

• • • • • GROWTH OF CHLORELLA ON PRODUCTS FROM
THE INCINERATION OF HUMAN WASTES

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INTRODUCTION

The United States Air Force has for some years been faced with the problem of disposal of human wastes and other materials normally present in sewage at isolated sites in the Arctic. The conventional system of waste disposal involving water carriage and biological treatment has not been adopted at these sites because of problems presented by the extremely cold climate.¹

For the past four years members of the Civil Engineering Department at Northwestern University have been carrying out research studies under a series of contracts, monitored by the Arctic Aeromedical Laboratories, United States Air Force, aimed at developing methods of waste disposal which may be adapted to arctic conditions. A system for the disposal of human wastes using fuel oil as the carriage medium and incineration for the destruction of the organic matter in the wastes was developed and a pilot unit installed at Point Barrow, Alaska, in 1960.

The oil carriage and incineration system for the disposal of human wastes requires appreciable quantities of fuel oil for flushing toilets and thus is not adaptable for small installations having a crew of only a few men and no great demand for power or heat production. For these small installations some type of direct incineration was envisioned as being the most satisfactory method of waste disposal.

A number of commercial incinerator toilets have appeared on the market from time to time. Those which have been tested in our laboratories have been found to be unsatisfactory due to the presence of highly objectionable odors in the effluent gas stream.² These devices were found to operate essentially as distillation units never reaching high enough temperatures for complete combustion of the waste material until all of the water and most of the organic matter had been volatilized. Because of the lack of data upon which to base a rational design of a unit for the incineration of human wastes, a study was undertaken to determine the temperature, detention time, and oxygen requirements of such a unit.

Incineration is a process which might be employed as a part of the waste recovery system in a closed ecological system.³ In order to recover the nutritive value of the elements present in human waste the organic matter must be broken down into compounds which can be assimilated by algae or other food organisms. This conversion of the waste material to plant nutrients may be carried out either biologically or chemically. The biological processing of the waste material does offer some attractive possibilities but also some interesting and difficult problems. The chemical oxidation of the waste organic matter, either with oxygen at elevated temperatures and

pressures or with some other oxidizing agent, might have some advantages over the biological processes in terms of reliability and weight economy.

Because of the possibility of using incineration as a method of converting wastes into nutrients for plants, it was decided to combine the study of the incineration of human wastes with an investigation of the growth of Chlorella on the incineration products. The products from the incineration include both gaseous products and residual ash. The major nutrients, carbon, nitrogen, hydrogen, and oxygen, should be present in the gaseous incineration products. However, phosphate, magnesium, sulfate, and the micronutrients should be present in the ash.

Although the primary purposes of this investigation were the collection of data upon which the design of an incinerator for human wastes could be based and a study of the recovery of the incineration products as nutrients for algae, it was necessary to give some consideration to the possible configuration of the completed incinerator before initiating the collection of data. As shown in Flow Sheet 1, the incineration was envisioned as a two stage process. The first stage is the volatilization of organic matter and the second stage, the actual oxidation of the volatilized organic matter with oxygen.

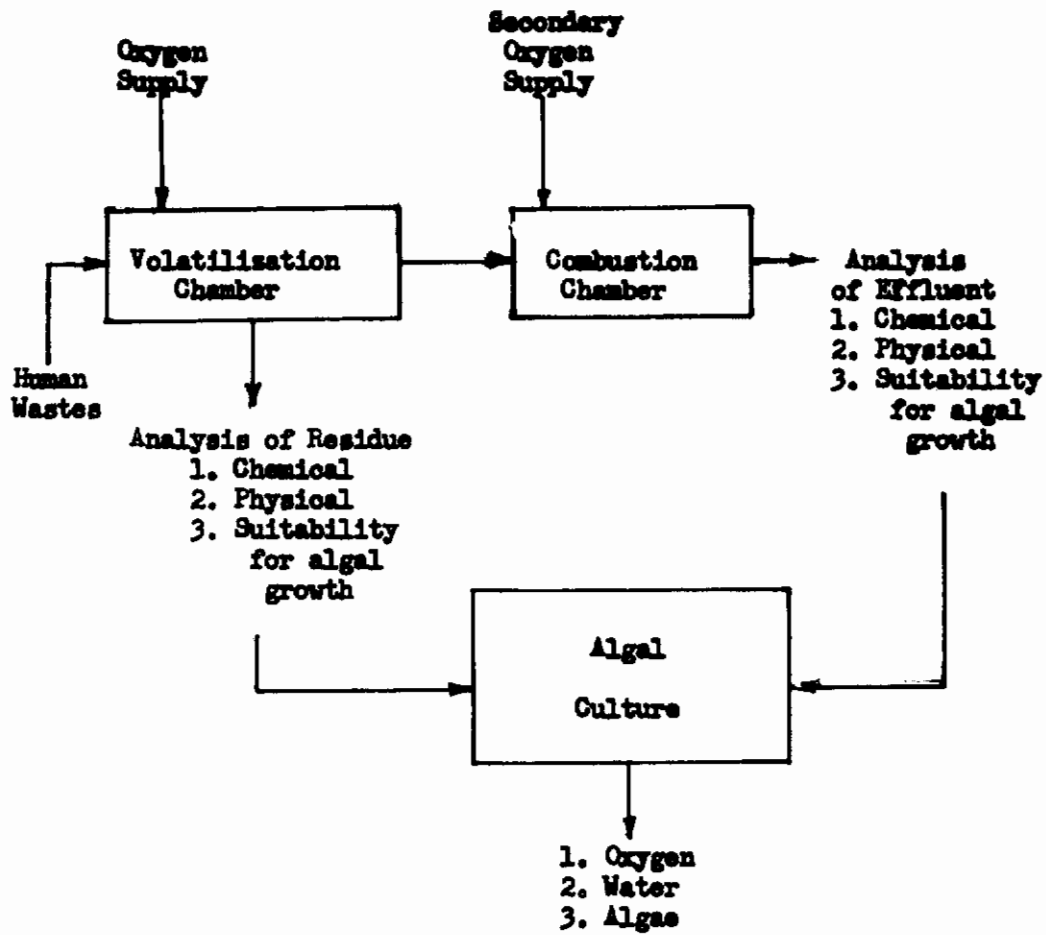
The volatilization of the wastes can be carried out at a relatively low temperature but will consume most of the heat input to the process because of the need to evaporate water. The volatilized organic matter has an extremely disagreeable odor and probably contains some toxic materials, so it must be retained in the incinerator until it has been completely oxidized. The residual ash remaining after volatilization of the organic matter must be heated for a duration of time at a sufficiently high temperature such that all of the carbon is oxidized and/or volatilized, but at the same time the ash should not be subjected to temperatures so high that some of the possible nutrients present for algae growth are converted to an insoluble form.

In the combustion stage of the process, the volatilized organic matter must be mixed with oxygen and allowed sufficient time for reaction at any given temperature such that all the carbon present is oxidized to CO_2 . The gaseous products from the combustion may then be cooled and stored for use as nutrients for the growth of food organisms.

This report covers the studies of the first stage of the incineration process; i.e., determination of the time and temperature requirements for the complete volatilization of the organic matter of human wastes, and the investigation of the properties of the residual ash as a nutrient for algae. Studies of the second (combustion) stage of the incineration process and of the value of the gaseous combustion products as algal nutrients are presently in progress.

MATERIALS AND METHODS

The first requirement for this investigation was to select a procedure for obtaining samples of human wastes and to determine the characteristics



Flow Sheet 1. Schematic diagram of waste incineration study.

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of the waste. Samples of urine and feces were collected separately and mixed at a fresh weight ratio of eight parts urine to one part of feces. The mixtures were blended in a Waring blender for a period of at least 20 minutes to insure uniformity. The percentage of solids in the samples was determined by drying at 103°C and weighing.⁴ A semi-micro carbon and hydrogen apparatus was used to determine the fraction of ash, volatile matter, and carbon in the dried samples.⁵ Approximately 20 mg samples were used. The weight remaining after ignition at 850°C for a period of thirty minutes in the carbon and hydrogen apparatus represents the fraction of ash; the weight loss represents the fraction of volatile matter; and the amount of carbon in the CO₂ produced upon ignition represents the carbon content in the sample.

Initial studies of the volatilization of the organic matter were carried out in a muffle furnace. During each test the muffle furnace was operated at a constant temperature in the range from 300°C to 700°C. The variation of the residual weight and residual carbon with respect to time for a given temperature was determined. The carbon content of the residue at any given time was determined by analyzing a 20 mg sample with the carbon and hydrogen apparatus. The amount of sample removed for each carbon analysis was recorded and the weight remaining as a function of time can be calculated from a knowledge of the residual weight, amount of sample used for the carbon determinations, and the assumption that the fractions removed would have lost weight at the same rate as that observed for the remainder of the sample. Solubility of the residue after ignition in both distilled water and 0.02N HCl was determined by filtering 100 ml of the solvent through a Gooch crucible containing the residue, drying at 103°C, and noting the weight loss.

While these initial studies were being completed, a pot furnace was set up for studies of the volatilization of the organic matter from human wastes in a chamber through which the flow of air or oxygen could be controlled. The pot was a steel container with gas tight seals made of "fibrafax" and equipped with a thermocouple well. The temperature controller used with the pot furnace can maintain the desired temperature within ±5°C. Samples of the dry solids from human wastes were introduced into the pot and held at constant temperatures in the range from 200°C to 700°C. The rate of air supplied to the pot was varied from about 1 l/min/gram of sample to about 7.5 l/min/gram of sample. Rotameters with 2% accuracy were used to meter the rate of air supply. The effluent gases from the pot were passed through a combustion furnace; however, during the experiments described herein the apparatus for collection and sampling of these gases were not in operation. The residual weight and residual carbon with respect to time for a given temperature and rate of air supply and the solubility of the residue in distilled water and 0.02N HCl were determined as described previously.

Samples of the residual ash from the volatilization experiments were collected over a period of months for use in determination of its value as a nutrient for algae. In the first series of experiments various amounts of the ash were suspended in distilled water to provide a medium for growth of algae. Dextrose, urea, and ethylenediaminetetraacetic acid (EDTA) were added in various concentrations to the several cultures to supply a carbon source, a nitrogen source, and a chelating agent, respectively. The cultures were inoculated with a strain of Chlorella pyrenoidosa and illuminated at

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150 foot candles. Samples were removed from the cultures each day and cell concentrations determined by counting in a hemacytometer.

In a second series of experiments carbon was supplied to the cultures by aeration with 1% CO₂ in air and the intensity of illumination was increased to 200 foot candles. In this series of experiments the need for supplementation of the ash with a nitrogen source and with a chelating agent was again studied. In particular, this series of experiments was an attempt to discover the ratio of nitrogen to ash at which some nutrient in the ash became limiting.

RESULTS

The results of the analyses of nine raw samples of the 3 to 1 mixtures of urine and feces are presented in Table I. The total solids in the samples varied from 29.1 to 65.0 grams per liter with an average of 48.6 grams per liter. Of the dry solids present, the average carbon content was 36.9%; the average volatile matter, 82.1%, and the average ash, 18.0%. Each entry in the table is the arithmetic average of three or five determinations which were made on each sample. The variation in the characteristics of the several mixtures of urine and feces probably reflect changes in the diet and water consumption of the subjects from whom the samples were obtained. Considerably less variation might be expected in the characteristics of the wastes from a subject on a monotonous diet and a strict water ration.

TABLE I

Analysis of Raw Samples of Urine and Feces

Sample	Solids (%, wet weight)	Carbon (%, dry weight)	Volatile Matter (%, dry weight)	Ash (%, dry weight)
1	—	34.7	78.9	21.2
2	4.79	28.2	72.3	27.4
3	6.19	40.6	78.8	21.2
4	3.23	38.4	90.2	9.7
5	2.91	41.9	88.4	11.6
6	—	48.8	91.2	8.8
7	6.50	25.3	78.3	22.4
8	6.50	32.5	77.6	22.7
9	3.89	42.1	83.3	16.7
Avg.	4.86	36.9	82.1	18.0

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As indicated by the data presented in Table II and plotted in Figure 1, the time required to reach constant weight decreases rapidly with increasing temperatures, particularly with temperatures above 400°C. At 300°C it required 18 hours for the sample of waste to reach a constant weight and 1.3% of the original carbon was still present in the ash. At 400°C only one hour was required for volatilization of the organic matter and 99.4% of the carbon was driven off. Ignition temperature of the dried urine and feces sample in a free atmosphere was observed to be about 425°C. The time necessary to reach constant weight at temperatures above 425°C reflect both more rapid oxidation at the higher furnace temperatures and the much higher flame temperature.

TABLE II

Carbon Remaining after Volatilization in Muffle Furnace

Temperature (°C)	Time to Constant Weight (hours)	Weight Remaining (%, dry weight)	Ash (%, dry weight)	Volatile Matter Loss (%, dry weight)	Carbon Remaining (%, dry weight)
300	18	18.3	9.7	90	1.30
400	1	35.0	27.3	90	0.62
500	0.5	12.2	11.6	99	0.17
600	0.5	31.2	27.3	95	0.17
600	0.2	12.2	11.6	99	0.19
700	0.2	11.7	9.7	98	0.21

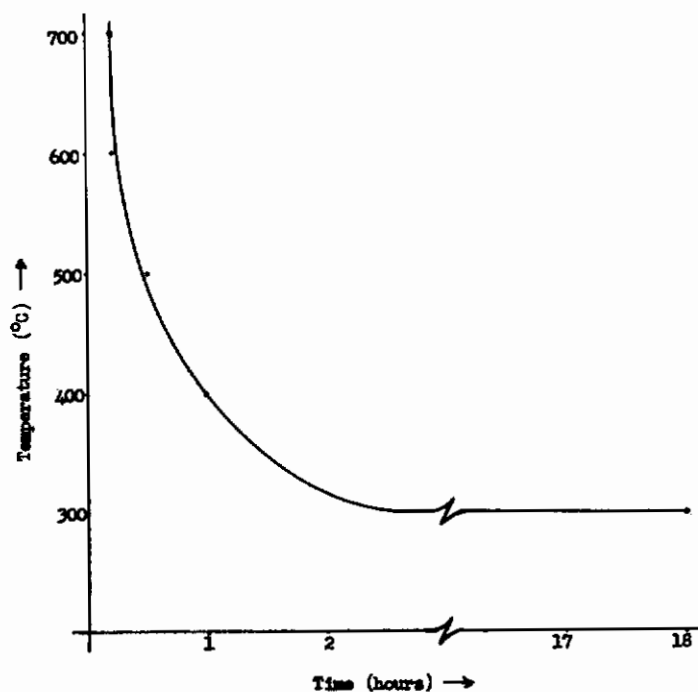


Figure 1. (left)

Time Required for Sample
to Reach Constant Weight

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The data collected on the volatilization of the waste in the pot furnace at 400°C did not indicate as rapid nor as complete volatilization as was obtained with the muffle furnace, as indicated in Table III. Although the rates of air supply to the pot furnace were more than the theoretical air requirements, experiments have indicated that better volatilization of the wastes may be obtained at higher rates of air supply. Typical curves giving the loss of volatile matter and the loss of carbon from the pot furnace are plotted in Figures 2 and 3, respectively.

TABLE III

Carbon Remaining after Volatilization in Volatilization Chamber

Temperature (°C)	Air Supply (l/m/gm)	Duration of Volatilization (min.)	Carbon Remaining (% dry weight)
400	7.56	241	1.22
400	2.08	248	2.81
400	1.01	240	1.51
300	7.56	240	44.0
300	7.56	240	41.6
200	7.56	450	41.4
600	7.56	15*	0.12

* Additional time after 450 min. at 200°C

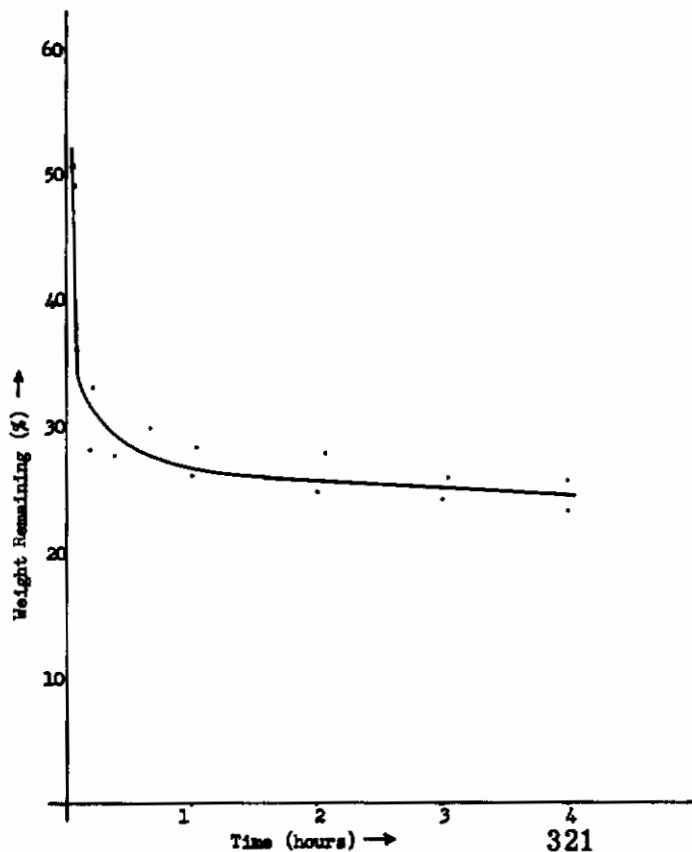


Figure 2. (left)

Volatile Solids vs
Time at 400° C

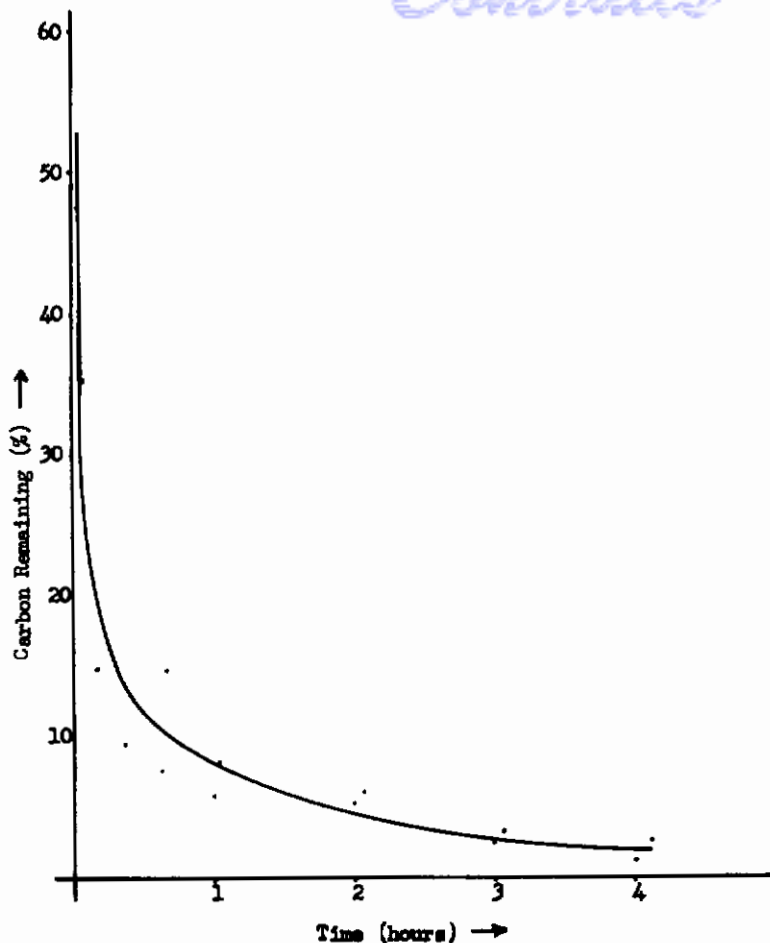


Figure 3. (left)

Carbon Loss vs
Time at 400° C

The results of the determination of the solubility of the ash is presented in Table IV. The solubility of the residual ash was apparently unaffected by volatilization temperatures in the range 300 to 600°C. Some determinations indicated a lower solubility for samples which were exposed

TABLE IV

Solubility of Residual Ash After Ignition in Muffle Furnace

Temperature (°C)	Duration of Volatilization (hours)	Solubility of Ash	
		Distilled Water (%, dry weight)	0.02 N HCl (%, dry weight)
300	96	49	75
300	96	86	98
400	2	69	79
600	2	84	92
600	2	70	94
700	0.5	37	73
700	0.5	70	96

to 700°C, although this was not consistently true. Solubility in 0.02N HCl was consistently greater than solubility in water for all samples and was nearly 100% for some samples.

The data presented in Table V showed that the residual ash from the volatilization of human wastes contains all of the required nutrients for algal growth except carbon and nitrogen. Supplementation of the ash with dextrose alone or with a combination of dextrose and EDTA did not produce algal growth. However, those cultures to which urea was added as a nitrogen source showed good growth either with or without dextrose or EDTA in the medium. Ash concentration from 30 mg/l to 120 mg/l proved to be a good source of all nutrients except carbon and nitrogen. However, when the ash was provided at concentrations of 5 gm/l no growth was observed even though the cultures were supplemented with dextrose and urea. The presence or absence of EDTA had little effect upon the growth of the algae in any of the cultures.

TABLE V

Chlorella Growth on Ash with Organic Carbon Source

Culture Number	Components of Medium				Generation Time (days)
	Ash (mg/l)	Dextrose (mg/l)	Urea (mg/l)	EDTA (mg/l)	
1	30	10	0	0	no growth
2	60	10	0	0	no growth
3	90	10	0	0	no growth
4	120	10	0	0	no growth
5	30	10	10	10	1.06
6	60	10	10	10	1.18
7	90	10	10	10	1.20
8	120	10	10	10	1.52
9	30	0	10	0	2.33
10	30	0	10	0	2.10
11	30	0	0	10	no growth
12	30	0	0	10	no growth
13	30	10	10	0	1.74
14	30	10	10	0	1.89
15	30	10	0	10	no growth
16	30	10	0	10	no growth
17	100	10	10	0	0.51
18	100	10	10	10	0.42
19	1000	10	10	0	0.28
20	1000	10	10	10	0.26
21	5000	10	10	0	no growth
22	5000	10	10	10	no growth

Conclusions

The results of the experiments on the growth of algae in batch cultures aerated with 1% CO₂ in air are presented in Figures 4 and 5. The cultures whose cell counts are presented in Figure 4 were provided with 30 mg/l of the ash. Two cultures were not supplemented, two cultures were supplemented with 10 mg/l of urea, and two cultures were supplemented with 10 mg/l urea and 10 mg/l of EDTA. Since the growth of the algae in both members of each pair of cultures was essentially parallel only one line was plotted for each pair of cultures. The data indicate again the need for supplementation of the ash with a nitrogen source and again no appreciable effect due to the presence of EDTA in the culture medium was demonstrated.

The cultures whose results are plotted in Figure 5 were provided with 1 gm/l of ash and supplemented with varying concentrations of urea from 3 mg/l to 1000 mg/l. The object of these experiments was to determine the ratio of nitrogen to ash at which some nutrient in the ash became limiting. Although the growth curves obtained from the data fit very nicely the classical picture of an algal growth curve, the experiment may be considered a failure since the concentration of urea at which the final algal cell count was independent of nitrogen concentration was never reached.

DISCUSSION

From the results of the experiments completed so far it is possible to make several tentative conclusions about the design and operation of an incinerator for human wastes and the possibility of growing algae on the incineration products.

The weight and carbon remaining versus time for different rates of air supply and different volatilization temperatures demonstrate that the rate of carbon loss from dried samples of urine and feces mixture can be regulated. The data indicate that regulations of the rate of carbon loss can be accomplished by varying the volatilization temperature or the rate of air supply; the former having a more pronounced influence than the latter. This flexibility in regulation permits variation of the detention time in the combustion chamber without changing its geometry and enables a reasonable uniform rate of carbon input to the combustion chamber, thus preventing peak loads on the combustion chamber and making a small physical size possible. The data indicate that a volatilization temperature of 300°C to 350°C is suitable for the purpose of minimizing peak carbon loads on the combustion chamber. The volatilization chamber should be operated in this relatively low incineration temperature for forty to sixty minutes and then at a temperature of 600°C for ten minutes. The latter phase of operation enables 99.8% of the carbon to be volatilized. Initial temperatures of greater than 400°C are to be avoided, since the ignition temperature of the dried feces and urine is about 425°C and ignition of the waste will create heavy peak loads on the combustion chamber. Even at 400°C, 80% of the carbon is volatilized in the first ten minutes.

Rough measurements of CO and CO₂ in the effluent gases from the volatilization chamber indicate that approximately 60% of the volatilized organic matter is in the form of particulates. This implies that if the carbon contained in the particulates are to be converted to CO₂ for use as a carbon source for algae, the combustion chamber must operate at relatively high temperatures (say above 600°C).

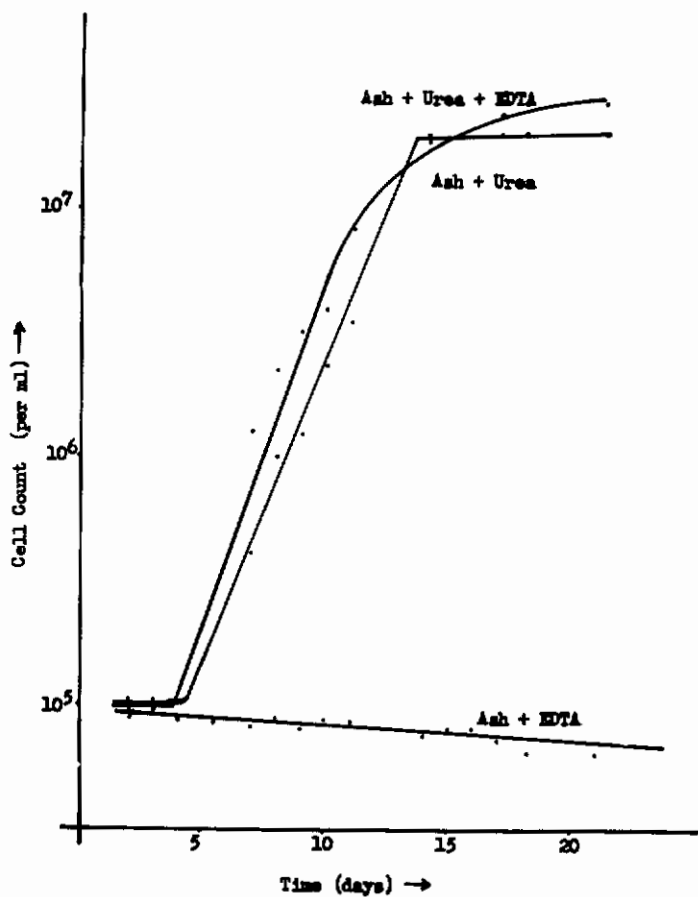


Figure 4. (left)

Growth of *Chlorella* on Ash with Added Nitrogen

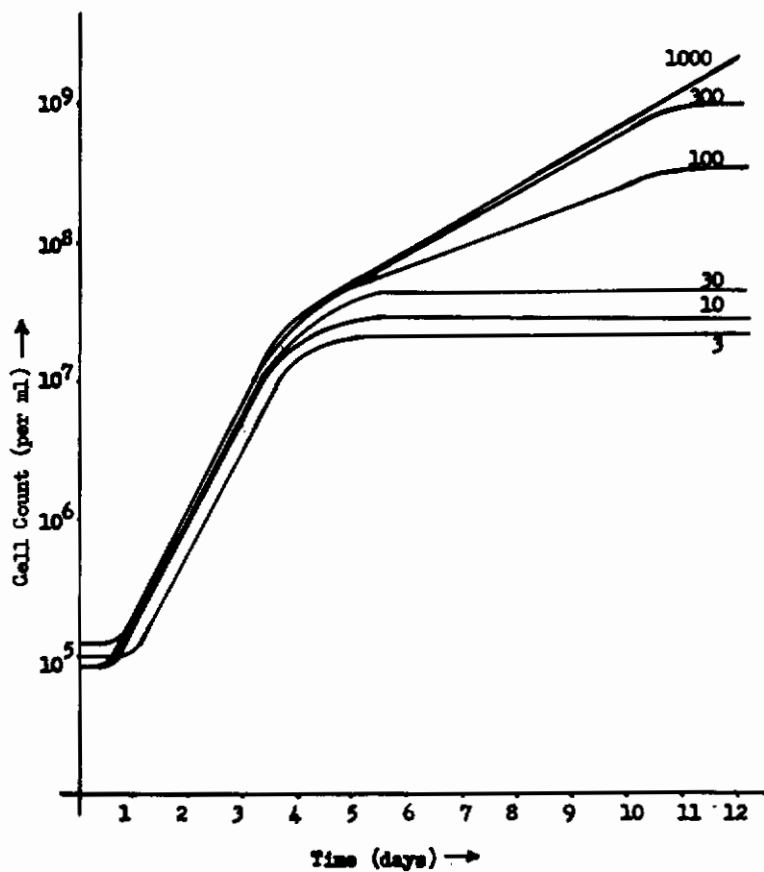


Figure 5. (left)

Growth of *Chlorella* on Ash with added Nitrogen

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The best results obtained from the volatilization experiments indicate that about 99.8% of the initial carbon content of the waste materials may be volatilized. Even assuming 100% efficiency for the combustion stage of the incineration process, at least 0.2% of the carbon will be lost. Although more carbon remained in the pot furnace after volatilization with a controlled rate of air flow than in the muffle furnace, it is expected that low residual carbon content may be obtained in the ash from the pot furnace if the air supply rates are increased, the sample size decreased, or the operating temperature elevated.

Approximately 75% of the residual ash is soluble in distilled water and 85% in 0.02N HCl. Thus for a typical sample with 20% ash on a dry weight basis, 5% of the original sample is insoluble in distilled water and 3% is insoluble in dilute acid. The solubility both in distilled water and dilute acid can be reproduced within 2% for a given sample. The solubility, like every other characteristic of the urine and feces mixture, varies considerably from sample to sample. This lack of uniformity in the waste to be treated poses serious limitations on the maximum efficiency of any recovery process.

The solubility of the residual ash in dilute acid, expressed as gm soluble material per gm ash, reveals an interesting phenomenon. The magnitude of the solubility are consistently near 1.0 and very frequently near 1.1. A possible explanation of this is that the organic compounds are converted to soluble material during the course of combustion. Another possible explanation is that the determination of ash content with the carbon and hydrogen apparatus operated at 850°C results in volatilization of some of the inorganic salts. The ash content after volatilization at a lower temperature will be higher than that corresponding to 850°C. This may account for a solubility in dilute acid of 1.1 gm per gm ash. The solubility in dilute acid also indicates that ten percent of the inorganic salts are volatilized by the carbon and hydrogen apparatus.

The algal growth experiments demonstrated that the ash will provide all nutrients required by the algae except for carbon, nitrogen and water. The ash apparently contains substances which inhibit the growth of the algae when the ash is added to the cultures in concentrations greater than 1 gm/l. This is not a high concentration for the inorganic components of an algal culture medium and there undoubtedly would be problems associated with developing dense algal cultures using the ash solely to supply the needed magnesium, phosphorous, and the micronutrients.

If the combustion stage of the incineration process can be made to operate efficiently, there should be no problem in recovering carbon dioxide and water from the effluent gas. However, some small further loss of carbon during the combustion would be expected.

It appears that the major problem with the incineration of human wastes to produce nutrients for algal growth is the recovery of nitrogen. The form of nitrogen in the combustion gases has not yet been determined but it is expected that a large fraction of it will be present as gaseous nitrogen. If this is true, then it would be necessary to provide a separate biological or chemical process for the conversion of gaseous nitrogen to a form usable by the algae.

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