FRASER RIVER ACTION PLAN

City of Prince George Radio Frequency Treatment of Partially Digested/ Dewatered Biosolids Final Report

DOE FRAP 1997-26

Environment Canada Environnement Canada

CITY OF PRINCE GEORGE:
RADIO FREQUENCY TREATMENT OF PARTIALLY DIGESTED/DEWATERED BIOSOLIDS
FINAL REPORT

DOE FRAP 1997-26

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CITY OF PRINCE GEORGE
RADIO FREQUENCY
TREATMENT OF PARTIALLY DIGESTED/DEWATERED BIOSOLIDS
FINAL REPORT

SUMMARY

The City of Prince George recently proposed to investigate the possibility of applying radio frequency (RF) technology to partially digested/dewatered biosolids from domestic wastewater treatment plants, in order to dewater the biosolids to the 40% to 50% liquid content range, and to improve the quality of the product by reducing pathogen levels. The purpose of the study was to evaluate the feasibility of applying dielectric (RF) drying technology to the sterilization and dewatering of anaerobically digested and partially dewatered biosolids from domestic wastewater treatment plants.

The University of British Columbia Faculty of Forestry owns a pilot-scale Radio Frequency/Vacuum (RF/V) kiln, which was recently developed for drying lumber in the forestry industry. Following preliminary discussions with Dayton & Knight Ltd., the UBC Faculty of Forestry agreed to assist in carrying out drying/sterilization trials on biosolids from the Prince George Wastewater Treatment Centre.

The study was divided into three phases. Phase 1 was to include two drying/sterilization trials, Phase 2 was to include three trials, and Phase 3 was to include four trials. The results were reviewed at the conclusion of each phase, to determine the advisability of proceeding with the work, in light of technical and budgetary constraints.

The study results showed that radio frequency (RF) sterilization of municipal biosolids is technically feasible. The time-temperature requirements for pathogen destruction of 20 minutes at greater than 70^{o}C, 30 minutes at 70^{o}C or 57 minutes at 68^{o}C can be met using RF technology.

Radio frequency/vacuum (RF/V) dewatering of biosolids was also shown to be technically feasible. The maximum degree of dewatering obtained in this study was approximately 35% solids by weight in the treated biosolids, compared to an initial solids content of approximately 17% by weight in the untreated biosolids.

Monitoring of energy inputs showed that sterilization and drying of municipal biosolids using RF/V technology requires higher energy inputs than natural gas drying. The RF/V kiln used in this study was designed for treating solid lumber; the available equipment proved to be inefficient for treating loosely packed biosolids, mainly due to shrinking of the biosolids during treatment, which increased the air gap between the electrode plates and the solids, and caused inefficient energy transfer to the biosolids. The

study was therefore terminated after the first two trials of Phase 2. The energy requirements for RF/V sterilization and drying of municipal biosolids could be substantially reduced over those observed in this study, if an RF/V kiln designed specifically to treat loosely packed solids were used. This possible next phase of the work is outside the scope of this present assignment.

In light of the study results, it was recommended that the City of Prince George continue with their existing biosolids handling program, using the solids dewatered in the belt filter presses. If the City wishes to dewater the treated biosolids beyond the 17% to 20% total solids typical of the solids leaving the belt filter presses, natural gas drying should be investigated. Waste methane gas from the anaerobic digesters might be used as a supplemental fuel, to reduce operating costs. If the City wishes to expand options for biosolids use by increasing the quality of the end product through pasteurization, digestion options which include high temperature treatment (e.g., thermophilic anaerobic digestion and pre-pasteurization) should be considered.

VILLE DE PRINCE GEORGE
RADIOFRÉQUENCE
TRAITEMENT DE BIOSOLIDES PARTIELLEMENT DIGÉRÉS OU DÉSHYDRATÉS
RAPPORT FINAL

RÉSUMÉ

La ville de Prince George a récemment proposé d'étudier la possibilité d'appliquer la technologie des radiofréquences (RF) aux biosolides partiellement digérés ou déshydratés dans les usines d'épuration des eaux usées domestiques afin d'extraire 40 % à 50 % du contenu liquide des biosolides et d'améliorer la qualité du produit en réduisant le nombre de bactéries pathogènes. Le but de l'étude était d'évaluer si la technique de séchage diélectrique (RF) pouvait être utilisée à l'étape de stérilisation et de déshydratation des biosolides digérés en anaérobiose et partiellement déshydratés des usines d'épuration des eaux usées.

Le département de Foresterie de l'Université de la Colombie-Britannique possède un séchoir sous vide à haute fréquence (Radio Frequency/Vaccum kiln) à échelle réduite, qui a été conçu récemment pour le séchage du bois d'oeuvre dans l'industrie forestière. Suite à des discussions exploratoires avec l'entreprise Dayton & Night Ltd., le département de Foresterie de UCB a accepté de procéder à des essais sur le séchage et la stérilisation des biosolides provenant de l'usine d'épuration des eaux usées de Prince George.

L'étude comprenait trois étapes. Au cours de la première étape, on allait procéder à deux essais de séchage et de stérilisation : trois essais au cours de la deuxième étape et à quatre essais à la dernière étape. Les résultats devaient être analysés à la fin de chaque étape pour évaluer la continuité des travaux, en tenant compte des contraintes techniques et budgétaires.

Les résultats de l'étude ont démontré l'efficacité de la technique RF dans la stérilisation des biosolides municipaux. À l'aide de cette technologie, on peut atteindre la plage thermique nécessaire à la destruction des pathogènes, soit 20 minutes à plus de 70 ºC, 30 minutes à 70 ºC ou 57 minutes à 68 ºC.

Cette technique s'est également révélée efficace à l'étape de déshydratation des biosolides. Au cours des travaux, le taux de déshydratation maximum obtenu à partir de biosolides traités correspondait environ à 35 % de matière solide, en poids, par rapport à un contenu solide initial d'environ 17 %, en poids, à partir de biosolides non traités.

L'analyse régulière des intrants énergétiques a démontré que la stérilisation et le séchage des biosolides municipaux à l'aide de la technologie RF/V exigent une demande en énergie plus grande que le séchage au gaz naturel. Le séchoir RF/V utilisé dans le cadre des

travaux d'étude a été conçu pour le bois d'oeuvre solide et il a été démontré qu'il était inefficace dans le traitement de biosolides détassés, surtout en raison du rétrécissement des biosolides au cours du traitement, ce qui entraînait une augmentation du volume d'air entre les plaques-électrodes et les solides, rendant ainsi inefficace le transfert d'énergie vers les biosolides. On a donc mis fin à l'étude après les deux premiers essais de la deuxième étape. La demande en énergie de la technique de stérilisation et de séchage RF/V des biosolides municipaux pourrait être sensiblement inférieure à celle observée au cours des travaux, si on utilisait un séchoir RF/V spécifiquement conçu pour traiter des solides détassés. Cette hypothèse ne sera toutefois pas vérifiée, car elle déborde le cadre des présents travaux.

À la lumière des résultats de l'étude, on a recommandé à la ville de Prince George de continuer d'utiliser les méthodes courantes de traitement des biosolides, en procédant à leur déshydratation à l'aide des filtres-presses. Si la Ville désire extraire des biosolides traités au-delà de 17 % à 20 % du contenu total moyen des solides passés dans les filtres-presses, il faudra envisager le séchage au gaz naturel. Les résidus de méthane provenant des digesteurs anaérobies pourraient être utilisés comme source d'énergie additionnelle afin de réduire les coûts d'opération. Si la Ville désire accroître l'utilisation des biosolides en obtenant un produit fini de qualité supérieure grâce à la pasteurisation, il faudra considérer diverses techniques de digestion à température élevée (p. ex., digestion anaérobie thermophile, prépasteurisation).

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TREATMENT OF PARTIALLY DIGESTED/DEWATERED BIOSOLIDS
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1.0 INTRODUCTION

The University of British Columbia (UBC) Faculty of Forestry is currently carrying out research work using dielectric (radio frequency) technology coupled with vacuum drying for lumber kiln drying. Pilot-scale work at UBC was followed by the development of a prototype full-scale facility for use by one of the sawmills in Vancouver, B.C., in 1994. The City of Prince George recently proposed to investigate the possibility of applying radio frequency (RF) technology to partially digested/dewatered biosolids from domestic wastewater treatment plants, in order to dewater the biosolids to the 40% to 50% liquid content range, and to improve the quality of the product by reducing pathogen levels.

Following initial discussions, the Fraser Pollution Abatement Office (FPA), the City of Prince George, and Dayton & Knight Ltd. contracted to work together to implement a pilot-scale research project for drying and sterilization of the biosolids produced by the belt filter presses at the Lansdowne Road Wastewater Treatment Centre at Prince George, B.C. The purpose of the study was to evaluate the feasibility of applying dielectric (RF) drying technology to the sterilization and dewatering of anaerobically digested and partially dewatered biosolids from domestic wastewater treatment plants. Prior to beginning the study, an on-line computer literature search was conducted, to determine if previous work had been carried out on RF treatment of municipal biosolids. No evidence of previous work in this area was found in the literature search.

Radio frequency heating is similar in some respects to microwave heating. In both technologies, electromagnetic waves are used to induce heating by causing a reversing electric field, which increases the kinetic energy of molecules and ions in the material being heated. Water with its polar molecules is susceptible to heating by this method, and RF and microwave technologies have applications in heating and drying of water-containing materials. Radio frequency heating is distinguished from microwave heating by its lower electromagnetic frequencies. In general, RF heating is done at frequencies between 1 MHz and 100 MHz, and microwave heating is done at frequencies between 300 MHz and 300 GHz. The longer wavelength of radio frequencies allows a greater depth of penetration into the material being dried, compared to the depth of penetration of microwaves.

Industrial applications of RF and microwave heating have increased in recent years, due to the advantages of these processes in some instances. Advantages of RF and microwave heating include uniform heating throughout the material, energy-efficiency, ease of process control, and relatively small space requirements.

The University of British Columbia Faculty of Forestry owns a pilot-scale Radio Frequency/Vacuum (RF/V) kiln, which was recently developed for drying lumber in the forestry industry. Following preliminary discussions with Dayton & Knight Ltd., the UBC Faculty of Forestry agreed to assist in carrying out drying/sterilization trials on biosolids from the Prince George Wastewater Treatment Centre. The UBC RF kiln was not available until late December, 1995, and the experimental work was begun on December 19, 1995.

The study was divided into three phases. Phase 1 was to include two drying/sterilization trials, Phase 2 was to include three trials, and Phase 3 was to include four trials. The results were reviewed at the conclusion of each phase, to determine the advisability of proceeding with the work, in light of technical and budgetary constraints.

2.0 OBJECTIVES

The study objectives were as follows:

- to carry out drying trials using the UBC RF pilot plant to evaluate the technical feasibility of drying the treated biosolids at the Lansdowne Wastewater Treatment Centre at Prince George from approximately 18% total solids by weight to 40% - 50% total solids by weight;

- to evaluate the destruction of pathogenic and/or indicator organisms during biosolids treatment in the RF pilot plant;

- to evaluate the quality of the condensate generated during the drying process;

- to compare the energy consumption of the RF process for biosolids drying to that of other biosolids dewatering processes.

3.0 MATERIALS AND METHODS

3.1 General

Experimental design, project scheduling, and project management were undertaken by Dayton & Knight Ltd., in consultation with the study participants. The UBC Faculty of Forestry contracted to carry out the drying trials, under the direction of Dr. Stavros Avramidis of the Faculty of Forestry. The RF kiln was operated by UBC staff, under the direction of Dr. Avramidis and Dr. Al Gibb of Dayton & Knight Ltd.

Samples of the treated biosolids from the belt filter presses at Prince George were collected in 20 L containers at the Lansdowne Road Treatment Centre by plant staff on Fridays, and shipped to arrive at UBC on Mondays. The samples were kept in refrigerated storage at UBC until use, usually the following day (Tuesdays). Before drying, samples were transferred to open-top plastic containers of the appropriate size for each test. The dimensions of the containers were determined to some extent by off-the-shelf availability. All of the containers were 200 mm to 250 mm wide, to approximately match the width of the RF kiln electrode plates. The height of the containers for each trial was chosen to match the desired vertical (adjustable) gap between the electrode plates. The containers were spaced evenly along the length of the electrodes.

The experimental work was evolutionary in nature, since a literature search turned up no previous work on RF or RF/V drying of municipal biosolids. Discussions were held with Dr. Avramidis of UBC and his staff prior to drafting the experimental plan, and the draft plan was reviewed by Dr. Avramidis and the study participants. Initially, the two controlled experimental variables to be evaluated were the time of sterilization/drying and the applied RF voltage. The response parameters of interest were the degree of drying (i.e., the percent reduction in the moisture content of the biosolids), the degree of sterilization (the reduction in

the number of pathogens and/or indicator organisms), and the total energy input required.

3.2 Description of the UBC Radio Frequency Pilot Plant

The RF/V laboratory kiln is located on the UBC campus, adjacent to the Wood Products Laboratory of the Faculty of Wood Science. The pilot plant uses radio waves at a fixed frequency of 13.56 MHz and an electrode voltage up to 5 kV to induce heating and evaporation of water contained in solid material. The use of radio frequencies is restricted by law; 13.56 MHz is one of three frequencies internationally approved for industrial and scientific use, and is the frequency commonly used in North America. Steam leaving the solid material is collected under vacuum and routed to a condenser. The purpose of the vacuum is to decrease the boiling temperature of water and improve the drying energy efficiency. The operating air pressure of the kiln under vacuum is 20-30 torr; at this pressure, the boiling point of water is approximately 20^{o}C to 30^{o}C, compared to 100^{o}C at atmospheric pressure. Further, the vacuum promotes rapid removal of water vapour from the kiln, and thereby increases the rate of water evaporation from the solids. Because of the necessity for maintaining a vacuum during drying, the pilot plant works on a batch feed system. The maximum volume of a single batch was approximately 0.22 cubic meters (0.3 m wide by 0.3 m high by 2.4 m long). The laboratory dryer includes fibre optic temperature probes to monitor the temperature of the material being dried.

The instrumentation associated with the UBC RF/V kiln produces time records of temperature, RF voltage input, amount of condensate collected, and kiln air pressure. An electrical meter is used to manually record the total power consumption of the kiln (see Photos 1 to 4).

3.3 Laboratory Testing

3.3.1 Bacteria

The category of treated biosolids with the least restrictions for recycling is designated Aretail grade.@ Draft criteria by B.C. Environment for pathogen destruction in retail grade biosolids with a total solids content of greater than 7% by weight specify minimum time/temperature

requirements of 57 minutes at 68^0 C, 30 minutes at 70^0 C, or 20 minutes at greater than 70^0 C (the biosolids leaving the belt filter presses at Prince George are typically about 18% total solids by weight). The B.C. Environment draft criteria further specify that retail grade biosolids shall have fecal coliforms less than 1000 most probable number (MPN) per gram dry solids, and salmonella less than 3 MPN per 4 grams dry solids.

The MPN confirmed test is required for bacterial testing of biosolids for recycling under the B.C. Draft Criteria. The MPN confirmed test takes 72 hours to produce results, while fecal coliform testing using the membrane filter technique (MF) takes only 24 hours to produce results. Further, fecal coliform analysis using the membrane filter technique is typically significantly cheaper than the MPN confirmed test. To increase the flexibility of the work schedule and to minimize the cost of analysis, some of the bacterial testing was done using the filter membrane technique; however, the MPN test was also carried out in parallel on common samples in some cases, to confirm the membrane filter results.

The biosolids tested in this study were subjected to extensive mixing and stabilization in the anaerobic digesters at Prince George, before being dewatered in the belt filter presses. However, the biosolids could not be assumed to be completely homogeneous in nature, and the samples taken from each batch of biosolids were relatively small in volume. Therefore, to assess the random variation associated with the sampling procedure, three replicate samples were taken from each batch before treatment and immediately after treatment, and each of the replicates was tested separately for fecal coliforms and total solids.

The B.C. Environment draft criteria state that biosolids samples must be tested for pathogens at least 21 days after required temperatures are achieved, to check for re-growth. Therefore, treated samples were tested for fecal coliforms 21 days after removal from the kiln, as well as immediately after removal from the kiln. To reduce analysis costs, bacterial testing for re-growth was conducted on composite samples, rather than on each individual replicate. Each composite was made up of equal portions of each of the three individual replicate samples associated with a particular treatment trial. Each composite sample was allowed to stand at room temperature for 21 days before testing for fecal coliforms.

In a full-scale process, the condensate from the RF/V kiln would likely be recycled to the liquid treatment train at the plant. Therefore, a sample of the condensate collected from each drying trial was analyzed for BOD and COD, to estimate the increases in organic loading to the liquid train resulting from RF drying/sterilization of the biosolids.

Wide variations in the results of bacterial testing for fecal coliforms and salmonella are often observed in testing samples of biosolids. To assess the random variation in laboratory testing results, a quality assurance/quality control (QA/QC) program was included.

For QA/QC, each sample was divided into two approximately equal portions, each portion was analyzed by a different laboratory, and the results were compared. A 1990 study of thermophilic digestion of municipal biosolids by Dayton & Knight Ltd. for Supply and Services Canada (Supply and Services Contract KE405-8-6575/01-SE UP-D8-010) included a comprehensive QA/QC program, where randomly-selected individual samples were divided and analyzed by three different laboratories. The QA/QC testing for that study was carried out on a random selection samples for the analyses which were expected to yield results with low precision (e.g., in the case of that study, COD and BOD). In the case of this study, the critical analyses were the numbers of fecal coliforms in treated and untreated samples.

Initially, the QA/QC program was conducted as follows: 1) for each group of three replicate samples, all three replicates were analyzed for fecal coliforms per unit of dry weight of solids by both laboratories using the MF technique, and 2) the samples were analyzed for fecal coliforms using the MPN technique by the one of the two laboratories. If the initial results between the two laboratories were consistent, it was intended to scale down the QA/QC program, so that one laboratory analyzed all the samples using either the MF or MPN technique, and the other laboratory analyzed randomly selected samples using the same technique. However, due to inconsistent results between the two labs, the QA/QC program was not scaled down for any of the work done to date. The reason for the inconsistent results has now been determined (see Section 4.1 later in this report), and the QA/QC program can likely be scaled down for future trials. The two laboratories used in this study were the Environmental Engineering Laboratory at the UBC Department of Civil Engineering, and the laboratory of Dr. W.D. Ramey, of the UBC Department of Microbiology and Immunology.

A description of laboratory procedures and methods used is included in Appendix 1.

3.3.2 Moisture Content

The total solids content by weight of each sample before treatment and after the initial heating phase of the treatment was reported by both the Environmental and Microbiology laboratories. To determine the total reduction in moisture content of the biosolids over each entire trial (heating phase plus dewatering phase), the empty (tare) weight of each biosolids container was recorded, and the container was then weighed after being filled with untreated biosolids and again after the completion of the dewatering phase.

3.4 Experimental Trials

3.4.1 Procedures Common to All Trials

A general procedure applying to all of the experimental trials is given in this section. Details of the methodology unique to each of Trials 1 to 4 are given in Sections 3.4.2 to 3.4.5.

Since the application of low air pressures (20-30 torr) to speed dewatering lowered the boiling point of water to less than the temperature required for sterilization, each trial was divided into two phases. The objective of the first (heating) phase was to sterilize the biosolids, by raising the temperature to at least 70^0 C and maintaining that temperature for 30 minutes (or, alternatively, raising the temperature to 68^0 C and maintaining that temperature for at least 57 minutes). The objective of the second (dewatering) phase was to subsequently dewater the biosolids to at least 50% total solids by weight, by applying low air pressures to 20 to 30 torr and using a similar RF voltage input to that of the heating phase.

It was necessary to obtain and review the results of each one-day trial before conducting the following trial, so that the need for changes to the procedure could be evaluated. Four of the planned eight one-day trials to determine the optimum combination of treatment time and input voltage have been conducted to date.

As described earlier, the project was divided into three separate phases. Two experimental trials were conducted during Phase 1. Phases 2 (three trials) and 3 (four trials) were only to be undertaken if warranted by the results of the previous phase, and if budgetary constraints allowed.

In general, each experimental trial proceeded as follows:

1) plastic containers of the appropriate size were weighed and then filled or partly filled with biosolids taken from the shipment received from Prince George;

2) three replicate samples of the untreated biosolids were taken - each replicate sample was taken from a separate container, at the approximate center of the container, midway between the upper and lower surface of the biosolids - each replicate sample was then divided into two approximately equal portions, each portion was placed into a sterile plastic twist-tie bag, and the bags were distributed within a period of several hours to the two laboratories for analysis;

3) each container of biosolids was weighed and then inserted into the RF kiln;

4) two temperature probes were inserted into one of the containers - one approximately 20 mm from the bottom of the container, and one midway between the bottom and the upper surface of the biosolids;

5) the biosolids were always treated in the RF kiln at the maximum voltage that could be sustained without causing arcing between the electrode plates;

6) the first phase of each treatment was heating for sterilization - the biosolids were treated until a temperature of 70 degrees C in the biosolids had been obtained and maintained for 30 minutes, or until it became evident that a temperature of 70 degrees would not be obtained within a reasonable time;

7) at the end of the heating phase, the kiln was shut down and opened, and three replicate samples of biosolids were removed for bacterial analysis, using the same procedure described in Step 2;

8) the second phase of each treatment was dewatering - the kiln was closed and restarted, the vacuum pump was turned on, and the RF kiln control system was programmed to achieve the desired level of dewatering (the amount of condensate collected was monitored to determine the approximate rate and degree of dewatering) - the dewatering treatment was continued until the desired degree of dewatering was achieved, or until it became evident that the desired degree of dewatering would not be achieved within a reasonable time period;

8) the RF kiln was shut down and opened, the containers of biosolids were removed, and each container was weighed to allow a calculation of the total amount of moisture removed.

9) the total power consumption for each trial was recorded, to estimate energy costs per unit weight of biosolids treated at each combination of drying time and input voltage.

3.4.2 Trial 1

Trial 1 was begun on December 19, 1995, and ended on December 20, 1995. Three plastic containers measuring 370 mm long by 215 mm wide by 280 mm high were used. Each container was weighed, and then filled with biosolids to a depth of approximately 200 (see Photo 5).

The containers were inserted into the RF kiln, resting on the lower electrode plate. The upper electrode plate was suspended approximately 25 mm above the upper lip of the container (i.e., the upper electrode was approximately 105 mm above the upper surface of the biosolids - See Photo 6).

The kiln was closed and sealed, and the voltage gradually increased to 1.65 kV (the maximum

value that could be obtained without arcing between the electrode plates). As described earlier in Section 3, the treatment was divided into two steps, heating (RF treatment only) and dewatering (RF treatment plus vacuum).

After approximately five hours of heating (vacuum pump off, kiln air pressure=atmospheric), the temperature probes indicated only 40^0 C, and the rate of temperature increase was very slow (see Section 5.1 later in this report). At that point, it was decided to proceed with the dewatering step of the treatment. The vacuum pump was started, and the kiln control system was programmed to shut down the kiln after the biosolids had been dewatered to approximately 50% total solids.

After approximately twenty hours of treatment at a RF voltage input of 1.65 kV and under a pressure of approximately 20 torr, the degree of dewatering was insignificant (see Section 4.1), and the trial was discontinued.

3.4.3 Trial 2

The results of Trial 1 were discussed with the kiln operators and Dr. Avrimidis of UBC, to determine what changes might be made to the procedure to increase the rate of heating of the biosolids. Their recommendation was to reduce the air gap between the upper surface of the biosolids and the upper electrode.

Trial 2 was begun on January 3, 1996, and ended on January 4, 1996. The procedure for Trial 2 was similar to that of Trial 1, and the same containers were used. However, for the Trial 2, the plastic containers were filled to the top (total depth 280 mm), rather than to a depth of only 200 mm as in Trail 1. The containers were inserted into the RF kiln, resting on the lower electrode plate. The upper electrode plate was suspended approximately 25 mm above the upper surface of the biosolids.

For Trial 2, the RF voltage input was initially set at 0.40 kV, and gradually increased to approximately 1.2 kV (the maximum that could be sustained without causing arcing between the electrode plates). After approximately five hours of treatment, the required time-

temperature (70^0 C for 30 minutes) had been obtained, and the kiln was shut down and opened to remove samples for bacterial analysis. The kiln was restarted with an input RF voltage of 1.2 kV, the vacuum pump was turned on, and the control system was programmed to shut the kiln down when the biosolids had been dewatered to approximately 50% total solids by weight. The next morning, it was found that the kiln had shut down automatically soon after the dewatering phase was begun, due to arcing between the electrode plates. The kiln was restarted and monitored throughout the day. After approximately 6.5 hours at an input RF voltage of 1.2-1.3 kV and a pressure of approximately 20 torr, the degree of dewatering was found to be insignificant, and the test was discontinued.

3.4.4 Trial 3

The results of Trial 2 were discussed with the kiln operators to determine what changes might be made to the procedure to achieve better dewatering of the biosolids. Their recommendations were to increase the surface area to volume ratio of the solids, to allow more effective gas transfer between the solids and the surrounding air.

Trial 3 was begun on January 9, 1996, and ended on January 10, 1996. Five plastic containers measuring 75 mm high by 330 mm long by 240 mm wide were used for Trial 3. Note that the height of the containers was approximately one quarter that of the containers used in Trials 1 and 2, while both sets of containers had similar cross sectional areas. The surface area to volume ratio of the containers used in Trial 3 was 1.3%, compared to a ratio of 0.4% for the containers used in Trail 2. The shallower containers resulted in a significant increase in surface area to volume ratio, and allowed a small (25 mm) air gap between the upper surface of the biosolids and the upper electrode.

The five containers were inserted into the RF/V kiln, resting on the lower electrode plate. The upper electrode plate was suspended approximately 25 mm above the upper lip of the container. The kiln was closed and sealed, and the RF voltage set to the maximum value that could be obtained without arcing between the electrode plates (i.e., 0.60 kV). Again, the treatment was divided into two steps, heating (RF treatment only) and dewatering (RF treatment plus vacuum).

During the initial 1.5 hours of the heating phase of Trial 3, the kiln shut down automatically three times due to arcing between the electrode plates. The voltage was then reduced to 0.40 kV, 0.30 kV and 0.20 kV, but arcing problems continued. When the voltage input was reduced to 0.20 kV, the temperature of the biosolids, which had not yet risen to 70 degrees C, began to decline (see Section 5.2 later in this report). At that point, the vacuum pump was started, and the dewatering phase of Trial 3 begun.

When the kiln was opened to remove samples for bacterial analysis at the conclusion of the heating phase, it was observed that the plastic containers had melted and deformed along the upper edges; this was attributed to the repeated arcing between the electrode plates (see Photo 7).

For the dewatering phase, the voltage was reduced to 0.15 kV, and the kiln was programmed to dewater the biosolids to 50% solids by weight. The next morning, it was determined that the kiln had again shut off due to arcing after approximately five hours of treatment. A 6 cm thick Teflon sheet was then inserted between the upper surface of the biosolids and the upper electrode, in an effort to stabilize the electric field and reduce arcing. The Teflon sheet allowed an increase in input voltage to 0.80 kV without arcing. The dewatering phase of Trial 3 was then continued at a voltage of 0.80 kV. The kiln subsequently kiln shut down twice more due to arcing, and had to be restarted. After a total drying time of approximately 16 hours, very little water had been collected in the condenser, indicating that the degree of dewatering was negligible (see Section 4.3 later in this report), and Trial 3 was terminated.

3.4.5 Trial 4

Following Trial 3, the results of the previous trials were again discussed with Dr. Avrimidis, to determine what changes might be made to the procedure to increase the rates of heating and dewatering of the biosolids. His recommendations were to continue to use the Teflon sheet to stabilize the field so that the maximum possible RF voltage could be used, to minimize the air gap between the upper surface of the biosolids and the upper electrode, and to use containers with porous sides to allow more efficient gas transfer between the solids and the surrounding air. It was further recommended that the risk of arcing could be reduced by maximizing the

thickness of the biosolids layer, to increase the distance between the electrodes.

Trial 4 was begun on January 24, 1996, and ended on January 26, 1996. Three containers measuring 175 mm high by 245 mm wide by 470 cm long were used for Trial 4. Each container had sides containing 20 mm square holes on approximate 40 mm centers. The containers were lined with mosquito netting to prevent biosolids from falling out through the holes (see Photo 8).

The containers were entirely filled with biosolids (see Photo 9), and inserted into the kiln. The upper electrode was positioned approximately 25 mm above the upper surface of the biosolids. For Trial 4, three temperature probes were used, one approximately 20 mm from the lower surface, one midway between the upper and lower surfaces, and one approximately 30 mm beneath the upper surface of the biosolids. A Teflon sheet was inserted between the biosolids containers and each of the upper and lower electrodes, to minimize the chance of arcing (see Photo 10).

The kiln was closed and sealed, and the RF voltage set to 0.70 kV. The RF voltage was then successively increased to 0.80 kV, 0.90 kV, 1.10 kV, and 1.90 kV over the first four hours of the test, in an effort to increase the rate of temperature rise. After the heating phase had continued for approximately 11 hours, the temperature of the biosolids began to decline, despite a constant input voltage of approximately 1.9 kV (see Section 4.4 later in this report), and the dewatering phase was begun. For the dewatering phase, the voltage was initially set at 1.6 kV; at approximately t = 26.5 hours, the voltage was increased to 2.2 kV, and the dewatering phase was continued for a further 26 hours. After a total dewatering time of 40 hours, the rate of rise in the water level in the condenser showed that dewatering to 50% solids by weight would require a further 40 hours of treatment, and the test was terminated.

3.5 Review of Interim Results

After the completion of Trial 4, a draft interim report describing the results to that point was prepared for review by the study participants, to determine whether the remaining trails should be carried out. The draft interim report was also reviewed by Glade Technologies Inc., a firm specializing in the development and commercialization of RF and RF/V drying technology.

The results contained in the draft interim report showed that little further knowledge could be gained by completion of the remaining trials using the RF/V kiln at UBC. As described later in this report, the UBC RF/V kiln, which was designed for treating solid lumber, proved to be unsuitable for treating loosely packed material. Following review of the draft interim report, it was agreed by the study participants to terminate the project without further experimental trials.

4.0 RESULTS

4.1 Trial 1

The RF kiln voltage input versus time during Trial 1 is shown on Figure 1. The RF voltage was gradually increased to approximately 1.6 kV at the outset, and was not further adjusted until the dewatering phase was terminated at t= 22 hours, at which point it was increased to approximately 1.75 kV. As shown in Figure 1, the kiln RF voltage remained relatively constant throughout the first 22 hours of the test, although there was a slight upward trend.

The output of the temperature probes during Trial 1 is shown on Figure 2. As described earlier in Section 3, it was intended to raise the temperature of the biosolids to at least 70 degrees C, and maintain that temperature for at least 30 minutes. Note that the kiln could not be left unattended during the heating phase, due to the possibility of overheating; the temperature had to be visually monitored on the computer screen to determine when the heating phase was complete, and then the vacuum pump had to be switched on manually to start the dewatering phase. At that point, the kiln control system could be programmed to continue the dewatering phase until a specified depth of condensate had been collected in the condenser cylinder, and the kiln would then shut down automatically.

As shown on Figure 2, during the initial sterilization (heating) phase, the temperature of the biosolids rose steadily; after a period of approximately 5 hours (at approximately 4:30 P.M.), the biosolids temperature had risen from 6 degrees C to near 40 degrees C. Since the UBC facility was closing for the night at that point, further heating was not possible, and the dewatering phase was begun. As soon as the vacuum pump was turned on, the temperature of the biosolids dropped sharply to approximately 25 degrees C, and remained near that level throughout the night. Note that the upper temperature probe (inserted midway between the upper and lower surfaces of the biosolids layer) consistently recorded a higher temperature

than the lower probe (inserted near the bottom of the biosolids layer) during the heating phase.

The rate of temperature rise of the two probes versus time over the heating phase of Trial 1 is shown on Figure 3. Note that the rate initially increased over the first hour, corresponding to the increase in input voltage shown earlier on Figure 1. The rate of temperature rise then declined over the remainder of the heating phase, despite a relatively constant input voltage.

The water level in the condenser cylinder versus time is shown on Figure 4. Calculations before the test showed that, for the mass of untreated biosolids inserted into the kiln, dewatering to a total solids content of 50% by weight would result in the collection of a volume of water sufficient to raise the water level in the condenser collection cylinder by 19.4 cm, from its original value of 44.6 cm to a level of 64 cm. As shown on Figure 4, the water in the condenser cylinder after 17 hours of dewatering had risen by only 5 cm to a level of 49.6 cm. At that rate of rise, it was estimated that it would take approximately another 50 hours to achieve a total solids content of 50% by weight. It was decided at that point to terminate the dewatering phase of Trial 1 (i.e., at approximately t=22 hours - see Figure 4). Based on the condenser water level, the biosolids were estimated to have a total solids content of 22% by weight, at the conclusion of the dewatering phase.

At the end of the dewatering phase of Trial 1 (t=22 hours), the vacuum pump was shut off, and the kiln voltage was increased to 1.75 kV for a period of approximately 2 hours (Figure 1). This resulted in an immediate increase in the temperature of the biosolids. The rate of temperature increase was similar to that observed earlier at a voltage of 1.6 kV (t=0 to t= 5 hours - see Figure 2), and Trial 1 was terminated at that point.

The results of the bacterial analyses for Trial 1 are summarized in Table 1. The average number of fecal coliforms in the untreated samples was approximately 27,000/g dry solids, according to the results of the membrane filter technique carried out by the UBC Environmental Engineering laboratory. The results of the membrane filter technique carried out by the UBC Microbiology lab did not produce reliable results for the untreated samples, due to the small number of colonies (3 colonies, 1 colony, and 2 colonies for the samples from Containers #1, #2, and #3, respectively). The average number of fecal coliforms according to

the results of the confirmed MPN test carried out on the untreated samples by the Microbiology lab was approximately 16,000/g dry solids. The results of the analyses on the treated samples are more variable than the untreated samples, with the average number of fecal coliforms ranging from 27,000 (membrane filter technique by the Microbiology lab) to approximately 270,000 (membrane filter technique by the Environmental lab). It has since been determined that there was a difference in technique employed in preparation of the samples between the two laboratories. The Microbiology lab mixed the solids vigorously with water in the required amount, and then let the sample to stand for 5 minutes to allow larger particles to settle, before conducting the analyses. On the other hand, the Environmental lab did not allow the any solids to settle before conducting the analyses. The larger numbers reported by the Environmental lab were likely due to fecal coliform bacteria adhering to the solids being included in the counts, while bacteria adhering to the larger solids were settled out and not included in the counts by the Microbiology lab. Since the bacterial content of the solids is of interest in this study, the results reported by the Environmental lab are likely the most realistic. Note also the wide variation among the three after-treatment replicates tested by the MPN technique (11,000 for Sample #1 compared to 460,000 for Sample #3 -see Table 1). The amount of solids used for the initial dilution was relatively small (10 g of sample in 100 mL of water), and the high degree of variability in some of the sets of results (particularly the MPN test on the treated samples) may have been due to variable numbers of bacteria in the portions of each sample used for the serial dilutions.

In any case, it is evident that the treatment during Trial 1 did not result in the destruction or inactivation of significant numbers of fecal coliforms in the biosolids. The results are not surprising, since the temperature of the biosolids did not exceed 43 degrees C at any time during the test (Figure 2).

Table 1: Trial 1 Fecal Coliform Results

Container	Number of Fecal Coliforms per Gram Dry Weight of Solids					
	Before Treatment			After Treatment		
	Membrane Filter Technique		MPN Technique	Membrane Filter Technique		MPN Technique
	Env. Lab[1]	Mirco Lab[2]	Micro Lab[2]	Env Lab[1]	Micro Lab[2]	Micro Lab[2]
#1	16,000	<17,000[3]	14,000	380,000	28,000	11,000
#2	37,000	<17,000[3]	16,000	240,000	24,000	20,000
#3	27,600	<17,000[3]	17,000	180,000	29,000	460,000
Average	26,867	<17,000[3]	15,667	266,667	27,000	163,667
Std Dev	10,519		1,528	102,632	2,646	256,672

[1] Environmental Engineering Laboratory, University of British Columbia Dept. of Civil Engineering
[2] Laboratory of Dr.W.D. Ramey, University of British Columbia Dept. of Microbiology and Immunology
[3] Number of colonies too low for reliable results

The results of the analyses for total solids are summarized in Table 2. The results of the Microbiology lab for percent total solids by weight were lower than those of the Environmental lab , both for the treated and untreated samples. The reason for this anomaly is unknown. However, the data from both labs show that the heating phase of the treatment during Trial 1 resulted in a relatively slight increase in the total solids content of the biosolids (i.e., an increase of less than 4%, according to both laboratories). The biosolids containers were not weighed after the dewatering phase, so no data are available on the total percent weight reduction beyond the plot of condenser water level described earlier (Figure 4).

Table 2: Trial 1 Dewatering Results

Container	Weight of Container (lb)			% Weight Reduction	% Total Solids by Wt in Replicate Samples			
	Tare	Before Treatment	After Dewatering[4]		Before Treatment		After Heating[3]	
					Env Lab[1]	Micro Lab[2]	Env Lab[1]	Micro Lab[2]
#1	1.6	20.5	no data	no data	18.3	11.8	20.5	15.7
#2	1.6	20.7	no data	no data	18.0	12.7	21.9	16.3
#3	1.6	20.6	no data	no data	18.7	12.7	21.5	16.5
Average	1.6	20.6	no data	no data	18.3	12.4	21.3	16.2
Std Dev	0.0	0.1			0.4	0.5	0.7	0.4

[1] Environmental Engineering Laboratory, University of British Columbia Dept. of Civil Engineering
[2] Laboratory of Dr.W.D. Ramey, University of British Columbia Dept. of Microbiology and Immunology
[3] At conclusion of heating phase (beginning of dewatering phase)
[4] At end of trial (at conclusion of dewatering phase)

4.2 Trial 2

As described earlier in Section 3, the air gap between the upper surface of the biosolids and the upper electrode plate was reduced to 25 mm in Trial 2 (compared to 100 mm in Trial 1), in an effort to improve the efficiency of energy transfer to the biosolids, and increase the rate of temperature rise and dewatering. The RF kiln voltage input versus time for Trial 2 is shown on Figure 5. The voltage was gradually increased to 1.2 kV, the maximum that could be sustained without arcing between the electrodes. At t=5 hours, the sterilization phase was complete, and the kiln was shut down to remove samples for bacterial analysis. At the conclusion of the heating phase, it was observed that the volume of the biosolids was less than at the outset of the test. The upper surface of the solids had slumped by approximately 50 mm, increasing the air gap to the upper electrode plate from 25 mm to 75 mm.

The kiln was restarted, the voltage was set at 1.2 kV, the vacuum pump was turned on, and the kiln control system was programmed to dewater the biosolids to a total solids content of 50% by weight. The system was then left on automatic overnight. As shown on Figure 5, the kiln shut down automatically (due to arcing between the electrode plates) and the voltage dropped to 0 kV at approximately t=5.5 hours, almost immediately after the dewatering phase had begun. This was not discovered until the next morning at approximately t=22.5 hours, at which point the voltage generator was restarted. The dewatering phase was continued for approximately 6 hours, until t=28.6 hours.

The biosolids temperatures versus time for Trial 2 are shown on Figure 6. Similar to the results of Trial 1, the upper temperature probe consistently recorded higher temperatures than the lower probe. As shown on Figure 6, the lower probe recorded a temperature of 70 degrees C at t=4.4 hours, and the temperature was held at that level for 30 minutes until t=4.9 hours. As soon as the vacuum pump was started, the temperature of the biosolids dropped to less than 30 degrees C. During the period when the kiln voltage generator had automatically shut down (t=6 hours to t=22.6 hours), the temperature of the solids declined to approximately 15 degrees C. When the voltage generator was restarted at t=22.6 hours, the temperature rose to near 30 degrees C and remained at that level for the remainder of the test (Figure 6).

The rate of temperature rise versus time for the heating phase of Trial 2 is shown on Figure 7. The rate decreased sharply during the first hour, and then continued to decrease at a much lower rate until the end of the heating phase. Note that the rate of temperature rise during the first hour of Trial 2 (10 to 80 C/hr - see Figure 7) was much higher than the rate of rise at any time during Trial 1, (normally 2 to 12 C/hr - see Figure 3), despite a higher voltage input during Trail 1. After the first hour of Trial 2, the rate of temperature rise was generally in the same range as that of Trial 1.

The water level in the condenser collection cylinder versus time for Trial 2 is shown on Figure 8. A decrease in the water content of the biosolids to 50% total solids by weight would have resulted in the collection of enough water to raise the level in the collection cylinder by 28.6 cm, from the initial level of 39.4 cm to a level of 68 cm. The water level rose by only 4.0 cm to 43.4 cm by the end of Trial 2. Based on the condenser water level, the biosolids were estimated to have a total solids content of 20% by weight, at the conclusion of the dewatering phase.

The results of bacterial testing for Trial 2 are summarized in Table 3. Similar to the results of Trial 1, there were wide variations among the results on the untreated samples between the two. The average number of fecal coliforms in the untreated samples using the membrane filter technique was 430,000/g dry solids according to the Environmental lab, and 40,000/g dry solids according to the Microbiology lab. The average was 49,000/g dry solids according to the MPN technique (Microbiology lab). As described earlier in Section 4.1, the larger numbers reported by the Environmental lab were due likely due to a difference in sample preparation technique between the two labs. Note that no fecal coliforms were detected in the treated samples by either laboratory. A test for regrowth by the Microbiology lab after 21 days on a composite sample made up of the three heat-treated replicates detected no fecal coliforms, using the membrane filter assay.

Table 3: Trial 2 Fecal Coliform Results

Container	Number of Fecal Coliforms per Gram Dry Weight of Solids					
	Before Treatment			After Treatment		
	Membrane Filter Technique		MPN Technique	Membrane Filter Technique		MPN Technique
	Env. Lab[1]	Mirco Lab[2]	Micro Lab[2]	Env Lab[1]	Micro Lab[2]	Micro Lab[2]
#1	262,000	39,600	93,400	none detected	none detected	none detected
#2	620,000	35,000	27,400	none detected	none detected	none detected
#3	401,000	45,500	27,100	none detected	none detected	none detected
Average	427,667	40,033	49,300			
Std Dev	180,484	5,263	38,192			

[1] Environmental Engineering Laboratory, University of British Columbia Dept. of Civil Engineering

[2] Laboratory of Dr.W.D. Ramey, University of British Columbia Dept. of Microbiology and Immunology

The results of the total solids analyses for Trial 2 are summarized in Table 4. The results of both labs show that the initial average solids content of the samples was 18.2% to 18.3% total solids by weight. After the heating phase, the average solids content had increased marginally (to 18.7% according to the Microbiology lab, and to 19.2% according to the Environmental lab). After the dewatering phase, the total weight of the biosolids in the containers had decreased by an average of 10.3% (Table 4). This represents an increase in total solids content to approximately 22% by weight, similar to the value of 20% by weight estimated from the condenser water level.

Table 4: Trial 2 Dewatering Results

Container	Weight of Container (lb)			% Weight Reduction	% Total Solids by Wt in Replicate Samples			
	Tare	Before Treatment	After Dewatering[4]		Before Treatment		After Heating[3]	
					Env Lab[1]	Micro Lab[2]	Env Lab[1]	Micro Lab[2]
#1	1.6	32.2	27.2	11	18.1	18.2	18.8	19.5
#2	1.6	30.7	26.6	9	18.1	18.3	21.0	19.2
#3	1.6	30.7	25.8	11	18.5	18.5	17.9	17.5
Average	1.6	31.2	26.5	10.3	18.2	18.3	19.2	18.7
Std Dev	0.0	0.9	0.7	1.5	0.2	0.2	1.6	1.1

[1] Environmental Engineering Laboratory, University of British Columbia Dept. of Civil Engineering
[2] Laboratory of Dr.W.D. Ramey, University of British Columbia Dept. of Microbiology and Immunology
[3] At conclusion of heating phase (beginning of dewatering phase)
[4] At end of trial (at conclusion of dewatering phase)

4.3 Trial 3

As described earlier in Section 3, the depth of the biosolids containers used in Trial 3 was 75 mm, compared to 215 mm in Trial 2. The computer monitoring system failed to save the data from Trial 3 to the computer hard drive, and no computer data plots are therefore available. However, some data were manually recorded from the computer screen during the heating phase of Trial 3.

The manual readings of kiln voltage input and biosolids temperature during the heating phase of Trial 3 are shown on Figures 9 and 10, respectively. At a RF voltage input of 0.60 kV, the kiln shut down due to arcing three times during the initial 1.5 hours of treatment (Figure 9). During that time, the temperature of the biosolids rose from 6.5-7 degrees C to 29-32 degrees C (Figure 10). The voltage input was then reduced to approximately 0.40 kV, and the kiln ran continuously for the next 3 hours, at which time it again shut down due to arcing (Figure 9). At that point, the temperature of the biosolids had risen to 62-67 degrees C (Figure 10). The maximum voltage that could be sustained without arcing at that point was 0.23 kV; at that voltage, it was observed that the temperature of the biosolids began to decrease (Figure 10), and the heating phase of Trial 3 was terminated. Similar to Trial 2, the upper surface of the biosolids had sunk away from the upper electrode plate, increasing the air gap to approximately 50 mm.

The rate of temperature rise with time during the heating phase of Trial 3 is shown on Figure 11. The pattern is similar to that shown earlier for Trial 2 (Figure 6), with a sharp initial decrease in the rate of temperature increase, followed by a much slower, but steady, decrease until the end of the heating phase.

No data on the condenser water level were recorded for Trial 3.

The results of bacterial testing for Trial 3 are summarized in Table 5. Unlike the results of Trials 1 and 2, the numbers for the untreated samples agreed closely between the two labs for Trial 3 (average 225,000 for the Environmental lab and 230,000 for the Microbiology lab). No fecal coliforms were detected in the treated samples by the Microbiology lab using the membrane filter technique. The Environmental lab results showed 15 fecal coliforms/g dry solids in one sample and none detected in the other two samples, using the MPN technique. A test for regrowth 21 days

after treatment conducted by the Microbiology lab on a composite sample made up of the three heat-treated replicates detected no fecal coliforms, using the membrane filter assay.

Table 5: Trial 3 Fecal Coliform Results

Container	Number of Fecal Coliforms per Gram Dry Weight of Solids					
	Before Treatment			After Treatment		
	Membrane Filter Technique		MPN Technique	Membrane Filter Technique		MPN Technique
	Env. Lab[1]	Mirco Lab[2]	Micro Lab[2]	Env Lab[1]	Micro Lab[2]	Micro Lab[2]
#1	237,000	270,000	no data	no data	none detected	none detected
#2	273,000	180,000	no data	no data	none detected	15
#3	164,000	240,000	no data	no data	none detected	none detected
Average	224,667	230,000				
Std Dev	55,537	45,826				

[1] Environmental Engineering Laboratory, University of British Columbia Dept. of Civil Engineering

[2] Laboratory of Dr.W.D. Ramey, University of British Columbia Dept. of Microbiology and Immunology

The results of solids analysis for Trial 3 are summarized in Table 6. Similar to Trials 1 and 2, the average solids content of the untreated biosolids was 17% to 18%, and the heating phase increased the average solids content marginally (by approximately 1% in this case). Following the completion of the dewatering phase, the weight of the biosolids had decreased by an average of 25%, representing a final total solids content of approximately 25% by weight.

Table 6: Trial 3 Dewatering Results

Container	Weight of Container (lb)			% Weight Reduction	% Total Solids by Wt in Replicate Samples			
	Tare	Before Treatment	After Dewatering[4]		Before Treatment		After Heating[3]	
					Env Lab[1]	Micro Lab[2]	Env Lab[1]	Micro Lab[2]
#1	0.6	8.3	5.9	23	17.5	12.8	20.3	20.1
#2	0.6	8.3	6.2	19	18.6	19.3	18.8	18.0
#3	0.6	8.3	5.4	30	18.6	18.0	19.0	20.5
#4	0.6	8.4	no data	no data	no data	no data	no data	no data
#5	0.6	8.2	5.3	30	no data	no data	no data	no data
Average	0.6	8.3	5.7	25.7	18.2	16.7	19.4	19.5
Std Dev	0.0	0.1	0.4	5.2	0.6	3.4	0.8	1.3

[1] Environmental Engineering Laboratory, University of British Columbia Dept. of Civil Engineering
[2] Laboratory of Dr.W.D. Ramey, University of British Columbia Dept. of Microbiology and Immunology
[3] At conclusion of heating phase (beginning of dewatering phase)
[4] At end of trial (at conclusion of dewatering phase)

Note-During Trial #3 the plastic containers melted along the top edges and the containers fused together

4.4 Trial 4

The kiln voltage versus time for Trial 4 is shown on Figure 12. The RF voltage was successively increased from 0.7 kV to 1.9 kV during the first four hours of the heating phase; the voltage then stayed relatively constant at around 1.9 kV until the end of the heating phase. When the kiln was opened at the conclusion of the heating phase, it was again observed that the upper surface of the biosolids had slumped away from the upper electrode, increasing the air gap to approximately 100 mm (see Photo 11). When the dewatering phase was begun at t=11 hours, the voltage was set at approximately 1.6 kV. At t=26 hours, the voltage was increased to about 2.2 kV, and it stayed at that level until the end of the test.

The temperature versus time data for Trial 4 are plotted on Figure 13, and the rates of temperature rise versus time are plotted on Figure 14. Similar to Trials 1 to 3, the rate of temperature rise tended to decay over time. Note that the rate of temperature rise increased at t=4.5 hours (Figures 13 and 14) when the RF voltage was manually increased from 1.1 kV to 1.9 kV (Figure 12). As shown on Figure 13, the lower probe recorded a temperature consistently lower than the middle and upper probes, and the upper probe usually recorded a temperature lower than that of the middle probe. At around t=10 hours, the reading the upper probe increased beyond that of the middle probe. To test the accuracy of the lower probe, when the kiln was opened at the conclusion of the heating phase, the lower probe (#1) was withdrawn and then re-inserted near the top of the biosolids layer, and the reading of probe #1 immediately increased to match the reading of Probe #3, which was also located near the top. Note that only the upper probe recorded a temperature as high as 70 C (from t=9.9 hours through t=10.6 hours. The middle probe recorded a temperature of at least 68 C for a period of 2.6 hours, from t=8.0 hours to t=10.6 hours. The maximum temperature recorded by the lower probe (prior to its removal and re-insertion near the upper probe) was 64.7 C (Figure 13). When the vacuum pump was turned on at t= 11 hours, the reading of all three probes dropped to approximately 30 C, and remained there throughout the dewatering phase.

The water level in the condenser versus time is shown on Figure 15. The rate of water collection was relatively constant throughout the dewatering phase, and did not appear to be affected by the increase in kiln input RF voltage from 1.7 kV to 2.2 kV at around t=26 hours (Figure 12). For dewatering to a total solids content of 50% by weight in the biosolids, the water level in the condenser would have risen by 28.6 cm, from an initial level of 18.7 cm to a level of 47 cm. At the conclusion of the dewatering phase (at t=52 hours after 40 hours of dewatering treatment), the water level had risen by 14.1 cm, to 32.8 cm; based on that level, the solids content of the biosolids is at the conclusion of the test is estimated at approximately 31% by weight. At the constant rate of rise observed (Figure 15), it is estimated that it would have taken a further 40 hours for the condenser water level to reach 47 cm.

The results of bacterial testing for Trial 4 are summarized in Table 7. Again, there is a wide discrepancy between the average number of fecal coliforms in the untreated samples between the two labs (1,130,000/g dry solids for the Environmental lab and 37,000/g dry solids for the Microbiology lab, both using the membrane filter technique). As described in Section 4.1, the difference in results between the two labs was likely due to a difference in sample preparation technique. For the treated samples, the Microbiology lab detected no fecal coliforms in any samples, using the membrane filtration technique. The Environmental lab found an average of 16 fecal coliforms/g dry solids, using the MPN technique.

Table 7: Trial 4 Fecal Coliform Results

Container	Number of Fecal Coliforms per Gram Dry Weight of Solids					
	Before Treatment			After Treatment		
	Membrane Filter Technique		MPN Technique	Membrane Filter Technique		MPN Technique
	Env. Lab[1]	Mirco Lab[2]	Micro Lab[2]	Env Lab[1]	Micro Lab[2]	Micro Lab[2]
#1	1,095,000	46,000	no data	no data	0	15
#2	765,000	30,000	no data	no data	0	25
#3	1,530,000	35,000	no data	no data	0	9
Average	1,130,000	37,000	no data	no data	0	16
Std Dev	383,699	8,185			0	8

[1] Environmental Engineering Laboratory, University of British Columbia Dept. of Civil Engineering

[2] Laboratory of Dr.W.D. Ramey, University of British Columbia Dept. of Microbiology and Immunology

The results of the solids analyses for Trial 4 are summarized in Table 8. According to the results of the Environmental lab, the average total solids content of the grab samples taken after the heating phase treatment (18.4%) was 1.4% higher than the average of the samples taken before treatment (19.8%). According to the results of the Microbiology lab, the average solids content of the before treatment samples (19.8%) was similar to that of the samples taken after the heating phase (19.6%). After the dewatering phase, the total weight of the biosolids had increased by an average of 40%; the estimated final total solids content of the biosolids calculated from the total weight reduction is approximately 35%, slightly higher than the value of 31% estimated from the condenser water level.

Table 8: Trial 4 Dewatering Results

Container	Weight of Container (lb)			% Weight Reduction	% Total Solids by Wt in Replicate Samples			
	Tare	Before Treatment	After Dewatering[4]		Before Treatment		After Heating[3]	
					Env Lab[1]	Micro Lab[2]	Env Lab[1]	Micro Lab[2]
#1	1.9	30.8	16.5	43	17.6	18.3	19.7	20.0
#2	1.9	31.1	18.1	38	18.6	20.5	20.2	21.4
#3	1.9	30.3	17.2	39	19.1	20.5	19.4	17.5
Average	1.9	30.7	17.3	40.1	18.4	19.8	19.8	19.6
Std Dev	0.0	0.4	0.8	2.5	0.8	1.3	0.4	2.0

[1] Environmental Engineering Laboratory, University of British Columbia Dept. of Civil Engineering
[2] Laboratory of Dr.W.D. Ramey, University of British Columbia Dept. of Microbiology and Immunology
[3] At conclusion of heating phase (beginning of dewatering phase)
[4] At end of trial (at conclusion of dewatering phase)

4.5 Quality of Condensate

A test on a sample of the condensate generated during Trial 4 showed that the chemical oxygen demand (COD) was 361 mg/L, and the five-day biochemical oxygen demand (BOD5) was 158 mg/L. This is similar in strength to a typical sewage, and routing the condensate back to the head of the treatment plant should therefore have no adverse effect on the liquid treatment processes, provided condensate volumes are a small percentage of plant inflows.

4.6 Energy Inputs

The initial and final power consumption meter readings (in kW-h) for both the heating and dewatering phases of Trials 1 to 4 are summarized in Table 9, together with the calculated specific energy inputs (the Environmental lab data for total solids content from Tables 2, 4, 6, and 8 were used in the calculations). As shown, the specific energy input was in the range 3 kW-h per kg dry solids to 8 kW-h per kg dry solids during the heating phases and 6 kW-h per kg dry solids to 27 kW-h per kg dry solids during the dewatering phases. The approximate rise in temperature and the initial and final solids contents of the biosolids for each trial are included in Table 9. As shown, there is no apparent direct relationship between the specific energy input and the temperature rise or the degree of dewatering. However, note that conditions were different for each of the tests (mass of biosolids used, size and shape of containers, voltage input, air gap).

Table 9: Specific Power Consumption, Trials 1 to 4

Trial #	Meter Reading (kW-hr)				Mass of Solids in Kiln (kg)	Energy Input (kW-hr/kg dry solids)		Avg. Temp Rise (^{o}C)	Total Solids Content (%)	
	Heating Phase		Dewatering Phase							
	Initial	Final	Initial	Final		Heating	Dewatering		Initial[1]	Final[2]
1	9348	9366	9366	9429	4.75	3.8	13.3	34	18	ND[3]
2	9613	9637	9637	9685	7.36	3.3	6.5	65	18	22
3	9722	9741	9741	9827	3.19	6.0	27.0	59	18	25
4	9944	9991	9991	10139	7.25	6.5	20.4	65	18	35

[1] Based on results of Environmental Lab
[2] Based on weights of containers before and after dewatering
[3] ND - No data

5.0 DISCUSSION

The results of temperature monitoring showed that the temperature near the center area of the biosolids consistently increased faster and reached a higher level higher than the temperature in the lower layers (Figures 2, 6, 10, and 13). The results of Trail 4, where a third temperature probe was inserted in the upper layer of the solids, further showed that the temperature of the upper layer closely followed that of the center area. If heating by the electric field were consistent throughout the mass of solids, the temperature of the upper layer would be expected to be the lowest, due to evaporative cooling from the upper surface. However, since the lower probe recorded the lowest temperatures during Trial 4, it appears that the input of heat energy by the electric field was consistently lowest near the lower electrode, possibly due to distortions in the electric field. In any case, it is apparent that uneven heating occurred during each of the four trials.

According to the output of the temperature probes, the time-temperature requirement to produce retail grade biosolids was met for the entire mass of biosolids during Trial 2, and for the middle and upper layers only during Trial 4. The time required to achieve these temperatures was 4.5 hours at an input RF voltage of 0.5 kV to 1.2 kV for Trial 2, and 9 hours at an input RF voltage of 0.6 kV to 1.9 kV during Trial 4. During Trial 3, the time-temperature requirement was not met, but temperatures in the range 60 C to 68 C were maintained for a period of approximately one hour. The results of bacterial analysis showed that all of the treated sample replicates for Trials 2, 3, and 4 were well under the Environment B.C. maximum of 1,000 fecal coliforms/g dry solids, indicating that the sterilization treatment was successful. However, the times required for sterilization were relatively long.

The rate of temperature rise typically increased when the voltage input was manually increased. However, the rate of temperature increase consistently decayed over time at a constant voltage input all four Trials. The decay in the rate of temperature increase was likely caused by slumping of the upper surface of the biosolids, which increased the air gap between the biosolids and the upper electrode plate. In dielectric heating, the effective field strength is a function of the thickness of the air gap

between the electrodes and the material being heated; as the air gap increases, the effective field strength decreases. Therefore, progressive slumping of the biosolids as heating progressed was probably the cause of the steadily decreasing rate of temperature rise.

None of the trials resulted in dewatering of the biosolids to the objective amount of 50% total solids by weight. The untreated biosolids typically contained approximately 18% total solids by weight. The maximum solids content after dewatering was 35% total solids by weight (Trial 4). Similar to the heating phase, the drying times were relatively long (40 hours in the case of Trial 4). However, note that the air gap between the upper electrode and the biosolids had increased to 50 to 75 mm before the beginning of the dewatering phases of Trials 2, 3, and 4, due to slumping of the biosolids during the previous heating phase. As described above, the greater the air gap, the weaker the field strength; therefore, the rate of dewatering would likely have been greater if the air gap could have been minimized.

The total specific energy inputs to the kiln over the combined heating and dewatering phases ranged from 9.8 kW-h/kg dry solids for Trial 2 to 33.0 kW-h/kg dry solids for Trial 4. The degree of energy consumption was high, considering the results achieved. By comparison, according to the US Environmental Protection Agency AProcess Design Manual for Sludge Treatment and Disposal,@ (EPA 625/1-79-011) conventional sludge dryers (using hot air or steam) typically require approximately 6.5 kW-h/kg dry solids, to reduce the moisture content of biosolids from 18% total solids by weight to 90% total solids by weight.

It should be noted that the pilot-scale RF kiln was designed for drying solid lumber, and not loose material. The most obvious problem encountered was slumping of the biosolids mass during the heating phase, which increased the air gap between the solids and the upper electrode plate, and caused a progressive decrease in field strength. A different approach designed for RF drying of loose materials should increase the efficiency of energy use. The two parameters of primary importance are continuous compaction of the solids between the electrode plates, and mixing to prevent uneven heating.

The comments by Glade Technologies Inc. on the draft interim report containing the results of Trials 1 to 4 are included in Appendix 2. The comments by Glade indicate that the UBC RF/V kiln might be

modified to dry viscous biosolids, at an estimated cost of $15,000, including engineering and construction. The modified RF/V kiln could be used to resolve the issue of poor energy transfer caused by shrinking and uneven heating of the biosolids, and consequently lower the energy requirement for RF and RF/V sterilization and/or drying of municipal biosolids. Other possibilities for further work are also discussed.

Treating of biosolids using RF/V technology might prove to be advantageous from the standpoint of odour control. Drying of biosolids in a sealed RF/V kiln under vacuum at low temperatures with subsequent condensation of the vapour should make odours relatively easy to contain and treat. On the other hand, drying of biosolids using conventional technologies (eg. natural gas dryers) produces relatively large volumes of moist high-temperature foul air requiring collection and treatment. Therefore, the use of RF/V technology for drying of biosolids might prove advantageous in situations where odour control is critical.

6.0 CONCLUSIONS

The following conclusions are based on the results of this study.

1. Radio Frequency (RF) sterilization of municipal biosolids is technically feasible. The time-temperature requirements for pathogen destruction of 20 minutes at greater than 70^{o}C, 30 minutes at 70^{o}C or 57 minutes at 68^{o}C can be met using RF technology.

2. Radio Frequency/Vacuum (RF/V) dewatering of municipal biosolids is technically feasible. The maximum degree of dewatering obtained in this study was approximately 35% solids by weight in the treated biosolids, compared to an initial solids content of approximately 17% by weight in the untreated biosolids.

3. The RF/V kiln used in this study was designed for treating solid lumber; the available equipment proved to be inefficient for treating loosely packed biosolids, mainly due to shrinking of the biosolids during treatment, which increased the air gap between the electrode plates and the solids, and caused inefficient energy transfer to the biosolids.

4. The energy requirements for RF/V sterilization and drying of municipal biosolids could be substantially reduced over those observed in this study, if an RF/V kiln designed specifically to treat loosely packed solids were used. This possible next phase of the work is outside the scope of this present assignment.

5. Sterilization and drying of municipal biosolids using RF/V technology requires higher energy inputs than natural gas drying.

7.0 RECOMMENDATIONS

1. The City of Prince George should continue with their existing biosolids handling program, using the solids dewatered in the belt filter presses.

2. If the City wishes to dewater the treated biosolids beyond the 17% to 20% total solids typical of the solids leaving the belt filter presses, natural gas drying should be investigated. Waste methane gas from the anaerobic digesters might be used as a supplemental fuel, to reduce operating costs.

3. If the City wishes to expand options for biosolids use by increasing the quality of the end product through pasteurization, digestion options which include high temperature treatment (e.g., thermophilic anaerobic digestion and pre-pasteurization) should be considered.

8.0 FIGURES

Figure 1 - Trial 1: Kiln Voltage vs Time

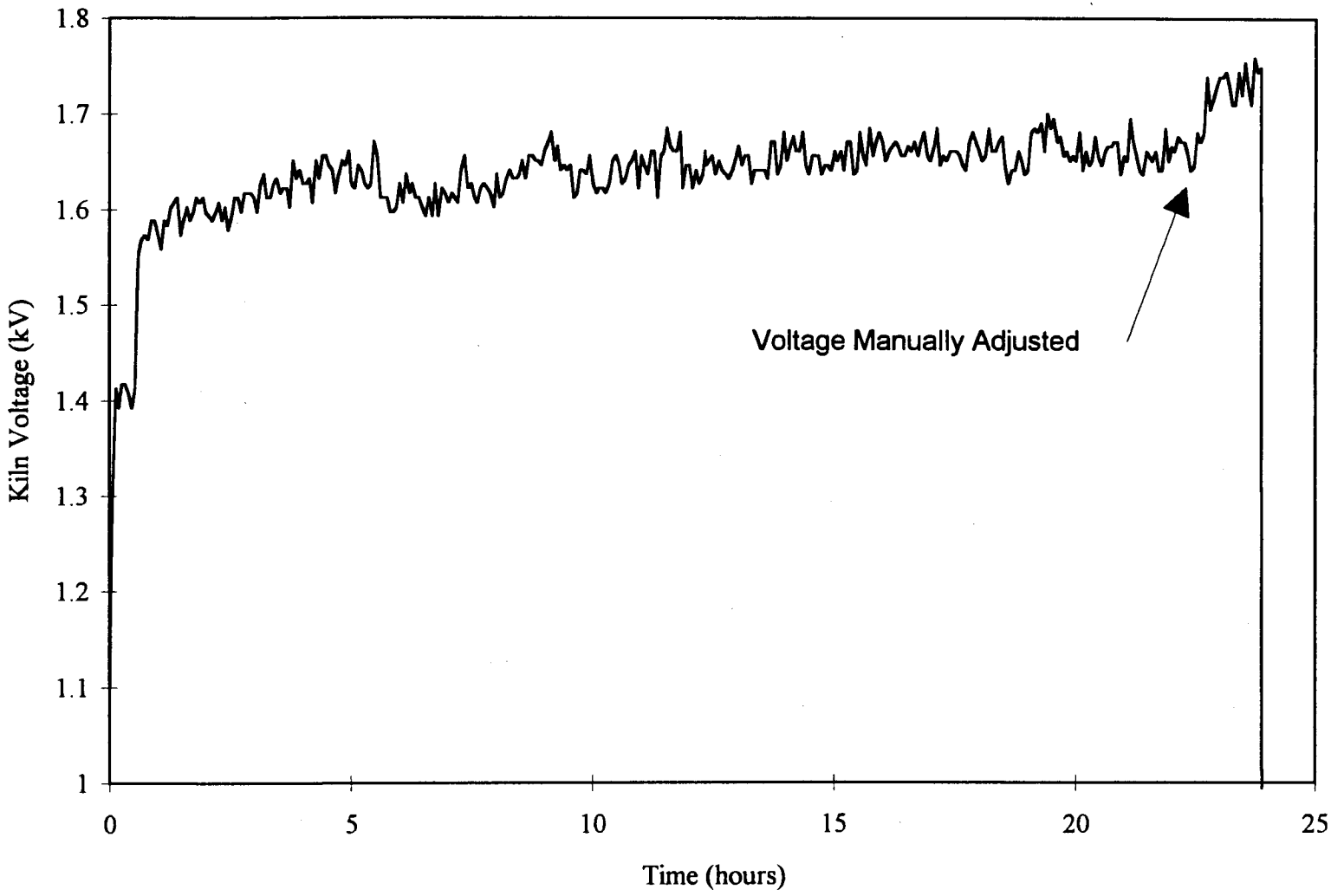


Figure 2 - Trial 1: Biosolids Temperature vs Time

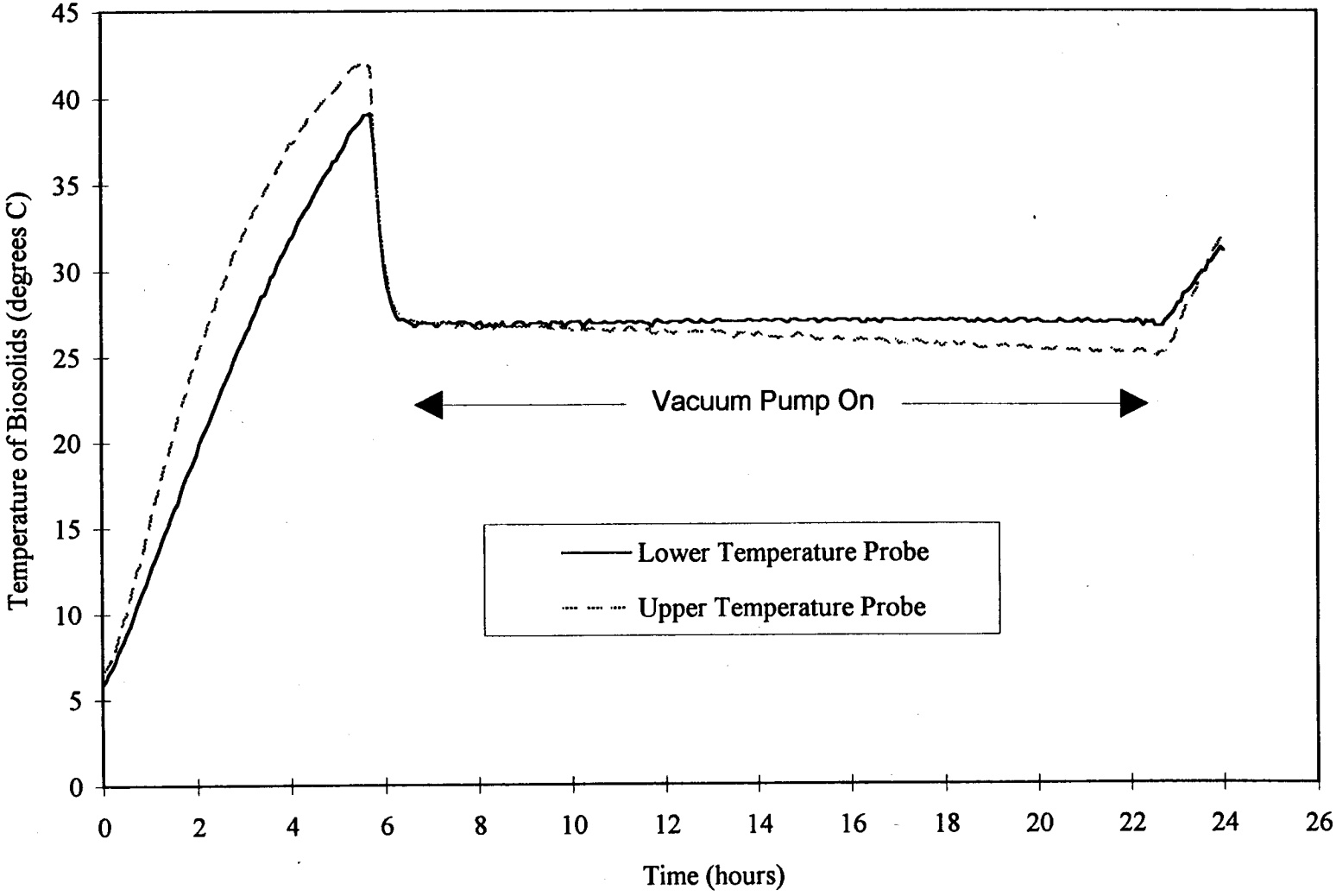


Figure 3 - Trial 1: Rate of Temperature Rise vs Time During Heating Phase Only

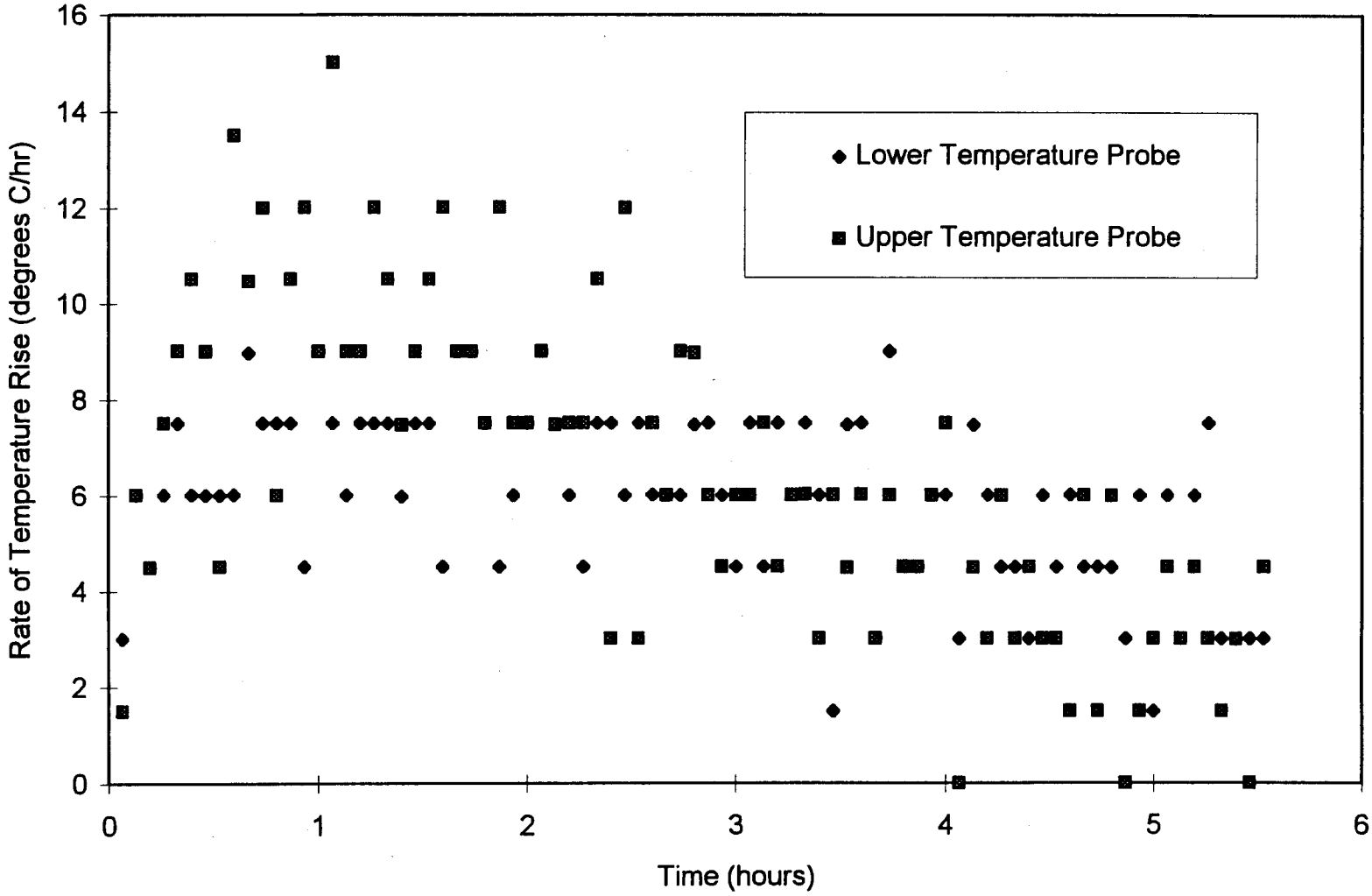


Figure 4 - Trial 1: Condenser Water Level vs Time

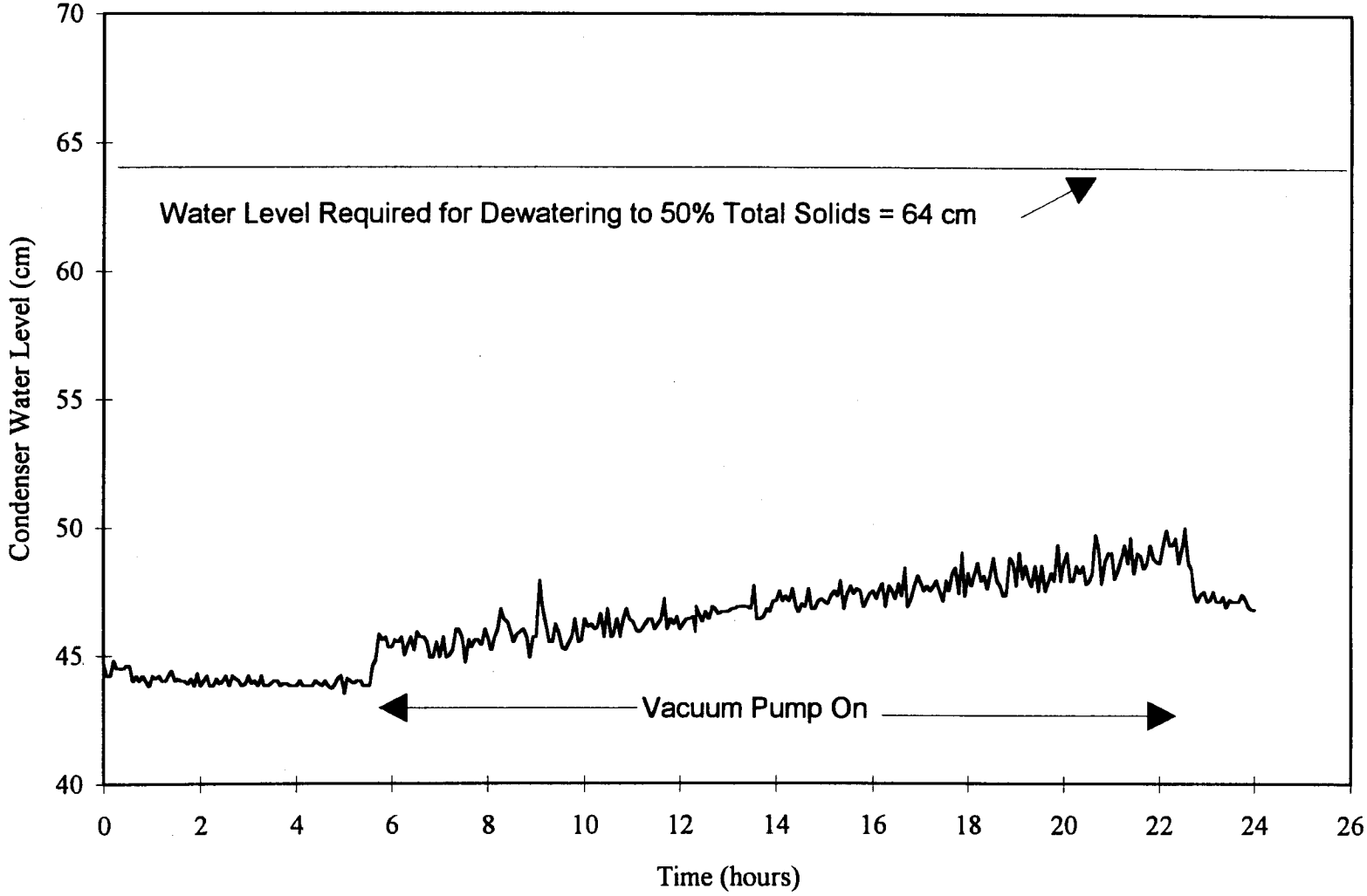


Figure 5 - Trial 2: Kiln Voltage vs Time

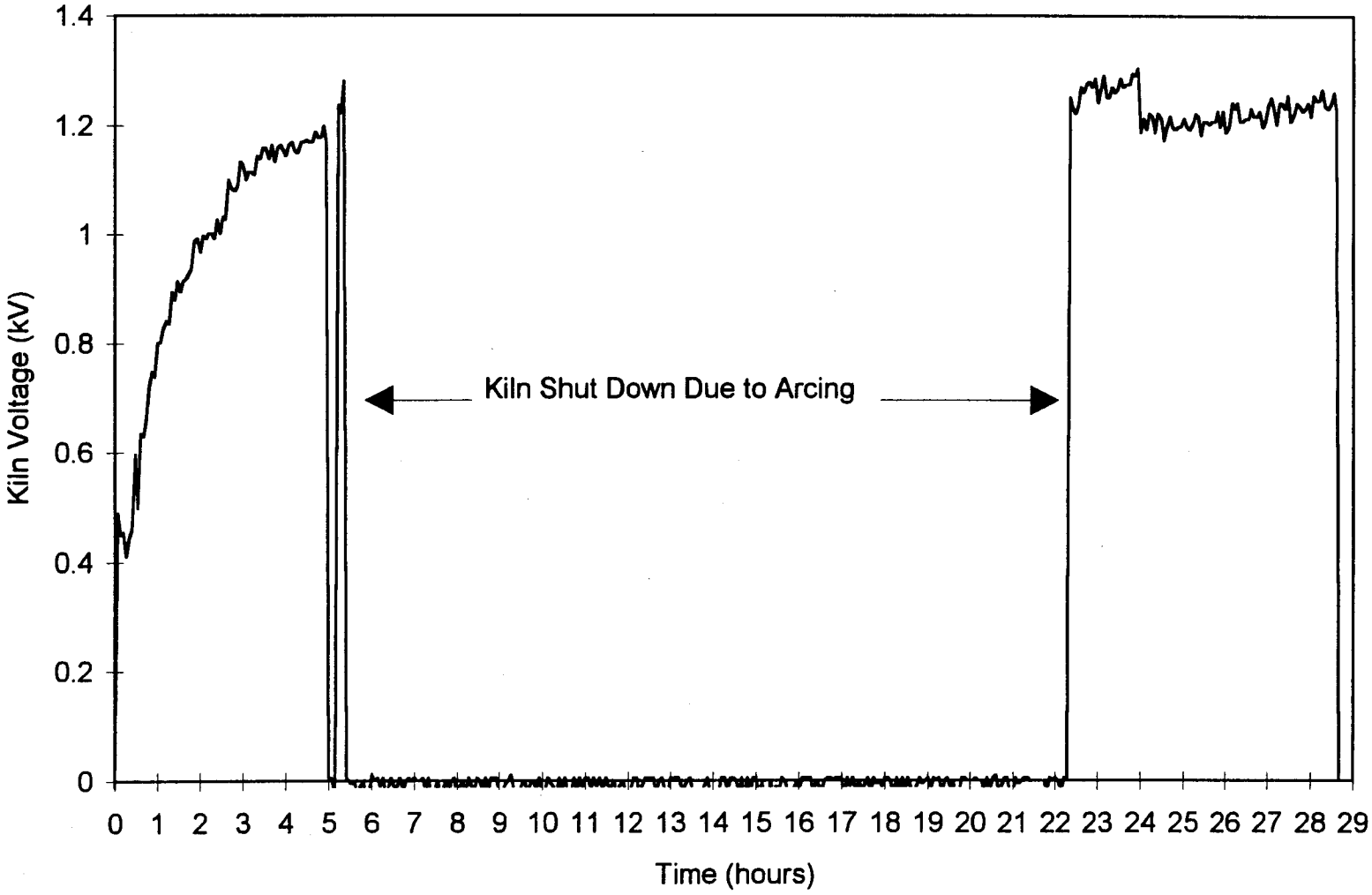


Figure 6 - Trial 2: Biosolids Temperature vs Time

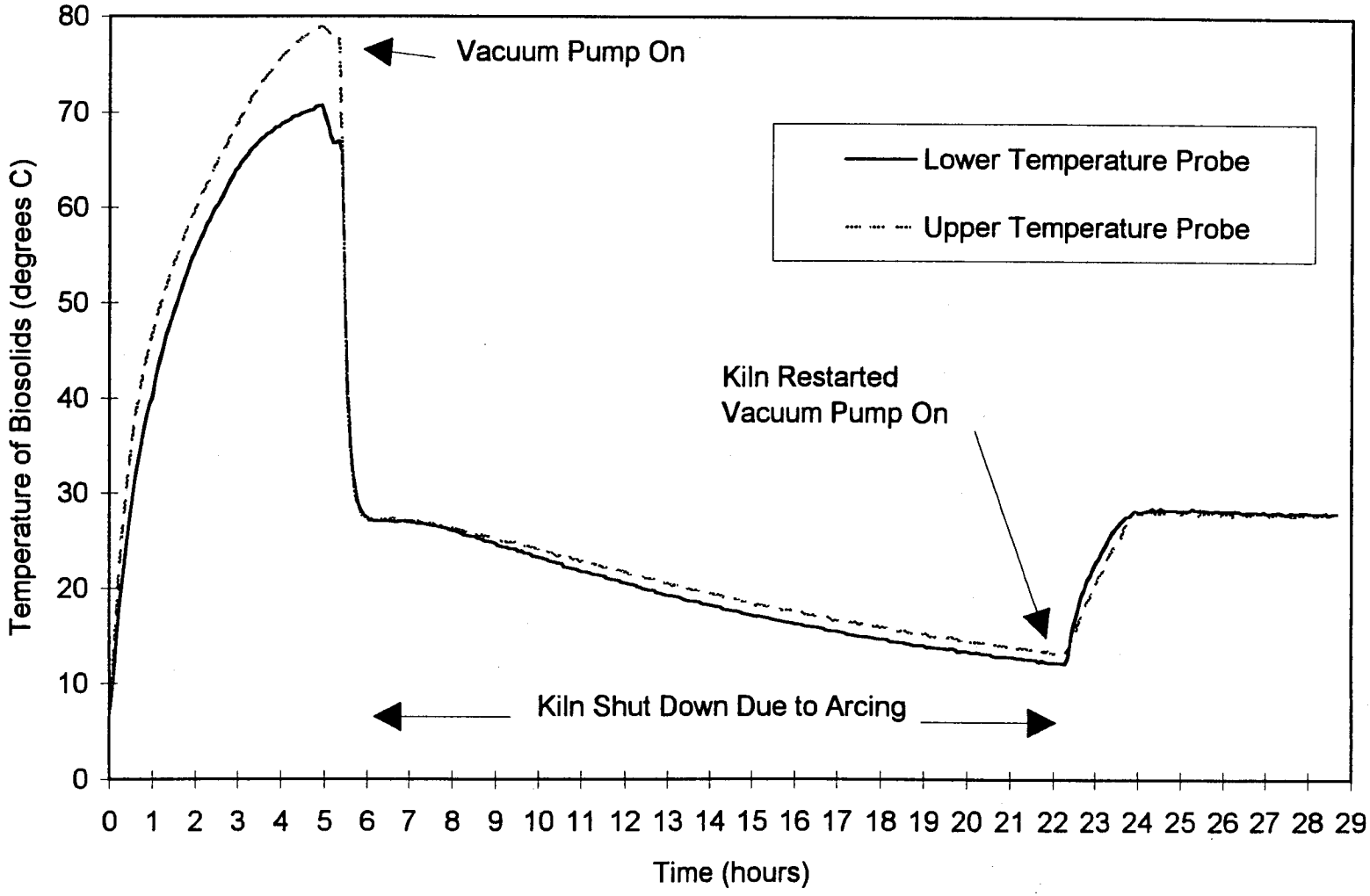


Figure 7 - Trial 2: Rate of Temperature Rise vs Time During Heating Phase Only

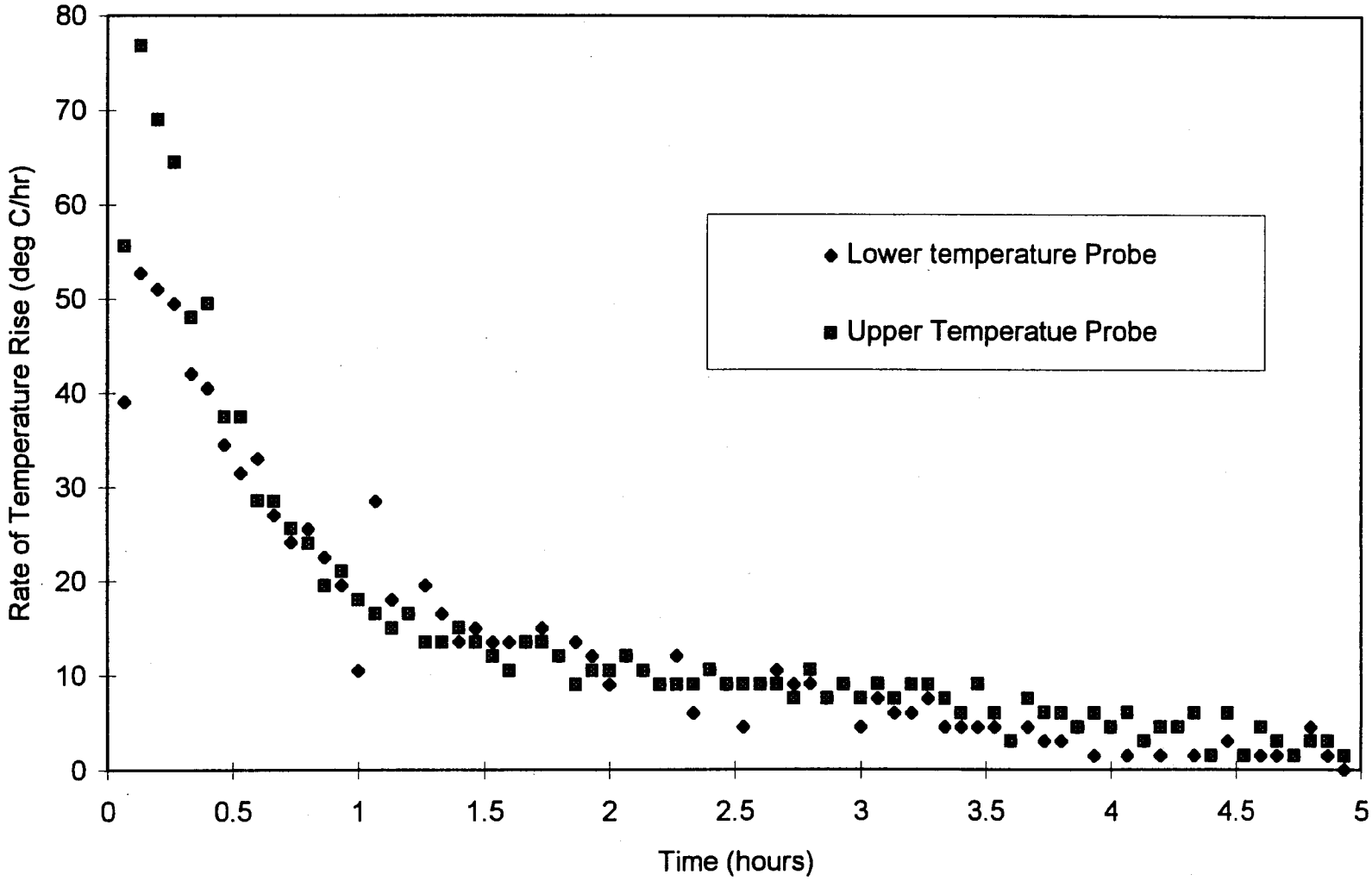


Figure 8 - Trial 2: Condenser Water Level vs Time

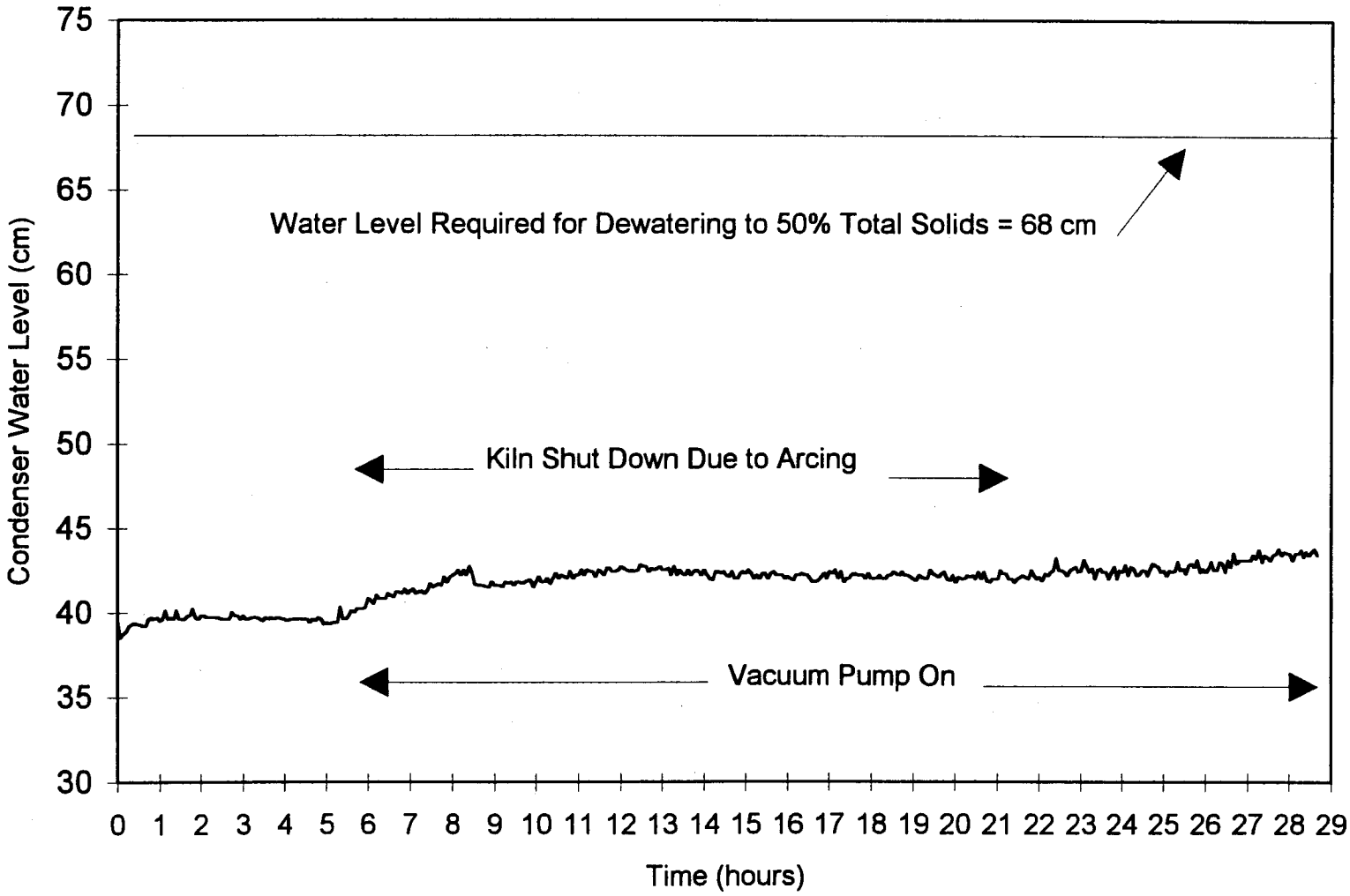


Figure 9 - Trial 3: Kiln Voltage vs Time - Heating Phase Only

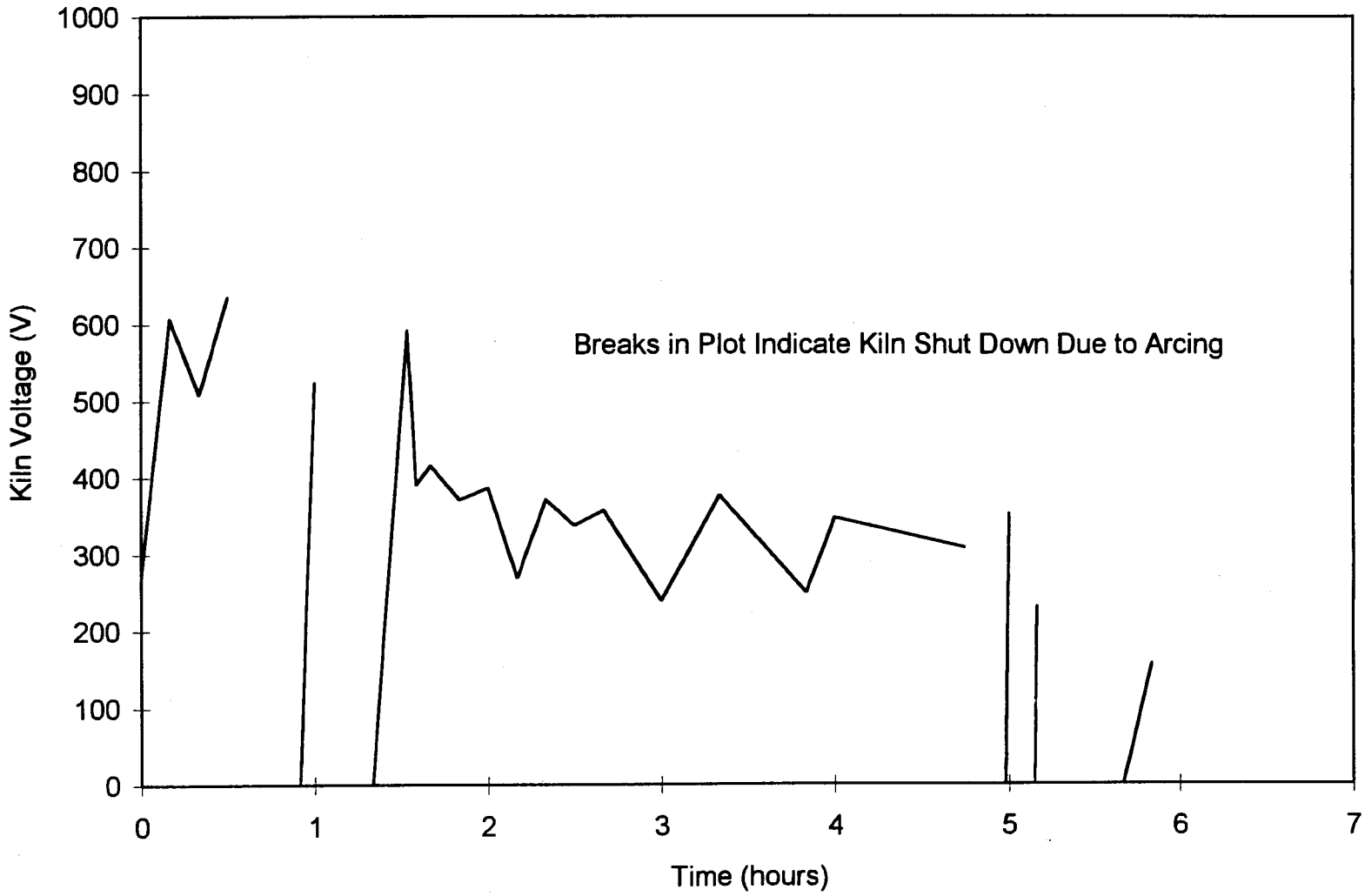


Figure 10 - Trial 3: Biosolids Temperature vs Time - Heating Phase Only

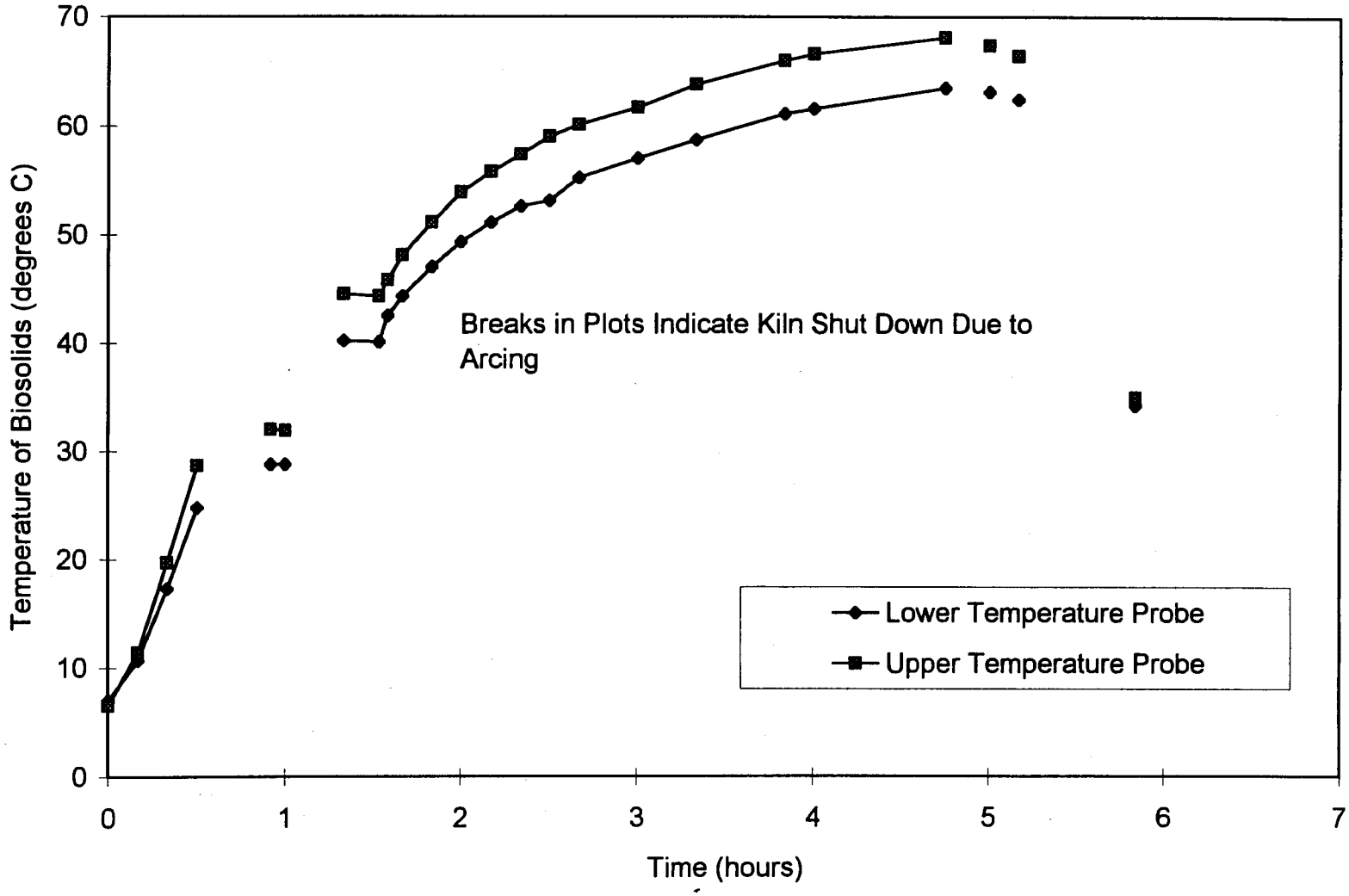


Figure 11 - Trial 3: Rate of Temperature Rise vs Time - Heating Phase Only

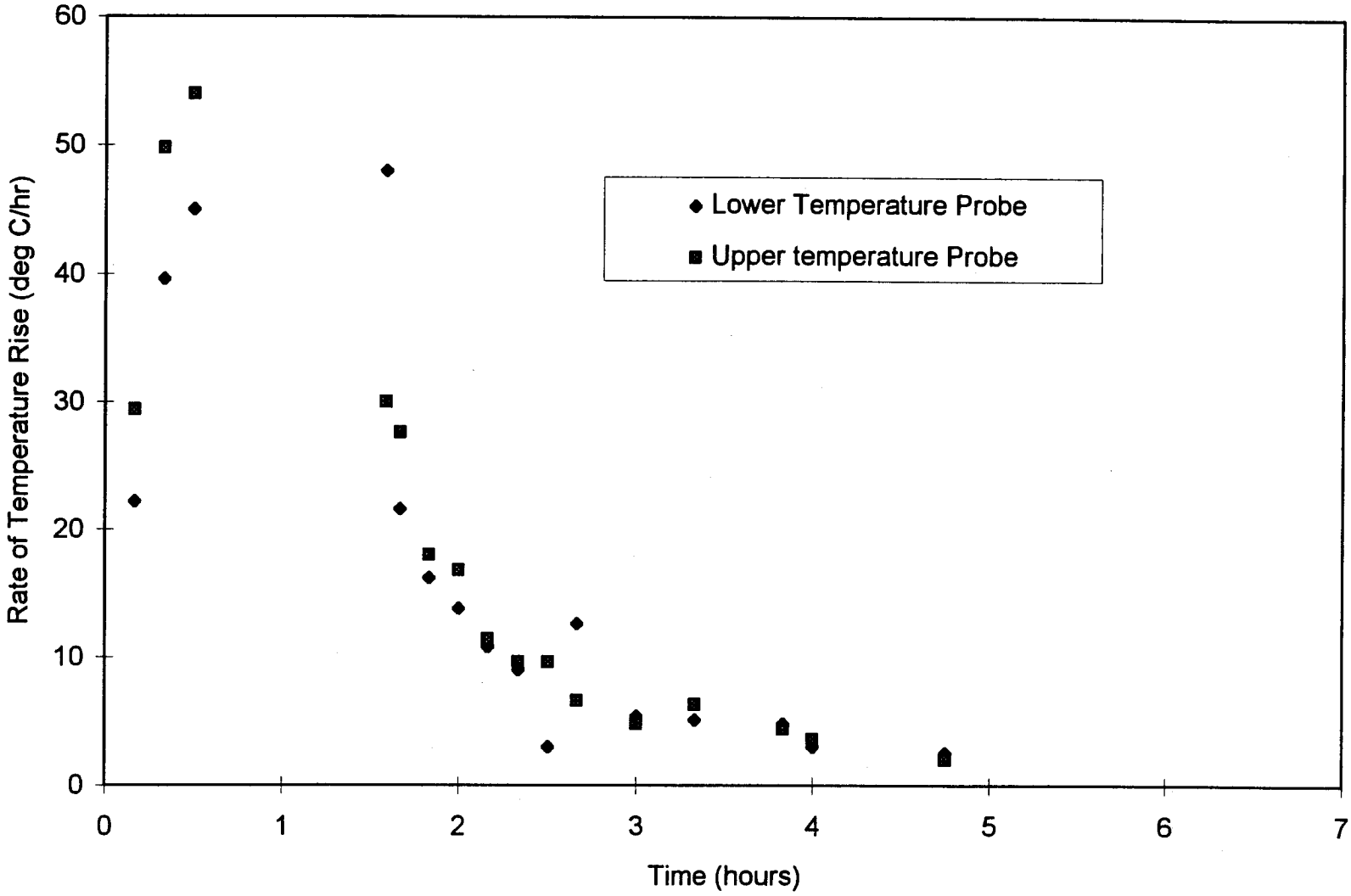


Figure 12 - Trial 4: Kiln Voltage vs Time

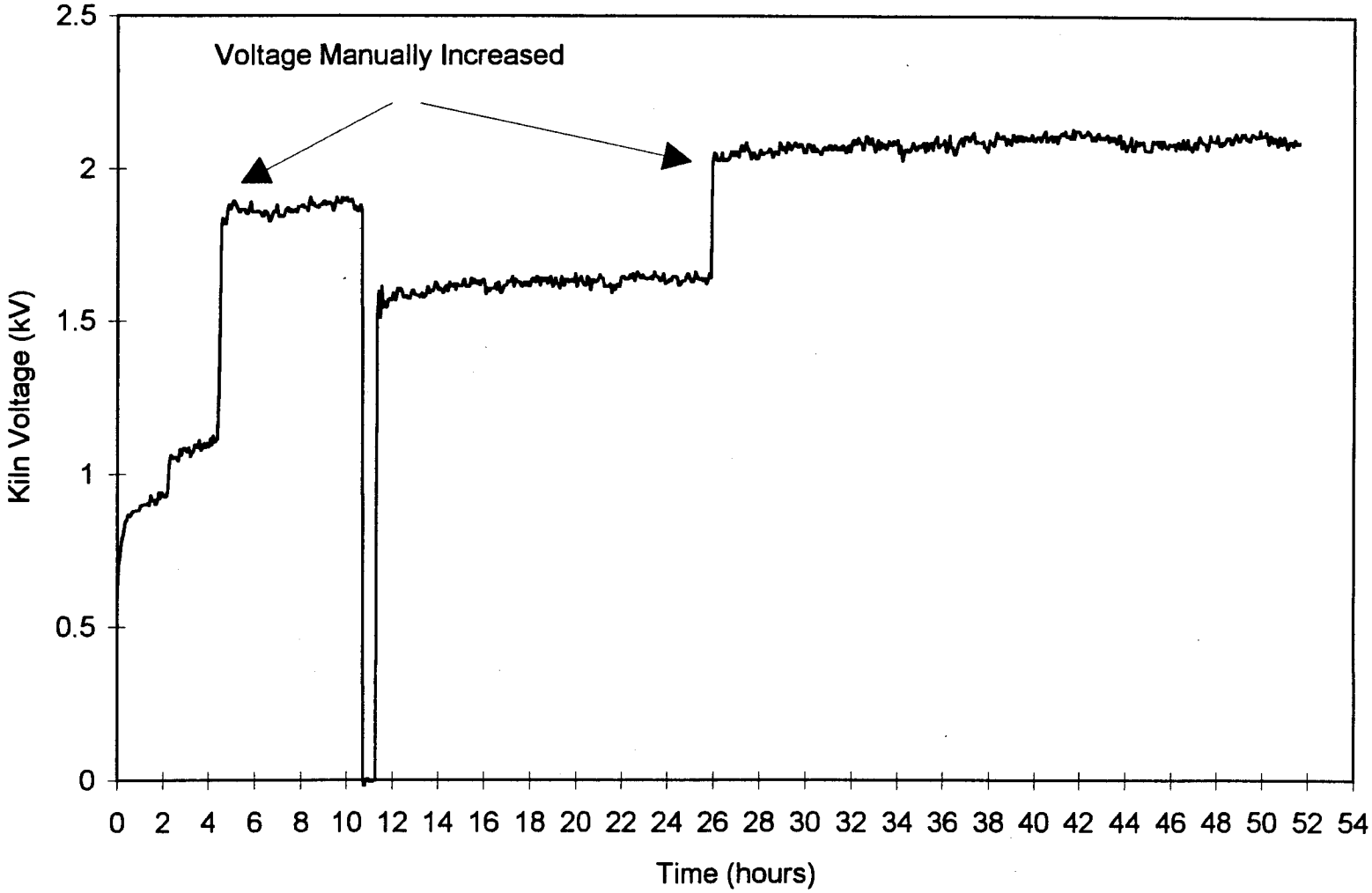


Figure 13 Trial 4: Biosolids Temperature vs Time

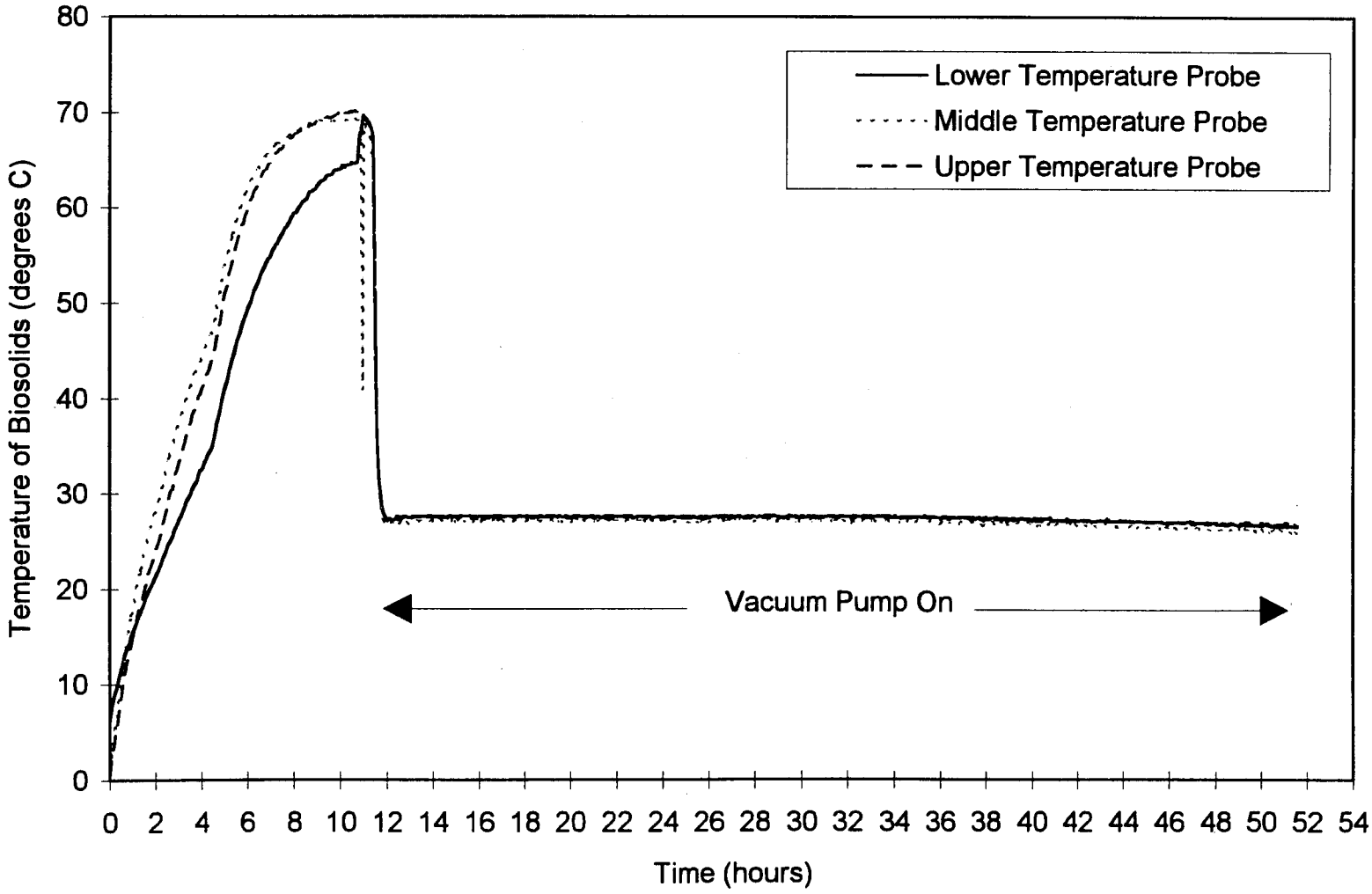


Figure 14 - Trial 4: Rate of Temperature Rise vs Time - Heating Phase Only

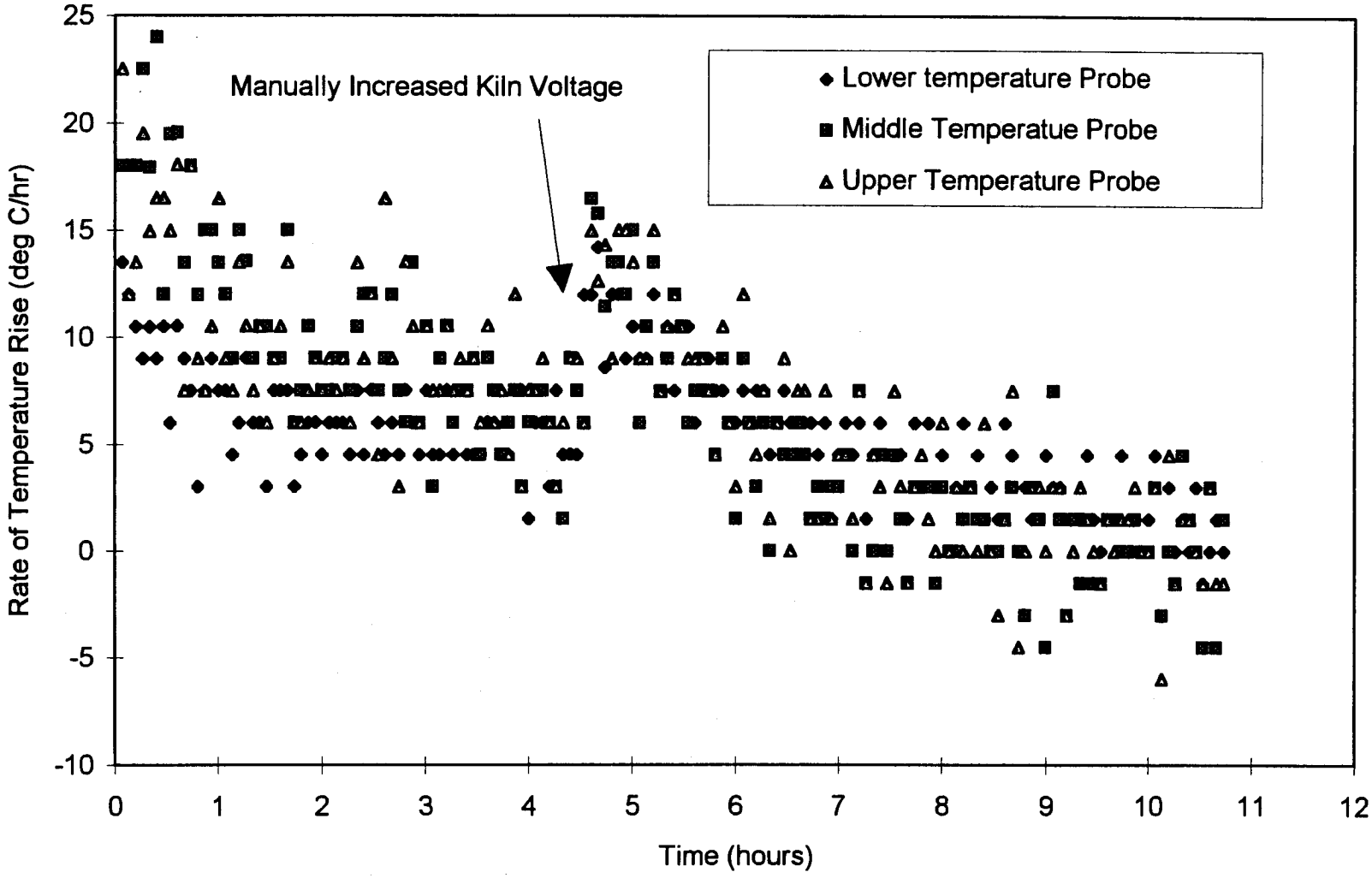
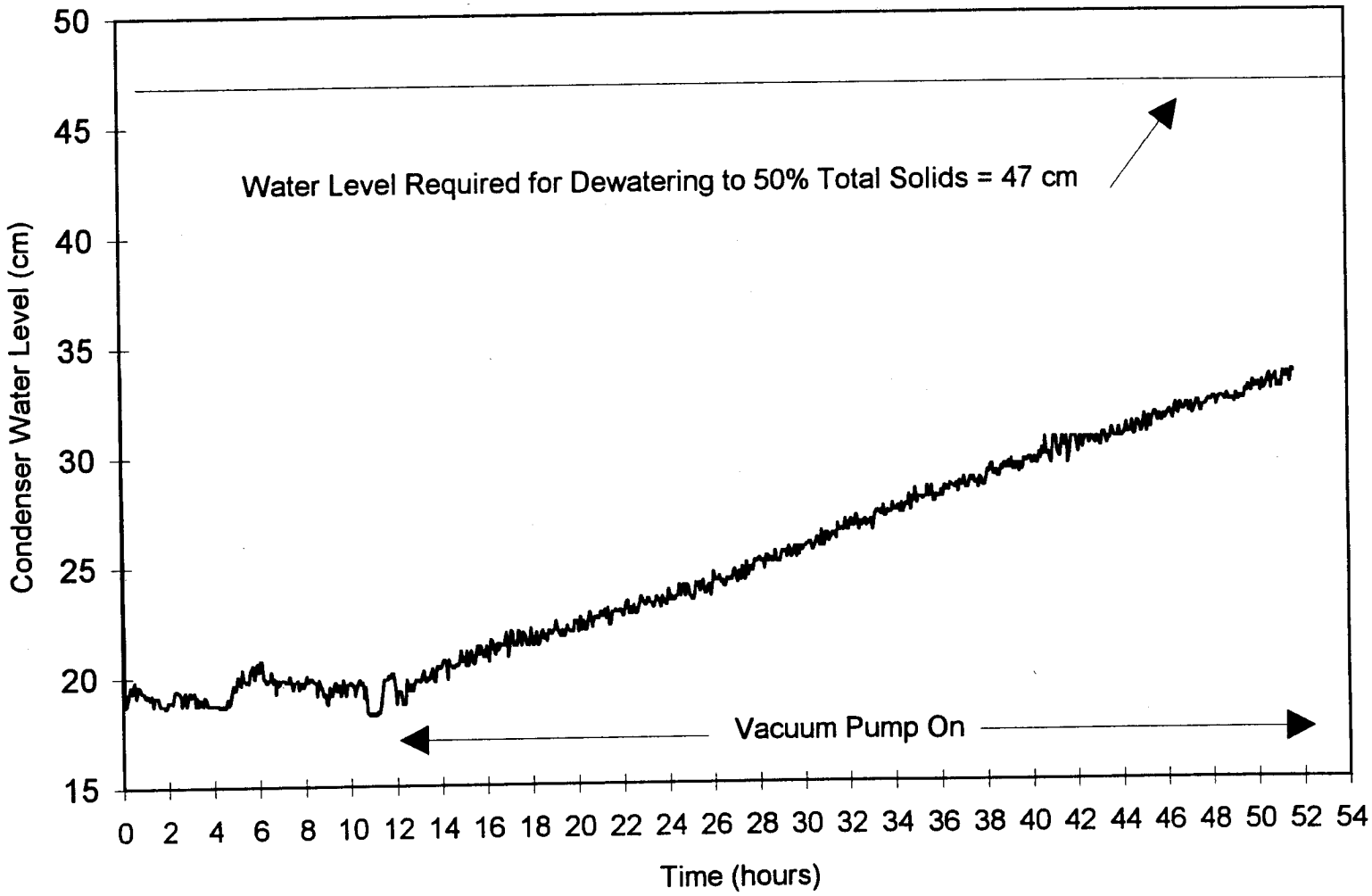


Figure 15 - Trial 4: Condenser Water Level vs Time



9.0 PHOTOGRAPHS

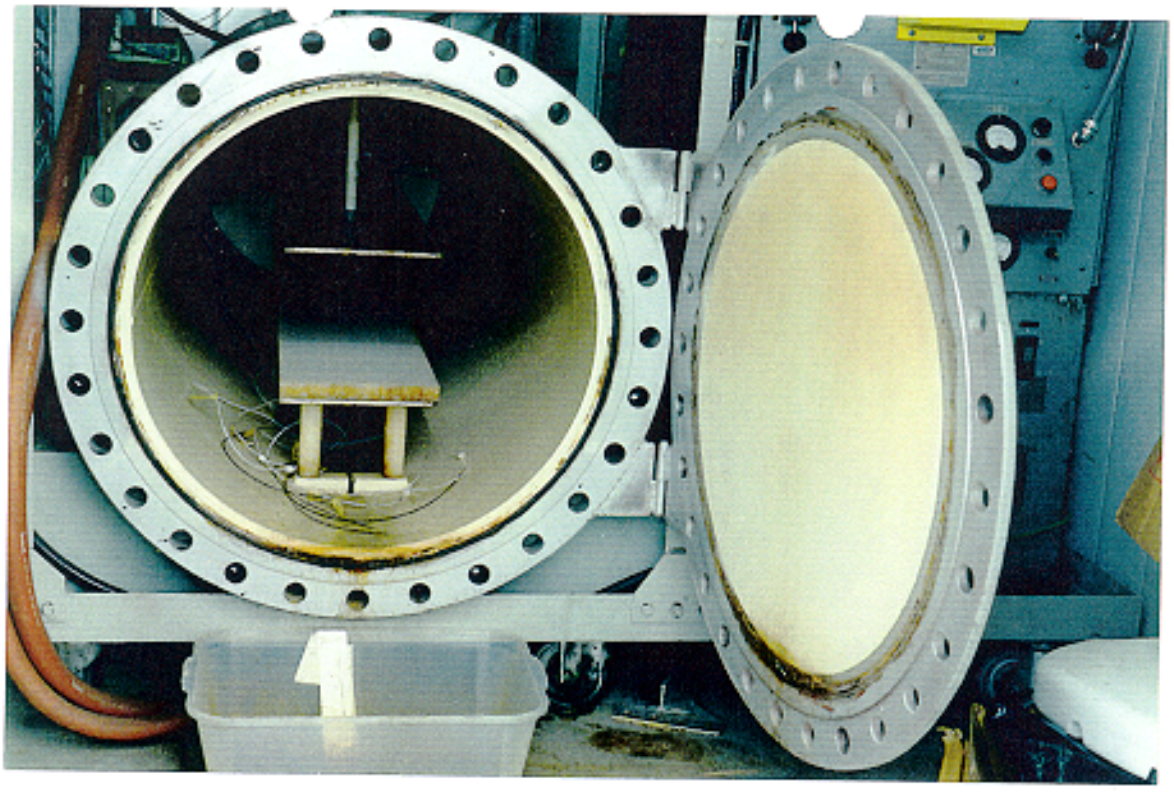


PHOTO 1 - RADIO FREQUENCY KILN

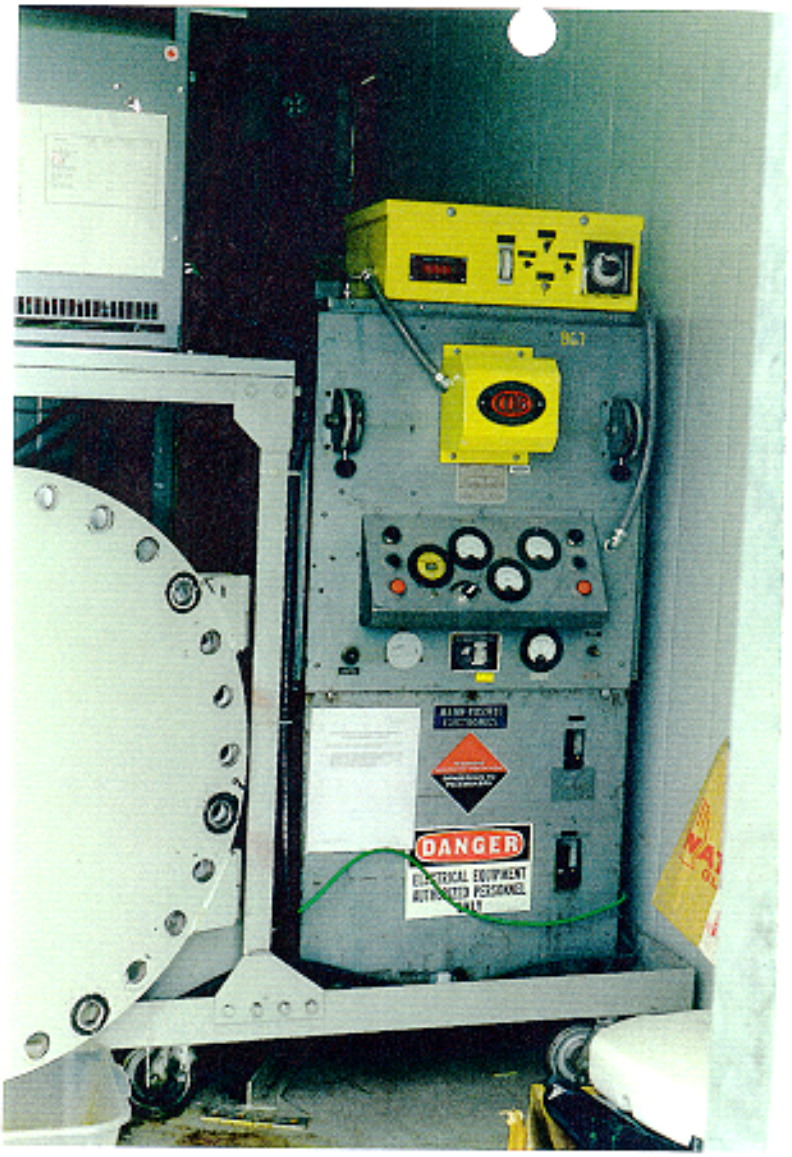


PHOTO 2 - RADIO FREQUENCY GENERATOR

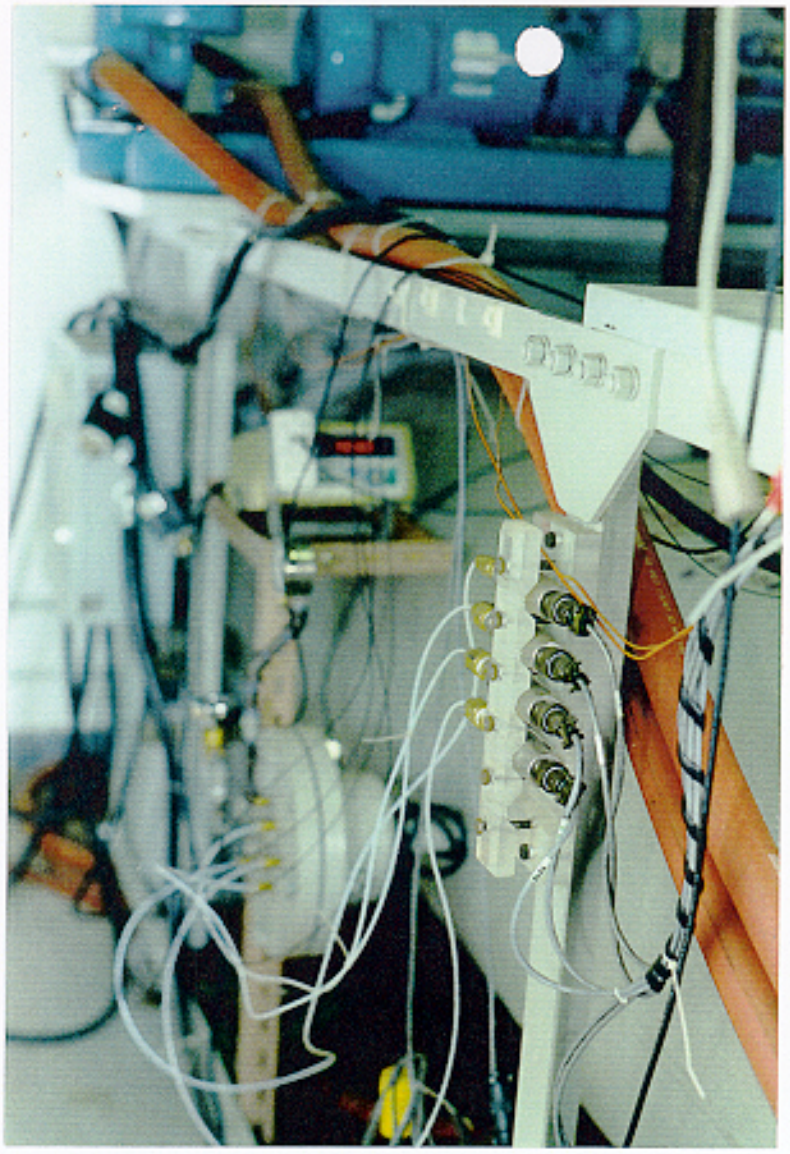


PHOTO 3 - TEMPERATURE/PRESSURE PROBES

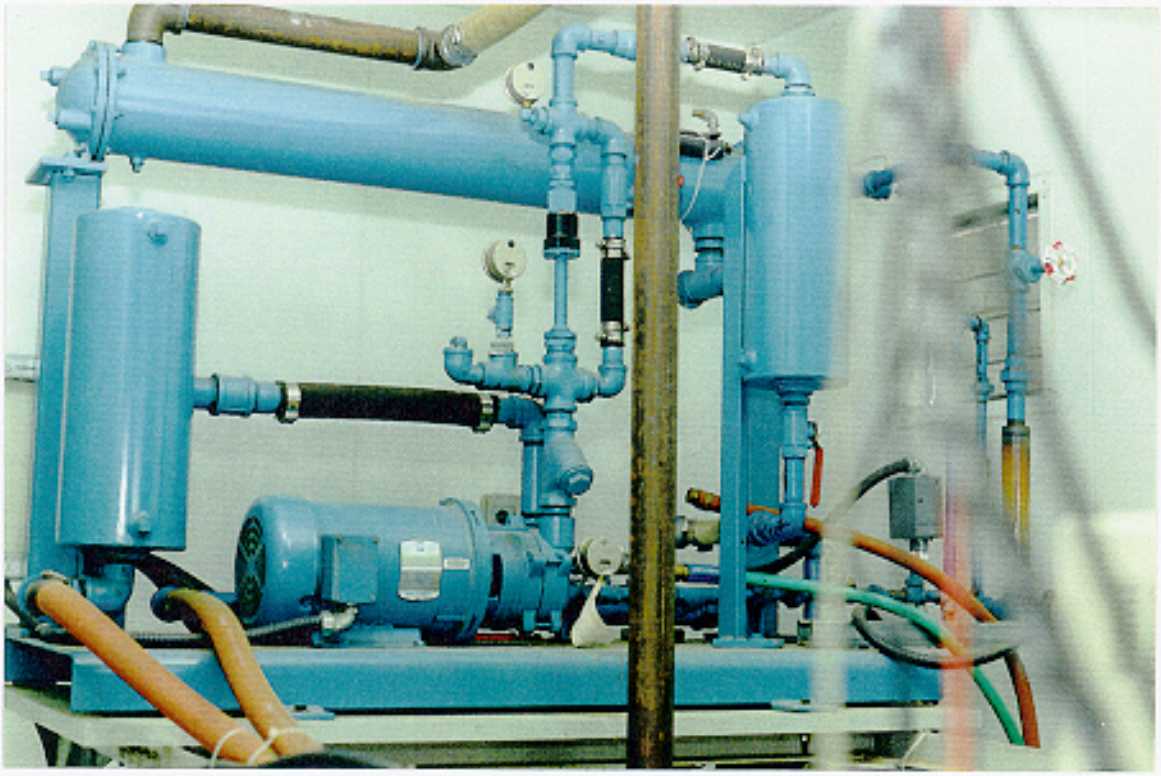


PHOTO 4 - VACUUM PUMP

PHOTO 5 - TRIAL 1 - BIOSOLIDS CONTAINERS WITH TEMPERATURE PROBES INSERTED ON LEFT SIDE

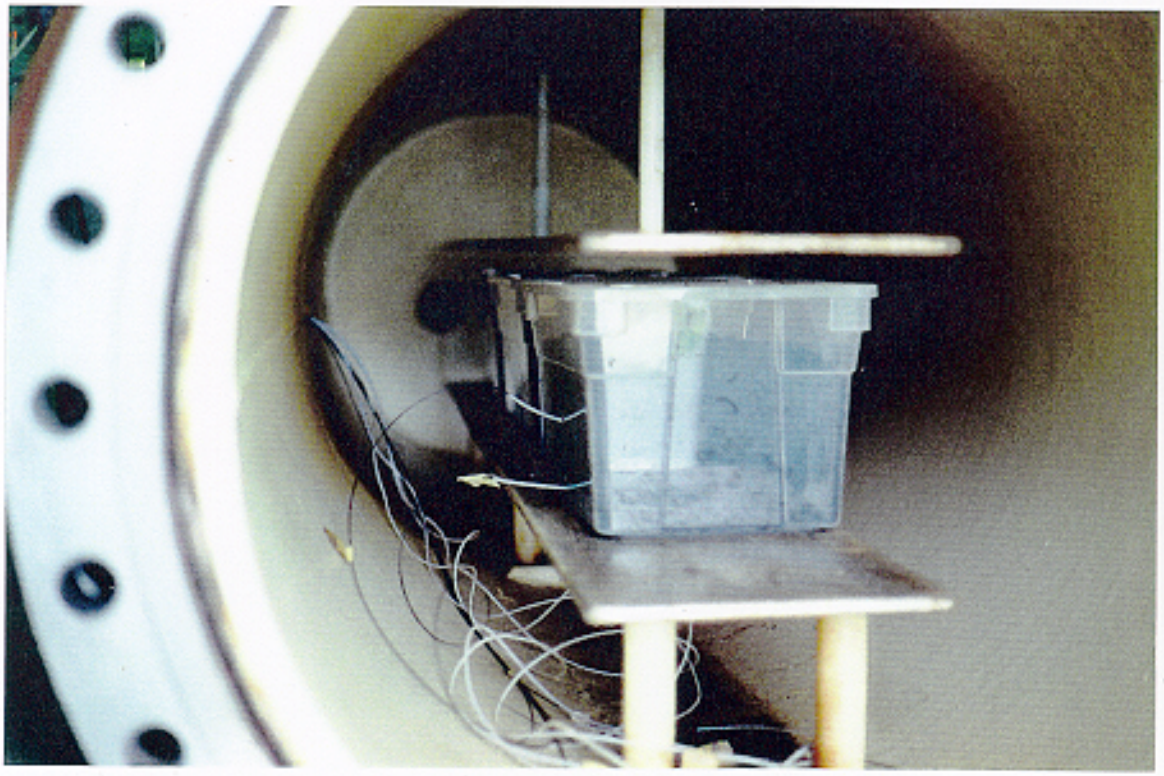


PHOTO 6 - TRIAL 1 BIOSOLIDS CONTAINERS

PHOTO 7 - TRIAL 3 - BIOSOLIDS CONTAINER AFTER HEATING PHASE (note melting along upper edges of container)

PHOTO 8 - TRIAL 4 - BIOSOLIDS CONTAINERS

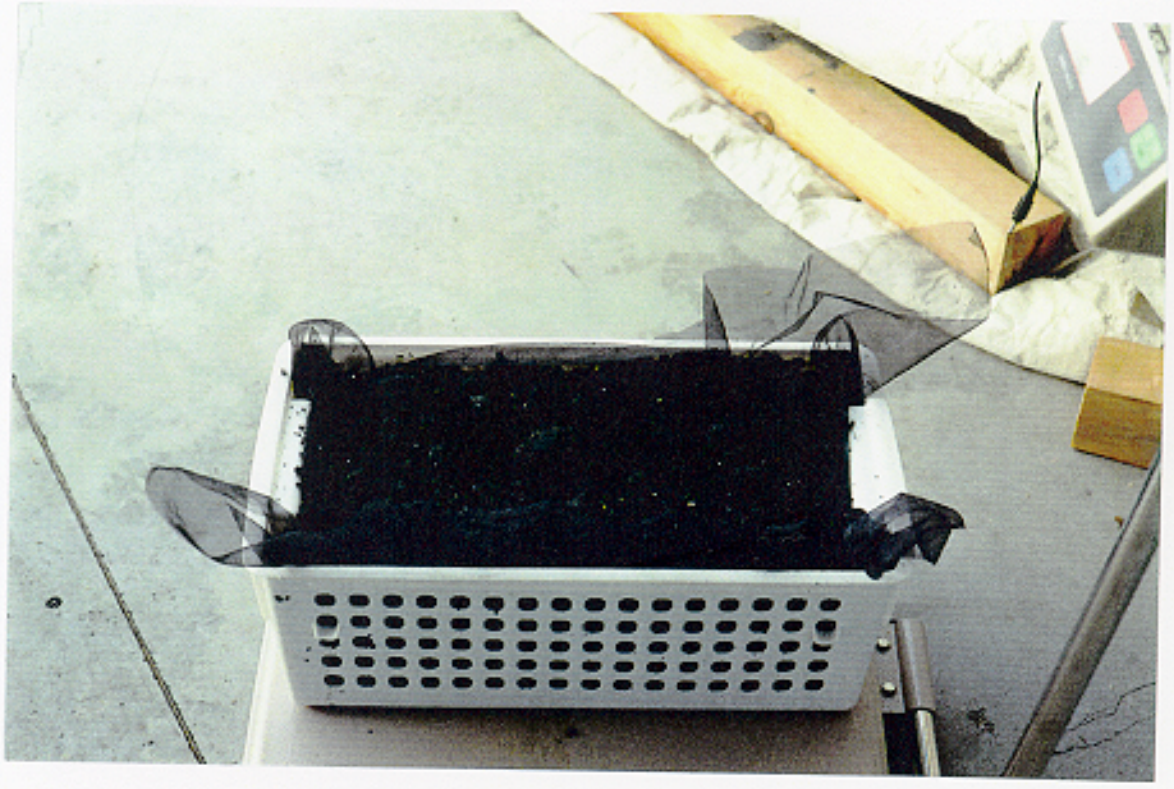


PHOTO 9 - TRIAL 4 - BIOSOLIDS BEFORE TREATMENT

PHOTO 10 - TRIAL 4 - BIOSOLIDS BEFORE TREATMENT

PHOTO 11 - TRIAL 4 - BIOSOLIDS AFTER TREATMENT
(note reduced volume)

CITY OF PRINCE GEORGE
RADIO FREQUENCY
TREATMENT OF PARTIALLY DIGESTED/DEWATERED BIOSOLIDS
FINAL REPORT

Appendix 1 - Laboratory Procedures

Methods - Laboratory of W.D. Ramey, University of British Columbia Department of Microbiology and Immunology

The Membrane Filtration (MF) assay used is described in the 18th edition of "Standard Methods for the Examination of Water and Wastewater".

The media used in m-FC media (BBL) supplemented with 0.1% Rosolic acid prepared as per manufacturer's directions.

Millipore filters #HAWG 047 S2 were used for the assay.

For the assay, 10 g of sample is mixed with 100 ml of sterile distilled water in dilution bottles. The bottle is vigorously shook 50 times and left to standard for 5 minutes to allow the large solid particles to sample. Addition 1 in 10 dilutions are made by removing an aliquot of the supernatant and resuspending it in a suitable volume of distilled water.

For the assay, volumes of diluted sample corresponding to known equivalent amount of sample are filtered through the membranes, which are then placed in plastic bags and submerged in a 44.5^0 C water bath for incubation for 22-24 hours. A blue colony is indicative of a fecal coliforms. Filters giving between 20 and 80 colonies are used in the calculation of the number of fecal coliforms of the original sample.

The Most Probable Number (MPN) assay used is described in the 18th edition of "Standard Methods for the Examination of Water and Wastewater".

The media used in A-1 (Difco) prepared as per manufacturer's directions. Each tube contains 10 ml of media with an inverted glass vial for detection of gas production.

For the assay, 10 g of sample is mixed with 100 ml of sterile distilled water in dilution bottles. The bottle is vigorously shook 50 times and left to standard for 5 minutes to allow the large solid particles to sample. Addition 1 to 10 dilutions are made by removing an aliquot of the supernatant and resuspending it in a suitable volume of distilled water.

For the assay, 5 tubes are inoculated for each dilution prepared. 1 ml of sample is used to inoculate each tube. The tubes are incubated at 35^0 C for 3 hours then incubated at 44.5^0 C for 21 hours. A tube is considered positive for fecal coliform when there is growth and gas production.

Methods - Environmental Engineering Laboratory, University of British Columbia, Department of Civil Engineering.

The methods used were as described above for the Microbiology Laboratory, except that the large solid particles were not allowed to settle prior to application to the filter in the membrane filter assay or prior to inoculation in the MPN assay.

CITY OF PRINCE GEORGE
RADIO FREQUENCY
TREATMENT OF PARTIALLY DIGESTED/DEWATERED BIOSOLIDS
FINAL REPORT

Appendix 2 - Review by Glade Technologies

Glade Technologies Inc.
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Ph (604) 399 - 0074
Fax (604) 399 - 0078
74230.3650@Compuserve.com

Date: April 3, 1996

To: Dr. Allan Gibb

From: **Rob Zwick**

Re: Commentary on "Radio Frequency Treatment of Partial Digested/Dewatered Biosolids"

Introductory Discussion

I must firstly commend your consortium in investigating the feasibility of this new application for RF/V drying technology. I've been working with this technology for 7 years now, and would never have predicted what the outcome of your investigation would be. Although your preliminary results were unsuccessful in the UBC laboratory RV/V kiln investigation, the information was very valuable in charting further directions should one wish to apply this technology to the environmental treatment of biosolids.

It might be interesting for you to note that I was independently approached to conduct a similar investigation for the city of New York, who have a massive problem in dealing with biosolids.

Your engineers correctly pointed out that the cause of unsuccessfully heating the biosolids was the fluid nature of the biosolids, and the resulting inability of the electrodes to uniformly heat the product. The resulting air gap created a case where high voltage arcing was occurring; which is one of the most serious issues related to RF/V drying. As always in RF/V drying, the radio frequency technology is the most critical aspect of the system.

There are a number of directions one now can take, after having assessed the results of your preliminary investigation. I would like to first discuss some of the general observations from a commercial perspective in applying RF/V drying technology, including those other than forest products.

RF/V Drying Costs

RF/V drying economics has been established as feasible when there is a substantial increase in product value as a result of this efficient, low-temperature drying method. For instance, we are presently applying the technology to dry high quality forage (hay) that is exported to Asian race horse markets. The increase in value of RF/V dried hay more than pays for the increased drying costs of this technology versus conventional high-temperature methods.

The amount of water required to be removed in agriculture products is similar to your requirements in drying biosolids. Based on our experience in the agriculture sector, your operating costs (including the capital cost of your dryer depreciated over 10 years) will be roughly the following:

1.	Natural gas dryer	$8.00/tonne
2.	Radio frequency dryer	$14.00/tonne
3.	Radio frequency/vacuum dryer	$20.00/tonne

The above costs include labor, material handling, energy and depreciation. In the case of the natural gas and radio frequency dryers, the high-temperature dried forage simply results in a drying cost, ie; there is no increase in value with the product. In the case of the RF/V dried forage, there is an improvement in product value anywhere from $50 - $100/tonne. Therefore, this expensive drying technology can easily pay for itself when there is an increase in product value.

We observe a similar drying economics for forest products. It has been shown (Avramidis and Zwick, 1996) that for high-valued appearance-grade lumber products, RF/V drying is more economical than conventional methods. But for lower-valued commodity wood products (such as SPF 2x4's), RF/V drying will never replace conventional drying technology. There are some isolated applications for RF/V dryers where it is feasible to dry lower-valued forest products. For instance, the solid packing of trim blocks (short pieces) or for a solid pile of sliced veneers allows for the economical RF/V drying of these wood products because conventional methods have exorbitantly high material handling costs. In summation, our experience has shown that RF/V drying has commercial applications if the dried product value is substantially increased or if there is a considerable material handling cost reduction.

RF/V Drying and Pasteurization of BioSolids

One would have to first establish what are the economic advantages with RF/V drying of biosolids. For instance, there are some obvious environmental benefits of closed-loop drying that might be of a commercial advantage for RF/V drying. If a significant economic advantage is established in having a closed-system drying process for biosolids, then that may warrant further investigation and development work for RF/V drying.

One can conservatively assume that biosolids drying costs will be $20/tonne with a commercial RF/V dryer (closed loop process) and $14/tonne by strictly dielectric heating and evaporation of the water (open system). I don't see any advantages of RF heating/drying over natural gas drying unless for material handling reasons. The operating cost for natural gas dryers are considerably less than for RF dryers. If the economics warrant any further investigation of RF/V drying (because of an increased value of the dried biosolids or possibly the commercial advantage of a closed loop drying process), then there will be several options available for further work.

Recommendations for Further Work

1. One should first do a detailed feasibility study on various drying technologies commercially available for water removal and pasteurization of biosolids. If you wish, Glade Technologies can provide assistance on evaluating the economics of RF/V and RF drying.

2. If the RF/V drying economics are warranted:

   a) Modification of existing laboratory RF/V kiln

      It is likely feasible the existing electrodes inside the laboratory RF/V kiln can be modified to dry viscous biosolids. RF engineering work will be required, coupled with some mechanical engineering and fabrication. Glade Technologies has qualified personnel on retainer to recommend and redesign the electrode arrangement. Budget price for the engineering is $5K. A proper RF electrode design will resolve the issue of nonuniform heating and consequently, the biosolids will be properly pasteurized

      If an engineering solution of the electrode redesign can be arrived upon, modification of the laboratory RF/V kiln will not cost much. Budget price is $10K.

      Dayton and Knight could then complete the experimental investigation and with the proper results, recommend the usefulness of RF/V drying technology for this application.

If the RF/V drying laboratory investigations are successful and the economics warrant the construction of a prototype biosolids dryer, then there are two options available:

   a) Construct a large batch dryer, based on the present RF/V kiln designs. The advantage in taking this route is that there is no development work required.

   b) Develop a continuous RF/V dryer, which Glade Technologies has a prototype design of, but has not been built yet. There would be R&D work necessary here, but at least half of the prototype development costs can be paid for by a variety of available government funding agencies.

      This continuous RF/V dryer is scheduled for development in 1997 by Glade Technologies, with the objective of applying RF/V drying technology to the agriculture seed market sector. It can technically be applied to drying/pasteurizing biosolids as well.

References

Avramidis, S., and R.L. Zwick. 1996. Commercial scale RF/V drying of softwood lumber - Part III. Energy consumption and economics. (submitted for publication, Forest Products Journal).