ 21,080,785

TABLE 11 DISPOSAL CREDITS FOR INCINERATION

INCINERTION CREDIT	\$23,778,640
GROSS SALE OF PRODUCT	\$ 0
TOTAL PRODUCT COST	\$ 34,480,881

TABLE 12 DISPOSAL CREDITS FOR NITROHYDROLYSIS WITH PRODUCT RECYCLE

CREDIT FOR LAND FARMING	\$10,678,250
GROSS SALE OF PRODUCT	\$ 0
TOTAL PRODUCT COST	\$ 12,776,306

4.6 SUMMARY

Running the nitro hydrolysis process using a 20% sludge concentration is an economically unviable process. The process economics depends significantly on the yield, capital and inlet sludge concentration. It is therefore imperative that the process be run at its designed yield conversion with the set sludge concentration. . The price of the products was also an important factor in the profitability of the process. Flooding the market with acetic acid and formic acid could see a drop in the prices, gravely affecting the profitability of the process. On the other hand, a nitro-hydrolysis process with no product recovery requires a considerably lower investment but gives -13% rate of return on capital. This may be a viable process, if the nitro hydrolysis process was to be used solely as an effective sludge disposal option not as an additional means of generating income.

Although economically unfeasible, the nitro hydrolysis process at 20% sludge concentration could have operational difficulties. Due to it's high viscosity, large solid lump compositions and fouling properties, running the process effectively could be challenging, if not difficult. The economics of the process was done on the assumption that the process could be run, without any major difficulties. The designs of the equipments to be used were also done with the above assumption. The only way to find out the operational feasibility of this process is to run a small-scale pilot plant. This could lead to more design changes unique to the process. Such changes would affect the rate of return. Lowering the sludge concentration would not be feasible, because the process will become economically non-viable.

Incineration as a disposal method was also considered, but high capital and operation costs, compounded with a huge energy demand for incineration makes it unrealistic for the incineration process to be considered an alternative

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APPENDIX

APPENDIX I

Design basis

Sludge produced / day = 65 tons

Sludge composition : 20% Sludge, 80% Water

Plant operating capacity = 90% = 7884 hrs. / year

Molecular weight of sludge = 30.827

Plant capacity = $360,000 \times 365 / 7884 \sim 16,000$ lbs/hr.

Nitric acid flow rate (70%) = 9445.2 lbs/hr.

Labor cost = \$ 16/hr. (Bureau of Industrial statistics)

Design And Capital Cost estimation

Reactor

Plug flow reactor

The reaction rate is 1st order w.r.t HNO₃ and Sludge and 2nd order all. With a 90% conversion of sludge.

Volumetric flow rate $25 \text{ ft}^3/\text{min.} = 1500 \text{ ft}^3/\text{hr.}$

Reaction rate = 47.73.

Concentration of sludge $C_{\text{dry}} = F_{\text{dry}} / V_o$ (ref)

Where,

$$C_{dry} = \frac{17000 * 40}{100 * 30.827}$$

$$= 0.14705 \text{ lb. mol/ft}^3$$

For 2nd order

$$CAOkt = \frac{X_A}{1 - X_A}$$

$$t = \frac{X_A}{(1 - X_A) * C_{AO}K} = \frac{0.9}{(1 - 0.9) * 0.14705 * 47.73}$$

$$t = 2.7 \text{ min.}$$

$$\text{Volume of the PFR} = 1500 * 1.3/60 = 63 \text{ft}^3$$

Construction

Assumption

Length = 25ft.

Radius = 0.97ft.

Corrosion allowance = 1/8th inch

Stainless Steel 316

Stress value = 11,500

Joint efficiency = 0.85

Flash tank

Density of liquid = 63.71 lb/ft³

Density of vapor = 0.825 lb/ft³

Velocity = 0.26 ft/sec.

Formic acid weight fraction = 0.98

Vapor flow rate = 22384 ft³/hr.

$$V_{\max} = 0.26\left(\frac{64.3 - 0.825}{64.3}\right) = 924.12 \text{ ft} / \text{hr}.$$

$$\text{Volumetric flow rate } V_v = \frac{F_v}{\rho_v} = \frac{22384}{0.825} = 27132 \text{ ft}^3 / \text{hr}.$$

Liquid-Liquid extractor

Tray spacing = 1.5 ft

Hole size $d_o = 0.25$

Triangular spacing $ds = 0.75$ inch

Density of raffinate = 63.0 lb/ft³

Density of extract = 45.5 lb/ft³

Volumetric flow rate of extract = 4927 ft³ / hr.

Volumetric flow rate of raffinate = 1415 ft³/hr.

Surface tension = 19.442

Theoretical trays = 12

Mass ratio = 3.54

Velocity of the downcomer

$$V_d = \left[\frac{Z_T}{(4.5 * \frac{\rho_R}{(2 * 4.18 * 10^8 * (\rho_R - \rho_E)))}} \right]^{0.5}$$

$$= \left[\frac{1.5}{\left[4.5 * \frac{63}{2 * 4.13 * 10^8 * (63 - 45.5)} \right]} \right]^{0.5} = 8795 \text{ ft / hr.}$$

Area of the downcomer = L/V_o

Diameter of the downcomer $D = (A_D/\pi)^{0.5} = (0.77/A)^{0.5} = 7.028 \text{ inch}$

Total hole area $A_h = (L_E/L_H * 3600) = (4927/0.8 * 3600) = 1.71 \text{ ft}^2$

Tray per hole area = $A_{\text{Tray}} = A_h(2.21)(d_s/d_o)$

$$= 1.710 * 2.21 * (0.75/0.25)^2 = 34.02 \text{ ft}^2$$

Total area is given by

$$A_{\text{Total}} = A_{\text{tray}} + 2(2 * D/12)^2 * \pi$$

$$= 34.02 + 2(2 * 7.028/12)^2 * \pi$$

$$= 42.640 \text{ ft}^2$$

Total diameter = $A_{\text{total}}^{0.5} + 2/12$

$$= (42.64)^{0.5} + 2/12 = 6.529 \text{ ft}$$

Tray efficiency

$$= \frac{0.35 * (1.5)^{0.5}}{(\sigma * \frac{do}{12})^{0.35} (\frac{Vo}{Vh * 3600})} = 0.27$$

Actual number of trays = $N/\epsilon = 12/0.27 = 43$

Height ration = $Z_T + \text{trays} * 6 = 70.5 \text{ ft.}$

Heat exchanger

Feed Heater

Co-current 1-1 shell & tube stainless steel exchanger

Heat transfer coefficient = 250 Btu/hr ft²

Maximum surface area = 800 m²

Assumed area = 500 m²

Temperature of sludge in 75°F

Temperature of sludge out 356°F

Temperature of water in 129°F

Temperature of water out 120°F

$$Q = 5400 * 250 * 36.62 = 49437000 = 49.437 * 10^6 \text{ Btu /hr.}$$

Pumps

Sludge pump, Centrifugal pump

Power rating

$$\frac{\frac{16000}{2.2 * 60} * 200}{1713 * 0.7} = 20$$

Discharge pressure = 200 psia

Nitric acid, Positive displacement pump

Solvent recycle pump, Centrifugal radial pump

Power rating = 14 BHP

Mixer, Axial flow impeller

Volume = 125% of PFR

=

Assumption

Height = 5 ft

Diameter = 3.23 ft

$$P = \frac{K_r * n^3 D^5}{32.17} = \frac{5.75 * (1.5)^2 * (3.23)}{32.17} = 45 Bhp$$

Thickner

Diameter of thickner = 10 m

Solvent recovery Distillation column

Number of trays = 8

Reflux ratio = 1.5

Tray efficiency = 80%

Tray spacing = 2 ft.

Heat transfer Coefficient = 100 Btu/hr.

Column pressure = 50 psia

Actual number of trays $N/0.8 = 10$

Tower height $H = 2.3 * N / 0.8 = 2.3 * 8 / 0.8 = 23$ ft.

$$A = 2.1 * 10^{-4} * V \left(\frac{M_a}{\rho_m} \right)^{1/2}$$

$$\rho_m = 45.5 \text{ lb/ft}^3$$

$$V = 4927 \text{ ft/hr.}$$

$$Ma = 189.508$$

$$A = 2.1 * 10^{-4} * 4927 * \left(\frac{189.508}{45.5} \right) = 2.1 \text{ ft}^2$$

$$\text{Diameter} = (4A/\pi)^{0.5} = 1.6396 \text{ ft}$$

Column condenser and cooling water

Cooling water

Temperature of water in 90°F

Temperature of water out 120°F

Temperature of

$$A = \left[\frac{\Delta H_v}{30 * 100} \ln \frac{Tb - 90}{Tb - 120} \right] = 179.2 \text{ ft}^2$$

Cooling water requirement

$$W_c = \left[\frac{\Delta H_v}{30} \right] V = 12926.54 \text{ lb} / \text{h} = 12.2197 * 10^6 \text{ gal} / \text{year}$$

Reboiler & steam supply

$$A_v = \left[\frac{\Delta H_v}{11,250} \right] V$$

$$A_v = 2788 \text{ ft}^2$$

Required steam

$$W_s = \frac{\Delta H_v}{\Delta H_s} \bar{V} = 56637 \text{ lb/hr.}$$

Product separation, Distillation Column

Number of theoretical stages = 40

Reflux rate = 17.2

Tray efficiency = 80%

Tray spacing = 2 ft.

Actual number of trays = H = N/E = 40/0.8 = 50

Height of column = 2.3 N/ ϵ_0 = 2.3*40/0.8 = 115 ft.

$$A = 2.1 * 10^{-4} * V * \left(\frac{M_g}{\rho_m} \right)^{0.5}$$

$$\rho_m=63.0$$

$$V=1415$$

$$M_g=40.89$$

$$A = 8.0424 \text{ ft}^2$$

$$\text{Diameter} = (4A/\pi)^{0.5} = (4*8.0424/3.142)^{0.5}$$

Column condenser and cooling water

Temperature of cooling water in 90°F

Temperature of cooling water out 120°F

$$A = \left[\frac{\Delta H_v}{30 * (100)} \ln \frac{T_b - 90}{T_b - 10} \right] V = 2688 \text{ ft}^2$$

Cooling water

Storage tanks

Nitric acid

30 day supply basis operation 24 h/day

Cone roof vertical fabrication = 592875 gallons

Solvent storage tank

30 day supply basis 24 h/day

Cone roof vertical fabrication = 11449 gallons

Cost of equipment +installation = \$ 105729

APPENDIX II

Capital for equipment

All estimates from literature

	Cost	installation	Total
Nitric Acid Pump	\$ 30,000.00	\$ 18,000.00	\$ 48,000.00
Sludge Pump	\$ 50,000.00	\$ 30,000.00	\$ 80,000.00
Nitric Acid storage tank	\$ 175,000.00	\$ 125,000.00	\$ 300,000.00
Feed Pre-Heater	\$ 11,000.00	\$ 6,600.00	\$ 17,600.00
Screen	\$ 20,000.00	\$ 10,000.00	\$ 30,000.00
PFR	\$ 17,053.00	\$ 8,257.00	\$ 25,580.00
Effluent Cooler	\$ 11,000.00	\$ 6,600.00	\$ 16,500.00
Flash Tank	\$ 36,000.00	\$ 21,600.00	\$ 57,600.00
Solvent Recycle Pump	\$ 10,000.00	\$ 6,000.00	\$ 16,000.00
Solvent Storage Tank	\$ 160,000.00	\$ 120,000.00	\$ 280,000.00
BioFilter	\$ 75,000.00	\$ 60,000.00	\$ 135,000.00
Extractor	\$ 168,854.00	\$ 151,969.00	\$ 320,823.00
Product Separation Col	\$ 250,000.00	\$ 225,000.00	\$ 475,000.00
Solvent Recovery Col	\$ 300,000.00	\$ 270,000.00	\$ 570,000.00
Thickener		\$ 50,000.00	\$ 50,000.00
Mixer	\$ 80,000.00	\$ 32,000.00	\$ 112,000.00

Landfill Cost

number of trucks= 10

rent per mile=\$ 2.00*

Gas consumption=\$ 0.5/mile*

*Source <http://www.bayviewinternational.com/>

Land fill credit= transportation cost

$(10 \cdot (2 + 0.5) + 10 \cdot 36000 / 365) / 140$

$\frac{16000 \cdot 20}{140} = \$0.18/\text{lb}$

16000*20

Incineration Credits

For 12.5%

$$\{65000*100/87.5*\{(202-70)*1 +1000 +(1500-202)*1200 +0.3*65000*100/12.5)-8000*65000*100/12.5\} *365=0.24 \text{ E+12 BTU}$$

Cost of equipment =\$ 19 million (www.processreigster.com)

$$\text{Incineration Credit} = \frac{\text{Capital recovery(15 years)} + \text{O\&M(10\%)} + \text{Energy Cost}}{\text{Sludge Capacity}}$$

Energy cost \$ 0.046 KWh

=\$0.42/LB

LANDFILLS

MAXIMUM METAL CONCENTRATIONS

Metal	Ceiling Concentration (mg/kg)	Cumulative Pollutant Loading Rates (kg/hectare)	Pollutant Concentrations (mg/kg)
Arsenic	75	41	41
Cadmium	85	39	39
Copper	4,300	1,500	1,500
Lead	840	300	300
Mercury	57	17	17
Molybdenum	75	NL	NL
Nickel	420	420	420
Selenium	100	100	100
Zinc	7,500	2,800	2,800

NL = No limit

Source: U.S. EPA, 1993 and 1994.

TABLE 2 TYPICAL BIOSOLIDS APPLICATION SCENARIOS

Type of Site/Vegetation	Schedule	Application Frequency	Application Rate
Agricultural land			
Corn	April, May, after harvest	Annually	5 to 10 dry tons per acre
Small grains	March-June, August, fall	Up to 3 times per year	2 to 5 dry tons per acre
Soybeans	April-June, fall	Annually	5 to 20 dry tons per acre
Hay	After each cutting	Up to 3 times per year	2 to 5 dry tons per acre
Forest land	Year round	Once every 2 - 5 years	5 to 100 dry tons per acre
Range land	Year round	Once every 1 - 2 years	2 to 60 dry tons per acre
Reclamation sites	Year round	Once	60 to 100 dry tons per acre

Source: U.S. EPA, 1994.

COST ESTIMATION

Despite the wide range of costs for land application programs, several elements must be considered in estimating the cost of any biosolids land application program:

- Purchase of application equipment or contracting for application services.
- Transportation.
- Equipment maintenance and fuel.
- Loading facilities.
- Labor.
- Capital, operation and maintenance of stabilization facilities.
- Ability to manage and control odors.
- Dewatering (optional).
- Storage or alternate management option for periods when application is not possible due to weather or climate.
- Regulatory compliance, such as permit applications, site monitoring, and biosolids analyses.
- Public education and outreach efforts.

The Part 503 Biosolids Rule regulates numerous biosolids management options, but communities must decide which options are most appropriate and cost-effective given their circumstances. Data developed for the proposed Part 503 rule (*Federal Register*, Vol. 54, No. 23, pp. 5476-5902, February 6, 1989) indicated that the least expensive management options were surface disposal and crop application. (Surface disposal has become significantly less prevalent because of the additional costs imposed by the Part 503 Biosolids Rule; crop application, prior to the promulgation of either the municipal solid waste landfill

regulations or Part 503, was roughly equal to an assumed average cost for landfilling [including transportation].) Land application costs (due to suburbanization and possible increases in hauling distances to agricultural land in some areas) may have increased in the intervening years. Monofilling of biosolids was roughly 20 percent more expensive than either surface disposal or land application on average and most likely is still more expensive following the implementation of Part 503. Furthermore, landfilling, since the municipal solid waste landfill regulations came into effect, has generally increased in cost disproportionately in comparison to these other methods, although landfill costs in some areas are very inexpensive due to the construction of increasingly large landfills, sometimes called “megafills.”

Cost information for different types of composting processes, researched by *BioCycle* magazine is shown in Table 5-1, including capital and operating and maintenance costs for different types of composting methods. The wide variations in costs are due to vast differences in size from the smallest to largest facilities. Small facilities will generally incur the smallest capital costs, but can incur relatively higher operation and maintenance costs on a per-ton basis. A high cost per ton is typical of facilities that compost only a few tons per year.

Table 5-1
Biosolids Composting Costs^a
(1997 data from 100 composting facilities)

Type of Composting Method	Capital Costs ^b	Operation and Maintenance Costs
Aerated Static Pile	\$36,000 - \$20 million	\$12 - \$500/dry ton
In-Vessel	\$850,000 - \$33 million	\$18.24 - \$540/dry ton
Windrow	\$50,000 - \$8 million	\$2.15 - \$245/dry ton
Aerated Windrow	\$450,000 ^c	\$50 - \$325/ton
Static Pile	not reported	\$25 - \$165/ton

Source: Goldstein and Block, 1997.

^aDoes not reflect revenue generated from the sale of composted products.

^bCosts reported by operations are estimates in many cases. The wide range reflects management differences at sites, as well as what each facility factors into the operating costs.

^cOnly one facility reported a capital cost.

Based on the research, distribution and marketing of biosolids products (e.g., composting operations) was, on average, more than three times the cost of the least expensive options, although this does not take into account revenue from

the sale of the compost, which will offset some of these costs (100 composting facilities reported revenues of from \$1 to \$35 per cubic yard, according to Goldstein and Block, 1997). Also, with reductions in nearby agricultural land in some areas and the fact that many users of compost provide their own transportation,

the difference in cost between composted biosolids and land application of less highly processed biosolids is likely to be decreasing. Furthermore, there are considerable economies of scale involved in composting, and some communities might find that composting operations using both biosolids and organic MSW materials, especially yard trimmings, might become more economical on a cost-per-ton basis than disposing of either waste individually.

Incineration and land reclamation were, prior to 1989 and most likely still are, the most expensive options on a unit cost basis. The cost of land reclamation as

presented in the *Federal Register*, however, includes the cost of the reclamation process itself. If one compares the cost of reclamation with biosolids to the cost of reclamation without biosolids (that is, using soils purchased or obtained from other locations), the cost of reclamation using biosolids could be relatively much lower, and might even represent a cost savings. In land reclamation, it is the expense of landshaping using costly earth-moving equipment, and not the biosolids use, that drives costs. Also, three times the amount of biosolids can be applied for land reclamation as for land spreading at the agronomic rate for crop growth. Furthermore, the costs of land reclamation reported in the *Federal Register* also do not take into consideration the difference between the costs of unused, unproductive land and reclaimed productive land through enrichment by biosolids or composted biosolids.

Although land application of biosolids is one of the least-cost management options, the cost to municipalities or farmers of applying biosolids, monitoring, recordkeeping, and meeting the management practices of federal, state, and local regulatory agencies can impede biosolids use. Although biosolids are valuable to farmers as a soil amendment, and some or all of these costs can be incurred by the contractor or POTW, the availability of low-cost commercial fertilizers may limit farmers' willingness to pay for biosolids (National Research Council, 1996). In some municipalities, however, such as Seattle, Washington, and Madison, Wisconsin, users pay for their biosolids. In others, POTW managers can promote biosolids use by setting up demonstration projects using biosolids, assisting in the recordkeeping tasks, and covering the cost of applying the biosolids. In several localities, marketing of biosolids for beneficial use is not a problem at all; in Madison, Wisconsin, for example, as well as other areas, the demand for biosolids as a soil amendment exceeds the local supply (see Section 5.3).

In comparison, composting is considerably more expensive than land application, based on EPA's Regulatory Impact Analysis (RIA) for the proposed Part 503 Biosolids Rule (U.S. EPA, 1989), although, as discussed above, the cost

differential may be shrinking in some areas. The cost of composting operations can affect whether this particular beneficial use option is chosen, but the desirability of the composted product and the potential market for a sellable product that is proven to be safe can offset some of this cost. In Columbus, Ohio, for example, the city's compost product, which is sold to the general public as a soil amendment, has been so successful that on various occasions demand has far exceeded supply. The case studies presented in Section 5.3 illustrate the demand for biosolids and the process that can be used to market composted and other types of biosolids.

Transportation of biosolids is also a substantial cost category for POTWs, and these costs can have the most significant effect on the total costs of land application. Furthermore, the distance to land application sites is increasing as available land closer to the point of generation becomes more developed (thus requiring biosolids to be hauled farther). Reducing biosolids volume through thickening, dewatering, conditioning, and drying can reduce these costs. Preparation and long-distance shipping of pelletized biosolids, for example, generally can be less expensive than for nonpelletized biosolids because the reduced water weight results in lower transport costs (communication with Massachusetts Water Resources Authority, February, 1998). Transportation costs also can be greatly reduced by finding local markets for biosolids compost.

VITA

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