New York State Energy Research and Development Authority

Feasibility of Using Microwave Radiation to Facilitate the Dewatering, Anaerobic Digestion and Disinfection of Wastewater Treatment Plant Sludge

Report 11-05
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Feasibility of Using Microwave Radiation to Facilitate the Dewatering, Anaerobic Digestion and Disinfection of Wastewater Treatment Plant Sludge

Final Report

Prepared for the

New York State Energy Research and Development Authority

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ABSTRACT

Wastewater treatment plant sludges are difficult to dewater and degrade anaerobically at a relatively slow rate. These sludges also require disinfectants or long periods of drying and/or composting to inactivate pathogens, if a Class A fertilizer is ultimately to be produced.

This project investigated the effects of microwave radiation on activated sludge (slurry) and rotating biological contactor (fixed film) wastewater sludges to determine whether exposure of sludges to a microwave field could improve sludge dewaterability, facilitate the release of soluble organics from the sludge to increase biogas production upon anaerobic digestion, and/or provide for rapid pathogen inactivation.

The experimental procedure involved application of variable doses of microwave energy at different power levels to polymer pretreated and non-pretreated sludges (both slurry and fixed film sludges). The microwave unit was a custom-made programmable multi-modal 3.2kW microwave cavity manufactured specifically for this project. Observation of the results reveal that microwave radiation can improve sludge dewaterability, increase the solubility of the organic fraction of the sludge, and eliminate pathogens in the sludges, above that which would be explained by temperature effects alone.

The slurry sludge generally yielded more favorable dewaterabilty and organic dissolution data than the fixed film sludge. Microwave application was less effective on polymer pretreated sludges compared to non-pretreated sludges. Microwave disinfection was shown to be effective but equivalent to that which would be achieved by conventional heating of the sludges to equivalent temperatures.

From a commercial perspective, the primary benefit associated with microwave treatment of sludge is the potential to produce a Class A biosolids product for use as a fertilizer, soil conditioner or nutrient supplement (for land application), which could be most strategically employed at small-scale facilities that have high disposal costs or at a central processing station for treating sludge from multiple small-scale facilities.

ACKNOWLEDGMENTS

The members of the Research Team gratefully acknowledge sponsorship of this project by the New York State Energy Research and Development Authority (NYSERDA), under the direction of Kathleen O'Connor. In addition, a good portion of the laboratory work was conducted by Jon Paul Anatra, a NYU-Polytechnic student, whose efforts are commended and appreciated by the Research Team.

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I. Summary

Objectives

In many wastewater treatment plants (WWTPs), sludge volume and odor reduction are the primary objectives of the sludge management process. A large portion of the potential energy (Btu value) embedded in the sludge is not recovered (i.e., the WWTP does not own or operate a digester) or is wasted (i.e., flared). And ultimately, large volumes of biosolids are disposed of in landfills (at ever-rising costs). Sludge management and disposal costs, including sludge conditioning and dewatering, typically comprise in excess of 50% of a WWTP's operating costs. The majority of the cost is associated with disposal, which can range from $50 to in excess of $200 per ton in many downstate communities.

Prior research has suggested that microwave radiation could be effectively used to:

1. Improve the dewaterability of sludge to facilitate dewatering and reduce disposal costs,
2. Improve the solubilization of sludge suspended solids thereby reducing sludge volume and enhancing biogas production via anaerobic digestion, and
3. Provide for more effective pathogen inactivation to facilitate the use of digested biosolids in higher-end product applications (i.e., Class A fertilizers).

The primary objective of this investigation was to determine if microwave application could be cost-effectively used to improve sludge management practices at municipal WWTPs.

Research Approach

Municipal wastewater sludge was collected from two municipal WWTPs; activated sludge (slurry) from Suffern Wastewater Treatment Plant (Suffern, NY) and rotating biological contactor (fixed film) sludge from Rockland County Sewer District No. 1 (Orangeburg, NY). Upon collection, the samples were immediately transported to the New York University-Polytechnic Environmental Engineering Laboratory (Brooklyn, NY), where they were either refrigerated or immediately underwent a series of microwave exposure tests.

The experimental procedure involved exposing polymer pretreated and non-pretreated sludges from both the slurry and fixed film systems to variable microwave doses at different power levels. The microwave unit was a programmable multi-modal 3.2kW microwave cavity fabricated specifically for this project.

After microwave exposure, sludge samples and controls (unexposed sludges) were subjected to a series of analytical tests to determine whether microwave exposure altered the properties of the sludge in a manner that might induce improved dewaterability, biodegradability and pathogen reduction. Vacuum testing was performed to assess dewaterability. Sludge supernatant was tested before and after microwave exposure for total and soluble COD, total dissolved solids, total and dissolved volatile solids, volatile acids, pH, and total alkalinity. These tests were conducted to determine whether radiation assists in promoting hydrolysis reactions, or disrupting the intracellular cell membrane or extracellular polymeric sludge matrix, thereby releasing additional inorganic and organic matter into solution. Coliform testing was done to assess disinfection efficiency. Additional testing was also conducted to determine whether the observed dissolution and disinfection were due to increases in temperature or whether the microwave radiation might induce special effects.

The experimental work began in April 2009 and was completed in February 2011.

Findings

Findings and conclusions associated with the testing program are summarized as follows:

Dewaterability

1. Exposure of non-pretreated sludges to microwave radiation resulted in an increase in the effectiveness of vacuum dewatering above that which would be explained by temperature effects alone. The increase in dewaterability was directly proportional to energy exposure.
2. Microwave radiation interfered with the beneficial effects of polymer addition; the dewaterability of polymer pretreated sludges decreased with increasing energy exposure.
3. Slurry sludges were more susceptible to microwave radiation; these sludges exhibited greater dewaterability after exposure to radiation than fixed film sludges.
4. Microwave treatment was not as effective as polymer treatment for sludge dewatering.

Extraction of COD, Dissolved Solids and Volatile Solids

1. When exposed to microwave radiation, an increase in the soluble mass of the sludge floc was observed, yielding higher concentrations of COD, dissolved solids and volatile solids in the free water of the sludge fraction, above that which would be explained by temperature effects alone.
2. Specific findings for COD, dissolved solids and volatile solids are as follows:
   a. Exposure of sludges to microwave radiation increased the extraction of COD, dissolved solids and volatile solids from slurry sludge samples above that which would be explained by temperature effects alone. The increase in extractability was directly proportional to the energy exposure.
   b. Slurry sludges and fixed film sludges exhibited similar effects.
   c. Polymers reduced the extractability of COD dissolved solids and volatile solids in fixed film sludges, but had little effect on slurry sludges.

Extraction of Volatile Acids

1. Exposure of sludges to microwave radiation had little effect on the volatile acid content of the sludge supernatant.
2. Slurry and fixed film sludges exhibited similar effects.

pH and alkalinity

1. Exposure of sludges to microwave radiation had little effect on the pH and alkalinity of the sludge supernatant.
2. Slurry and fixed film sludges exhibited similar effects.

Disinfection

1. Exposure of sludge to microwave radiation and conduction heating within the same target temperature ranges resulted in equivalent coliform destruction. Still, microwave heating occurred 20 times faster than conduction heating due to the rapid transmission of heat energy and corresponding increase in temperature.
2. Temperatures above 60^{o} C resulted in 100 percent disinfection.

Design and Cost of Microwave Applicator

1. The cost of processing dewatered sludge in treatment plants ranging in size from one (1) to 10 million gallons per day (mgd) ranges from \$28 to \$46 per ton (wet weight at 20% dry solids).

2. Processing sludge with high moisture content may increase the aforementioned costs by an order of magnitude.

Conclusions

1. Despite the improvement in dewaterability, microwave treatment of sludge to enhance sludge dewatering is not a cost effective treatment strategy.
2. Despite the improvement in COD, solids and volatile solids dissolution, microwave treatment of sludge to induce greater dissolution of the solids fraction is not a cost effective treatment strategy.
3. Microwave disinfection of sludge to produce a Class A biosolids material at small-to-medium-sized wastewater treatment facilities may be a cost effective treatment strategy, if transportation and disposal costs exceed $50 per ton and if a biosolids market is available.

Recommendations

Small-to-medium wastewater treatment facilities and perhaps farms generating large quantities of biosolids that do not have low cost sludge disposal options should consider microwave disinfection as a tertiary sludge treatment process to convert the sludge to a higher-end product biosolid fertilizer.

II. Background and Introduction

Wastewater treatment plant sludge is difficult to dewater, degrades anaerobically at a relatively slow rate, and requires disinfection or long periods of drying and/or composting to inactivate pathogens if a Class A fertilizer is ultimately to be produced. The research described in this report was designed to assess the feasibility of using microwave radiation to facilitate dewatering, improved anaerobic digestion, and disinfection of wastewater treatment plant sludge.

During the past decade, a series of investigations have assessed whether beneficial interactions between a microwave electromagnetic field and wastewater treatment plant sludge might be possible. The potential for such interaction is inferred by the colloidal nature of the sludge floc and its complex surface chemistry, which should be susceptible to disruption by microwave induced water-molecule dipolar rotation or perhaps more directly by the influence of the electromagnetic field on the molecular structure of the floc itself.

In large part, the difficulty in dewatering sludge results from its large surface area and high surface chemical activity. High chemical activity induces an arrangement of charges on and surrounding the individual sludge particles that attract and hold polar water molecules to the particles' surfaces. This attraction is especially pronounced in sludge with high volatile organic content (e.g., secondary sludge), which also tend to be the most difficult to dewater.

To disrupt the surface chemistry and release the bound water, chemical conditioners (e.g., polymers and/or iron salts) are used. Thermal conditioning has also been shown to positively affect sludge dewaterability (Neyens 2003); and recently published data suggest that the electromagnetic field induced by microwave radiation can produce similar results (Wang 2005, Sergio 2006). Nevertheless, it is yet unclear if the induced effect is the result of temperature alone or a unique microwave effect. One might postulate that if a microwave effect does exist, it is due to a disruption of the surface chemistry induced by the microwave electromagnetic field, the heating and release of bound water in the sludge floc, or perhaps the expansion and opening of the pore structure of the sludge floc.

Biogas production from the anaerobic digestion of sludge is rate limited due to the length of time required to solubilize the organic fraction of the sludge. It has been reported that exposure of sludge to microwave radiation can induce solubilization of suspended solids beyond that which would be predicted by ordinary temperature increases (Sergio 2006, Toreci 2006). It is hypothesized that this increase results from a combination of effects - the microwave radiation induces desorption of the organics sorbed to the particles, thus making them more available in the bulk solution (Sergio 2006) and increases cell membrane lysis (most notable in secondary sludge) with the resulting release of soluble, readily biodegradable organic compounds (mostly proteins) to the bulk solution; and perhaps, even, some enzymes and co-factors that accelerate the anaerobic degradation reactions (Dohányos 2000). This solubilization has been shown to translate into more rapid biodegradation of organics in anaerobic digesters and increased rates and quantities of biogas production (up to 40 percent) (Eskicioglu 2010).

Studies have shown microwave radiation to inactivate pathogens or pathogenic indicators (i.e., E. coli), however the mechanism by which this occurs is not fully understood. Work from the University of Wisconsin has shown that microwave processing inactivates pathogens found in sludge (Sergio 2004). Additionally, Sergio (2006) reported that microwave treatment could result in longer inactivation periods for pathogens than conventional heat treatment. Lagunas-Solar (University of California, Davis; 2005) reported that microwave treatment resulted in the disinfection of dairy and animal wastewater. In all of these studies, applied microwave radiation resulted in sludge temperatures between 60 and 65 degrees C. A notable difference between the project described in this report and prior studies, is our use of a microwave applicator capable of generating significantly higher power densities.

This report presents our research approach and the results of our investigation. The report is divided into several sections that include a discussion of the experimental procedures, experimental findings, process and economic considerations and overall conclusions and recommendations. We also included an examination of the type of microwave application system that might be employed at a wastewater facility, the cost of such a system, and the energy requirements of the system, to provide a complete picture of the cost and benefits of microwave sludge processing for municipal wastewater treatment sludge.

III. Experimental Procedures

Overview

Both slurry and fixed film sludge samples were exposed to microwave radiation at three different power levels for three different lengths of time. A schematic of the experimental approach is presented in Figure 1. Following microwave exposure, the sludge samples were subjected to a battery of analytical tests to determine whether microwave exposure had affected the sludge characteristics, or more specifically, altered the properties of the sludge in a manner that might induce improved dewaterability and/or biodegradability and disinfection. Control samples (i.e., unexposed sludges) were also subjected to the analytical tests. Analytical testing included total and soluble COD, total and volatile solids, pH, total alkalinity, volatile acids in the dewatered sludge fraction (i.e., sludge filtrate), and coliform bacteria count as represented by E. coli. Additional testing (i.e., temperature comparison testing) was conducted to determine whether the observed effects were due to increases in temperature or whether the electromagnetic radiation associated with the microwaves induced special effects.

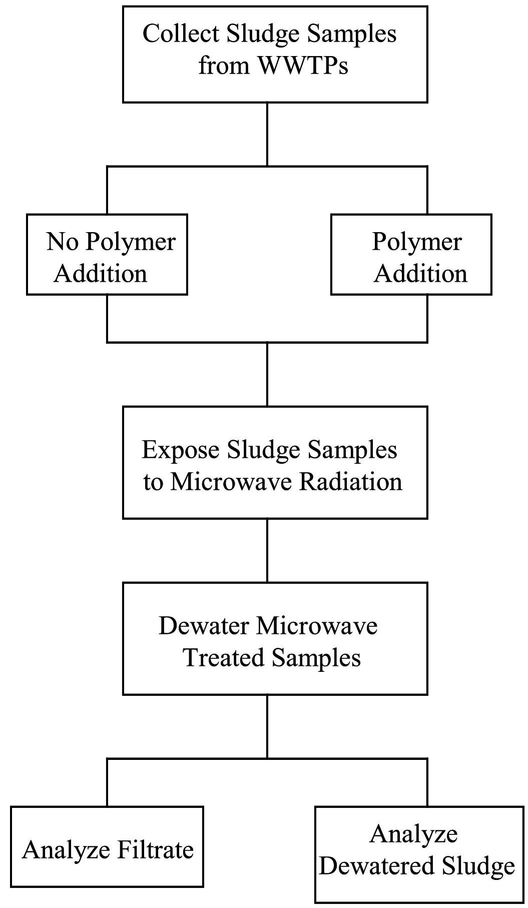


Figure 1. Experimental Plan Overview

Sludge Types and Sources

The investigation focused on the two major types of sludges produced at wastewater treatment plants: activated sludge (slurry) and rotating biological contactor (fixed film) sludges. The slurry sludge was obtained from the 1.2 mgd Suffern Wastewater Treatment Plant (Suffern, NY). The fixed film sludge was obtained from the 31 mgd Rockland County Sewer District No. 1 Wastewater Treatment Plant (Orangeburg, NY). The typical solids contents were 2.2 % for the slurry sludge and 2.9 % for the fixed film sludge.

Sludge Collection and Handling

Sludge samples were typically collected in the morning on days that experimentation was scheduled. After collection, the samples were transported to the New York University-Polytechnic Environmental Engineering Laboratory (Brooklyn, NY), where they were either refrigerated or immediately tested. Before each experiment, the sludge was removed from the refrigerator for a period of time to acclimate to room temperature. Sludge samples (wet weights-100 grams; dry weights-2.9 g for the fixed film sludge, 2.2 g for the slurry sludge) were prepared for testing as shown in Table 1.

Table 1. Four Sludge Samples Used in Testing

Suffern WWTP (slurry)	Rockland County WWTP (fixed film)
No polymer addition (untreated)	No polymer addition (untreated)
Polymer addition (treated)	Polymer addition (treated)

Polymer Addition

Both WWTPs add cationic polymers to their sludges to improve dewaterability. The Suffern Plant adds a cationic polymer (ACP 22, Atlantic Coast Polymer). The Rockland County plant adds a "High Charge" cationic polymer (Charge Pack-270, Clearwaters, Inc.). During testing, polymers were added to the sludge samples in the same concentrations as those added at each respective WWTP; Suffern employs a polymer dosage rate of 250 gallons of polymer per 20,000 gallons of sludge; Rockland County employs a polymer dosage rate of 55 gallons per 130,500 gallons of sludge. Therefore, 12.5 ml of polymer was added per liter of the Suffern sludge, and 0.42 ml of polymer per liter of the Rockland County sludge.

Microwave Applicator

Sludge samples were exposed to microwave energy in a variable power 3.2 kW oven fabricated by Microwave Research and Applications (Laurel, MD), using specifications defined by Thermex-Thermatron. The unit, which employs four mode stirrers and has a 21" x 13" x 9 7/8" cavity, was designed to enable uniform application of microwave energy at high power settings. A photograph of the unit is shown in Figure 2.

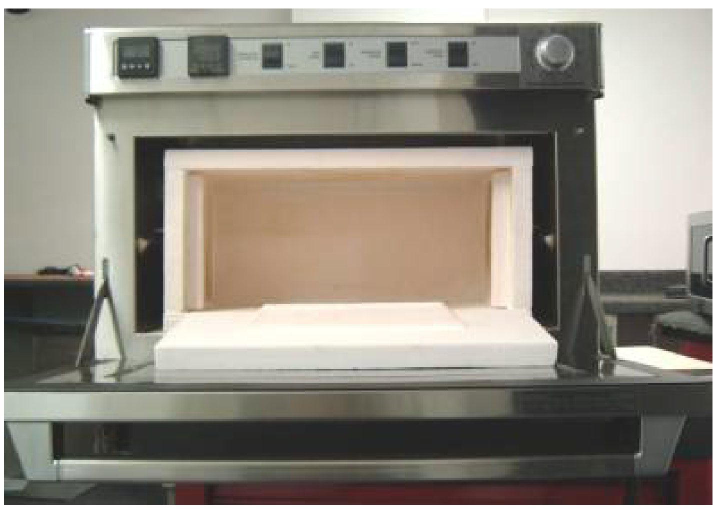


Figure 2. Microwave 3.2 kW Multimodal Variable Power Applicator

Preliminary Microwave Applicator Tests

Initially, exploratory testing of the sludge samples was performed to determine the range of power intensity and exposure (duration) that the sludges could tolerate before complete drying and thermal decomposition of the samples were observed. Based on exploratory testing, a maximum process temperature of 137 degrees Fahrenheit was established for all but the disinfection testing; the maximum process temperature for disinfection testing was 176 degrees Fahrenheit. To achieve these temperatures, three power intensities were selected (3.2 kW, 1.6 kW and 0.8 kW) as well as exposure times.

Temperature Monitoring Procedures

Process temperature was measured using an NBS traceable thermometer; a pre-calibrated thermometer equipped with a flexible temperature probe that allows for remote temperature readings on a digital scale. Readings were taken as soon as the microwave oven door was opened and the flexible temperature probe could be inserted into the sludge, which was always within seconds of opening the microwave oven. The samples were then removed from the microwave unit for immediate testing.

Microwave Power Density and Energy Dose

Microwave radiation was applied at varied power and energy levels. The maximum power applied was 3.2 kW. Power levels were varied based on calibrating the power adjustment knob to 100%, 75% and 50% of the rated power (i.e., ~3.2 kW, 2.1 kW and 1.05 kW). The calibration was performed by monitoring the increase in temperature of a 1000 ml beaker filled with water at a given setting, then applying the heat transfer equation to calculate heat (energy) input, and finally dividing heat (energy) input by the applied duration (60 seconds) to determine the power level at the given setting.[1]

Dewaterability

Dewaterability was measured using the Buchner Funnel test (Standard Methods for the Examination of Waters and Wastewaters [APHA, 19th Ed. Section 2710H]). No filter media is specified for the test, and finding a filter media that permitted a useful measurement of the water drainage rate took time. Ultimately, a commercial toweling (Bounty) was found to perform satisfactorily. An experimental correction for absorption was calculated and used as a standard during testing. Dewaterability tests were performed by placing the filter in the Buchner funnel, and inserting the funnel into a graduated 100 mL cylinder that was attached to a vacuum pump. The filter paper was rinsed with deionized (DI) water under suction and the DI rinse water voided from the cylinder. A given volume of sludge was then poured on to the surface of the filter media and the porous plates of the funnel, at which time the vacuum was applied, and the volume of the filtrate was recorded once dewatering was complete.

Filtrate and Sludge Sample Preparation

A series of analytical tests were run on microwave treated samples and control (untreated) samples of the sludge filtrate (ie, supernatant). Filtrate samples were collected as described above, and subjected to total and soluble COD, dissolved solids, total and volatile solids, pH, total alkalinity and volatile acid analysis.

Analytical Methods

The analytical methods used are summarized as Table 2. All methods are consistent with Standard Methods for the Examination of Waters and Wastewaters (APHA), with the exception of the method used for total alkalinity and volatile acids. The method that was used for these analyses is presently used by the Rockland County Sewer District's Wastewater Treatment Laboratory; an ELAP approved and certified lab.

[1] $Q = mc\Delta T$, where; Q is heat (energy), m is mass, c is specific heat capacity and ΔT is the change in the temperature.

Table 2: Use of Microwave Applications for Treatment of WWTP Sludges Analytical Methods

Analytical Test	Reference[1]	Description
Buchner Funnel	SM 2710(H)	Filtration and measurement of flow rate
Total Solids	SM 2540 (G)	Weight after Drying at 103ºC
Volatiles	SM 2550(E)	Loss of weight after Ignition at 550ºC
Total Suspended Solids	SM 2550 (D)	Filtration through Glass Fiber Filter Weigh after drying at 103 ºC
Chemical Oxygen Demand (COD)	SM 5220 (D)	Hach prepared dichromate-acid tubes, Digestion and Spectrophotometric reading
Temperature	ELAP, NYCDOH	Measurement with NBS Traceable Thermometer
Total Alkalinity	SM 2320 (B)	Acid Titration to pH 4.5
Volatile Acids	Rockland County[2] Analytical Methods	Calculations based on titrations at two pH end points and correction for Ka of volatile acid component
pH	SM 4500-H (B)	Glass electrode, measurement of millivolts
Escherichia coli and total coliform counts	SM 9221 (Hach)[3]	Decimal dilutions, filtration and incubation on m-coli blue, incubation for 24 hrs at 35ºC and colony counts

1. SM - Standard Methods for the Examination of Waters and Wastewaters, 19th Ed, APHA (1995)
2. Rockland County Sewer District No. 1, a Certified NYSDOH ELAP Laboratory
3. Hach Chemical Company pre-poured nutrient plates

Filtrate COD Content

Filtrate COD analysis was performed as per Table 2. Soluble COD (SCOD) analysis required that the filtrate be filtered through the glass fiber filters a second time.

Filtrate Volatile Solids Content

Volatile solids analysis was performed as per Table 2. The analysis requires the ignition of the solids fraction, remaining after drying the sample at 103ºC, in a muffle furnace at 550ºC and subsequently calculating weight loss (e.g., the volatile component).

Filtrate Volatile Acid Content

Volatile acids analysis was performed using the method from the Rockland County's Laboratory.

pH and alkalinity

pH was determined following procedures specified in the NYSDOH ELAP Manual as per Table 2; a calibrated, temperature-compensated, glass electrode and meter were used. Total Alkalinity analysis was performed as per Table 2; a standard acid titration to a pH end point of 4.3 was performed.

Temperature and Microwave Effect

To determine whether the observed differences in data associated with microwave-treated samples was attributed to effects associated with electromagnetic radiation, rather than temperature alone, temperature comparison testing was performed. Sludge samples were placed in beakers identical to those used in the microwave tests, the beakers were placed on a hot plate and the contents gently mixed until the desired temperature was attained, after which the samples were removed for analytical testing. If differences were not detected between the microwave-treated and conductively-heated samples, temperature would be considered the prominent factor driving the effect; while if differences were detected, microwave radiation would be considered the prominent factor driving the effect.

Disinfection and Sludge Coliform Content

Disinfection testing was performed to assess how effectively microwave radiation reduces coliform bacteria in sludge samples. Testing was also performed on samples heated conductively, and the results compared. This testing was performed on 100 g of sludge (approximately 2% solids) placed in 250 ml beakers. Selected microwave power levels were calibrated to determine the time of exposure needed to bring sludge samples to temperatures of 30, 40, 60, and 80 degrees C. Samples were also heated convectively to these same temperatures. Once the desire temperatures were achieved, samples were diluted, filtered through a standard 0.45 µM Millipore membrane, placed on m-Coli24 (Hach Chemical Company) pre-poured nutrient plates, and placed in a controlled-temperature water bath at 35degrees C for 24 hours. This EPA-approved method simultaneously detects for total coliform and E. coli with no confirmation required.

IV. Experimental Findings

This section details the findings of each of the research activities described in the previous section in a graphical format. Detailed tabulated data are presented in the Appendix. The graphical results are presented as a function of the applied microwave energy, expressed in terms of watt-hours (wh); data at all power levels (~3.2 kW, 2.1 kW and 1.05 kW) are presented on the same graph. Linear regression with a coefficient of determination (R^2) was used to analyze the data. The hypotheses used are as follows:

- Analytical differences in the data are a function of the applied radiation dose
- High positive or high negative slope values (m in the linear regression) imply that microwave treatment induced measurable changes in sludge properties; low slope values (m) imply that microwave treatment had little affect on sludge properties.
- High values of the coefficient of determination (R^2) (or expected experimental variability) imply that applied power (kW) does not have a significant effect on the results. R^2 values were characterized as good, fair and poor based on the following rating scale: Good = 0.8 to 1.0; Fair = 0.5 to 0.8; Poor = less than 0.5.

The graphical results are preceded by an itemized list of findings. The finding are detailed in the Discussion of Findings section. The graphical results are presented in the order listed below:

- Dewaterability Analysis (without polymer – Figures 1 and 2)
- Dewaterability Analysis (with polymer – Figures 3 and 4)
- Supernatant COD Analysis (without polymer – Figures 5 and 6)
- Supernatant COD Analysis (with polymer – Figures 7 and 8)
- Supernatant Dissolved COD Analysis (without polymer – Figures 9 and 10)
- Supernatant Dissolved COD Analysis (with polymer – Figures 11 and 12)
- Supernatant Dissolved Solids (without polymer – Figures 13 and 14)
- Supernatant Dissolved Solids (with polymer – Figures 15 and 16)
- Supernatant Total Volatile Solids Analysis (without polymer – Figures 17 and 18)
- Supernatant Total Volatile Solids Analysis (with polymer – Figures 19 and 20)
- Supernatant Dissolved Volatile Solids Analysis (without polymer- Figures 21 and 22)
- Supernatant Dissolved Volatile Solids Analysis (with polymer – Figures 23 and 24)
- pH Analysis (without polymer – Figures 25 and 26)
- pH Analysis (with polymer – Figures 27 and 28)
- Total Alkalinity Analysis (without polymer – Figures 29 and 30)
- Total Alkalinity Analysis (with polymer – Figures 31 and 32)
- Volatile Acid Analysis (without polymer – Figures 33 and 34)
- Volatile Acid Analysis (with polymer – Figures 35 and 36)
- Temperature Effects: Microwave vs Conduction Heating Dewatering (Figures 37 and 38)
- Temperature Effects: Microwave vs Conduction Heating Supernatant COD (Figures 39 and 40)
- Temperature Effects: Microwave vs Conduction Heating Dissolved COD (Figures 41 and 42)
- Temperature Effects: Microwave vs Conduction Heating Dissolved Solids (Figures 43 and 44)
- Temperature Effects: Microwave vs Conduction Heating Dissolved VS (Figures 45 and 46)
- Temperature Effects: Microwave vs Conduction Heat Total VS (Figures 47 and 48)
- Disinfection Effects: Microwave and Conduction Heating (Figure 49).

Dewaterability Analysis (without polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~35% moisture extraction)
2. Slight increase in dewaterability (slightly positive slope – 0.1) with applied energy
3. No major differences between applied power densities were apparent
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Findings Slurry:

1. Control (no microwave energy: ~39% moisture extraction)
2. Measurable increase in dewaterability (positive slope – 0.38) with applied energy
3. No major differences between applied power densities were apparent
4. Coefficient of determination (R^2) for combined data exhibits good linear correlation

Figure 1. Dewaterability Profile
(Fixed Film without Polymer)

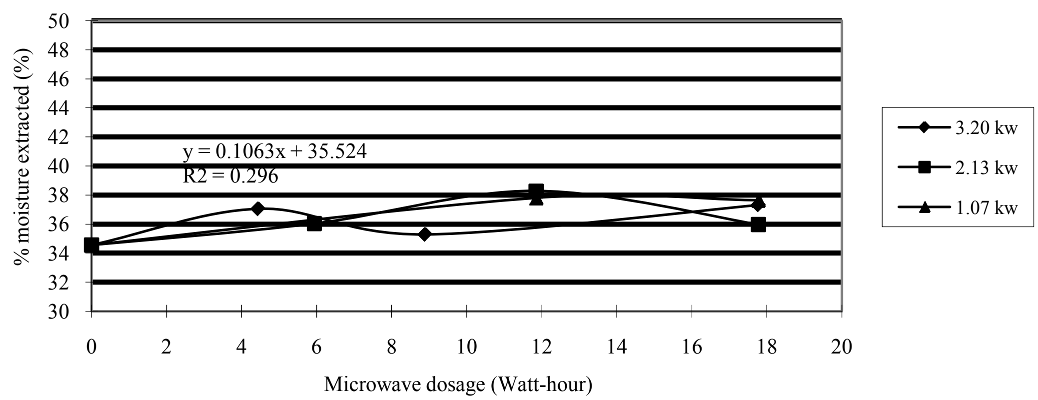
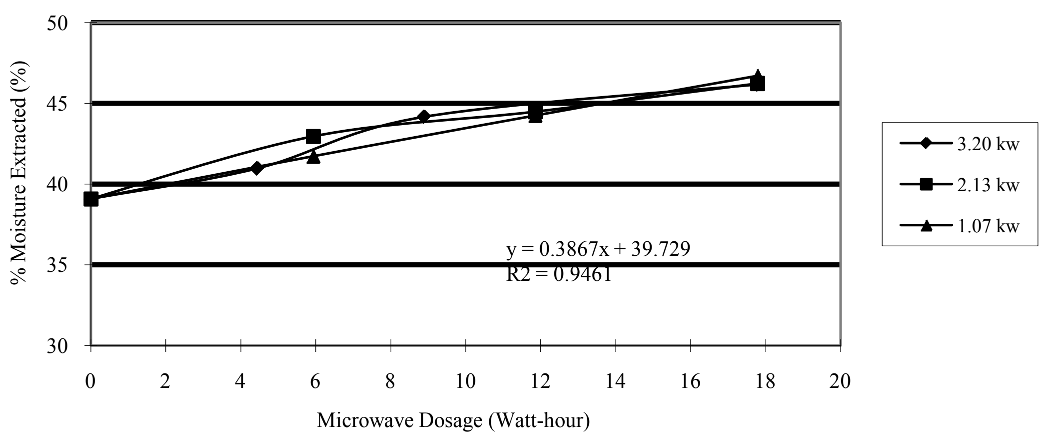


Figure 2. Dewaterability Profile
(Slurry without Polymer)



Dewaterability Analysis (with polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~96% moisture extraction)
2. Moderate decrease in dewaterability (mildly negative slope – 0.21) with applied energy
3. Higher power density exhibits greater decline; significance unknown
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Findings Slurry:

1. Control (no microwave energy: ~87% moisture extraction)
2. Measurable decrease in dewaterability (negative slope – 0.46) with applied energy
3. Lower power density exhibits greater decline; significance unknown
4. Coefficient of determination (R^2) for combined data exhibits fair linear correlation

Figure 3. Dewaterability Profile (Fixed Film with Polymer)

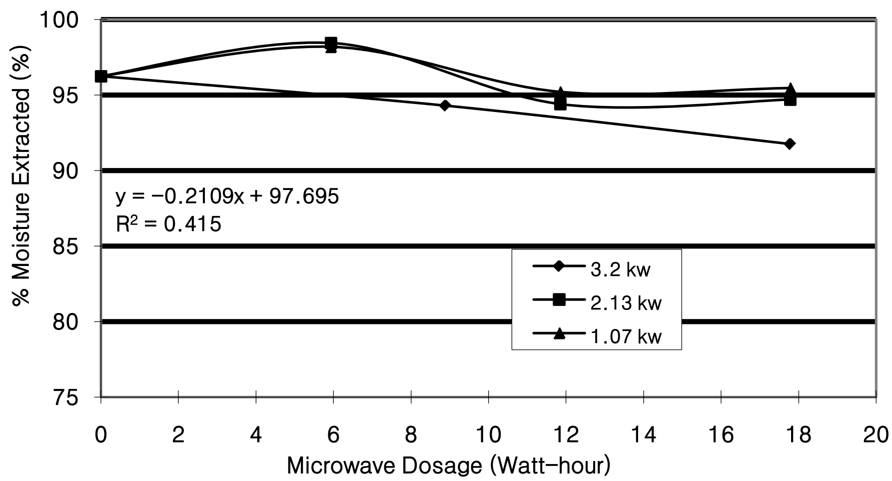
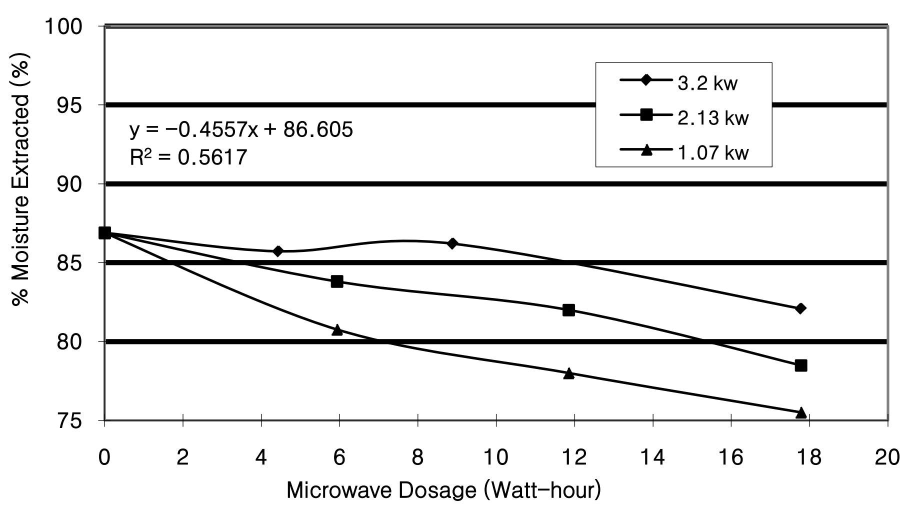


Figure 4. Dewaterability Profile (Slurry with Polymer)



Supernatant COD Analysis (without polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~2500 mg/l COD)
2. Measurable increase in COD extraction (positive slope – 64 mg/l per watt-h) with applied energy
3. No major difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits good linear correlation

Findings Slurry:

1. Control (no microwave energy: ~1400 mg/l COD)
2. Moderate increase in COD extraction ((positive slope – 32 mg/l per watt-h) with applied energy
3. No major difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits fair linear correlation

Figure 5. Supernatant COD Profile
(Fixed Film without Polymer)

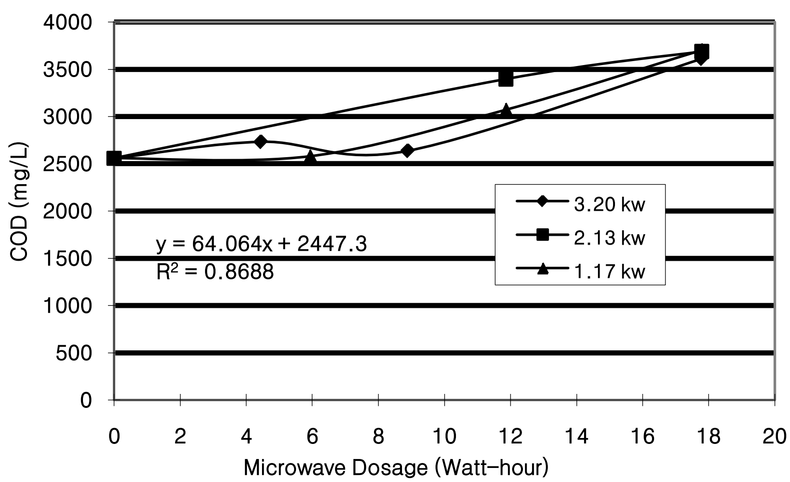
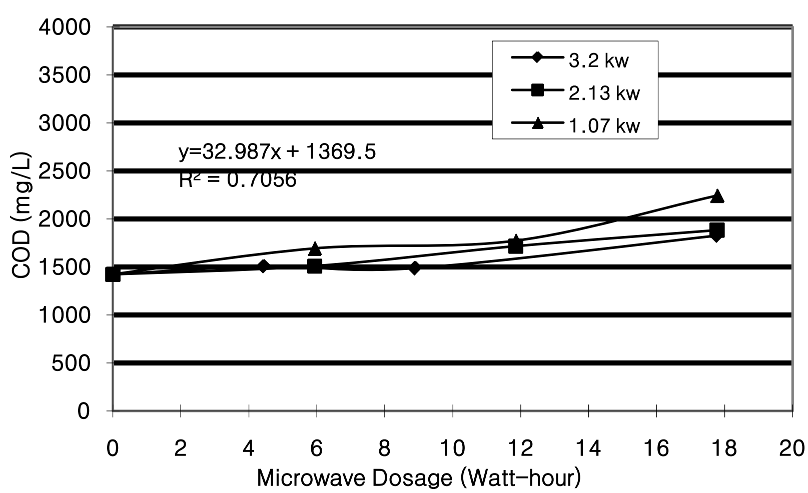


Figure 6. Supernatant COD Profile
(Slurry without Polymer)



Supernatant COD Analysis (with polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~900 mg/l COD)
2. No measurable increase in COD extraction (flat slope – 1.8 mg/l per watt-h) with applied energy
3. No major difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Findings Slurry:

1. Control (no microwave energy: ~750 mg/l COD)
2. Moderate increase in COD extraction (positive slope – 32 mg/l per watt-h) with applied energy
3. No major difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits fair linear correlation

Figure 7. Supernatant COD Profile
(Fixed Film with Polymer)

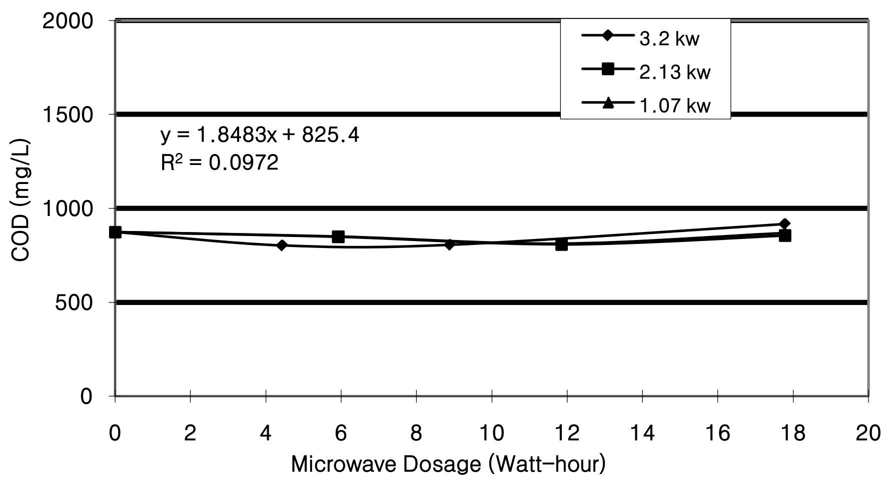
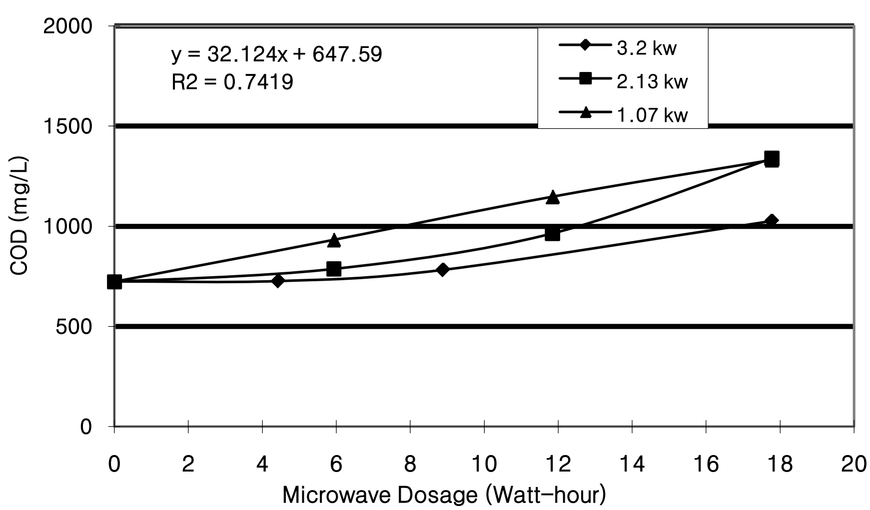


Figure 8. Supernatant COD Profile
(Slurry with Polymer)



Supernatant Dissolved COD Analysis (without polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~900 mg/l COD)
2. Measurable increase in COD extraction (positive slope – 45 mg/l per watt-h) with applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits good linear correlation

Findings Slurry:

1. Control (no microwave energy: ~700 mg/l COD)
2. Measurable increase in COD extraction (positive slope – 45 mg/l per watt-h) with applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits good linear correlation

Figure 9. Dissolved COD Profile
(Fixed Film without Polymer)

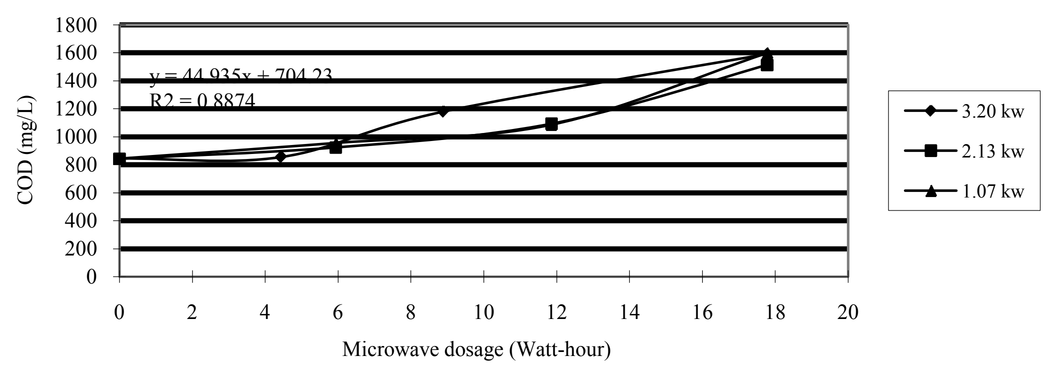
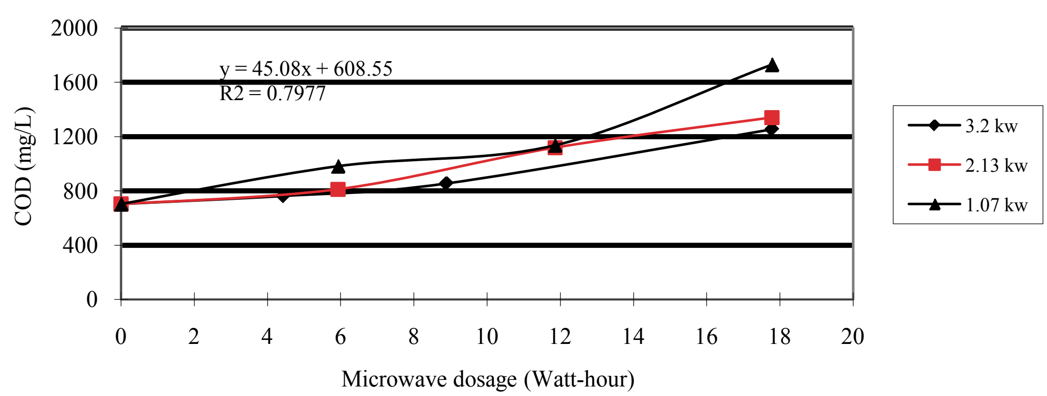


Figure 10. Dissolved COD Profile
(Slurry without Polymer)



Supernatant Dissolved COD Analysis (with polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~550 mg/l COD)
2. Minor increase in COD extraction (positive slope – 6.5 mg/l per watt-h) with applied energy
3. No major difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits good linear correlation

Findings Slurry:

1. Control (no microwave energy: ~550 mg/l COD)
2. Measurable increase in COD extraction (positive slope- 30 mg/l per watt-h) with applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits fair linear correlation

Figure 11. Dissolved COD Profile (Fixed Film with Polymer)

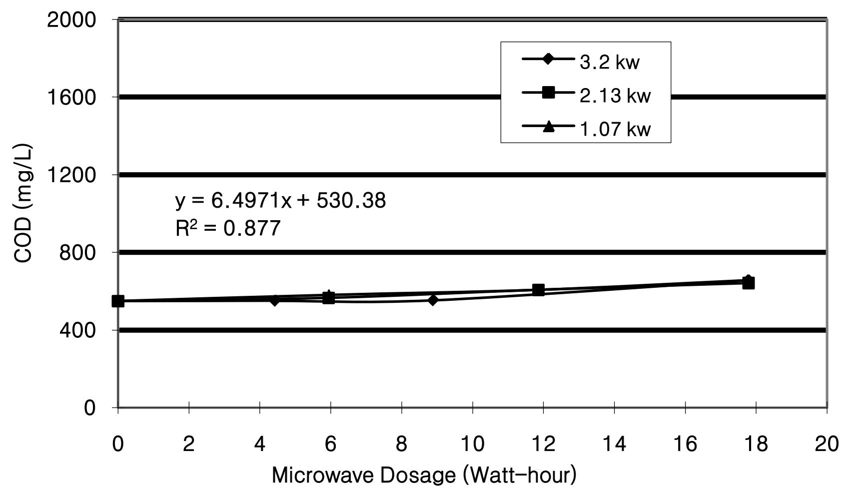
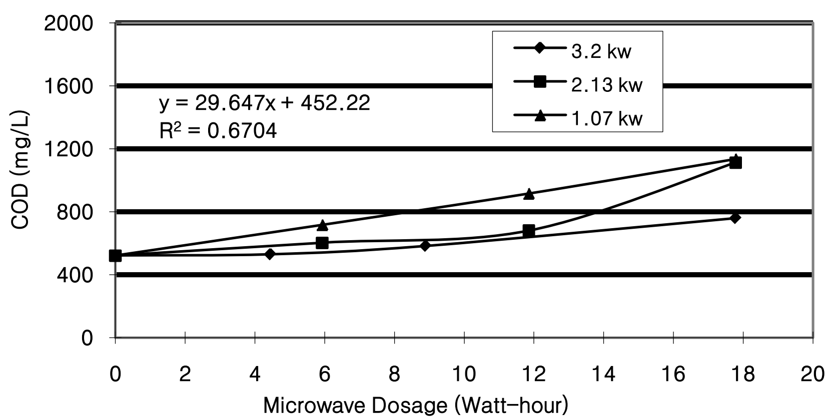


Figure 12. Dissolved COD Profile (Slurry with Polymer)



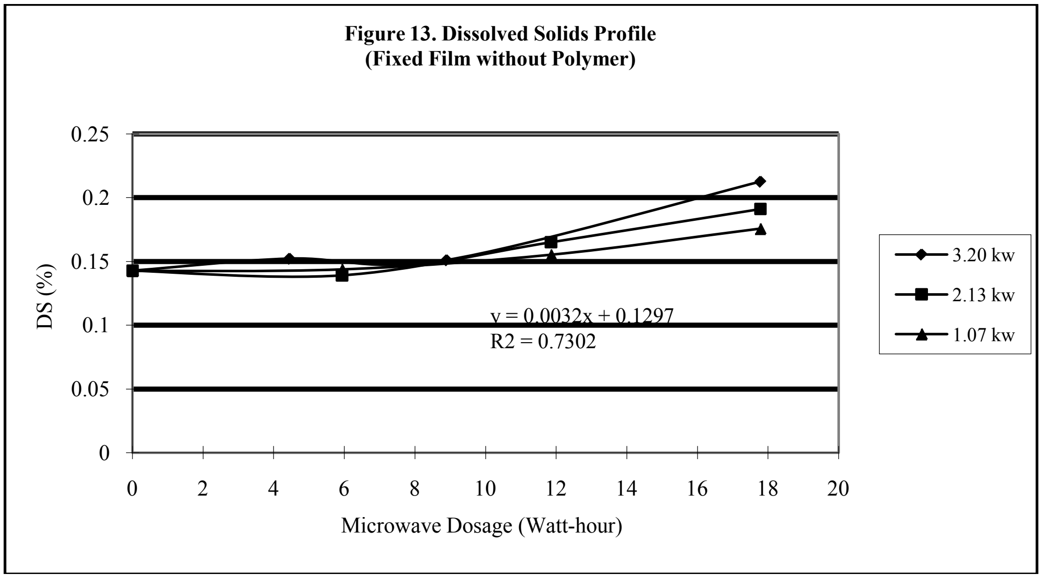
Supernatant Dissolved Solids Analysis (without polymer):

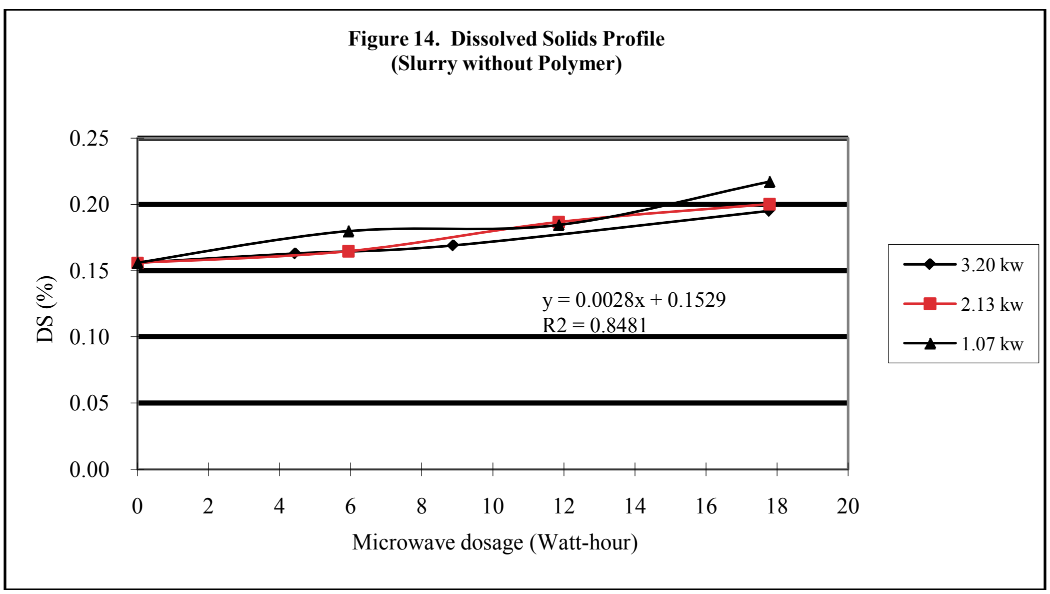
Findings Fixed Film:

1. Control (no microwave energy: ~.145%)
2. Measurable increase in dissolved solids extraction (positive slope – .0032% per wh) with applied energy
3. Higher power density exhibits improved dissolution
4. Coefficient of determination (R^2) for combined data exhibits fair linear correlation

Findings Slurry:

1. Control (no microwave energy: ~0.155%)
2. Measurable increase in dissolved solids extraction (positive slope – .0028% per wh) with applied energy
3. No major difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits good linear correlation





Supernatant Dissolved Solids Analysis (with polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~.125%)
2. No measurable increase in dissolved solids extraction with applied energy
3. No major difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Findings Slurry:

1. Control (no microwave energy: ~0.155%)
2. Measurable increase in dissolved solids extraction (positive slope – .0011% per wh) with applied energy
3. No major difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits fair linear correlation

Figure 15. Dissolved Solids Profile
(Fixed Film with Polymer)

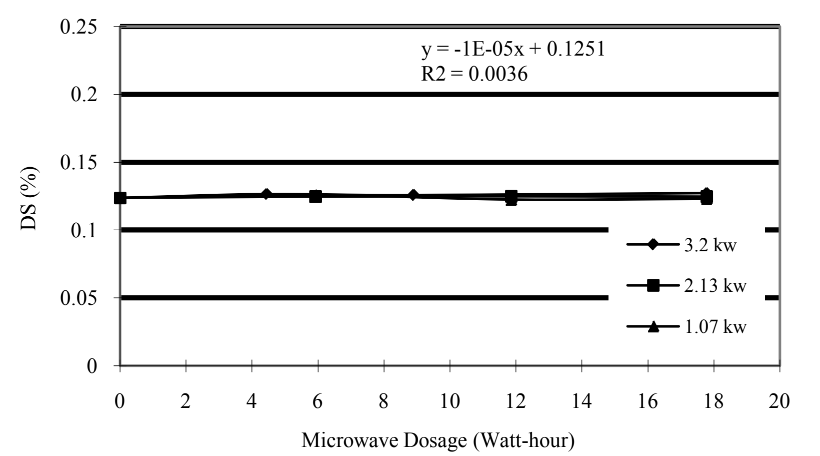
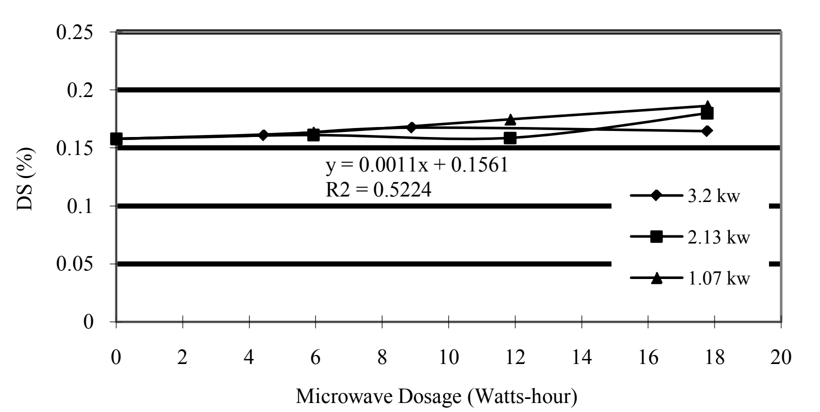


Figure 16. Dissolved Solids Profile
(Slurry with Polymer)



Supernatant Total Volatile Solids Analysis (without polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~ 0.175% VS)
2. Minor increase in COD extraction (positive slope – 0.0028% per wh) with applied energy
3. No major difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits good linear correlation

Findings Slurry:

1. Control (no microwave energy: ~10% VS)
2. Measurable increase in COD extraction (positive slope – 0.0021% per wh) with applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits good linear correlation

Figure 17. Supernatant Total Volatile Solids Profile (Fixed Film without Polymer)

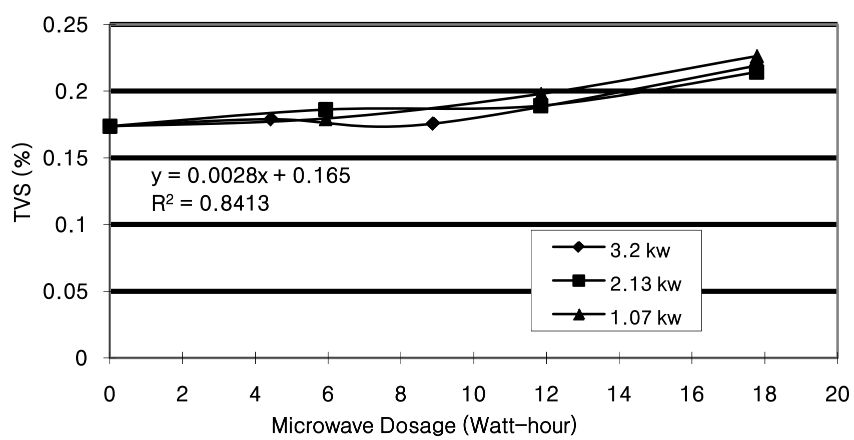
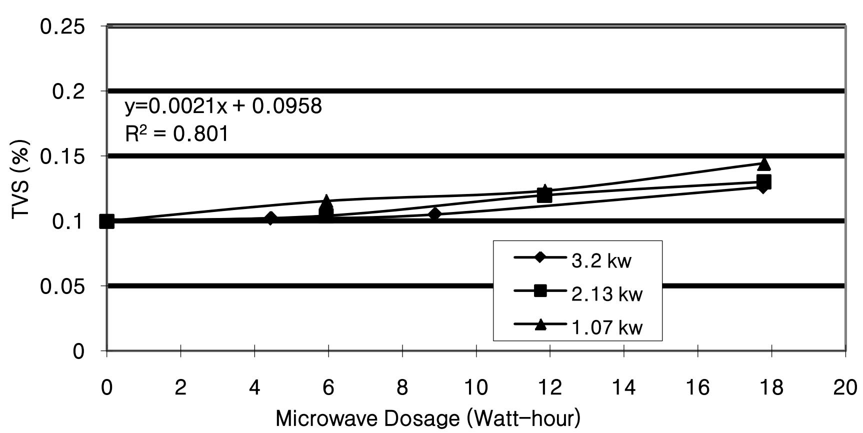


Figure 18. Supernatant Total Volatile Solids Profile (Slurry without Polymer)



Supernatant Total Volatile Solids Analysis (with polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~0.06% VS)
2. No measurable change in TVS extraction with applied energy
3. No major difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits fair linear correlation

Findings Slurry:

1. Control (no microwave energy: ~0.06 VS)
2. Minor increase in TVS extraction (positive slope – 0.0016 % per wh) with applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits fair linear correlation

Figure 19. Supernatant Total Volatile Solids Profile (Fixed Film with Polymer)

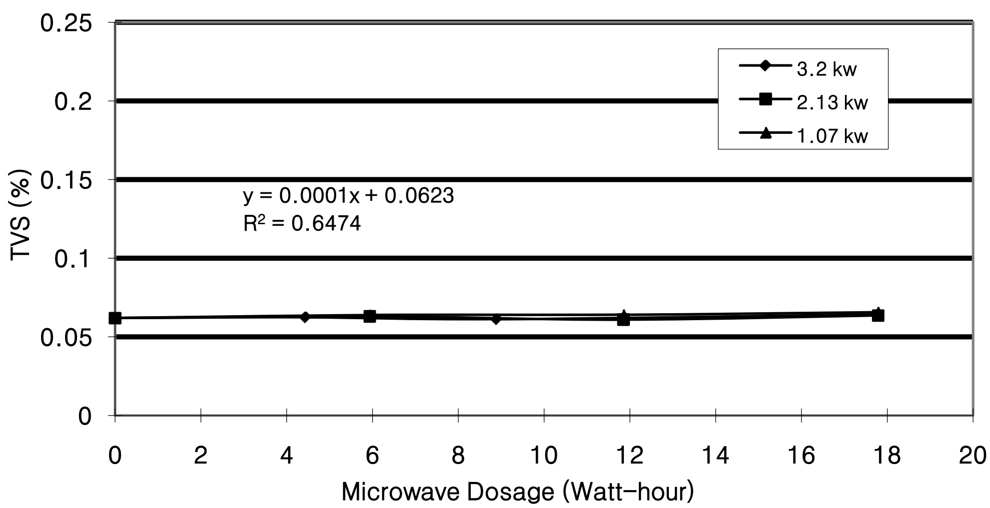
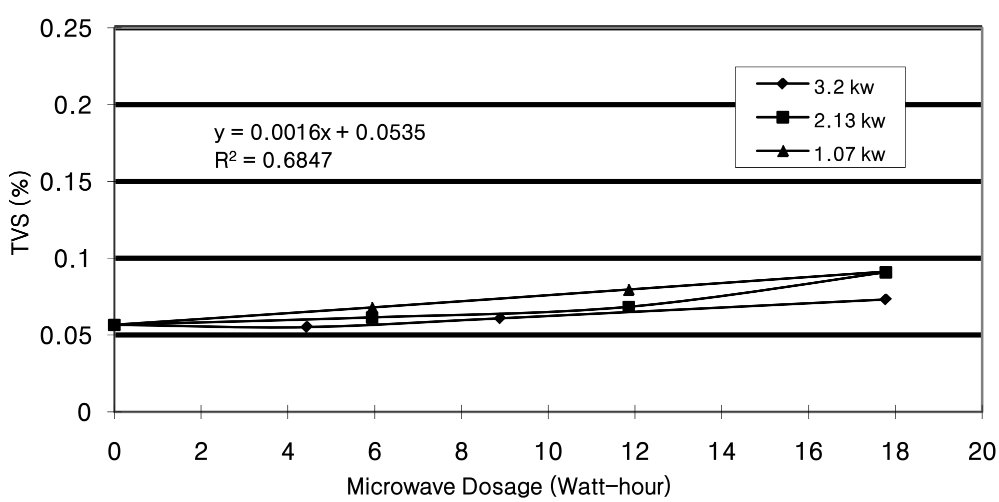


Figure 20. Supernatant Total Volatile Solids Profile (Slurry with Polymer)



Supernatant Dissolved Volatile Solids Analysis (without polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~0.06% DVS) Units.
2. Moderate increase in DVS after ~ 6 wh (positive slope – .003% DVS per wh) applied energy
3. No major difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits good linear correlation

Findings Slurry:

1. Control (no microwave energy: ~.055 DVS)
2. Measurable increase in DVS (positive slope – .0028 % DVS per watt-h) with applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits good linear correlation

Figure 21. Dissolved Volatile Solids Profile (RCSD #1 without Polymer)

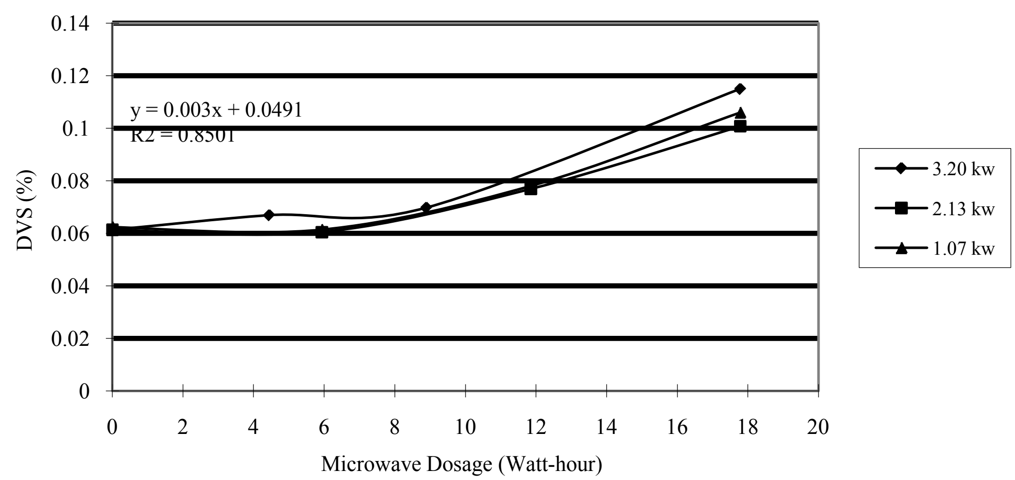
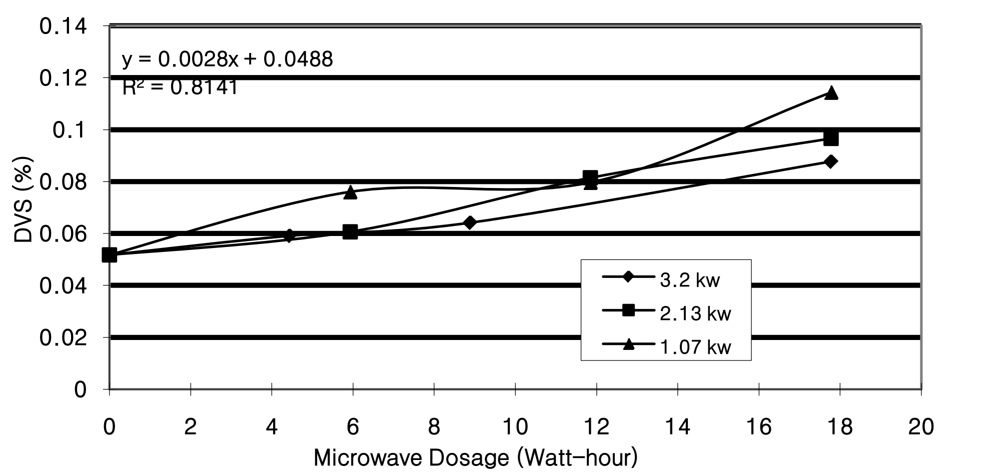


Figure 22. Dissolved Volatile Solids Profile (Slurry without Polymer)



Supernatant Dissolved Volatile Solids Analysis (with polymer):

Findings Fixed Film:
1. Control (no microwave energy: ~0.05 DVS) Units
2. Slight increase in DVS (positive slope – .0004% DVS per wh) applied energy
3. No major difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits good linear correlation

Findings Slurry:
1. Control (no microwave energy: ~0.045 DVS)
2. Measurable increase in DVS (positive slope – .0015 % DVS per wh) applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits fair linear correlation

Figure 23. Dissolved Volatile Solids Profile
(Fixed Film with Polymer)

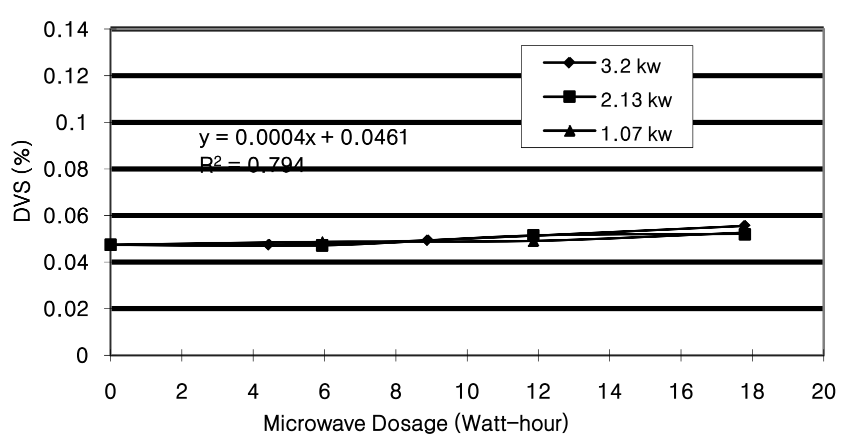
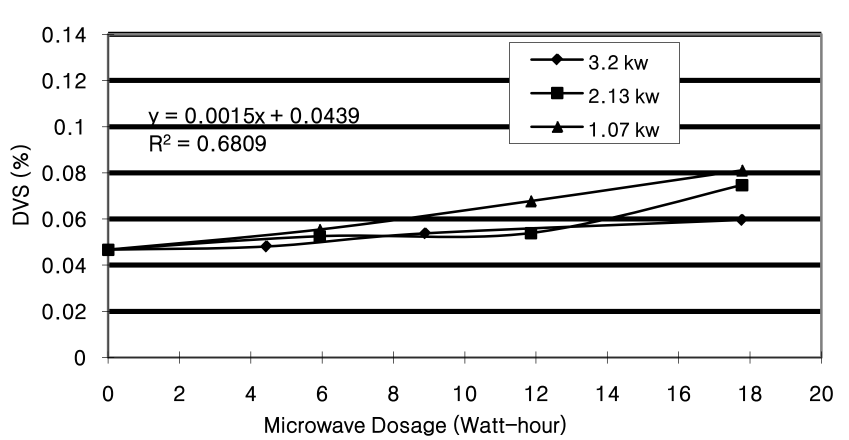


Figure 24. Dissolved Volatile Solids Profile
(Slurry with Polymer)



Volatile Acid Analysis (without polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~110 mg/l)
2. No measurable change in volatile acid content with applied energy
3. No observable difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Findings Slurry:

1. Control (no microwave energy: ~ 100 mg/l)
2. Slight increase in volatile acid content at 18 wh applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Figure 25. Volatile Acid profile (Fixed Film without Polymer)

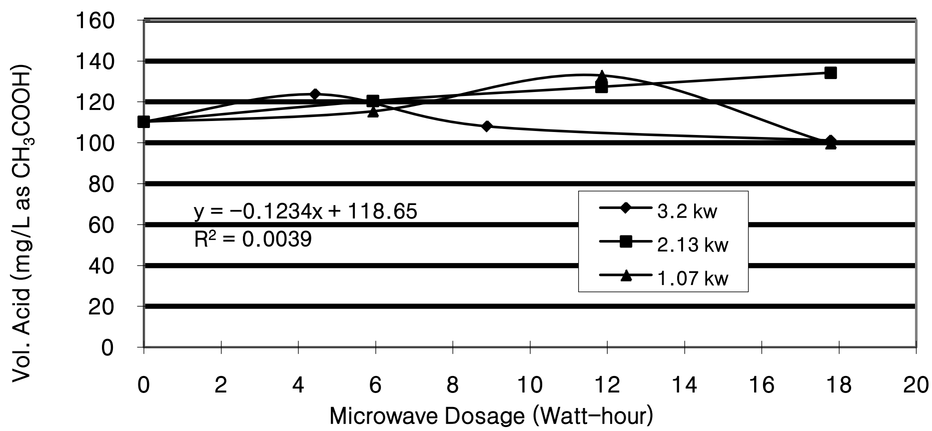
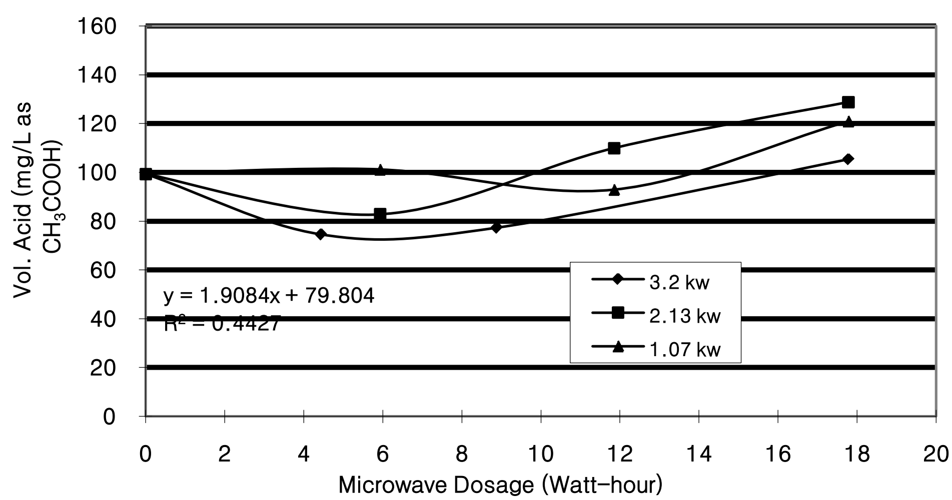


Figure 26. Volatile Acid Profile (Slurry without Polymer)



Volatile Acid Analysis (with polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~108 mg/l)
2. No measurable change in volatile acid content with applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Findings Slurry:

1. Control (no microwave energy: ~ 130 mg/l)
2. Slight decrease in volatile acid content with applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R2) for combined data exhibits poor linear correlation

Figure 27. Volatile Acid Profile (Fixed Film with Polymer)

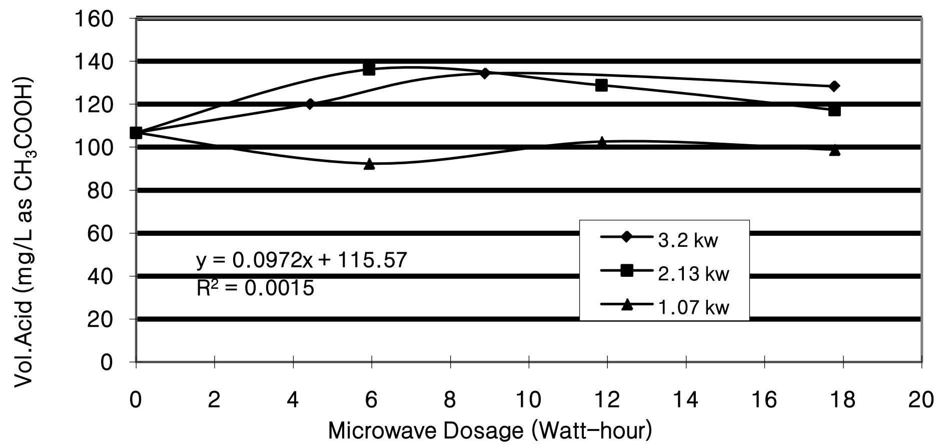
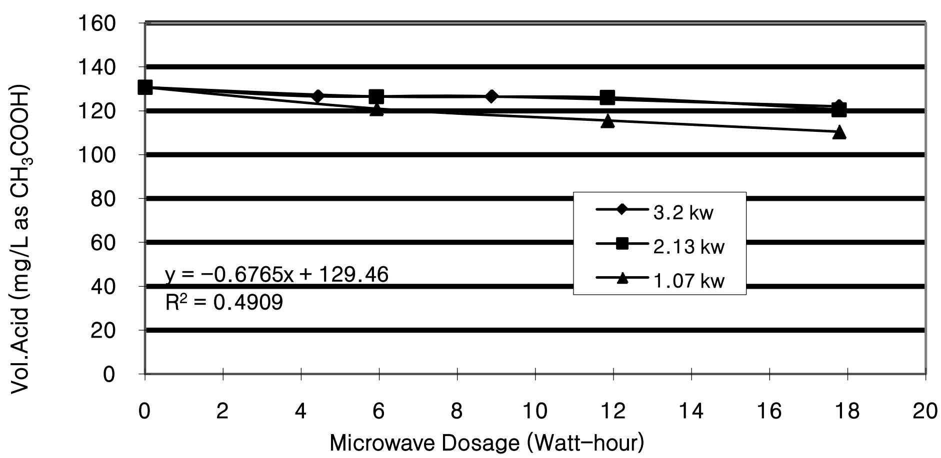


Figure 28. Volatile Acid Profile (Slurry with Polymer)



pH Analysis (without polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~8.1 pH)
2. No measurable increase in pH (slight positive slope – after ~6 wh applied energy)
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Findings Slurry:

1. Control (no microwave energy: ~.7.9 pH)
2. No measurable increase in pH with applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Figure 29. pH Profile
(Fixed Film without Polymer)

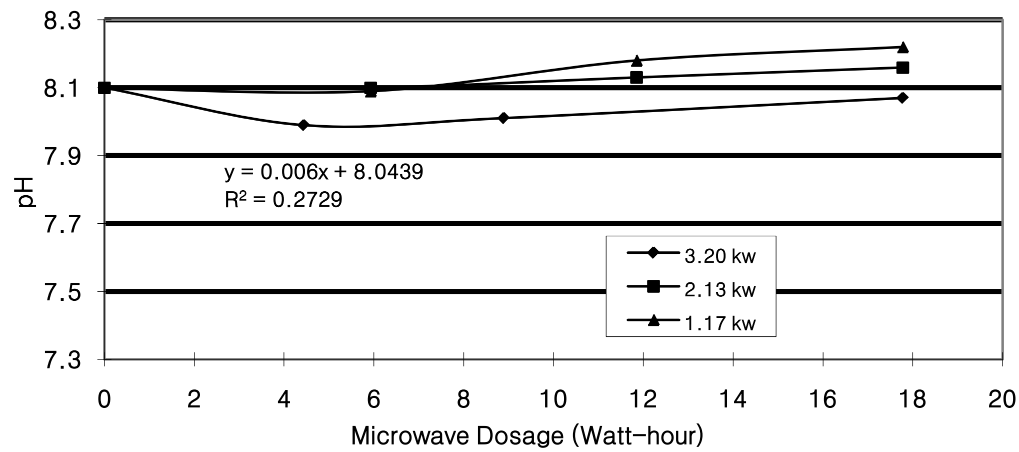
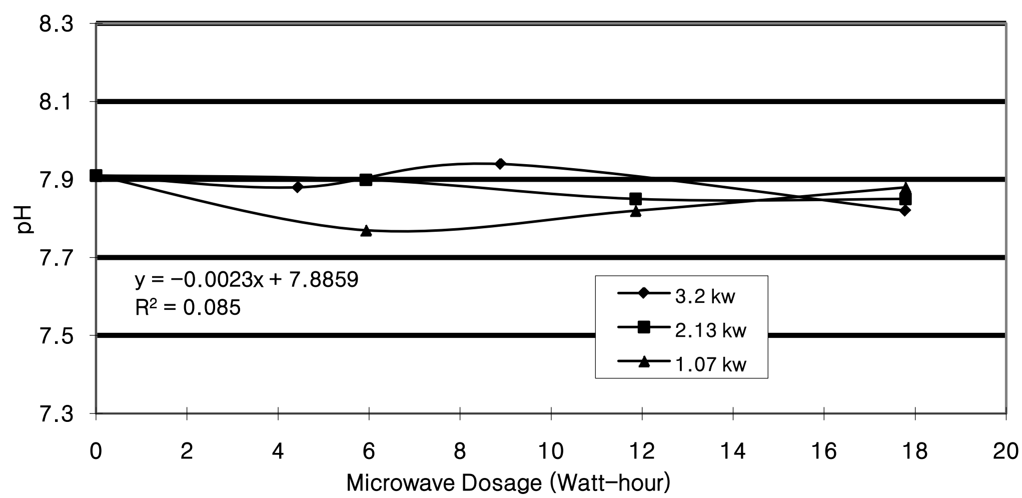


Figure 30. pH Profile
(Slurry without Polymer)



pH Analysis (with polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~7.6 pH)
2. Slight increase in pH (slight positive slope – after ~6 wh applied energy)
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits fair linear correlation

Findings Slurry:

1. Control (no microwave energy: ~.7.4 pH)
2. No measurable increase in pH with applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Figure 31. pH Profile
(Fixed Film with Polymer)

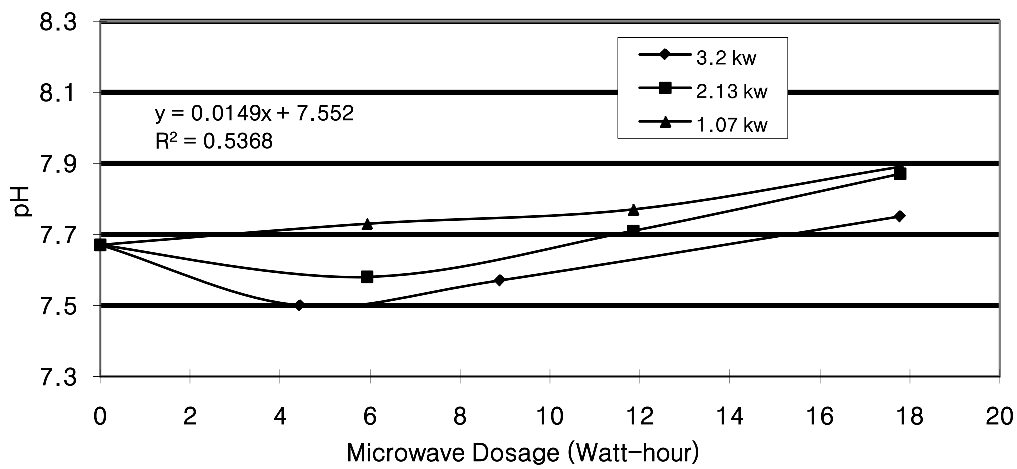
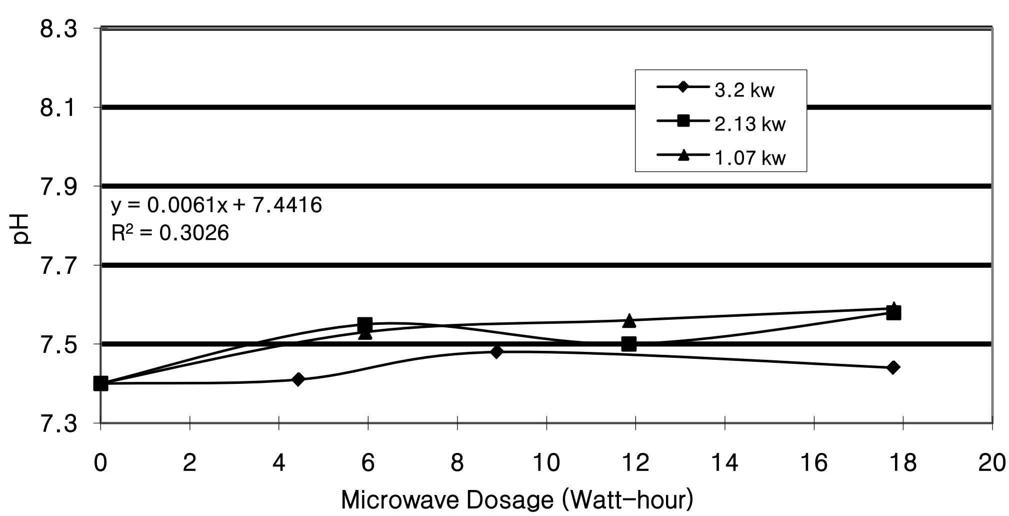


Figure 32. pH Profile
(Slurry with Polymer)



Total Alkalinity Analysis (without polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~4000 mg/l CaCO3)
2. Slight decrease in alkalinity (slightly negative slope – after ~6 wh applied energy)
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Findings Slurry:

1. Control (no microwave energy: ~.2250 mg/l CaCO3)
2. No measurable change in alkalinity with applied energy
3. Some observable difference between applied power densities; but data inconclusive
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Figure 33. Total Alkalinity Profile
(Fixed Film without Polymer)

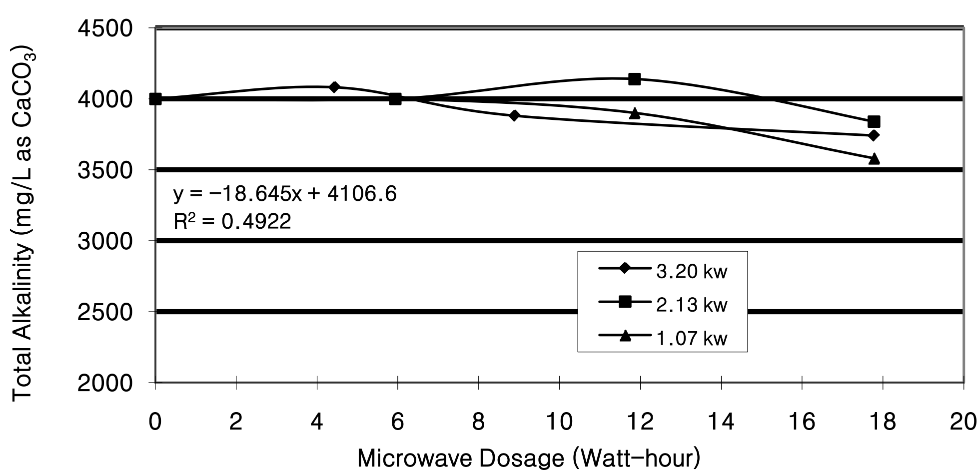
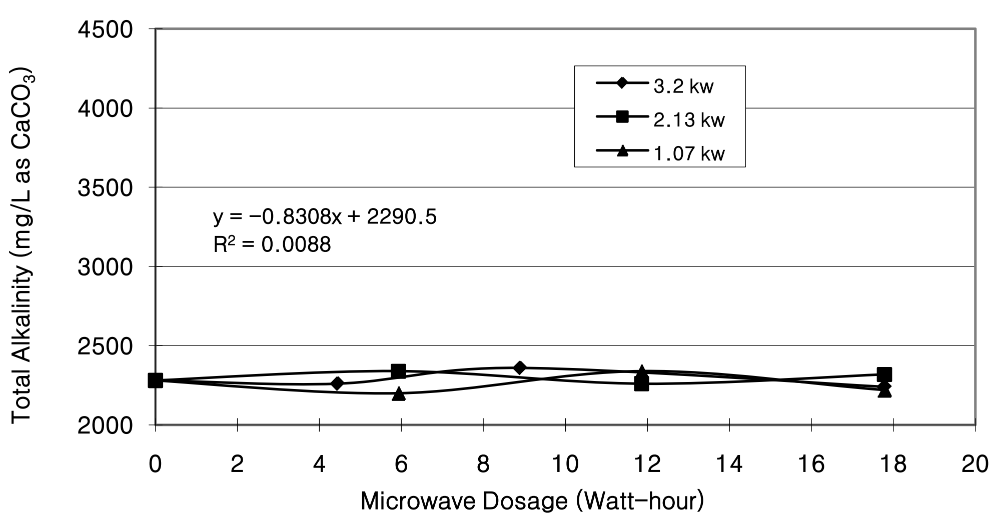


Figure 34. Total Alkalinity Profile
(Slurry without Polymer)



Total Alkalinity Analysis (with polymer):

Findings Fixed Film:

1. Control (no microwave energy: ~2900 mg/l CaCO3)
2. No measurable change in alkalinity with applied energy
3. No observable difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Findings Slurry:

1. Control (no microwave energy: ~ 2250 mg/l CaCO3)
2. No measurable change in alkalinity with applied energy
3. No observable difference between applied power densities
4. Coefficient of determination (R^2) for combined data exhibits poor linear correlation

Figure 35. Total Alkalinity Profile (Fixed Film with Polymer)

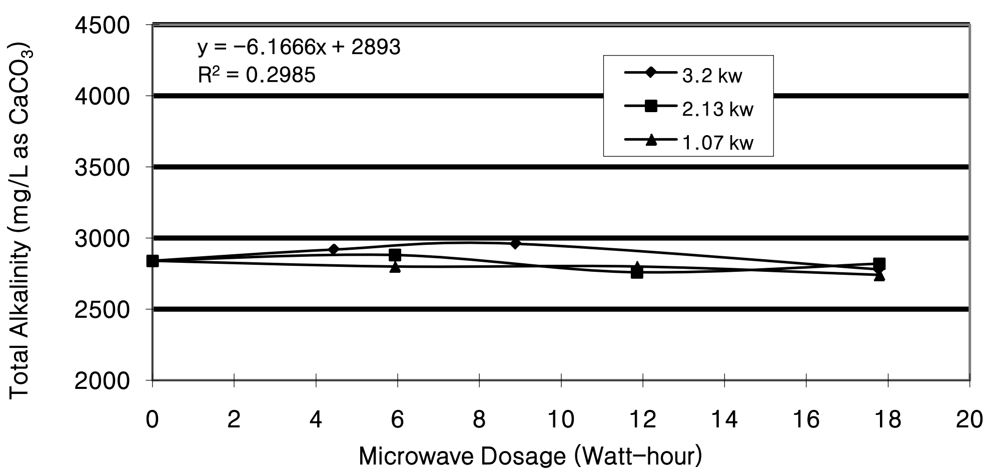
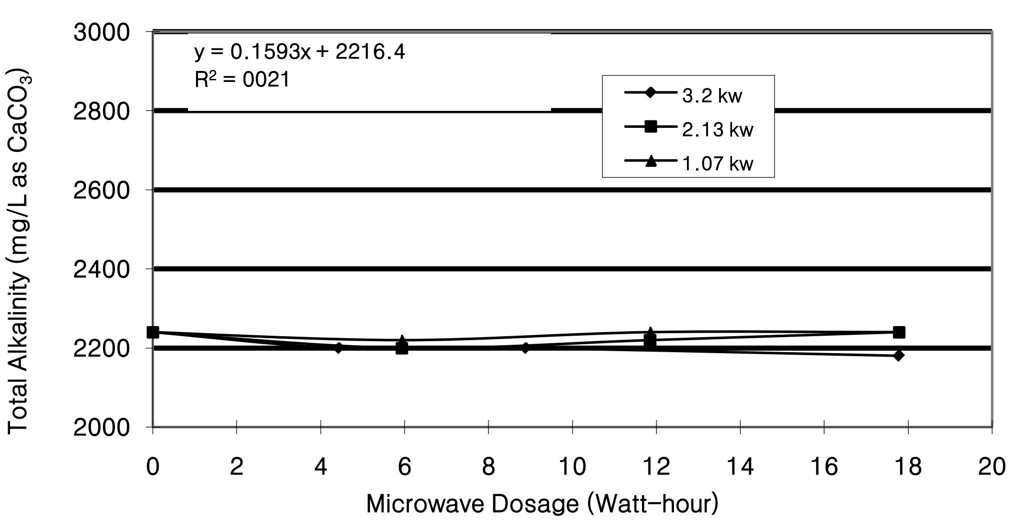


Figure 36. Total Alkalinity Profile (Slurry with Polymer)



Temperature Effects: Microwave vs Conduction Heating Dewatering

Conditions:
Sludge Sample from City of Suffern (No Polymer)
Comparison test (conventional conduction heating and microwave)
Heating plate (conduction heating) used to reach the desired temperature (83, 112 137 deg F)
3.2 kW microwave power used to reach the desired temperature

Findings:
1. Measurable differences between conduction and microwave heating effects
2. Applied heat energy increases dewaterability
3. Applied microwave increases dewaterability from 7-15 percent above conduction heating
4. Maximum difference at 112 deg F

Figure 37. Microwaved vs. Conduction Heating - Milliliters of Liquid Extracted (3 min. Dewaterability Comparison test)

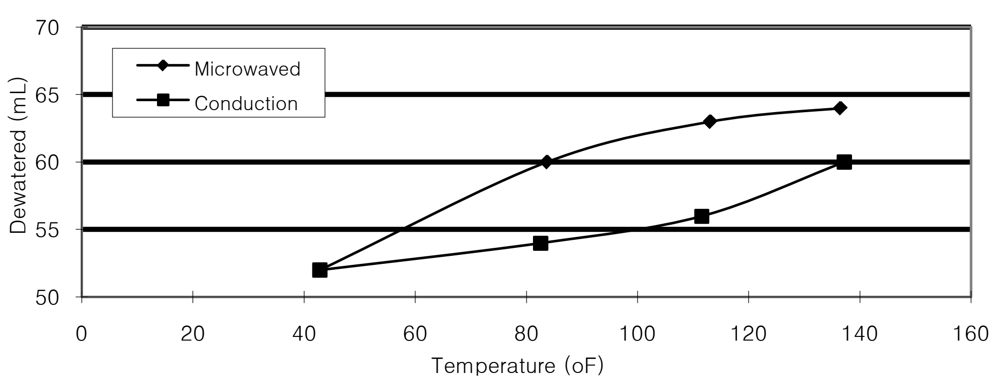
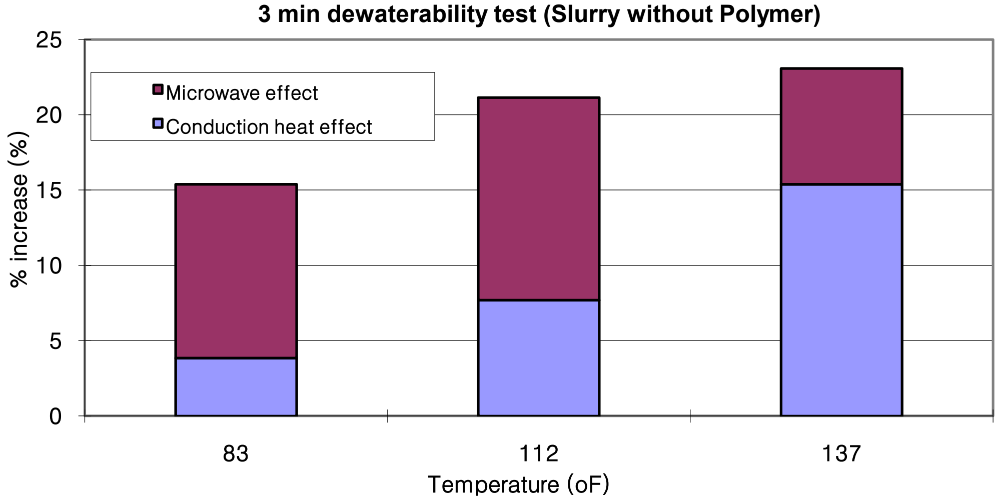


Figure 38. Microwave vs Conduction Heating- % Dewaterability Increase 3 min dewaterability test (Slurry without Polymer)



Temperature Effects: Microwave vs Conduction Heating Supernatant COD - Slurry without Polymer:

Conditions:
Sludge Sample from City of Suffern
Comparison test (conventional conduction heating and microwave)
Heating plate (conduction heating) used to reach the desired temperature (83, 112 137 deg F)
3.2 kW microwave power used to reach the desired temperature

Findings:

1. Control (Supernatant COD ~ 1550 mg/l)
2. Measurable differences between conduction and microwave heating effects.
3. Applied heat energy increases
4. Applied microwave increases Supernatant COD from 7-11 percent above conduction heating
5. Maximum difference at 137 deg F

Figure 39. Microwaved vs. Conduction Heating (3 min. Supernatant COD Comparison test)

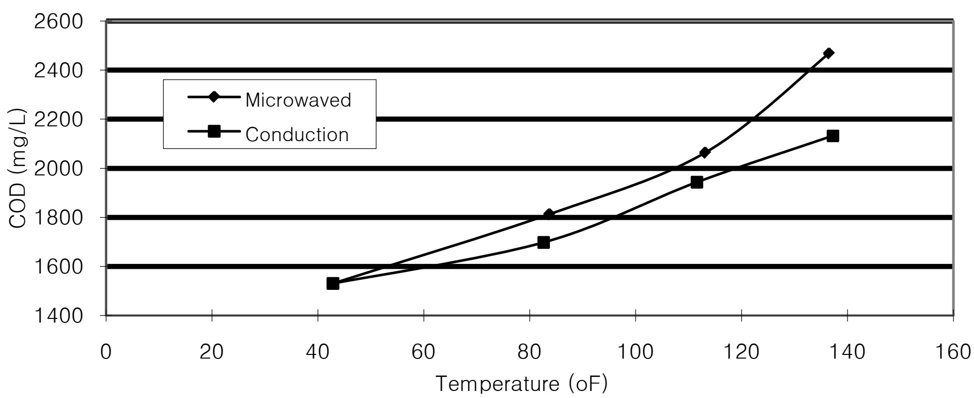
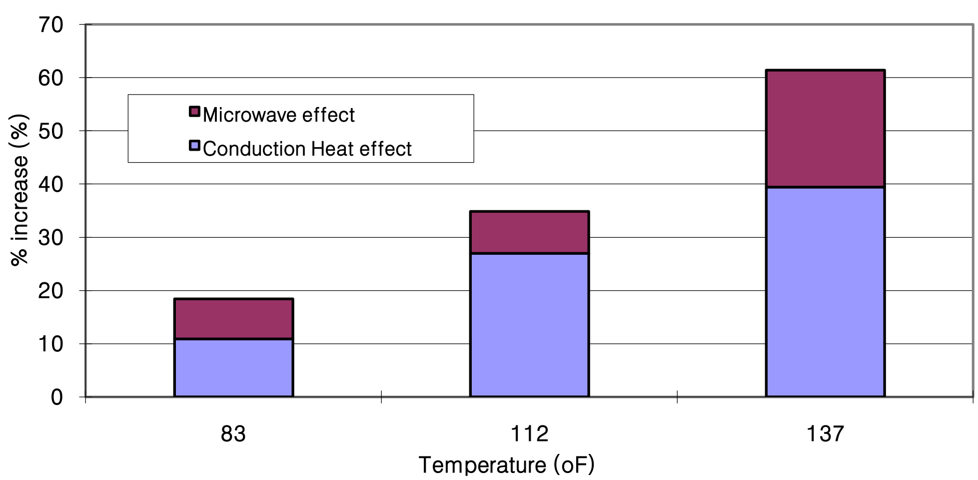


Figure 40. Supernatant COD % increase (Slurry without Polymer)



Temperature Effects: Microwave vs Conduction Heating Dissolved COD - Slurry without Polymer:

Conditions:
Sludge Sample from City of Suffern
Comparison test (conventional conduction heating and microwave)
Heating plate (conduction heating) used to reach the desired temperature (83, 112 137 deg F)
3.2 kW microwave power used to reach the desired temperature

Findings:
1. Control (Dissolved Supernatant COD ~ 800 mg/l)
2. Measurable differences between conduction and microwave heating effects
3. Applied heat energy increases
4. Applied microwave increases Dissolved Supernatant COD from 2-11 percent above conduction heating
5. Maximum difference at 137 deg F

Figure 41. Microwaved vs. Conduction Heating (Dissolved COD Comparison test)

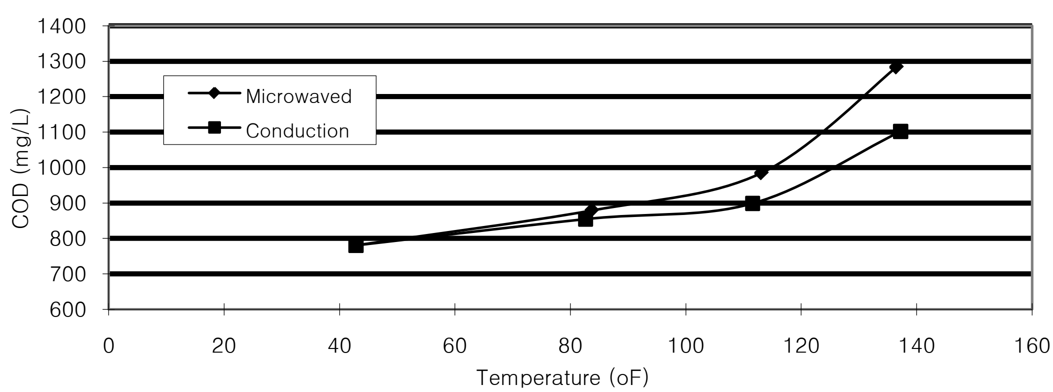
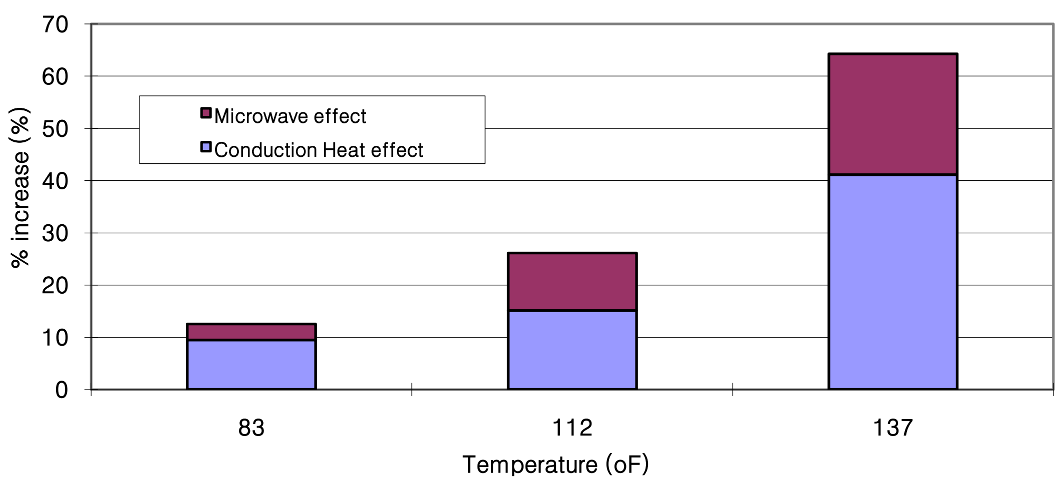


Figure 42. Dissolved COD % increase (Slurry without Polymer)



Temperature Effects: Microwave vs Conduction Heating Dissolved Solids - Slurry without Polymer:

Conditions:
Sludge Sample from City of Suffern
Comparison test (conventional conduction heating and microwave)
Heating plate (conduction heating) used to reach the desired temperature (83, 112 137 deg F)
3.2 kW microwave power used to reach the desired temperature

Findings:
1. Control (Dissolved Supernatant Dissolved Solids ~ 0.177%)
2. Measurable differences between conduction and microwave heating effects
3. Applied heat energy increases
4. Applied microwave increases Dissolved Supernatant COD from 2-11 percent above conduction heating
5. Maximum difference at 137 deg F

Figure 43. Dissolved Solids Comparison test (Microwaved vs. Conventional)

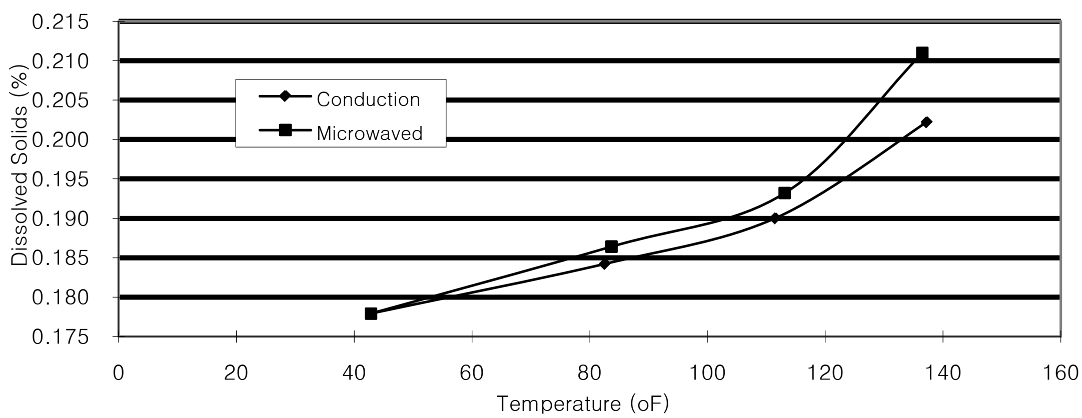
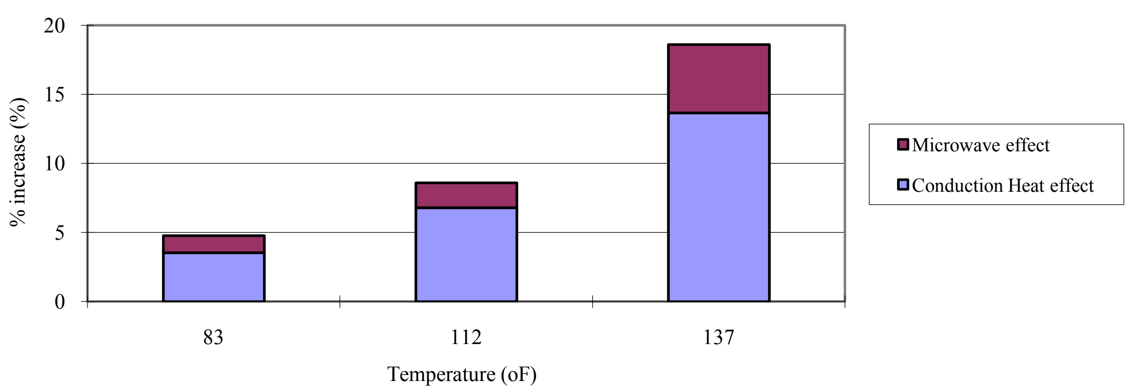


Figure 44. Dissolved Solids % Increase (Slurry without Polymer)



Temperature Effects: Microwave vs Conduction Heat Total VS - Slurry without Polymer:

Conditions:
Sludge Sample from City of Suffern
Comparison test (conventional conduction heating and microwave)
Heating plate (conduction heating) used to reach the desired temperature (83, 112 137 deg F)
3.2 kW microwave power used to reach the desired temperature

Findings:

1. Control (Volatile Solids ~ 0.128%)
2. Inconsistent data in mid-temp range, with negative effect indicated
3. Microwave heating increases VS up to 15-20% greater than conduction heating
4. Maximum difference at 137 deg F

Figure 45. Microwaved vs. Conduction Heating (3 min. supernatant Volatile Solids Comparison test)

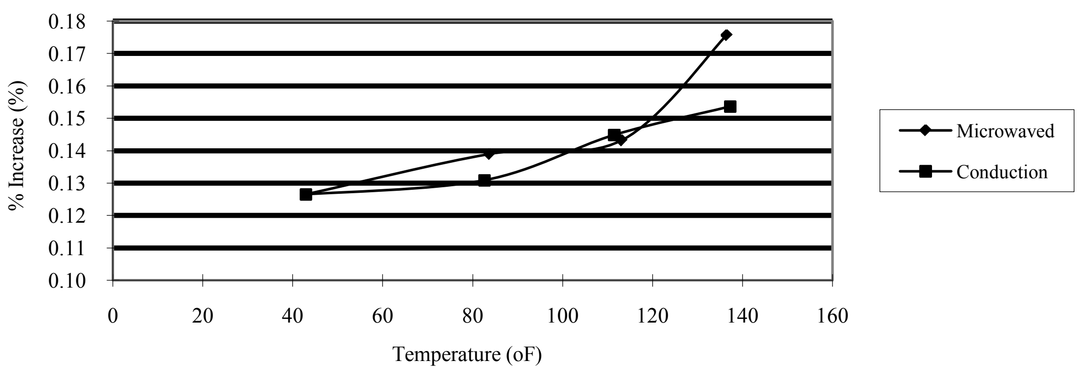
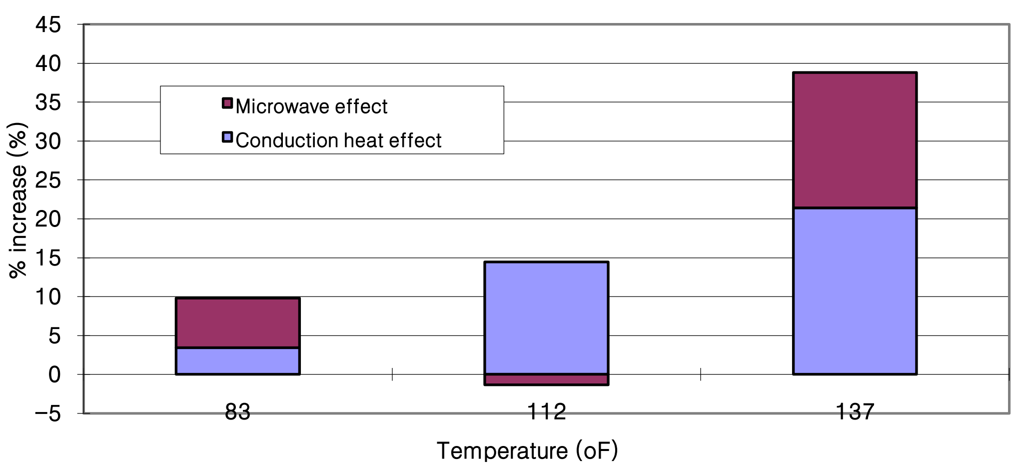


Figure 46. Supernatant Volatile Solids % increase (Slurry without Polymer)



Temperature Effects: Microwave vs Conduction Heating Dissolved VS - Slurry without Polymer:

Conditions:
Sludge Sample from City of Suffern
Comparison test (conventional conduction heating and microwave)
Heating plate (conduction heating) used to reach the desired temperature (83, 112, 137 deg F)
3.2 kW microwave power used to reach the desired temperature

Findings:
1. Control (Dissolved Volatile Solids ~ .073%)
2. Slight differences between conduction and microwave heating effects at higher temperatures
3. Microwave heating increases Dissolved VS up to 10% higher than conduction heating
4. Maximum difference at 137 deg F

Figure 47. Microwaved vs. Conventional (Dissolved Volatile Solids Comparison test)

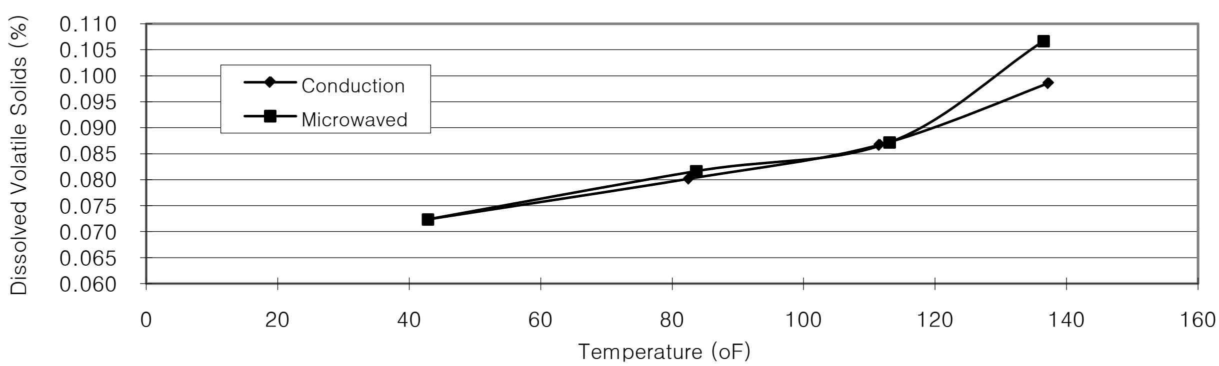
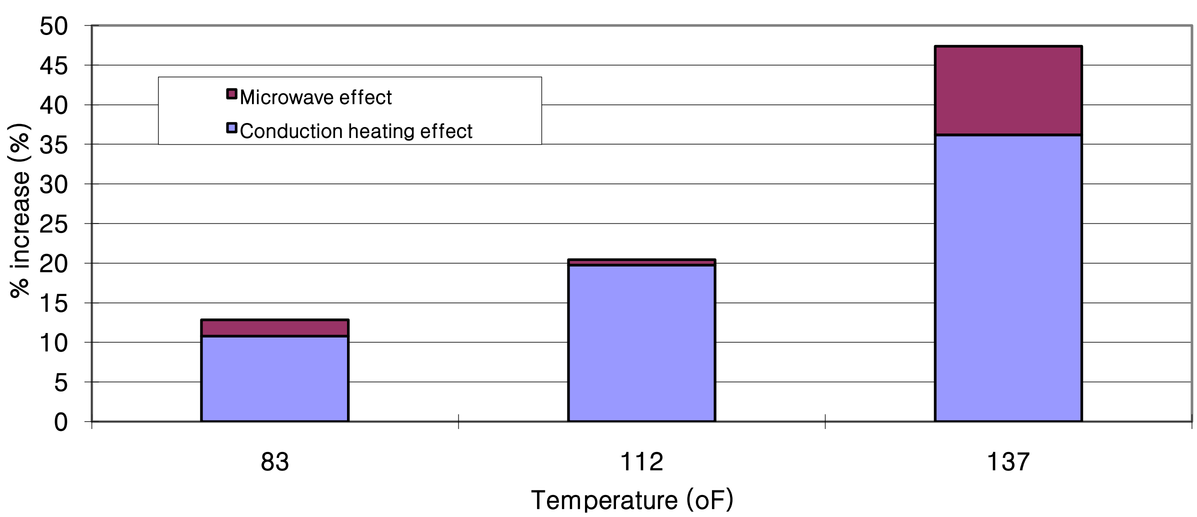


Figure 48. Dissolved Volatile Solids % increase (Slurry without Polymer)



Sludge Disinfection:

Conditions:
Sludge Sample: from Rockland County (No Polymer Added)
Comparison test: microwave applied at 2 kW versus conduction heating
Target treatment temperatures: 30, 40, 60, 80 deg C

Findings

4. Both microwave radiation and convection heating resulted in effective kills in excess of a six log reduction in total coliform bacteria at temperatures in excess of 60 deg C
5. No differences between microwave and conduction heating could be determined
6. At 2 kW power application and 45 deg C sludge temperatures, the microwave applicator achieved the disinfection temperature of 60 deg C in 20 seconds
7. Using a _ kW hot plate the disinfection temperature of 60 deg C was achieved in 467 seconds (7 minutes and 47 seconds); or approximately 23 times as long as the microwave applicator

Figure 49
Coliform Testing - Microwave and Convection Heating

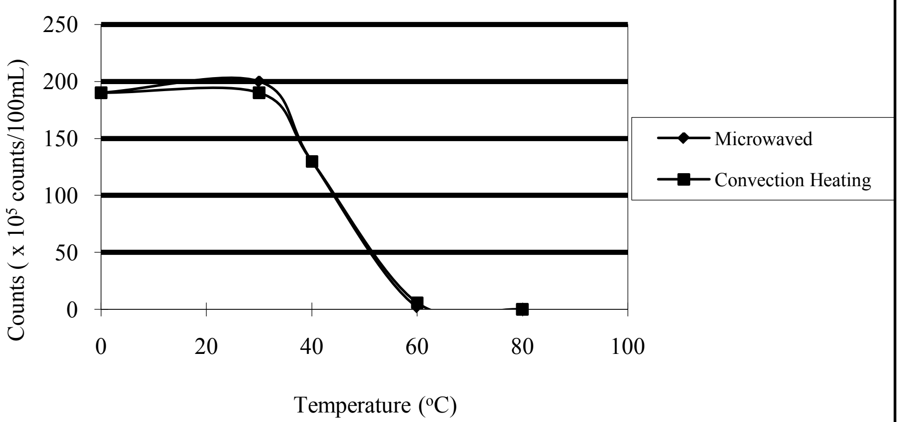


Table 3. Microwave vs Conduction Heating Coliform Reduction Data Table		
Test Run[1,2,3]	Count/100mL	Time to Temperature (sec)
Control	1.9×10^7	NA
M30	2.0×10^7	7
M40	1.3×10^7	12
M60	2×10^5	20
M80	0	33
H30	1.9×10^7	188
H40	1.3×10^7	295
H60	6×10^5	467
H80	0	643

1. The Control is raw Rockland County sludge without polymer.
2. M designates microwave test and H designates the hot plate test.
3. Numbers following the designation represent the treatment temperatures.

V. Discussion of Findings

The experimental findings are discussed in this section. Table 4 presents a list of the regression line slope and coefficient of determination data. This information, reviewed collectively with the graphical information presented in the prior section, provide a mechanism for comparing the effect of microwave exposure (energy) on each sample tested.

Table 4. Regression Line Data

Test	Units	Sample Analysis	Regression Line Slope	Coefficient of Determination
Dewaterability	% moisture extracted	Fixed Film w/o polymer	0.106	0.296
		Fixed Film w/ polymer	-0.211	0.415
		Slurry w/o polymer	0.387	0.946
		Slurry w/ polymer	-0.456	0.562
Total COD Solubility	mg/L COD	Fixed Film w/o polymer	64.1	0.869
		Fixed Film w/ polymer	1.85	0.097
		Slurry w/o polymer	32.9	0.701
		Slurry w/ polymer	32.1	0.742
Dissolved COD Solubility	mg/L COD	Fixed Film w/o polymer	44.9	0.887
		Fixed Film w/ polymer	6.49	0.877
		Slurry w/o polymer	45.1	0.797
		Slurry w/ polymer	29.7	0.670
Total Dissolved Solids	% TDS	Fixed Film w/o polymer	0.0028	0.841
		Fixed Film w/ polymer	0.0001	0.647
		Slurry w/o polymer	0.0021	0.801
		Slurry w/ polymer	0.0016	0.684
Total Volatile Solids	% TVS	Fixed Film w/o polymer	0.0028	0.841
		Fixed Film w/ polymer	0.0001	0.647
		Slurry w/o polymer	0.0021	0.801
		Slurry w/ polymer	0.0016	0.684
Dissolved Volatile Solids	% TVDS	Fixed Film w/o polymer	0.003	0.850
		Fixed Film w/ polymer	0.0004	0.794
		Slurry w/o polymer	0.0028	0.814
		Slurry w/ polymer	0.0015	0.681
Volatile Acids	mg/L as CH3COOH	Fixed Film w/o polymer	-0.123	.0039
		Fixed Film w/ polymer	0.097	.0015
		Slurry w/o polymer	1.91	0.443
		Slurry w/ polymer	-0.676	0.491
pH Analysis	pH units	Fixed Film w/o polymer	0.006	0.273
		Fixed Film w/ polymer	0.0149	0.537
		Slurry w/o polymer	-0.0023	0.085
		Slurry w/ polymer	.0061	0.303
Alkalinity	mg/L as CaCO3	Fixed Film w/o polymer	-18.6	0.492
		Fixed Film w/ polymer	-6.17	0.299
		Slurry w/o polymer	-0.831	0.009
		Slurry w/ polymer	0.159	0.0021

Dewaterability Analysis:

The graphical data presented in Figures 1, 2, 3, and 4, along with the regression line data provided in Table 4, lead to the conclusion that the exposure of microwave radiation to sludges not pretreated with polymer will improve sludge dewaterability; and this improvement is essentially proportional to the microwave energy applied (i.e., dose). Slurry sludges (with three times the regression line slope) were observed to be much more susceptible to this improvement than fixed film sludges; slurry sludge dewaterability improved by 15-to-20 percent, compared to 5-to-10 percent for fixed film sludge. In addition, microwave radiation appeared to interfere with the effectiveness of dewatering the polymer treated sludges, which decreased with energy exposure (negative regression line slope).

Previous studies (Sergio 2006) have noted similar effects of increasing temperature on improved dewaterability. The most obvious mechanism is the reduction in viscosity resulting from increased temperature. Lower viscosity reduces interstitial frictional forces between the liquid and sludge solids, which results in less energy required to separate the liquid from the solids under vacuum. A secondary mechanism is the solubilization of solids, thereby releasing more liquid into the bulk solution. Finally, it is possible that heating the sludge disrupts the solids-liquid interface, which results in easier separation of the solids and liquid during dewatering.

The latter mechanism is that which potentially differentiates microwave and conduction heating. The electromagnetic field associated with microwave radiation affects polar molecules (e.g., H_2O) by inducing rapid rotation of such molecules, which ultimately results in heating and temperature rise. This electromagnetic field could also affect the surface chemistry of sludge, which likely has organic molecules with weak polar or dipolar bonds (i.e., van der Waal forces). Disruption of the electrical orientation of these molecules could induce an effect similar to that of a thickening polymer, which acts to reorient the surface molecules with a resulting flocculation effects, and subsequently improved dewatering. Similar affects could explain the adverse impact of microwave radiation on sludges that have been treated with polymer; the electromagnetic field may reversibly disrupt the polymer.

To answer the question of whether the effects were due to temperature rise or the induced electromagnetic field, dewatering data from samples heated via conduction were compared to those receiving microwave radiation. These results are presented in Figures 37 and 38. In particular, Figure 38 highlights the increase extraction from microwaved samples, approximately 11%, 13% and 8%, respectively, from samples heated to temperatures of 83 deg F, 112 deg F and 137 deg F.

Slurry, Fixed Film and Polymer Analysis:

Differences between slurry and fixed film sludge dewaterability results were notable; slurry samples exhibited a more dramatic response to microwave radiation than fixed film samples. Differences were also observed in the COD, dissolved solids and volatile solids results for the two sludge types; the data are discussed below. These differences may be the result of the higher initial solids content associated with the fixed film sludge, which subsequently may result in a lower power density received per dry gram of fixed film sludge. More likely, however, these differences are the result of the more open floc structure of slurry sludge, which may facilitate more efficient microwave penetration into the pore structure. In addition, the intermolecular bonding (or interstitial frictional forces) of water and solids in this open floc structure may be weaker than that of the floc structure of the fixed film sludge. This latter point is reinforced to a degree by the reduced response of polymer treated sludge to microwave exposure; polymer treatment would tend to strengthen the intermolecular bonding, tightening up the floc structure.

Reductions in dewaterability (see Figures 3 and 4), reflected in the negative regression line slopes presented in Table 4, suggest that microwave radiation may also be reacting with the polymer and reducing its effectiveness. Absorption of microwave energy by the polymer could also be a factor associated with the reduced extraction of COD, and dissolved and volatile solids.

Supernatant Total and Dissolved COD Analysis:

The graphical data presented in Figures 5, 6, 7 and 8 and the regression data listed in Table 4 lead to the conclusion that the exposure of sludge to microwave radiation (not pretreated with polymer) should result in an increase of total COD in the sludge supernatant. This was shown to be true (see high coefficient of determination) and to be nearly directly proportional to the microwave energy applied (i.e., dose); similar results to those observed in the dewaterability data. In the graphical data presented in Figures 7, one observes that microwave radiation had little affect on total COD dissolution from fixed film samples pretreated with polymer. Similar results are observed in Figures 9, 10, 11 and 12 for dissolved COD, which increase almost linearly with microwave exposure. Once again, polymer treated fixed film sludge exhibited much lower dissolved COD solubilization than polymer treated slurry sludge.

Previous studies (Jin 2009, Sergio 2006) have noted the effect of increasing temperature on improved COD solubilization. Increased COD solubilization has been attributed to the leaching of soluble intercellular content into the bulk liquid and/or solubilization of the organic matter component of the extracellular polymeric matrix (the structural matrix of a waste activated sludge floc). The question of whether the results are due to temperature rise or the induced electromagnetic field was examined by comparing COD dissolution data from sludge heated conductively to that heated by microwave radiation; these results are presented in Figures 39 through 42. Figures 39 and 41, respectively, show the increase of total and dissolved COD levels in microwaved and conductively heated samples at temperatures of 83 deg F, 112 deg F and 137 deg F. Figures 40 and 42, respectively, show the percent total and dissolved COD levels attributed to conventional heating versus microwave heating. Observation of the data indicate that microwave radiation induces approximately 8-to-20 percent more dissolution of COD than conventional heating; an observation also reported by others (Jin 2009). The reduction in COD solubilization in fixed film polymer treated samples (Figures 7 and 11) suggests polymeric interference when microwave is applied to these samples.

Supernatant Dissolved Solids Analysis:

The graphical data presented in Figures 13, 14, 15 and 16 and the regression line data listed in Table 4 suggest that there is a moderate release of dissolved solids for fixed film and slurry sludge without polymer, but much less so for fixed film and slurry sludge with polymer pretreatment, shown in Figure 15.

The question of whether the results are due to temperature rise or some special microwave effect was examined by comparing dissolved solids dissolution data from samples heated convectively to those receiving microwave radiation. The results of these tests are presented in Figures 43 and 44. The data indicate that microwave treatment increases dissolved solids dissolution. The relative differences were not apparent at lower temperatures, but at 137 degrees Fahrenheit, there was a measurable microwave effect observed.

Supernatant Total and Dissolved Volatile Solids Analysis:

The graphical data presented in Figures 17, 18, 19 and 20 and the regression line data listed in Table 4 lead us to draw the conclusion that there was a moderate release of total volatile solids into the supernatant solution at the exposure levels applied. Similar data are shown for dissolved volatile solids, the results of which are presented in Figures 21, 22, 23 and 24, and Table 4. The observed increase in total and dissolved volatile organic concentrations (see high coefficients of determination in Table 4) are nearly directly proportional to the energy applied (i.e., dose); results similar to the trends observed for the COD test data. Similarly, the graphical data presented in Figures 19 and 23 show essentially no effect on total or dissolved volatile organic solubilization on fixed film polymer treated sludge. The reduction in COD solubilization in fixed film polymer treated samples (Figures 19 and 23) suggests polymeric interference when microwave is applied compared to polymer free samples.

The question of whether the results are due to temperature rise or some special microwave effect was examined by comparing TVS and dissolved VS dissolution data of samples heated conductively versus those receiving microwave radiation; the results are presented in Figures 45 through 48. The relative differences were not apparent at lower temperature, but at 137 degrees Fahrenheit, there was a measurable microwave effect observed, indicating an increase in TVS and dissolved VS dissolution with microwave exposure.

Volatile Acid, pH and Alkalinity Analysis:

Microwave exposure had no measurable affect on volatile acid content, pH or alkalinity.

Disinfection (Coliform) Evaluation:

Heating is commonly used for disinfection, pasteurization or to control the growth of microorganisms. The bacterial response to increasing temperature is more or less linear, following the Arrhenius plot until the temperature reaches about 70 degrees C, at which point the DNA begins to uncoil and protein denaturation takes place. Samples heated conductively were compared to those receiving microwave radiation to determine if any special microwave effects that enhanced microorganism kill could be ascertained.

Prior researchers have reported differences between microwave treatment and conventional heat treatment studies. Yaghmaee and Durance (2005), studying the effect of 2450 MHz microwave radiation under vacuum on survival and injury of E. coli in bacterial suspensions, reported that the impact of temperature on E. coli destruction was different when microwaves were the medium of heat transfer, which suggests the existence of factors other than heat that contribute to the lethal effect of microwaves. Vacuum was used to control the boiling point of water and to maintain temperature in the bacterial suspensions at specified levels (49–64°C).

Sergio (2006) conducted work to assess whether better pathogen inactivation occurs following microwave radiation after initial disinfection at temperatures of 60 to 65 degrees C, and reported that microwaved digested sludge achieved better bacterial inactivation than conventionally heated sludge. Sergio attributed this to the rapid thermal stratification of the sludge matrix induced by the preferential adsorption of the microwave energy by the surface of the sludge samples; in other words, the large fractions of the bacterial mass were experiencing much higher temperatures than 60 to 65 degrees.

The results obtained in our study, similar to prior work, showed lethal effects at temperatures exceeding 65 degrees C; although, as shown in Figure 49 and Table 3, no differences between samples receiving microwave radiation versus conduction heating were observed; coliform kill appeared to be solely the result of high temperature. Still, the times to reach lethal temperatures were achieved over 20 times faster when microwave was applied as opposed to convective heating.

VI. Processing and Economic Considerations

Wastewater treatment plant sludge, particularly non-polymer treated slurry sludge, that is exposed to microwave radiation exhibited improved dewaterability and dissolution of COD, total solids and volatile solids. In addition, microwave radiation was observed to disinfect wastewater sludge. Nevertheless, the question remains as to whether the deployment of a microwave application system in a wastewater treatment facility is a cost effective strategy. A conceptual design of a microwave system that could be used for such an application is described in this section. The section is divided into four subsections. The first provides the design basis for locating a system within a treatment facility. The second provides the conceptual design of the system. The third provides sizing considerations. And the fourth presents a cost and energy analysis.

Microwave Applicator Location

Sludge is generated from the primary and secondary treatment processes of most wastewater treatment plants. In primary treatment the settleable and floatable solids are removed from the wastewater stream. In secondary treatment the soluble and biodegradable organic material are removed.

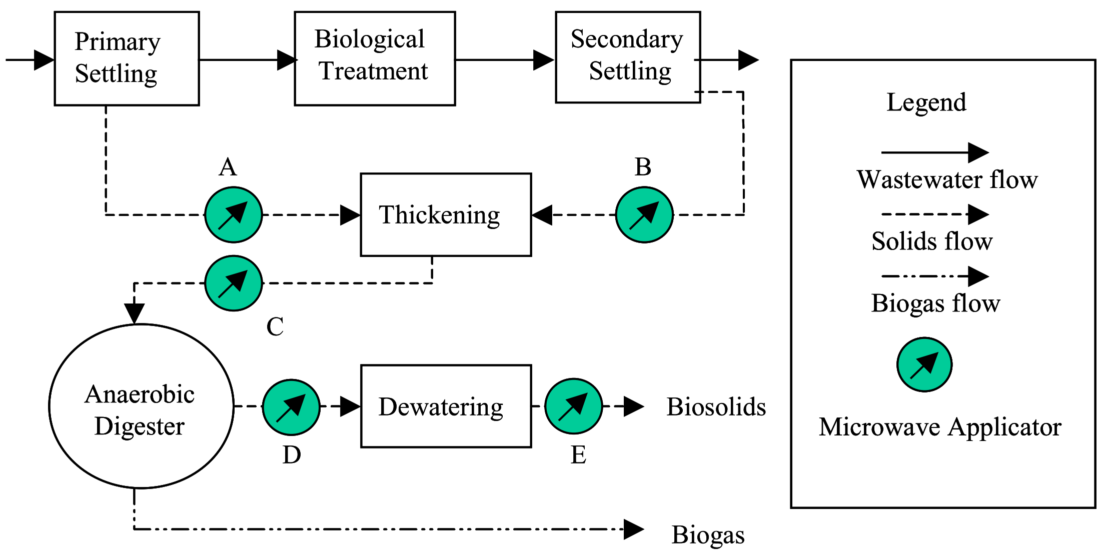


Figure 50. Potential Microwave Application Locations

Sludge generated from the primary and secondary processes is concentrated in a thickening tank, and then often pumped to an anaerobic digester.[1,2,3] Following anaerobic digestion the sludge is dewatered.[4] A flow schematic of a wastewater treatment process, along with potential locations for a microwave applicator, is shown in Figure 50. Combined, primary and secondary sludge (Figure 50, A and B) generally contain no more than 4% solids.[5] Thickened sludge (Figure 50, C) typically contains between 4% to 6% solids. Post-digestion biosolids (Figure 50, D) typically contain between 3% and 8 % solids.

[1] The simplest method is gravity thickening (i.e., sedimentation). Thickening can also be performed using flotation, belts, rotating drums, and centrifuges.

[2] Alternatively, in smaller facilities the sludge may be treated aerobically.

[3] For optimal performance, anaerobic digesters must be maintained between 95 to 100 degrees Fahrenheit.

[4] Drying beds or lagoons are the simplest dewatering processes. Dewatering can also be performed using mechanical equipment such as filter presses, vacuum filters, and centrifuges.

[5] Primary sludge typically contains 5-to-8% solids; fixed film sludge 3-to-10%; and activated (slurry) sludge from 0.5-to-2%.

Polymer-treated, mechanically-dewatered solids (Figure 50, E) typically contain between 20% and 45% solids.[1]

Practically, the energy requirements and corresponding size of a microwave applicator will be heavily dependent on the quantity of sludge requiring treatment, the solids/moisture content of the sludge, and the design temperature of the system. Sludge having excess moisture will require additional energy, and if temperatures are raised above the boiling point of water, the heat of vaporization will impose a significant energy penalty on the process. While pressurization is an option, the introduction of high-pressure microwave applicator would be an extremely costly process.

Location E was selected as the most practical design location for several reasons:

1. The solids contents at this location are well over five times higher than any other location, which would significantly reduce the applicator energy requirements and subsequently, the size of the microwave required to process the sludge.
2. Since disinfection was selected as the process with the maximum potential benefit from microwave application, and in addition to the above, the back-of-plant location is the most practical.
3. The limited apparent benefits of using microwave energy for dewatering or for the dissolution of organic matter to enhance biogas recovery did not justify consideration of other locations.

Microwave Applicator Design

A modular microwave system designed to process the estimated sludge throughput is proposed. Figure 51 is a photograph of a modular system that was manufactured by Thermex-Thermatron, Inc.; each module is an oven is capable of applying 30 kW, 75 kW or 100 kW., and is connected to the others by a continuous conveyor system. An isometric schematic of the conveyor-module system is shown in Figure 52.

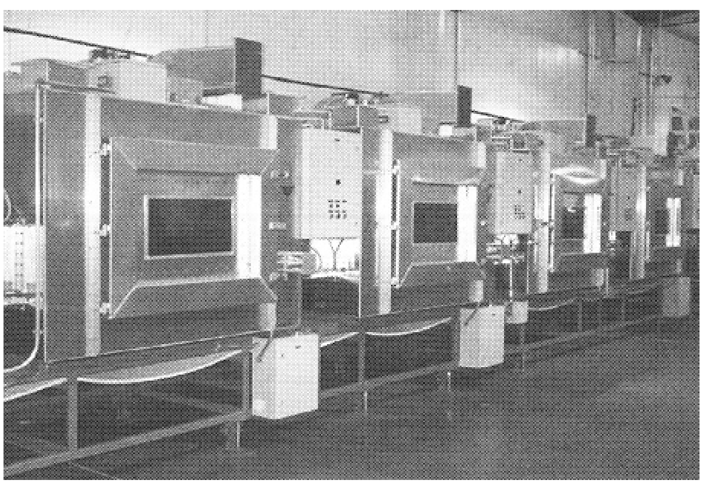


Figure 51. Modular Conveyor Oven

Conventional microwave ovens are compact and operate at 2450 MHz with low-power (600-1500 Watts). In most cases, industrial microwaves operate at 915 MHz with high power (100 kilowatts). There are several reasons to use a 915 MHz microwave in an industrial environment. First, the efficiency of the 915 MHz (100 kW magnetron) is 88%, as opposed to the 2450 MHz oven (60%). Second, a 100 kW, 915 MHz magnetron is about 50% of the price of seven 15 kW, 2450 MHz magnetrons. Finally, the penetration depth of 915 MHz magnetrons is about three times greater than a 2450 MHz magnetron.

[1] At 20 - 25% solids, sludge behaves like a fluid; up to 35%, a "cake"; up to 60-65%, a solid; up to 80%, granule formation begins; and above 80%, a fine powder.

Microwave Applicator Sizing

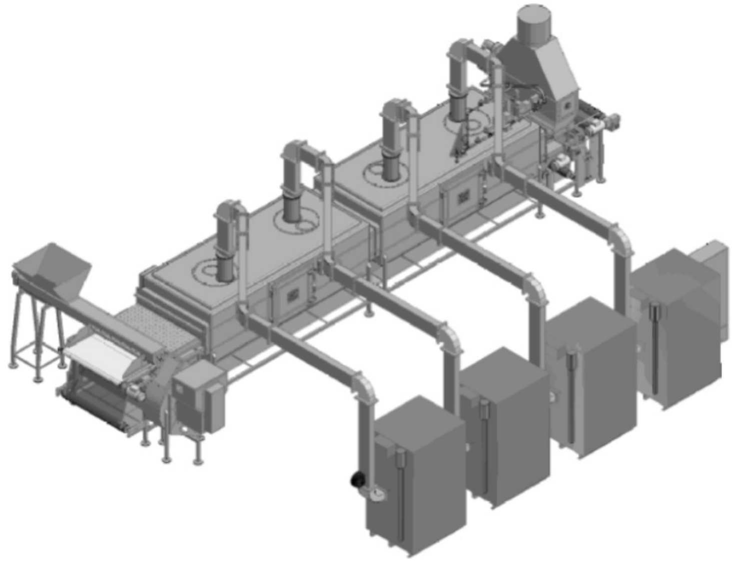


Figure 52. Schematic Modular Conveyor Oven

Solids Generation

As a general rule of thumb, the quantity of dry solids generated per million gallons of wastewater treated is one ton. Assuming a 20% solids content, the total (wet) solids input into a microwave applicator situated at Location E would be five tons per day for a one mgd plant.[1]

Applicator Mass Throughput Rates

For applicator sizing purposes, a 1, 5 and 10 mgd facility were considered. Facilities of these sizes would generate approximately 5, 25 and 50 tpd of wet solids, respectively. Based on a 20 hour operating day, the applicator would be sized to process 500, 2500 and 5000 pounds per hour. The design mass throughput rates are listed in Table 5.

Volumetric Throughput Rates

Assuming sludge weighs 60 lb per ft^3, the conveyer systems would be designed to transport approximately 8.3, 41.7 and 83.3 ft^3 per hour, respectively. The design volumetric throughput rates are also listed in Table 5.

Table 5. Design Throughput Rates

Treatment Facility Size (mgd)	Sludge Quantities (tpd)	Mass Throughput Rate (lb per h)	Volumetric Throughput Rate (ft^3 per h)
1	5	500	8.3
5	25	2500	41.7
10	50	5000	83.3

Conveyor Sizing

The maximum conveyor length would not exceed 60 feet, would be three feet in width, and would be designed to carry three inches of sludge. Belt speeds were assumed at 12, 56 and 112 feet per hour, respectively, for the 500, 2500 and 5000 pounds per hour throughput rates. These design assumptions results in retention times of one hour, one hour and 30 minutes, respectively.

[1]Microwave processing of sludge at locations A, B,C or D would result in mass throughput rates in the range of 5-to-20 times those projected at Location E; and would be problematic as well as energy intensive.

Table 6. Conveyor Design Conditions
(Conveyor Width = 3 ft; Bed Thickness = 3 inches)

Mass Throughput Rate (lb per h)	Volumetric Throughput Rate (ft^3 per h)	Belt Speed (ft per h)	Conveyor Length (ft)	Retention Time (h)
500	8.3	12	12	1
2500	41.7	56	56	1
5000	83.3	112	56	0.5

Energy Requirements

Projected energy requirements were based on the following assumptions: the sludge bed temperature is increased from 65 degrees F to 176 degrees F,[1] the sludge moisture content is 80%, the specific heat of water is one (1) Btu per pound per degree F, and line losses are 33%. The projected energy requirements are 24, 122 and 244 kwh for the 500, 2500 and 5000 pound per hour systems, respectively.

Table 7. Projected Energy Requirements[1]

Mass Throughput Rate (lb per h)	Temperature Rise (deg F)	Energy Use (Btu)	Energy Use (kwh)	Energy Use (kwh with 1/3 rd line loss)
500	111	55500	16	24
2500	111	277500	81	122
5000	111	555000	163	244
1. Based on the heat transfer equation: $Q= mc\Delta T$				

Power Requirements

Based on the projected energy requirements, power requirements were calculated for the required retention times. The energy requirements are presented in Table 8.

Table 8. Power Requirements

Mass Throughput Rate (lb per h)	Energy Projections (kwh)	Retention Time (h)	Power Needs (kW)
500	24	1	24
2500	122	1	122
5000	244	0.5	458

Generator Sizing

Industrial microwave generators come in conventional sizes of 15, 30, 75 and 100 kW. Based on the calculated power requirements, the number of generators (and oven modules) for each throughput design were calculated; as shown in Table 9.

Table 9. Generator Sizing

Mass Throughput Rate (lb per h)	Power Needs (kW)	No. of Generators	Generator Size (kW)
500	24	1	30
2500	122	2	75
5000	458	5	100

[1] Note that 176 degrees F (80 degrees C) is a relatively high disinfection temperature and should result in effective pathogen inactivation. Prior studies have suggested that microwave exposure can result in longer periods of inactivation than conventional heating (Sergio 2006). Further studies are needed to confirm these results.

Microwave Applicator Costs and Energy Use

For costing purposes, estimates for the following components were gathered:

1. Microwave Generator
2. Waveguide
3. Oven
4. Conveyor

An itemized list of the capital costs for each component is presented in Table 9.

Table 9. Capital Cost Projections

System Component	Design Processing Rate = 500 lb/h	Design Processing Rate = 2500 lb/h	Design Processing Rate = 5000 lb/h
Generator	$75,000[1]	$270,000[2]	$800,000[3]
Waveguide	$25,000	$50,000	$125,000
Oven Section	$30,000	$60,000	$150,000
Conveyor and Drives	$15,000	$30,000	$75,000
Subtotal	$145,000	$410,000	$1,150,000
Contingency (25%)	$36,000	$102,000	$287,500
Total Installed Cost	$181,000	$512,000	$1,437,500

1. Based on one, 30 kW generator at $75,000.
2. Based on two, 75 kW generators at $135,000 each.
3. Based on five, 100 kW generators at $160,000 each.

Annual operating costs and assumptions are presented in Table 10. Projected energy requirements for each the three systems are 180,000, 890,000 and 1,178,000 kwh per year, based on the energy requirements outlined in Table 7.

Table 10. Annual Operating Cost Projections

Cost Items	Design Processing Rate = 500 lb/h	Design Processing Rate = 2500 lb/h	Design Processing Rate = 5000 lb/h
Labor Costs[1]	$13,000	$13,000	$13,000
Maintenance Costs[2]	$18,000	$51,000	$144,000
Energy Costs[3]	$18,000	$89,000	$178,000
Subtotal Annual Cost	$49,000	$153,000	$335,000
Contingency (25%)	$12,000	$38,000	$84,000
Total Annual Cost	$61,000	$191,000	$419,000

1. Based on one operator, one h per day, 365 days per y at $50 per h
2. Based on 10% of installed capital cost.
3. Based on energy use (see Table 7) for 20 h per day and 365 days per yr at $0.10 per kwh.

Assuming a system with a 10-year lifespan, and financing at 5% per year, the total amortized capital costs are approximately $23,000, $66,000, and $186,000, respectively, for the 1-mgd, 5-mgd and 10-mgd plants. The total annual amortized capital and operating costs are approximately $84,000, $257,000 and $605,000, respectively.

Table 11. Amortized Costs

Cost Items	1 mgd Plant	5 mgd Plant	10 mgd Plant
Capital Cost[1]	$181,000	$512,000	$1,437,000
Amortized Capital Cost[2]	$23,000	$66,000	$186,000
Annual Operating Cost[3]	$61,000	$191,000	$419,000
Total Amortized Cost[4]	$84,000	$257,000	$605,000

1 Based on capital cost projections presented in Table 9.
2. Based on amortizing capital cost at 5% interest for 10 years
3. Based on annual operating cost presented in Table 10.
4. Sum of amortized capital and annual operating cost

The resulting microwave applicator cost per wet ton of sludge processed, are presented in Table 12. Costs vary from $28 to $46 per ton.

Table 12. Sludge Processing Cost ($/ton)

Cost Items	1 mgd Plant	5 mgd Plant	10 mgd Plant
Total Amortized Cost[1]	$84,000	$257,000	$605,000
Annual Tons of Sludge Processed Capital Cost[2]	1825	9125	18250
Cost per Ton[3]	$46	$28	$33

1 See Table 11.
2. Based on 5, 25, and 50 tpd of sludge, 365 days per y.
3. Total Amortized Cost/Annual Tons of Sludge

VII. Conclusions and Recommendations

Despite improved dewaterability and enhanced dissolution of the organic and inorganic fraction of the wastewater treatment plant sludge when exposed to microwave radiation, microwave treatment of raw or anaerobically digested sludge prior to dewatering is not a cost effective treatment strategy.

Nevertheless, disinfection of sludge using microwave energy to produce a Class A biosolids material at small to medium sized wastewater treatment facilities is a practical option for consideration, if transportation and disposal costs exceed $50 per ton and if a biosolids market is available.

It is recommended that small wastewater treatment facilities, or perhaps farms that generate large quantities of animal waste, that do not have low cost sludge disposal options, consider the possibility of microwave disinfection as a tertiary sludge treatment process to convert the sludge to a higher end product biosolid fertilizer.

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Table A-1. Dewaterability Analysis without Polymer (Volume Recovered in Buchner Funnel Test –ml.)

a) Fixed film

Time (min)		100% Power			75% Power			50% Power		
		watt-h			watt-h			Watt-h		
	Control	4.44	8.89	17.78	5.93	11.85	17.78	5.93	11.85	17.78
Milliliters Recovered										
15	16	17	18	18	16	16	18	16	20	20
30	18.5	20	21	20	18	19.5	21	18	22	23
45	20.5	22.5	22.5	23	21.5	21	23	20	24	25
60	22	23.5	24.5	24.5	22.5	22.5	25	21.5	26.5	26.5
90	24	26	25.5	26.5	24	25	26	23	28.5	28.5
120	26	28	27.5	28.5	26	27	28	24.5	30	30
150	27.5	29.5	28.5	30	28	28.5	29.5	25.5	31	31
180	28.5	30.5	29.5	31	29.5	29.5	30.5	26.5	32	32
210	29.5	32	30.5	32	30.5	30.5	31.5	27.5	33	33
240	30.5	33	31.25	33	31.5	31.5	32.25	28.5	34	33.75
270	31.5	34	32	34	32.5	32.25	32.75	29.5	34.75	34.5
300	32.5	34.75	33	35	33.5	33	33.5	30.5	35.5	35.25

b)Slurry

Time (min)		100% Power			75% Power			50% Power		
		watt-h			watt-h			Watt-h		
	Control	4.44	8.89	17.78	5.93	11.85	17.78	5.93	11.85	17.78
	Milliliters Recovered									
15	15	16	17	18	17	18	20	17	18	20
30	18	19	21.5	23	20	22	24	20	22	24
45	19	21	24	25.5	23	24.5	26.5	22.5	24.5	26.5
60	21.5	23.5	26	27.5	25	27	28.5	24.5	26.5	28.5
90	24.5	26	29	31	28	30	32	28	29.5	32
120	26.5	28	31	34	30	32.5	34	30.5	32	34
150	29	30	33	36	32	34.5	36.5	32.5	34	36.5
180	30.5	32	35	37.5	34	36	38.5	34	36	38.5
210	32	34	37	39.5	36	38	40	35.5	37	40
240	34	35.5	39	41	37	39.5	41	36.5	39	41
270	35	36.5	40	42	39	40.5	42	37.5	40	42
300	36	38	41	42.75	40	41.5	43	38.5	41	43

Table A-2. Dewaterability Analysis with Polymer (Volume Recovered in Buchner Funnel Test –ml.)

a) Fixed film

Time (min)		100% Power			75% Power			50% Power		
		watt-h			watt-h			watt-h		
	Control	4.44	8.89	17.78	5.93	11.85	17.78	5.93	11.85	17.78
	Milliliters Recovered									
15	90.5	84	85	86.5	90	88	88	92	89.5	89.5
30	90.5	84	86.5	86.5	91.5	88.5	88.5	92	89.5	89.5
45	90.5	84.5	87	86.5	92.5	88.5	88.5	92	89.5	89.5
60	90.5	84.5	87.25	86.5	92.5	88.5	88.5	92	89.5	89.5
90	90.5	84.5	87.25	86.5	92.5	88.5	88.5	92	89.5	89.5
120	90.5	84.5	88	86.5	92.5	88.5	88.5	92	89.5	89.5
150	90.5	84.5	88	86.5	92.5	88.5	88.5	92	89.5	89.5
180	90.5	84.5	88	86.5	92.5	88.5	88.5	92	89.5	89.5
210	90.5	84.5	88	86.5	92.5	88.5	88.5	92	89.5	89.5
240	90.5	84.5	88	86.5	92.5	88.5	88.5	92	89.5	89.5
270	90.5	84.5	88	86.5	92.5	88.5	88.5	92	89.5	89.5
300	90.5	84.5	88	86.5	92.5	88.5	88.5	92	89.5	89.5

b)Slurry

Time (min)		100%			75%			50%		
		watt-h			watt-h			watt-h		
	Control	4.44	8.89	17.78	5.93	11.85	17.78	5.93	11.85	17.78
	Milliliters Recovered									
15	33.5	47	47	47	43	46	40	36	33	37
30	53.5	54.5	54	54.5	49	50	45	41	44	42.5
45	58	59	60	58	55	56	49	46.5	48	46
60	63.5	63	63.5	62.5	59.5	58	52.5	50	51	49
90	69	68	68.5	66.5	64.5	63.5	57.5	56	57	54
120	72	71	71.5	69.5	68.5	67	61.5	60	60.5	57.5
150	74	74	74	71.5	71.5	70	65	64	63.5	61
180	76	75.5	76	73	73.5	72	67.5	67	66	63
210	77	76.5	77	74.5	75	73.5	69	69	68.5	65
240	78	77.5	78	75.25	76	74.5	71	71	70.5	67
270	79	78.5	79	75.5	77	75.5	72	73	71.5	68.5
300	80	79.5	80	76	78	76.5	73	74.5	72.25	69.5

Table A-3. Supernatant COD Analysis without Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (mg/L)	Slurry (mg/L)
	Control	2560	1424
100%	4.44	2732	1508
	8.89	2636	1487
	17.78	3611	1827
75%	5.93	3353	1511
	11.85	3395	1717
	17.78	3687	1882
50%	5.93	2580	1693
	11.85	3069	1774
	17.78	3700	2244

Table A-4. Supernatant COD Analysis with Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (mg/L)	Slurry (mg/L)
	Control	874	724
100%	4.44	803	726
	8.89	806	782
	17.78	917	1026
75%	5.93	848	787
	11.85	808	965
	17.78	855	1339
50%	5.93	850	932
	11.85	813	1148
	17.78	869	1331

Table A-5. Dissolved COD Analysis without Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (mg/L)	Slurry (mg/L)
	Control	844	702
100%	4.44	854	763
	8.89	1179	855
	17.78	1591	1254
75%	5.93	923	812
	11.85	1092	1119
	17.78	1514	1341
50%	5.93	956	982
	11.85	1086	1136
	17.78	1597	1730

Table A-6. Dissolved COD Analysis with Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (mg/L)	Slurry (mg/L)
	Control	549	522
100%	4.44	550	529
	8.89	553	582
	17.78	657	759
75%	5.93	566	603
	11.85	607	679
	17.78	641	1112
50%	5.93	581	717
	11.85	607	915
	17.78	657	1135

Table A-7. Total Volatile Solids Analysis without Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (%)	Slurry (%)
	Control	0.1736	0.0999
100%	4.44	0.1788	0.1020
	8.89	0.1756	0.1050
	17.78	0.2190	0.1262
75%	5.93	0.1860	0.1039
	11.85	0.1890	0.1197
	17.78	0.2141	0.1301
50%	5.93	0.1793	0.1154
	11.85	0.1979	0.1232
	17.78	0.2261	0.1444

Table A-8. Total Volatile Solids Analysis with Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (%)	Slurry (%)
	Control	0.0620	0.0568
100%	4.44	0.0624	0.0552
	8.89	0.0613	0.061
	17.78	0.0642	0.0732
75%	5.93	0.0630	0.0616
	11.85	0.0610	0.0685
	17.78	0.0637	0.091
50%	5.93	0.0639	0.068
	11.85	0.0641	0.0796
	17.78	0.0657	0.0914

Table A-9. Dissolved Solids Analysis without Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (%)	Slurry (%)
	Control	0.1427	0.1560
100%	4.44	0.1522	0.1629
	8.89	0.1510	0.1690
	17.78	0.2125	0.1950
75%	5.93	0.1390	0.1646
	11.85	0.1650	0.1866
	17.78	0.1911	0.2001
50%	5.93	0.1439	0.1798
	11.85	0.1553	0.1845
	17.78	0.1757	0.2170

Table A-10. Dissolved Solids Analysis with Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (%)	Slurry (%)
	Control	0.1239	0.1578
100%	4.44	0.1266	0.1609
	8.89	0.1258	0.1676
	17.78	0.1273	0.1646
75%	5.93	0.1247	0.1611
	11.85	0.1248	0.1587
	17.78	0.1247	0.1799
50%	5.93	0.1260	0.1633
	11.85	0.1225	0.1747
	17.78	0.1232	0.1863

Table A-11. Dissolved Volatile Solids Analysis without Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (%)	Slurry (%)
	Control	0.0613	0.0517
100%	4.44	0.0669	0.0591
	8.89	0.0697	0.0641
	17.78	0.1149	0.0877
75%	5.93	0.0604	0.0606
	11.85	0.0769	0.0815
	17.78	0.1007	0.0967
50%	5.93	0.0614	0.0760
	11.85	0.0780	0.0797
	17.78	0.1060	0.1144

Table A-12. Dissolved Volatile Solids Analysis with Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (%)	Slurry (%)
	Control	0.0474	0.0468
100%	4.44	0.0475	0.0481
	8.89	0.0494	0.0538
	17.78	0.0556	0.0596
75%	5.93	0.0471	0.0526
	11.85	0.0513	0.054
	17.78	0.0520	0.0748
50%	5.93	0.0487	0.0555
	11.85	0.0491	0.0678
	17.78	0.0526	0.0811

Table A-13. pH Analysis without Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film	Slurry
	Control	8.1	7.91
100%	4.44	7.99	7.88
	8.89	8.01	7.94
	17.78	8.07	7.82
75%	5.93	8.1	7.9
	11.85	8.13	7.85
	17.78	8.16	7.85
50%	5.93	8.09	7.77
	11.85	8.18	7.82
	17.78	8.22	7.88

Table A-14. pH Analysis with Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film	Slurry
	Control	7.67	7.4
100%	4.44	7.5	7.41
	8.89	7.57	7.48
	17.78	7.75	7.44
75%	5.93	7.58	7.55
	11.85	7.71	7.5
	17.78	7.87	7.58
50%	5.93	7.73	7.53
	11.85	7.77	7.56
	17.78	7.89	7.59

Table A-15. Total Alkalinity Analysis without Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (mg/L as $CaCO_3$)	Slurry (mg/L as $CaCO_3$)
	Control	4000	2280
100%	4.44	4080	2260
	8.89	3880	2360
	17.78	3740	2240
75%	5.93	4000	2340
	11.85	4140	2260
	17.78	3840	2320
50%	5.93	4000	2200
	11.85	3900	2340
	17.78	3580	2220

Table A-16. Total Alkalinity Analysis with Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (mg/L as $CaCO_3$)	Slurry (mg/L as $CaCO_3$)
	Control	2840	2240
100%	4.44	2920	2200
	8.89	2960	2200
	17.78	2780	2180
75%	5.93	2880	2200
	11.85	2760	2220
	17.78	2820	2240
50%	5.93	2800	2220
	11.85	2800	2240
	17.78	2740	2240

Table A-17. Volatile Acids Analysis without Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (mg/L as CH_3COOH)	Slurry (mg/L as CH_3COOH)
	Control	110.4	99.36
100%	4.44	123.74	74.52
	8.89	108.10	77.28
	17.78	101.20	105.34
75%	5.93	120.52	82.80
	11.85	127.42	109.94
	17.78	134.32	128.80
50%	5.93	115.46	101.20
	11.85	132.94	92.92
	17.78	99.82	120.98

Table A-18. Volatile Acids Analysis with Polymer

Power level (%)	Microwave Dosage (Watt-hour)	Fixed Film (mg/L as CH_3COOH)	Slurry (mg/L as CH_3COOH)
	Control	106.72	130.64
100%	4.44	120.06	126.5
	8.89	134.32	126.5
	17.78	128.34	121.9
75%	5.93	136.16	126.5
	11.85	128.8	126.04
	17.78	117.30	120.52
50%	5.93	92.46	120.98
	11.85	102.58	115.46
	17.78	98.90	110.4

Table A-19. Disinfection Effects: Microwaved and Conduction Heating

Sample ID		Counting (count/100 mL)
Fixed Film w/o Polymer (count/10 mL)	Control	3.1×10^{6}
	Microwaved	0
	Conduction Heating	0
Fixed Film with Polymer (count/10 mL)	Control	2.6×10^{6}
	Microwaved	0
	Conduction Heating	0

Table A-20. Temperature Effects: Microwave vs Conduction Heating Dewatering - Slurry w/o Polymer

		Microwaved			Conduction Heating		
Time (sec)	Control 42.86°F	7 seconds 83.71°F	11 seconds 113.11°F	14 seconds 136.49°F	3 minutes 82.58°F	4 minutes 111.52°F	5 minutes 137.23°F
30	32	38	39	44	36	38	38
60	39	45	47	52	42	44	46
90	44	51	52	57	46	48	52
120	47	54	56	60	49	52	56
180	52	60	63	64	54	56	60
240	56	64	68	68	58	60	64
300	59	68	72	72	62	62	68

Table A-21.Temperature Effects: Microwave vs Conduction Heating Supernatant COD - Slurry w/o Polymer

	Temperature	Supernatant COD (mg/L)
Control	42.86 ^{o}F	1530
Microwaved	83.71^{o}F	1812
	113.11^{o}F	2063
	136.49^{o}F	2469
Conduction Heating	82.58^{o}F	1697
	111.52^{o}F	1943
	137.23^{o}F	2133

Table A-22.Temperature Effects: Microwave vs Conduction Heating Dissolved COD - Slurry w/o Polymer

	Temperature	Dissolved COD (mg/L)
Control	42.86 ^{o}F	781
Microwaved	83.71^{o}F	879
	113.11^{o}F	985
	136.49^{o}F	1283
Conduction Heating	82.58^{o}F	855
	111.52^{o}F	899
	137.23^{o}F	1102

Table A-23.Temperature Effects: Microwave vs Conduction Dissolved Solids - Slurry w/o Polymer

	Temperature	Dissolved Solids (%)
Control	42.86 ^oF	0.1779
Microwaved	83.71^oF	0.1864
	113.11^oF	0.1932
	136.49^oF	0.2110
Conduction Heating	82.58^oF	0.1842
	111.52^oF	0.1900
	137.23^oF	0.2022

Table A-24.Temperature Effects: Microwave vs Conduction Dissolved Volatile Solids - Slurry w/o Polymer

	Temperature	Dissolved Volatile Solids (%)
Control	42.86 ^oF	0.0724
Microwaved	83.71^oF	0.0817
	113.11^oF	0.0872
	136.49^oF	0.1067
Conduction Heating	82.58^oF	0.0802
	111.52^oF	0.0867
	137.23^oF	0.0986

Table A-25.Temperature Effects: Microwave vs Conduction Total Volatile Solids - Slurry w/o Polymer

	Temperature	Total Volatile Solids (%)
Control	42.86 ^{o}F	0.1266
Microwaved	83.71^{o}F	0.1390
	113.11^{o}F	0.1432
	136.49^{o}F	0.1757
Conduction Heating	82.58^{o}F	0.1309
	111.52^{o}F	0.1449
	137.23^{o}F	0.1537

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Feasibility of Using Microwave Radiation to Facilitate the Dewatering, Anaerobic Digestion and Disinfection of Wastewater Treatment Plant Sludge

April 2011

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