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VOLATILITY OF HUMAN WASTE AT ELEVATED
TEMPERATURES

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ARCTIC AEROMEDICAL LABORATORY

AEROSPACE MEDICAL DIVISION
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NOTICES

ABSTRACT

The present study was undertaken to provide information
upon which a more rational approach to the design of
incinerators for human waste can be based. The volatile
matter and carbon remaining as a function of time were
determined for different operating conditions of the vola-
tilization chamber. An equation is proposed to describe
the volatilization process, and the dependence of the con-
stants in the volatility equation upon temperature and
upon the rate of air supply to the volatilization chamber
was determined. Volatilization temperatures as low as
300° C may be feasible for some incinerator designs
which provide a reactor for the oxidation of the material
volatilized.

PUBLICATION REVIEW

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Director of Research

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SYMBOLS

The following symbols have been adopted for use in this report:

A	=	weight of ash
C	=	weight of carbon
E	=	minimum energy possessed by an escaping molecule
F	=	proportionality constant
K	=	initial rate of change in the fraction of material remaining
K_c	=	initial rate of change in the fraction of carbon remaining
K_v	=	initial rate of change in the fraction of volatile matter remaining
k	=	Boltzmann constant
N	=	fraction of molecule with energy E
n	=	exponential constant in Equation 2
n_c	=	exponential constant in Equation 2, referred to carbon
n_v	=	exponential constant in Equation 2, referred to volatile matter
S	=	frequency factor
T	=	temperature, in degrees centigrade or degrees Kelvin
V	=	weight of volatile matter
W	=	weight of total solids
X	=	fraction of material remaining

VOLATILITY OF HUMAN WASTE AT ELEVATED TEMPERATURES

SECTION 1. INTRODUCTION

The problem of providing adequate waste treatment facilities for small, sometimes isolated, military posts which serve 100 to 1000 persons is of continual concern to the United States Air Force. Conventional sewage treatment and underground filter units, involving water carriage and biological processes, have proved to be excessively expensive (Koruzo, 1957). Difficult waste disposal problems, for both large and small military installations, in the Arctic are complicated further by the extremely cold climatic environment. The necessity for developing waste disposal methods not dependent on biological processes and suitable for use at isolated sites in the Arctic has prompted the development of a prototype oil-carriage waste disposal system employing incineration. One such system has been operating successfully for over a year at Point Barrow, Alaska.

Increasing population, greater awareness of the need for both air and water pollution abatement, and scarcity of land within metropolitan areas have also created a need for developing better methods of waste disposal. Notable among recent developments is the Zimmermann process (Hurwitz and Dundas, 1960) for treatment of sewage sludge under high temperature and pressure.

Incinerator toilets for the disposal of human waste are available commercially. Incineration as a method for disposal of municipal refuse and sewage sludge is fairly common practice. However, the small incinerator toilets invariably have serious engineering defects in design and do not perform satisfactorily (Miholits, 1961). Indeed, even large incinerators for refuse or sewage sludge disposal have failed miserably on occasions as a waste treatment process. This is exemplified by frequent odor problems (Sawyer and Khan, 1960) and the abandonment of the use of backyard and municipal incinerators in Los Angeles.

One of the primary reasons for the inadequacies of the available incinerator toilets and many of the refuse and sewage sludge incinerators is the lack of basic information on incineration as a waste treatment process. Published information of the various different methods of waste incinerator design are meager. Most of the capacity parameters employed in the design of incinerators are based solely upon heat release and heat transfer

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considerations patterned after the design of industrial furnaces (Meissner, 1959, Blanke, 1959). Oxygen or air requirements for complete combustion of solids are calculated on the basis of the Btu content of the material used as fuel, again patterned after the design of industrial furnaces which endeavors to maximize the thermal efficiency of the unit. These considerations are necessary but clearly insufficient when incineration is to be designed as a waste treatment process. The quantity and types of combustion products have been shown to be dependent upon the type of fuel used (Schalla et al, 1954, Quon et al, 1961) and upon the "completeness" of oxidation (Tebbens et al, 1956). Complete oxidation of solids is difficult to attain and reaction time needed for the oxidation of volatilized material, although frequently ignored in design, should be a prime consideration.

The development of meaningful capacity parameters and operating conditions for the design of an effective waste incinerator depends upon a detailed knowledge of the process of destructive volatilization of the waste material and of the oxidation of the volatilized compounds to innocous end products. The character of human waste and the rate of volatilization as a function of time, temperature and available oxygen were investigated with particular emphasis upon providing information for developing rational design parameters for processes depending upon the destructive volatilization of human waste. The experimental methods reported herein are applicable to further studies with domestic sewage sludge and, to a more limited extent, industrial waste sludge.

SECTION 2. SUMMARY

The present study was undertaken to provide information upon which a more rational approach to the design of incinerators for human waste can be based. The laboratory techniques and method of data analysis may be adapted to provide similar information on sewage sludge solids or domestic refuse.

The volatile matter and carbon remaining as a function of time was determined for different operating conditions of the volatilization chamber. The time rate of loss of material was found to be proportional to an exponential function of the fraction of material remaining. The equation proposed for describing the process of volatilization for human waste represented the observations very well. Values of the correlation coefficients generally were above 0.95. The exponent and proportionality constant were found to be dependent upon both temperature and upon the rate of air supply

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to the volatilization chamber. The gross characteristics of the raw feces and urine mixtures were similar to those of primary domestic sewage sludge.

The initial rate of change in the fraction of material remaining, K_v, based on volatile matter measurements, was found to vary but slightly with variations in the rate of air supply when the rate was greater than two liters per minute per gram of material. The initial rate of change in the fraction of material remaining, K_c, based on carbon measurements, was found to be proportional to the rate of air supply. The implication is that the initial carbon loss is due to both vaporization and surface oxidation and the relative role of oxidation increases with an increase in the air supply. The ratio of maximum to minimum initial rate of volatilization was about three to one for air supply rates corresponding to constant initial time rate of change in the fraction of volatile matter. The initial rate of volatilization increases markedly for temperatures greater than 350° C. The time required for a given percentage of reduction of volatile matter or carbon depends more upon the exponent, n, in the rate equation than upon the proportionality constant, K. The exponent, n, was found to be primarily dependent on temperature for air supply rates exceeding 3.8 l/m/gm material, for air rates less than 3.8, a small increase in n (lower volatility) was observed.

Material loading should be a major consideration in the design of a reactor to oxidize the material volatilized in any incineration process. The information presented indicates that a temperature as low as 300° C may be feasible for some incinerator designs.

SECTION 3. EXPERIMENTAL METHODS

Samples of human waste (feces and urine) were obtained from a small group of laboratory people. Urine and feces were collected separately and mixed at a fresh weight ratio of eight parts urine to one part feces. The mixtures were blended in a Waring blender for a period of at least 20 minutes to insure uniformity of characteristics throughout the mixtures. The percentage of solids in the samples was determined by drying at 103° C and weighing (APHA, 1960). A semi-micro carbon and hydrogen apparatus was used to determine the fraction of ash, volatile matter, carbon and hydrogen in the dried samples (Niederl and Niederl, 1942). 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 was taken as the weight of ash, the weight loss, as the weight of volatile matter,

the amount of carbon in the carbon dioxide produced upon ignition, as the carbon content, and the amount of hydrogen in the water produced upon ignition, as the hydrogen content in the sample. Samples dried at 103° C, kept in a desiccator and refrigerated may be stored for a period of a month without significant changes in the gross characteristics. Analyses were made on the dried raw samples periodically.

A schematic diagram of the system used to study the volatility of the dried raw samples of urine and feces is shown in Figure 1. The volatilization chamber used was a gastight retort approximately 12 cm I. D. and 13 cm deep with a total effective volume of 1.40 liters. The graphite gastight retort sealing gasket was replaced with "Fiberfrax" ceramic fiber, type XV Board, to prevent possible interference from the carbon in the graphite seal. The thermal conductivity of the Fiberfrax insulating seal used is 1.4 Btu/hr/ft^2/in at 2000° F and its melting point is 3200° F. All hot connections were of the sleeve quick-coupling type, made with Fiberfrax insulating material. The temperature within the retort was measured with a shielded Chromed-Alumel thermocouple with air flow through the retort at the desired rate. The retort was heated with a Lingberg pot furnace whose temperature was controlled with an input adjuster and pyrometer unit. The temperature within the retort can be controlled to within $\pm 5^\circ$ C. The rate of air supplied to the volatilization chamber was metered with rotameters calibrated for 2% accuracy. The air supply was regulated with a constant output pressure "pancake" valve. The head loss through the entire system was negligible and the position of the rotameter was immaterial and selected for convenience.

The change in weight and other characteristics of the human waste with respect to time for a given rate of air supply and temperature were studied, using dried samples of approximately 2 gm each (corresponding roughly to a wet weight of 50 gm). The weight as a function of time was determined by weighing at significant time intervals, as dictated by experience. Upon removal from the volatilization chamber, the sample was air quenched in a small aluminum desiccator for a few minutes, then transferred to a large pyrex desiccator to attain temperature and moisture equilibrium before weighing. Weights were determined to the nearest 0.1 mg, using an automatic Mettler balance.

After each weighing, the sample was milled with either a small stainless steel spatula or a porcelain pestle, as needed to insure uniformity, and a 20-mg portion was removed for carbon and hydrogen analysis. The weight of material removed was determined to the nearest 0.1 mg. The fraction of material removed was assumed to undergo the same changes as those experienced by the bulk sample in subsequent time periods.

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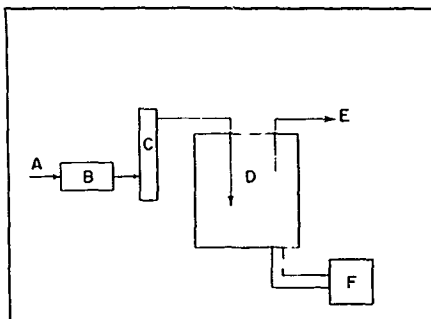
LEGEND

    A = Compressed Air Supply
    B = Pancake Constant Output Pressure Regulator
    C = Rotameter
    D = Volatilazation Chamber
    E = To Reactor and Cooling Coil
    F = Temperature Controller

FIGURE 1.

Schematic Flow-Sheet For Volatility Studies

It was observed that the weight and other characteristics of dried human waste change very slowly at temperatures less than 200° C and the fire ignition temperature in air at atmospheric pressure was determined to be 425°C. Thus, the temperature range for the study of the volatility of human waste was varied from 200° to 400° C. The rate of air supply used ranged from 1 to 7.5 liters per minute per gram sample, reported at 21° C and 760 mm Hg.

SECTION 4. RESULTS AND DISCUSSION

Raw Sample Characteristics

The characteristics of the five raw samples used to study the volatilization of human wastes are presented in Table I.

TABLE I. RAW SAMPLE CHARACTERISTICS

Raw Sample Number	Carbon % dry basis	Total Solids % dry basis	C/A by weight	C/V by weight	V/W by weight
B2	45.8	--	5.53	0.535	0.912
C2	32.5	6.50	1.43	0.419	0.773
D	42.1	3.89	2.53	0.506	0.833
E	45.1	3.80	4.27	0.504	0.894
H	41.8	3.81	2.77	0.493	0.849

Each value tabulated represents the arithmetic average of three determinations. Variations are usually less than one unit in the third significant figure. The variations in the carbon and solids content, and in the ratios of carbon to ash (C/A), carbon to volatile (C/V), and volatile to total solids (V/W), reflect in part the variation in the diets of the individuals who contributed the samples. A fairly wide variation in the characteristics of heterogeneous waste materials such as domestic sewage sludge and human waste is typical. The total solids and the carbon to ash ratio show the greatest variation: total solids shows a two-fold variation, and the carbon to ash shows a four-fold variation. The percent carbon and volatile matter

in the samples vary only within a narrow range of values, being approximate-
ly 42% and 85%, respectively. A total solids of 4% and an 85% volatile matter
are also typical values for primary domestic sewage sludge from primary
sedimentation units which are preceded by grit removal.

Vaporization

The volatility of a given solid or the time rate of loss of a given solid
from the bulk phase to the gas phase depends upon the imbalance between
the number of molecules escaping from and condensing onto the bulk phase.
According to classical physical chemistry (Moelwyn-Hughes, 1961), the
fraction of molecules escaping the bulk phase in a given time is proportional
to the Boltzmann factor, the fraction of molecules with energies greater than
a certain critical value,

$$N = FS\, e^{-E/kT}, \qquad (1)$$

where

N = Fraction of molecules escaping per time,
S = Frequency factor,
F = Proportionality constant,
E = Minimum energy possessed by an escaping molecule,
k = Boltzmann constant, and
T = Temperature in degrees Kelvin.

The proportionality constant, F, is usually a function of both temperature
and the type of material. The number of molecules condensing in a given
time is primarily a function of their velocity and of the concentration of
molecules in the gas phase. The process of condensation is considered to
require no energy of activation. Following the above concept, the fraction
of material loss per time is proportional to the Boltzmann factor. The
amount of material condensing is small for large air flows or flushing rates.
From Equation 1, the fraction of material loss with respect to time is a con-
stant for a given temperature and material. However, the waste material
undergoes decomposition at elevated temperatures and the value of the Boltz-
mann factor and of the frequency factor will change with the time. It is
reasonable to assume that thermal decomposition of waste material involves
a rearrangement of atoms or a change in configuration of the molecules in
the waste. The relative change of the frequency factor is thus very large
compared to the change in the critical energy necessary for vaporization as
the waste undergoes decomposition. An exponential function of the fraction
of material remaining at a given time was used to represent the frequency
factor,

$$\frac{dX}{X\,dt} = -FS\, e^{-E/kT} = -K\, X^{(n-1)} \qquad (2)$$

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where

X = Fraction of material remaining measured either by volatile matter or carbon

n, K = Constants, and

t = time.

Separating variables and integrating:

$$\frac{1}{K(1-n)} \left[1^{(1-n)} - X^{(1-n)} \right] = t. \qquad (3)$$

Rearranging,

$$X^{(1-n)} = (n-1) Kt + 1. \qquad (4)$$

When one is small compared with $(n-1) Kt$,

$$\log X = \frac{1}{(1-n)} \log t + \frac{1}{(1-n)} \log (n-1) K \qquad (5)$$

Equation 2 predicts that the logarithm of K will be inversely proportional to the temperature for the simplest molecules and deviations from the linear relationship can be expected for more complicated molecules. Values for n and K will, in general, be dependent upon both temperature and oxygen supply since a variation in either parameter will affect the opportunity for changes in the molecular structure of the waste material. It should be recognized that n and K are average values representative of a conglomeration of different types of material in the waste.

A typical set of observations is shown in Table II and presented graphically in Figures 2 and 3 in accordance with Equation 5. The values for n and K were calculated from the slope of the line representing the linear regression of $\log X$ on $\log t$ and the intercept of the regression line at $t = 1$.

TABLE II. WEIGHT OF RESIDUAL MATERIAL VERSUS TIME
(Run 106)

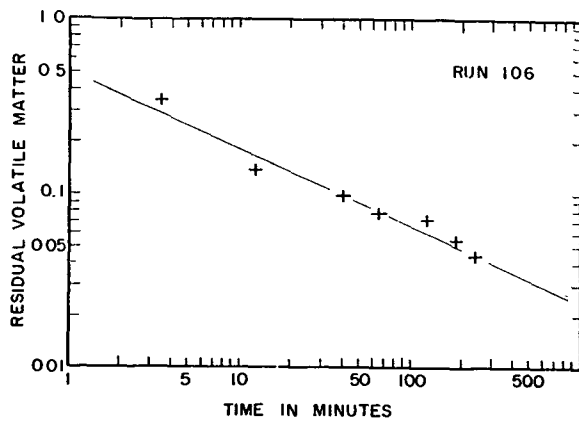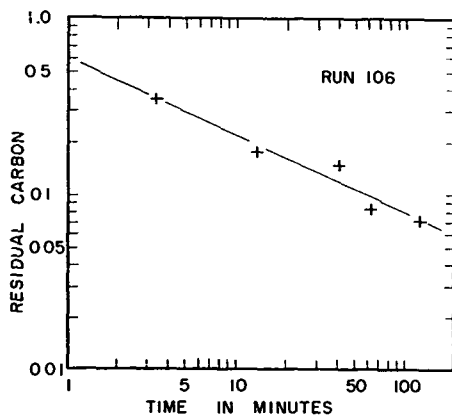| Time min	Carbon Remaining % by weight	Volatile Matter Remaining % by weight
3.5	35.4	34.4
13.5	17.7	13.7
40.5	14.9	9.7
62.5	8.36	7.7
125	7.16	7.1
184	-----	5.4
248	-----	4.4

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FIGURE 2. Residual Volatile Matter Versus Time

FIGURE 3. Residual Carbon Versus Time

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Correlation studies indicate that Equation 5 is a reasonable representation of the volatilization process. Values of correlation coefficients for the observations summarized in Table III are greater than 0.98. The values of correlation coefficients for observations summarized in Table IV are 0.78 for runs 101 and 111 and greater than 0.95 for the rest.

The volatility of the feces and urine mixtures as measured by volatile matter and by carbon are presented in Tables III and IV, respectively. The volatility is a function of temperature, rate of air supply and the material involved. The parameters, n and K, which describe the rate of material loss as a function of time are summarized for different operating conditions of the volatilization chamber. The time required for 90% material loss for a given temperature and rate of air supply was computed by Equation 5. Figures 4, 5 and 6 are graphical presentations of selected information contained in Tables III and IV.

The fraction of material remaining at time zero is one. At time zero, according to Equation 2, the value of K can be interpreted as the initial time rate of change of X, the fraction of material remaining. The initial rate of volatilization is proportional to X. The non-linear relationship between K and $(1/T)$, for an air supply of 7.5 liters per minute per gram sample, shown in Figure 4 reflects the influence of two factors: (1) The proportionality constant in Equation 1, F, is a function of temperature for complicated molecules, and (2) the average critical energy required for a molecule to be volatilized, E, may vary from sample to sample even though the gross characteristics show only a limited variation. The information calculated for the data describing the rate of loss of volatile matter or carbon indicates that the initial time rate of change in the fraction of material remaining increases very markedly for temperatures greater than 350° C. The dependence of the initial rate of decrease in X upon the rate of air or oxygen supply with the temperature at 400° C is represented graphically by the lower two curves in Figure 5. The initial rate of decrease for the fraction of volatile matter remaining, K_v, was found to be highest for oxygen supply of 0.56 to 1.0 liters per minute per gram volatile matter $(1/m/gm\ V_o)$ decreasing slightly with increasing oxygen supply, and decreasing sharply for lower oxygen supply. The low value of K_v at the low oxygen supply rates may be attributed to the influence of condensation which is ignored by Equation 2. Values of K_v for oxygen supply greater than 0.56 $1/m/gm\ V_o$ may be considered essentially constant. The initial rate of decrease for the fraction of carbon remaining, K_c, might be roughly proportional to K_v were it not for processes such as dehydration. The observation that K_c increases linearly with increases in oxygen supply indicate that both vaporization and surface oxidation contribute to K_c and, therefore, to K_v. A typical value for the ratio of V_o/C_o is two (Table I). Thus, the ratio of K_v/K_c would be approximately one-half if the initial rate of change in the fraction of volatile matter were equal to the initial rate of change in the

TABLE III

VOLATILITY OF HUMAN WASTE BASED UPON VOLATILE MATTER

Run Number	Raw Sample	Constants for Volatility Equation Slope	Intercept	n_v	K_c	Temperature °C	Air Supply[1] Rate l/m	Oxygen l/m/gm V_o	Time for 90% Volatilization min
108	D	-0.358	-0.0388	3.79	0.459	400	2.03	0.256	480
106	C2	-0.443	-0.283	3.26	1.92	400	4.16	0.565	42
102	C2	-0.528	-0.300	2.89	1.95	400	7.56	0.973	21
103	C2	-0.692	-0.224	2.45	1.46	400	15.13	2.06	13
105	C2	-0.707	-0.149	2.42	1.15	400	15.13	2.06	16
201	H	-0.175	-0.134	6.71 (5.79)[2]	1.02 (0.686)	350	4.16	0.515	*[3]
109	D	-0.281	0	4.56	0.281	300	15.13	1.91	*
110	D	-0.272	0	4.68	0.272	300	15.13	1.91	*
101	E	-0.0764	0	14.1	0.076	200	7.56	0.890	*
111	D	-0.0899	0	12.1	0.090	200	15.13	1.91	*

1 Volumetric rates reported at 21°C, 760 mm Hg
2 Values in parenthesis are corrected to air supply rate of 15.13 l/m
3 Asterisk indicates time greater than 10 days

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TABLE IV.

VOLATILITY OF HUMAN WASTE BASED UPON CARBON

Run Number	Raw Sample	Constants for Volatility Equation				Tempera- ture °C	Air Supply[1]		Time for 90% Volatilization min
		Slope	Intercept	n_c	K_c		Rate l/m	Oxygen l/m/gm C_o	
107	B2	-0.400	0	3.50	0.400	400	2.03	0.436	317
108	D	-0.353	0	3.83	0.353	400	2.03	0.506	677
106	C2	-0.445	-0.218	3.25	1.37	400	4.16	1.33	57
102	C2	-0.587	-0.0858	2.70	0.822	400	7.56	2.44	36
103	C2	-0.501	-0.397	3.00	3.12	400	15.13	4.89	16
105	C2	-0.485	-0.319	3.06	2.21	400	15.13	4.89	25
201	H	-0.214	0	5.66 $(4.84)^2$	0.137 (0.418)	350	4.16	1.05	*[3]
109	D	-0.168	0	6.95	0.168	300	15.13	3.78	*
110	D	-0.173	0	6.78	0.173	300	15.13	3.78	*
101	E	-0.0492	0	21.4	0.0490	200	7.56	1.76	*
111	D	-0.154	0	7.50	0.154	200	15.13	3.78	*

[1] Volumetric rates reported at 21°C, 760 mm Hg.
[2] Parenthesis value corrected to air supply rate of 15.13 l/m.
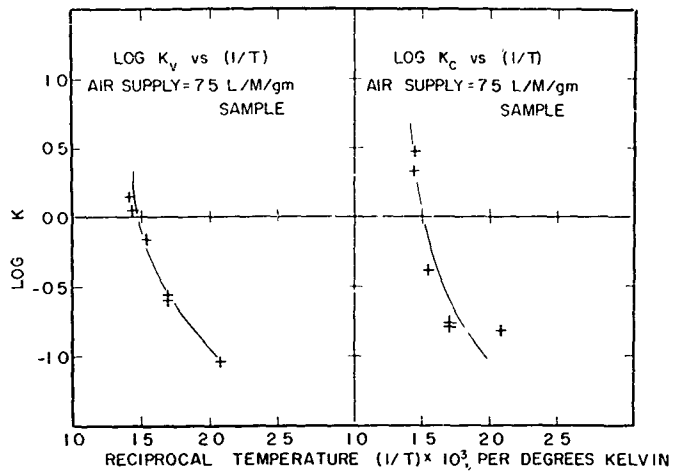[3] Asterisk indicates time greater than 10 days.

FIGURE 4.

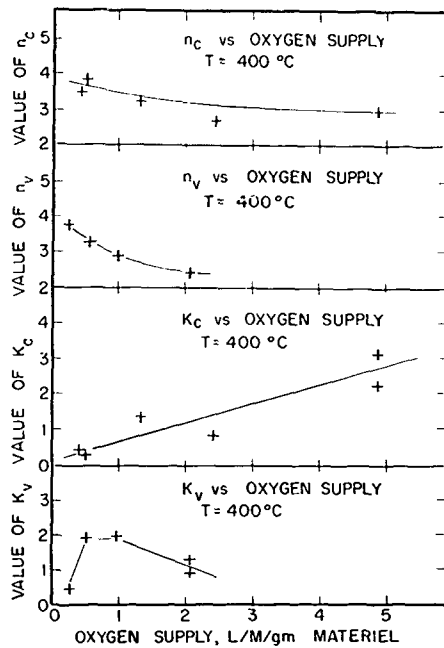Initial Rate Constant, K Versus Temperature

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FIGURE 5

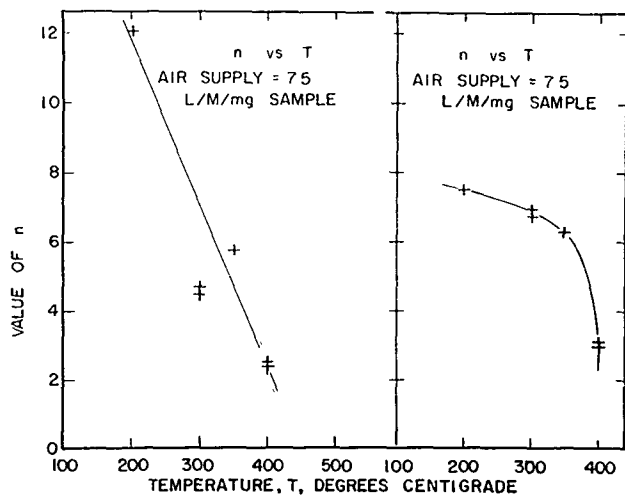Parameters of Volatility Versus Oxygen Supply

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FIGURE 6

Parameter of Volatility, n Versus Temperature

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fraction of volatile matter were equal to the initial rate of change in the fraction of carbon. The ratio of K_v/K_c at 400° C for an air supply greater than 2 l/m/gm sample varies from 2 to 0.5. This merely indicates that for high values of K_c, the loss in volatile matter is predominately a loss in carbon. Obviously, (dV/dt) must be greater than (dC/dt) at all times where V is volatile matter and C is carbon.

The value of X is, by definition, between zero and one. The larger the value of the exponent, n, in Equation 2 the lower the rate of loss of material, indicating lower volatility. The slight dependence of n upon oxygen supply at 400° C is shown in the top half of Figure 5. Figure 6 indicates that n_c increases rapidly for temperatures less than 400° C, n_v appears to increase linearly with decreases in temperature. From Equation 5 it is noted that variations in the value of n influences the rate of material loss more than corresponding variations in the value of K. The rate of volatilization is thus primarily temperature dependent, influenced only slightly by air supply provided it be greater than 3.31/m/gm material.

The intercept tabulated in Tables II and III represents the value of log X for time equal to one minute. The fraction of material remaining after one minute is essentially 100% for temperatures less than 300° C or air supply not exceeding one l/m/gm material. A significant amount of material is volatilized in one minute only for temperatures greater than 350° C. The time required for 90% volatilization of the material was computed from Equation 5 with the experimentally determined constants and the values tabulated in Tables II and III. The values indicate that temperatures less than 400° C are impractical and air rates of less than 2 l/m/gm material are not desirable if one is interested in a large reduction of volatile matter by thermal decomposition.

The percent of material to be volatilized to obtain biological stability of the waste may be estimated from data on domestic sewage sludges (ASCE, 1959). It should be recognized that the percentage reduction of volatile matter to achieve biological stability is less for volatilization of the waste accompanied by thermal decomposition than for biologic oxidation of the waste. A temperature of 400° C and an air supply rate of 3.8 l/m/gm material appear to be the minimum practical conditions if greater than 80% of the volatile matter is to be volatilized in a short time, say less than one hour. If volatile matter reduction of 50% to 70% is acceptable, then a temperature as low as 300° C may be used.

Effective incineration of human waste involves volatilization of the waste and oxidation of the material volatilized. Material loading is generally a major consideration in the design of a reactor involving an oxidation process. The information on the volatilization process presented will aid in determining and regulating the load to the reactor and in selecting the proper operating conditions for the volatilization process to enable an optimum

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overall design. Low volatilization temperatures, less than the fire ignition temperature, may be used if a two-stage operation with respect to temperature is provided. The first stage involves volatilization of the waste at 300° C and a 3.8 l/m/gm material-air supply which reduces the volatile content to less than 50% of the original value in ten to fifteen minutes. The second stage subjects the residual solid waste to a temperature of 600° C or higher and reduces the volatile content to any desired level. The second stage volatilization can be provided by transferring the residue from the first stage volatilization to the oxidation reactor where a high temperature is provided for another purpose.

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