INCINERATION OF SOLID/LIQUID HUMAN WASTE

BY

THEODORE JOSEPH WAYNE

A THESIS
PRESENTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE
OF
MASTER OF SCIENCE IN CHEMICAL ENGINEERING
AT
NEWARK COLLEGE OF ENGINEERING

Newark, New Jersey
1971

ABSTRACT

This thesis encompasses the design criteria required to produce an effective incineration system for the disposal of solid/liquid human waste. Coupled with the overall design parameters is an investigation of the chemical decomposition of the waste during the incineration process, odor treatment and control, and the physiological effects on the human body due to the inhalation of the toxic gases given off during the combustion of human waste.

The variables involved in the combustion process are studied and equations presented that relate the combustion variables of flame temperature, residence time and air requirements. These equations are tested based upon published data concerning present incinerating systems in use.

A study of the established reaction kinetics shows that the relationship between combustion temperature and reaction time as a function of incinerator loading can be predicted quite readily. A design procedure is outlined supplying equations for the major design parameters to be used in order to minimize reaction time and gaseous effluents at optimal loading conditions.

APPROVAL OF THESIS

INCINERATION OF SOLID/LIQUID HUMAN WASTE

BY

THEODORE JOSEPH WAYNE

FOR

DEPARTMENT OF CHEMICAL ENGINEERING

NEWARK COLLEGE OF ENGINEERING

BY

FACULTY COMMITTEE

APPROVED:___________________________

____

____

NEWARK, NEW JERSEY

JUNE, 1971

PREFACE

In an era when the solid waste disposal problem has become so acute, the author has attempted to relate the variables associated with the incineration process as a means to obtain ultimate disposal of solid waste materials. The combustion process incorporates the advantages of minimum operating costs and greatest volumetric size reduction as opposed to biological and/or chemical treatment. Research and development in the areas of odor elimination and air pollution control should result in the incineration process becoming the major solid waste disposal technique of the future.

The author wishes to express his sincerest graditude to Dr. Angelo Perna for his guidance and constructive comments in the area of solid waste disposal and to Theresa M. Allen for her clerical expertise used in assembly and typing of this text.

TABLE OF CONTENTS

LIST OF FIGURES i

LIST OF TABLES iii

NOMENCLATURE iv

INTRODUCTION 1

INCINERATION 4

COMBUSTION OF SOLID WASTE 12

THE INFLUENCE OF MOISTURE ON THE COMBUSTION INTENSITY 29

FUNDAMENTALS OF HUMAN WASTE INCINERATION 34

STUDY ON A INCINERATOR SYSTEM 37

DESIGN OF FUEL-FIRED INCINERATOR SYSTEM 72

THERMAL DECOMPOSITION OF HUMAN WASTE 83

CONCLUSIONS 95

TABLES 97

FIGURES 118

APPENDIX

Appendix A - HEATING TIMES OF SOLID SPECIMENS 146

Appendix B - DERIVATION OF BURNING TIME EQUATIONS 151

Appendix C - DEFINITION OF MEDICAL TERMS 157

LIST OF REFERENCES 158

LIST OF FIGURES

Figure		Page
1	Adiabatic Temperature of a Cellulose Fuel Versus excess air	118
2	Availability of Heat from Auxiliary Fuel Firing vs. Combustion Temperature	119
3	Equilibrium Nitric Oxide Produced in Flames	120
4	Heating Times of Spheres; Approximate Pyrolysis Times	121
5	Heating Times of Flat Plates Approximate Pyrolysis Times	122
6	Kinetics of Carbon-Oxygen Reaction	123
7	Identification of Rate-Controlling Step in Carbon Combustion	124
8	Burning Times of Solid Specimens	125
9	Test Results of Incinemode Unit	126
10	Venturi Type After-Burner Using A Target and a Multiport Burner	127
11	Equipment Layout for Odor Elimination Tests	128
12	Pressure vs. Flow Rate for Various Nozzles	129
13	Exhaust Gas Constituents	130
14	Conveyor With Remote Incinerator	131
15	One Burner Unit Without Bags or Conveyors	132
16	Suggested Design for Incinerator System	133
17	The Specific Heat of Gases at Atmospheric Pressure	134
18	The Specific Heat of Gases at Atmospheric Pressure	135
19	Residual Volatile Matter vs. Time @ 400°C	136
20	Residual Carbon vs. Time @ 400°C	137
21	Initial Rate Constant K_v vs. Temperature	138
22	Initial Rate Constant K_c vs. Temperature	139
23	Parameter of Volatility Versus Oxygen Supply @ 400°C	140

LIST OF FIGURES (Cont.)

Figure		Page
24	Parameter of Volatility vs. Oxygen Supply @ 400°C	141
25	Parameter of Volatility vs. Oxygen Supply @ 400°C	142
26	Parameter of Volatility vs. Oxygen Supply @ 400°C	143
27	Parameter of Volatility, N_v vs. Temperature	144
28	Parameter of Volatility, N vs. Temperature	145

LIST OF TABLES

TABLE PAGE

1 Basic Data Considerations 97

2 Furnace Temperature Versus Firing Rate 98-99

3 Comparison of Stack Gas Emissions 100

4 Urine Analysis 102

5 Feces Analysis 103

6 Carbon Monoxide in the Blood 104

7 Carbon Monoxide in the Air 105

8 Concentrations and Effects of Ammonia Gas 106

9 Acute Effects of Sulfur Dioxide 107

10 Concentrations of NO_2 and Average Time to Produce 108

11 Ignition Temperatures of Various Gases and Liquids 109

12 Degree of Odor Index 60

13 Odor Test Results 63

14 Temperature Variations 64

15 Exhaust Gas Concentrations 65

16 Flow Parameters and their Variations with draft 69

17 Quantity of Wastes 70

18 Combustion Constants 110-115

19 Primary Heat Requirements 80

20 Secondary Heat Requirements 82

21 Raw Samples Characteristics 86

22 Weight of Residual Material Versus Time 90

23 Volatility of Human Waste Based on Volatile Matter 116

24 Volatility of Human Waste Based on Carbon 117

NOMENCLATURE

A - frequency factor, g-moles/sq cm-sec

A - weight of ash

B - calorific value of waste, BTU/lb

B_O- calorific value of dry waste, BTU/lb

Bi- Biot number, $hr_o/_s$

C - weight of carbon

c_p- specific heat, BTU/lb °F

d - thickness of flat plate and diameter of sphere, cm

D - coefficient of diffusion of oxygen in ambient gas,
sq cm/ sec

E - activation energy, kcal/mole

E%- excess air percentage

f_a- mole fraction of oxygen in ambient gas

F - moles of solid material burned per mole of oxygen
reacting

F_o- Fourier number

F - firing rate, lb/hr

F_o- firing rate of dry waste, lb/hr

h - coefficient of heat transfer from ambient gas to
surface of waste specimen, cal/sq cm-sec-deg C

h_g- evaporation enthalpy of water

H_w- total wall loss, BTU/hr

J - factor defined by equation (16)

J'- J factor modified for auxiliary fuel equation (17)

k - reaction rate constant, g-moles/sq cm-sec

k_p- pyrolysis rate constant, 1/sec

k_f - mass transfer codfficient for oxygen flow to burning surface, g-moles/sq cm-sec

k - Boltzmann constant

K - ratio of burning time of solid sphere to the square of the initial sphere diameter, sec/sq cm

K_1 - a constant, cm-sec/g-mole

K_2 - a dimensionless function of U

K_3 - the stoichiometric ratio of the moles of oxygen required to burn unit volume of solid material, g-moles/cc

K_4 - a constant for combustion in air, sq cm-sec$^{1/2}$/g-mole

K_5 - a constant for the carbon-oxygen reaction, sec/cm

K_6 - a constant for the carbon-oxygen reaction, sec/cm

K_c - initial rate of change in the fraction of material remaining

K_v - initial rate of change in the fraction of volatile matter remaining

L - length of flat plate of waste specimen, cm

m - order of the temperature dependence of the relative velocity between solids and ambient gas

m - moisture fraction

M - molecular weight

n - order of the pressure dependence of the relative velocity between solids and ambient gas

n_c - exponential constant referred to carbon

n_v - exponential constant referred to volatile

N - fraction of molecules with energy E

$\dot{N}$ - oxygen flux reaching burning surface, g-moles/sq cm sec

Nu - Nusselt number for heat transfer from ambient gas to surface of waste

P - absolute pressure, atm

Pr - Prandtl number of ambient gas: ratio of kinematic viscosity to thermal diffusivity

r - half-thickness of a flat-plate, waste specimen, or radius of spherical specimen, at any time during burnout, cm

$\dot{r}$ - specific reaction rate, g-moles/sq cm-sec

R - ideal gas constant, 82.05 cc-atm/g-mole-degK

$\dot{R}_s$ - specific burning rate, grams solid material/sq cm-sec

Re - Reynolds number for flow of ambient gas past waste specimen

S - frequency factor

Sc - Schmidt number of ambient gas: ratio of kinematic viscosity to thermal diffusivity

t - time, sec

t_b - burning time, sec

t_h - heating time, sec

T_f - flame temperature, deg R

T_{f_o} - flame temperature of dry waste, deg R

T_o - surroundings temperature, deg R

T_b - boiling temperature of water, deg R

U - a dimensionless, temperature-dependent function of Re

v - relative velocity between waste pieces and ambient gas, cm/sec

V - weight of total solids

W - moisture weight ratio

W' - moisture weight ratio adjusted for auxiliary fuel

X - weight fraction of material remaining

x - distance from center of spherical specimens, and perpendicular distance from midplane of flat plates, cm

y - integration variable

z - integration variable

α - thermal diffusivity of solid waste, sq cm/sec

η - steric factor for oxygen adsorption on carbon

θ - fraction of active sites on carbon surface occupied by absorbed oxygen

λ - thermal conductivity, cal/cm-deg C-sec

ν - kinematic viscosity of ambient gas, sq cm/sec

ρ - density of solid material, g/cc

SUBSCRIPTS

1 - adsorption

2 - desorption

a - in ambient gas; adsorption-controlled burning

c - carbon

c.c.- chemically controlled burning

d - desorption controlled burning

m.t.- mass-transfer controlled burning

o - initial value

p - pyrolysis

s - at solid surface

INTRODUCTION

The design of an efficient incineration system requires adequate knowledge of the basic operating parameters. These factors include knowledge of the chemistry of combustion, control of temperature by various means, control of turbulence, regulation of burning time and predicting mechanisms of combustion reactions in order to ascertain the kinetics involved.

The combustion of solid waste involves heat and mass transfer, pyrolysis of both solid and gaseous material, and both gas-phase and heterogenous chemical reactions. These processes convert the solid waste material into gaseous combustion products and an inert solid residue. An understanding of the important factors involved in this stepwise conversion of solid waste is essential in order to achieve optimum results.

Since the composition of human waste is made up of both solid and liquid constituents, the thermal load of an incinerator designed to handle human waste must be calculated based upon the additional heat required to completely vaporize the liquid components. This thermal balance has an effect upon the flame temperature and the firing rate of the system. The vaporization process has a very definite effect on the burning rate equations specified for strictly solid waste samples.

Present methods used to dispose of solid waste, such as biological and chemical treatment and dumping and burial present serious technological problems and result in excessive contruction and operational costs.

The development of meaningful capacity parameters and operating conditions for the design of an effective waste incinerator depends on 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 major operating variables are necessary in order to develop a rational design procedure that outlines the methods to be used for describing the processes involved in the destructive volatilization of human waste.

In order to satisfy the criteria described above, the following factors have been investigated:

1. The burning time of solid waste specimens under various conditions of rate control in order to establish a basis of comparison between the burning rate equations and published experimental data.
2. The design criteria necessary to evaluate an incineration system for human waste
3. Test methods used to determine the products of combustion and the chemistry and physiological effects of these combustion products.
4. Methods used for the control of combustion variables in order to obtain a practical design procedure used to coordinate theoretical equations with accepted design practice.
5. The volatile matter and carbon remaining as a function of time is determined for different operating conditions of the

volatilization chamber. An equation is proposed to describe the volatilization process, and the dependence of the constants in the volatility equation on temperature and on the rate of air supply to the volatilization chamber is determined.

INCINERATION

Combustion

Ordinarily, combusion is regarded as the oxidation of hydrocarbons with the simultaneous release of heat. While this is a valid assumption for many incinerators, there are frequently additional chemical reactions which may be of major importance. These must be considered carefully if good incinerators are the objective. For example, if a cyanide gas is to be disposed of, the oxidation step is of minor importance. It is of major importance that the cyanide radical be destroyed completely. The thermodynamics of the reaction which converts the toxic gas to a nontoxic gas must be evaluated carefully.

Accurate analysis of the waste and the quantities to be burned may be difficult to get or nonexistent. Without this information, the possibility of an adequate design with good performance may disappear. Without question, the first step toward good combustion and consequently a good incinerator is good basic data. Table 1 lists some of the major items which should be known as a first step in the design of any incinerator system.

When adequate basic data are obtained, one can proceed to design a satisfactory unit. If no halogens, sulfur, or metals are involved, the problem may be a simple one of combustion, requiring time, temperature and turbulence. All of these factors are influenced by the basic data and the design. Once the incinerator unit is constructed, only temperature may be readily controlled. This can be done by varying the air/fuel ratio. Time and turbulence can be controlled only over a limited range, fixed by the design. Figure 1 shows the adiabatic combustion temperatures of a cellulose waste that will occur with variations in excess air. In practice, the actual temperatures will be less because of thermal conduction losses through the furnace walls, thermal radiation to cold surfaces and possible incomplete combustion of the waste.

Control of Temperature

The temperature in an incinerator must be controlled either by the design or by regulation of the fuel/air ratio to achieve successful operation. If solid carbonaceous waste is to be burned without smoke, a minimum temperature of 1400°F must be maintained in the combustion chamber. Upper temperature limits in the incinerator are dictated by the refractroy materials available. Whenever a temperature of 2400°F is exceeded, special refractories are required. A design range of 1800 to 2000°F is usually desirable, unless thermodynamic equilibrium considerations dictate some other temperature requirement. The rates of most combustion reactions increase rapidly with increases in temperature, while a few peak at relatively low values. The latter are rare but must not be overlooked when unusual fuels are burned.

There are four basic methods of controlling the combustion temperatures:

(1) Excess air control: This is shown in Figure 1. However, control is not obtained by assuming a feed rate and providing an air supply of ample proportions. Unless the operation is automatically controlled or strenuously supervised, it is human nature to overfeed the incinerator with waste. The designer can and should provide limiting orifices, nozzles, or pumps to prevent overfiring during continuous feeding of liquids and gases. For solid fuels the problem is aggravated as the volatility of the fuel increases. If an incinerator is fed with discrete amounts at intervals, the hourly sum of these amounts must not exceed the rated capacity, and the intervals between feeding must be regulated. The greater the volatility of the waste, the smaller these discrete amounts must be and the more frequent the feed intervals.

(2) Radiant heat transfer: Most combustion processes exist for the purpose of heat transfer. This is not usually the case for incinerators. Some large municipal waste incinerators use heat transfer surface as a means to control temperature and this design practice is growing. It is seldom economically feasible for industrial incinerators. It should be considered, however, whenever economics might make it attractive. Radiation to the sky is feasible, and several designs are capable of doing this. Where either heat transfer surface or radiation to the sky is used,

table 2 can be used to estimate the combustion temperature. (1)

(3) Two-stage combustion. If the combustion step is divided into two distinct steps and the first stage is supplied with the deficiency of air, the first stage can act as a gasifier for certain fuels while burning incompletely. The air-deficient combustion results in a reduced temperature. A second stage is necessary to burn the combustible products produced in the first stage, and its temperature must be limited by either the first method discussed (excess air control) or by heat transfer. Whenever feeding is stopped the first stage progressively moves toward complete combustion, and combustion temperatures will increase (see Figure 1).

(4) Direct heat transfer. If heat-absorbing materials or other fuels are added to the waste fuel the temperature of combustion can be controlled. The most common method of achieving lower temperatures is to add water to the fuel. Since each pound of water that is added absorbs approximately 1000 Btu to evaporate and 1/2 Btu for every degree F of temperature rise, the maximum temperature of the combustion products can be reduced. The water may be added with the fuel or sprayed into the combustion zone. Water sprays must be carefully controlled to avoid quenching the fire or damaging the refractory. Temperatures may be increased by burning other fuels with the waste stream. Figure 2 shows

the benefits of burning auxiliary fuel. It should be noted that only a fraction of the heating value of the auxiliary fuel is usuable to heat the waste stream. (2)

Control of Turbulence

The degree of intimate mixing of the air for oxidation with the waste fuel will affect the incinerator performance significantly. In general, either mechanical or aerodynamic means are utilized to achieve the intimate scrubbing and mixing of the air and fuel. The completeness of combustion and the time required for complete combustion are significantly affected by the amount and the effectiveness of the flame turbulence. There is no accepted parameter that will quantitatively define an amount of turbulence. Turbulence can best be judged by the combustion results that are produced.

The degree of mixing achieved is proportional to the energy expended in moving gas in the combustion region. Since natural draft is limited by stack dimensions and atmospheric conditions, the best performance can be achieved using mechanical draft for air handling. The forced vortex produced in the liquid and gas burner requires high fan horsepower for the air supply, but the combustion is proportionately improved. For solids, the turbulence can be improved by directing high velocity air jets over the fuel bed. (3) For fixed nozzles and vanes, and sometimes for variable ones, the degree of turbulence is almost always at its maximum with the maximum air flow. For this reason best results are often obtained if the incinerator is fired at its maximum rating. Shorter firing periods at maximum rate may produce better results than continued operation at low firing rates. (4)

Control of Time

The third major requirement for good combustion is time. Sufficient time must be provided to the combustion process to allow slow-burning particles or droplets to completely burn before they are chilled by contact with cold surfaces or the atmosphere. The amount of time required depends on the temperature, fuel size and degree of turbulence achieved. It is customary to specify certain furnace volumes for heat releases in an attempt to obtain proper combustion times. It is now recognized that this method is inadequate. In the absence of specific data, combustion chambers with heat releases of 20,000 to 60,000 Btu/cu ft-hr are common. These values may be too conservative for high performance burners, and small compact incinerators can mean lower investment and lower maintenance. The evaluation of this factor of time can only be made by tests of individual burners and furnaces. If slow-burning items are present, such as carbon particles, or carbon monoxide, additional chambers (secondary combustion chambers) may be needed to allow time for complete combustion. (5)

Equilibrium Combustion

The mechanisms of combustion reactions are extremely complex. The combustion process is one of many reaction chains forming, branching, and ending. Many intermediate compounds are formed that do not appear in the initial or final constituents. (6)

In general, combustion products will seek the level in which they contain a minimum amount of free energy. Excellent tables of thermodynamic properties of a wide variety of substances are available in reference 3. Even more important is the fact that the combustion process must be carried out under equilibrium conditions. For example, Figure 3 shows the calculated equilibrium amounts of nitric oxide (NO) that will occur in burning a wide range of fuels. These were calculated for ordinary fuels such as natural gas, coal, and oil as well as for wastes containing nitric acid and nitrogen dioxide (NO_2). If one wishes to abate nitrogen dioxide or other nitrogen compounds, it is not sufficient to heat the NO_2 to the temperature shown. The NO_2 must pass through the combustion flame of an equilibrium burner. Adding NO_2 to hot combustion gases will only convert it to nitric oxide (NO) and decolorize it. Once it cools in the atmosphere it reverts to NO_2 and no pollution abatement has been achieved. For gas and liquid burners, the burner must demonstrate on any fuel that it is capable of approaching stoichiometric combustion. A burner that gives complete combustion at zero excess air proves that it can achieve equilibrium. Time, temperature and turbulence are all at sufficient values to achieve the desired thermodynamic results. For solid fuel incinerators it is often not practical to operate a unit at zero excess air. While a gas or liquid unit can be adjusted quickly to such conditions and tested, it is seldom possible to quickly adjust solid fuel incinerators. The long periods required can create excessive temperature rises in the furnace enclosure and result in their destruction.

COMBUSTION OF SOLID WASTE

Introduction

The waste is assumed to be converted to gaseous combustion products and an inert solid residue in a series of steps including drying, pyrolysis, and combustion. Drying is assumed to occur before pyrolysis and combustion, and the time required for drying is not considered in the following. Furthermore, pyrolysis and combustion are treated as independent processes, even though the combustion of pyrolyzing solids has been shown to be influenced by the pyrolysis process. (7)

Pyrolysis

Pyrolysis of carbonaceous materials, even those as simple in structure and composition as cellulose, includes many individual reactions, some of which are endothermic, bond-breaking, or cracking reactions, and others of which are exothermic, bond-forming reactions. In general, the cracking reactions occur as an early stage of pyrolysis and convert the original material into a new, sometimes plastic structure. These reactions generate gaseous products with a composition that varies from mainly CO_2 and H_2O at first, to mainly hydrocarbons (tar, light oil, and fixed gases) in the later stages of pyrolysis. The bond-forming reactions are accompanied by solidification of plastic material to form char with the evolution of volatiles that become progressively hydrogen-rich as pyrolysis is carried to higher temperatures. The overall pyrolysis reaction is generally endothermic.

The extent of pyrolysis of a given material depends upon the temperature to which the material is heated and the time spent at that temperature. It is now generally believed that pyrolysis is fast enough to keep up with the heating process, unless the rate of temperature rise is faster than some critical value which is probably around 10^4 deg C/sec. [2]

Pyrolysis is an activated process; therefore, the temperature dependence of the rate of pyrolysis may be expressed in terms of an activation energy in the standard form

$$K_p = A_p \exp(-E_p/RT) \qquad (1)$$

where k_p is the pyrolysis rate constant, A_p is the frequency factor, E_p is the activation energy for pyrolysis, R is ideal gas constant, and T is the absolute temperature. However, the "pyrolysis" process observed in practice includes not only pyrolysis as described in the foregoing, but also the processes of heat transfer from the surroundings to the decomposing material and mass transfer of the pyrolysis products both out of the solid specimen and into the surroundings.

Some disagreement exists among different investigators about the rate-controlling step of the overall pyrolysis process. For example, Pitt (8) and van Krevelen (9) support the proposition that the rate of pyrolysis of bituminous coal is controlled by the decomposition of the material, whereas Berkowitz (10) argues that the rate is controlled by diffusion of volatiles to the surface of the particle. Such disagreement probably results from differences in experimental conditions. The overall pyrolysis rate is known to depend upon properties of the system, such as particle size, heating rate, upper temperature attained, and the type of material, but to account for variations in these quantities between different experiments is very difficult. Until sufficient data are available, prediction of the pyrolysis rate for a given material, under a given set of conditions, required judgment based on qualitative knowledge of the relative rates of the individual processes (11).

In general, if particle size is small enough, or if heating rate is slow enough so that significant pressure and temperature gradients are not established within the solid material, then the overall rate of pyrolysis is simply the rate of decomposition of the material; otherwise, the processes of heat and mass transfer influence the rate.

In order to estimate the time required for the overall pyrolysis process, it is assumed that the overall rate is equal to the rate of heating, thus implying that both the pyrolysis reaction and the flow of pyrolysis products out of and away from the particles are infinitely fast.

The pieces of waste are assumed to be plunged suddenly into a hot combustion chamber, maintained at a certain temperature which, for purposes of discussion, is assumed to be 1300°C (2375°F). The times required for the surface temperature, the center temperature, and the space-mean temperature of the pieces to rise by 95 percent of the initial temperature difference between the waste and the combustion chamber are calculated. These times serve as a measure of pyrolysis time. Heat transfer by radiation and by direct contact with hot particles already in the chamber is neglected.

The calculations are described in Appendix A. The pyrolysis (heating) times are given in Figures 4 and 5 as a function of particle size and relative velocity between the pieces and the surroundings. Two different shapes, thin slabs and spheres, are considered, but space-mean temperatures are given for slabs only. With regard to heating times, these two shapes should bracket the particle shapes found in practice.

The particle-size dependence of the pyrolysis time is very significant. Within the range of conditions studied here, the time varies approximately with the square of the dimension of the specimen for both spheres and the flat plates. For example, if the ambient velocity is 1 fps, the heating time for the center of a sphere drops from about 3 to about 0.5 min. as the diameter is reduced from 3/8 to 1/8 in.

The effect of ambient velocity is also significant. Relative velocities between the specimens and the surroundings of up to 100 fps are considered, even though such large values may be difficult to achieve in practice. The curves labeled $2\lambda_s/hd_o = 0$ represent an infinitely large surface heat-transfer coefficient, which is equivalent to an infinitely large velocity of the ambient gas relative to that of the particle. Under such conditions, the surface of the specimen attains the temperature of the combustion chamber immediately upon entering the chamber, and the rate of heating is determined solely by the properties of the specimen.

Combustion

Although incineration of solid waste includes both gas-phase and heterogeneous combustion, only heterogeneous combustion is considered here, since we are mainly interested in the time required for burning, and heterogeneous combustion is, by far, the slower of the two processes. The material experiencing heterogenous combustion includes both solid residues of pyrolyzed material and non-pyrolyzing pieces.

Ignition of the solid pieces of waste requires that certain conditions of temperature and oxygen concentration be satisfied at the solid surfaces. If we visualize, for the purpose of discussion, a well-mixed combustion chamber containing a certain concentration of oxygen, then the oxygen concentration at the surface of an unignited pyrolyzing particle is less than that in the ambient gas, owing to the outward flow of volatiles from the surface. If pyrolysis (i.e., heating) is fast enough, ignition may be delayed, even though the surface may be very hot, until the surface flux of volatiles drops below a certain critical value which depends heavily upon particle size (7). For present purposes, we shall define the burning time of a piece of waste as the time between ignition and complete conversion to gaseous combustion products and an inert solid residue (ash), and we shall assume this time to be independent of the details of the ignition process.

Heterogeneous combustion of waste consists of the physical processes of heat and mass transfer and the chemical process of reaction between the solid material and the gaseous surroundings. The physical processes are largely independent of the type of material being burned and may be formulated, even though the chemistry of the combustion of some of the materials in waste is unknown.

The chemistry of heterogeneous combustion depends upon the material being burned. One or more reactions may be involved, and parallel or sequential steps, or both may occur. A large portion of the solid material encountered in incineration is mainly carbon, whose reaction with oxygen is relatively well understood.

The chemistry of the combustion of carbon with oxygen has been shown to agree well with a mechanism involving two steps in series (12). The first step is adsorption of oxygen on the carbon surface; the second step is desorption of oxides of carbon. Adsorption is first-order, and desorption is zero-order with respect to oxygen concentration. The activation energy of adsorption depends upon surface coverage and is generally low. At low surface coverage (rapid desorption), the adsorption activation energy corresponds to a temperature dependence similar to that of heat and mass transfer (12). Conversely, the activation energy of desorption is large, so that the temperature dependence of desorption is very strong. The rates of these two steps are given in the following.

Adsorption rate:

$$\dot{R}_1 = K_1 f_s (1 - \theta) \tag{2}$$

Desorption rate:

$$\dot{R}_2 = K_2 \theta \tag{3}$$

where $\dot{r}_1$ and $\dot{r}_2$ are the specific rates of adsorption and desorption (g-moles carbon equivalent/sq cm-sec), k_1 and k_2 are the rate constants for adsorption and desorption, f_s is the mole fraction of oxygen at the solid surface, and θ is the fraction of the active sites on the carbon surface that is occupied by adsorbed oxygen.

At low temperatures, less than about 750°C (1400°F) for the case of chemically controlled combustion in air, the rate of the combined chemical steps of the carbon-oxygen reaction is completely controlled by the rate of desorption. At high temperatures, greater than about 1150°C (2100°F) for the case of chemically controlled combustion in air, the rate is controlled by adsorption. In the transition region, both steps influence the rate. This behavior is illustrated in Figure 6, which gives results obtained by fitting the data of Tu, Davis, and Hottel (13) with the mechanism described in the foregoing. The transition region between adsorption and desorption control is seen to depend upon the concentration of oxygen at the solid surface, which, in turn, depends not only upon the oxygen concentration in the ambient gas, but also upon the rate of mass transfer between the ambient gas and the burning surface.

The rate of transport of oxygen to the burning surface of a carbon specimen is given as follows:

Mass transfer rate:

$$\dot{N} = K_f \left(f_A - f_s \right) \tag{4}$$

where k_f is the mass transfer coefficient, f_a is the mole fraction of oxygen in the ambient gas, and $\dot{N}$ is the molar flux of oxygen reaching the surface. A similar equation could be written describing convective heat transfer from the specimens; however, consideration of heat transfer is avoided in the present analysis by assuming that the solids and ambient gas are at the same temperature during burning.

Thus, the rate of carbon combustion is described in terms of three sequential steps. Since the rates of these steps are all equal at steady state, an equation for the rate of the overall process is obtained from equations (2), (3), and (4), by eliminating both the surface coverage and the partial pressure of oxygen at the reacting surface. The overall burning rate, $\dot{R}_s$, is expressed in terms of the ambient oxygen partial pressure and the chemical and physical rate constants as follows:

Overall burning rate:

$$\dot{R}_S = \frac{1}{\frac{1}{2}\left[\frac{1}{K_f f_A} + \frac{1}{K_1 f_A} + \frac{1}{K_2}\right] + \left[\left(\frac{1}{2}\left[\frac{1}{K_f f_A} + \frac{1}{K_1 f_A} - \frac{1}{K_2}\right]\right)^2 + \frac{1}{K_1 K_2 f_A}\right]^{1/2}} \tag{5}$$

The burning rate described by equation (5) is studied best by considering specific, limiting conditions. Since the rate of the overall process is no faster than the rate of the slowest step, the rate-controlling step, under a given set of conditions, is identified by comparing the rate of the three individual steps. Information for such a comparison is given in Figure 7. Mass transfer becomes more important as a rate limiting step as particle size increases; for the given set of conditions, there is a critical particle size above which mass transfer completely controls the rate. For example, if we consider the combustion of carbon spheres in air at 1527°C (2780°F) with a relative velocity of 3.5 cm/sec (0.11 fps) between the sphere and air, then the burning rate is limited by mass transfer, if the sphere diameter is larger than about 3/8 in. Under the same conditions, the rate is adsorption controlled, if the particle size is less than about 0.01 in.

Most of the residues from waste pyrolysis are probably porous. Under conditions where mass transfer is much faster than the chemical reaction, a non-zero concentration of oxygen exists at the outer surface of a specimen, and oxygen may diffuse into and burn out the pores. The rate of pore combustion increases as the concentration of oxygen at the surface increases, but the reaction on the superficial surface, plus the reaction in pores, can never exceed the rate of transport of oxygen to the specimen. In general, the importance increases, as total pressure increases, as particle size increases, and as the relative velocity between the specimen and the surroundings decreases.

The technique, used for studying the time required to burn pieces of refuse with air, is to consider simplified, limiting cases. Basically, two categories of cases are considered: combustion of any solid material under such conditions that the rate is completely masstransfer controlled, and combustion of carbon specimens under conditions where both chemical and mass transfer phenomena limit the burning rate.

Burning Time of Any Solid Material with the Burning Rate Controlled by Mass Transfer. The case of mass-transfer controlled burning rate is realized when the solid pieces are so reactive that the chemical rate exerts negligible resistance to burning. Mass transfer through the gaseous surroundings of the solids is assumed to be the rate-limiting physical process, thus neglecting possible contributions from accumulated oxide on the burning surface.

The results are valid, under conditions of mass-transfer control, whether the material is porous or nonporous, and for material of any composition, provided the stoichiometry is accounted for properly.

The following equations, derived in Appendix B, give the mass-transfer controlled burning time (t_b) m.t. of spheres of diameter, d_o, and slabs of thickness, d_o, and length, L, as functions of known properties of the system.

Sphere; mass-transfer control:

$$(t_b)_{M.T.} = \left[K_1 K_2 K_3 (T_o/T)^{1/2} (1/f_A)\right] d_o^2 \qquad (6)$$

where K_1 is a constant, K_2 is a dimensionless function of the relative velocity between the specimen and the ambient gas, K_3 is a function of the combustion stoichiometry, and T_o is 273°K.

Flat plate; mas-transfer control:

$$(t_b)_{M.T.} = \left[K_3 K_4 (T_o/T)^{1/4} (L/V_o)^{1/2} (1/f_A)\right] d_o \qquad (7)$$

where K_4 is a constant for combustion in air, and V_o is the relative velocity (at STP) between the specimen and the ambient gas.

<u>Burning Time of Solid Carbon Under Various Conditions of Rate Control</u>. The equations given in the following,

derived in Appendix B, give the burning times of carbon specimens in air. When the burning rate is completely controlled by the adsorption of oxygen on the carbon surface, the burning time is:

Carbon sphere or flat plate; adsorption control:

$$(t_b)_A = K_5 (P_0/P)(1/f_A)[1/(T_0/T)^{1/2} \exp(-E/RT)] d_0 \qquad (8)$$

where K_5 is a constant, P is absolute pressure ($P_0 = 1$ atm), and E_1 is the activation energy of oxygen adsorption on carbon.

If desorption controls the burning rate, the burning time is:

Carbon sphere or flat plate; desorption control:

$$(t_b)_d = K_6 [1/\exp(-E_2/RT)] d_0 \qquad (9)$$

where K_6 is a constant, and E_2 is the activation energy of the desorption of combustion products (assumed to be CO_2) from the carbon surface.

When the burning rate is controlled jointly by adsorption and mass transfer (i.e., desorption infinitely fast); the burning time is found to be:

Carbon sphere or flat plate; joint adsorption and mass-transfer control:

$$t_b = (t_b)_{M.T.} + (t_b)_A \qquad (10)$$

When adsorption is infinitely rapid relative to the rates of desorption and mass transfer, the burning time is not given by the sum of the burning times predicted for complete desorption control and complete mass-transfer control as might be expected in view of the form of equation (10). The case of infinitely rapid adsorption differs from that of infinitely rapid desorption, because desorption; unlike adsorption, is not coupled with mass transfer, since it is independent of the concentration of oxygen at the solid surface. Thus,when adsorption is infinitely fast, the burning time is given by:

Carbon sphere or flat plate; desorption and mass-transfer control:

$$t_b = (t_b)_{M.T.} \text{ OR } (t_b)_d$$

where (t_b) m.t., from equations (6) and (7), is used if mass transfer is slower than desorption, and $(t_b)_d$, equation (9), is used if desorption is slower than mass transfer.

Test of Equations with Experimental Data. Few data exist for testing the foregoing equations. In the case of mass-transfer controlled burning, Essenhigh (15) finds that existing data on the burning times of coal and carbon particles are correlated by an equation of the form $t_b = Kd^2{}_o$, which is similar in form to equation (6). These data cover the size range .05 to .4 cm, but pertinent information, such as temperature and ambient velocity, is missing. Nevertheless, Essenhigh's estimated values of K range from 330 to 2125 sec/sq cm for the different data.

The expression for K obtained from equation (6) is:

$$K = K_1 K_2 K_3 (T_o/T)^{1/2} (1/f_A)$$

Values of K predicted from this expression are very similar to the larger values in Essenhigh's summary. For example, if the particles are assumed to be burning in air, with natural convection creating an ambient velocity of 1 fps past the particle, and if the particle surface is assumed to be at 1400°C (2550°F), then K in equation (6) is found to be 2100 and 2640 sec/sq cm for 0.05 and 0.4 cm particles, respectively. In order to predict K values near the lower limit of the experimental data, either ambient velocity or temperature (or both), would have to be much higher than the foregoing values. Nevertheless, the agreement appears to be good enough to allow equation (6) to be used with considerable confidence; and, by inference, equation (7) should also be useful for the case of flat-plates.

Data on burning times of carbon particles under chemically controlled conditions appear to be limited to particle sizes less than about 0.005or 0.01 cm, the reason being that, under the conditions of most experiments, the combustion of particles larger than about 0.01 cm is mass transfer controlled. However, in spite of the lack of data on burning times, equations (8) and (9) receive considerable experimental backing for two reasons: 1) the kinetics parameters are evaluated with experimental data (see AppendixB); and 2) burning times predicted from these equations agree well with data from pulverized-coal flames operating under chemically controlled conditions.

Calculated Burning Times. Burning times for mass-transfer controlled conditions, calculated from equations (6) and (7), are presented in figure 8. Even though this figure applies specifically to a very limited set of conditions, it does demonstrate the influence of some of the important variables and shows the range of burning times to be expected.

The times, shown in Figure 8, are minimum values, since chemical resistance is neglected. The effect of chemical resistance can be accounted for in the case of carbon combustion. For example, the combustion of a 2-in. x 2-in, x 0.1-in. carbon plate in air at a temperature of 817°C (1500°F), and an air velocity of 1fps (at STP) is controlled jointly by desorption and mass transfer. Therefore, according to the earlier discussion, the burning time is the larger of the two values predicted by assuming a) complete desorption control, and b) complete mass-transfer control. The times predicted by equations (7) (mass-transfer control) and (9) (desorption control) are 1450 and 2000 sec, respectively. Hence, the burning time is 2000 sec, which is about 3.4 percent larger than that predicted in figure 8.

A second example is the combustion of a 0.1-in. carbon sphere in air at 1-atm and 1300°C (2370°F) with no ambient velocity past the particle. In this case, the burning rate is controlled jointly by adsorption and mass transfer; therefore, the burning time is given by equation (10). The separate contributions to burning time by adsorption and mass transfer are found to be 171 sec from equation (8) and 210 sec from equation (6), respectively. Therefore, the burning time is 381 sec, which is 81 percent larger than that given in Figure 8.

In the case of materials of unknown combustion characteristics, the effect of chemical resistance cannot be accounted for, and the burning times obtained from mass transfer considerations serve as limiting values.

THE INFLUENCE OF MOISTURE ON THE COMBUSTION INTENSITY

Introduction

There are several ways in which moisture can influence the combustion intensity in an incinerator. The most obvious is by straight dilution. The presence of evaporated moisture increases the gas volume so that the concentrations of the fuel (smoke, volatiles, etc.) and the oxygen are reduced. At the same time the increased volume of gas decreases the residence time in the combustion chamber so that, either combustion is completely outside the chamber, or else the residence time is increased again by reducing the air input which in turn must be balanced by reducing the overall combustion rate. The presence of moisture also provides an extra thermal load so that the flame temperature will drop. In general, as shown by calculations given elsewhere on coal (21), the moisture has to be at a very high level before the extra thermal load becomes appreciable, but relatively small changes in flame temperature can have a big effect on the rate of reaction if the activation energy of the process is high, and this affects the burning time. Finally, the moisture may interfere directly (chemically) with the progress of the reaction, though this is thought to be unlikely.

Heat and Mass Balance

The flame temperature, T, may be estimated by means of a heat and mass balance on the incinerator. In principle this is quite simple to set up since all the heat of combustion must go either into the sensible heat of the stack gases or the wall loss, H_W (Btu/hr). Two complications to be considered are the magnitude of the unknown wall loss and the effect of supplementary fuel.

At a firing rate F lb/hr the total heat input is FB Btu/hr. Equating this to the sensible heat in the stack gases plus the wall loss leads to an equation with the firing rate, F, appearing in every term but the wall loss. Dividing through by F gives a balance on the basis of one lb of waste

$$B = [(1-m) + (\rho_o B/100)\ (1 + E/100)]\ \ c_p(T_f - T_o) + [h_g + 2c_p\ (T_f - T_b)]\ \ (m) + (H_w/F) \qquad (11)$$

This simple balance on the common assumption that the specific heat (c_p) of the total mass of fuel (with ash) and air is the same as that of the same mass of combustion products. The heat in the moisture is the evaporation enthalpy (h_g) plus the sensible heat above the boiling point, T_b, with the specific heat of the moisture taken as twice that of the combustion products (= 0.5 for c_p = 0.25).

Substituting for B gives approximately [for the ratio 0.05/(0.95-m) assumed small]

$$B_o = [1 + (\rho_o B_o/100)\ (1 + E/100]\ \ c_p\ (T_f - T_o) + [h_g + 2c_p\ (T_f - T_b)]\ \ [m/(0.95-m)] + H_w/F\ (0.95-m) \qquad (12)$$

If the material is dry this becomes

$$B_o = [1 + (\rho_o B_o/100)\ (1 + E/100)]\ c_p(T_{fo} - T_o) + H_w/0.95F_o \qquad (13)$$

The wall loss can be taken into account in one of two ways. The first is by direct calculation. The second is by its elimination. So far as direct calculation is concerned, this would be very much a matter of guess work. The range of possibilities can be reduced somewhat by using known ranges of the heat utilization factor defined by Thring (22) and used in furnace analysis by MacLellan (23).

In the absence of any other method of estimating the wall loss, this way would be acceptable. However, a better way may be the elimination of the loss term. Inspection of the two loss terms in equation (12) and (13) shows that H_w is divided by the rate of input of combustible alone. As this drops and the moisture rises the flame temperature drops, and so must H_w. As a first approximation H_w is likely to be roughly proportional to the actual thermal input, BF, or $B_oF(0.95-m)$. (H_w/FB) is then approximately constant so subtracting equation (13) from (12) would eliminate the loss terms. Performing this subtraction gives

$$[1 + (p_o B_o/100)(1 + E/100)]\quad c_p(T_{fo} - T_f) = h_g + [2c_p(T_f - T_b)]W \qquad (14)$$

where W is the weight ratio of moisture, lb/lb, fuel = m/(0.95-m)

Rewriting this in terms of T we have

$$(T_f/T_{fo}) = [1 + (T_b - h_g/2c_p)\ (2J/T_{fo})W]\ /\ (1 + 2JW) \tag{15}$$

where $$J = 1/\ [1 + (\rho_o B_o/100)(1 + E/100)] \tag{16}$$

These can be evaluated if T_{fo} is evaluated from equation (13) making some reasonable assumption about the ratio $(H_{wo}/0.95\ F_o B_o)$.

So far as the heat balances are concerned the effect of supplementary fuel is clear. In equations (12) and (13) a quantity B' for the supplementary Btu input should be added to B_o, Then on the R. H. S. of each equation the gas volume should be increased by $(p_o B'/100)$. By subtraction to obtain equation (14) the extra B' terms on the L.H.S. will cancel out again and the overall effect will be replacement of the J term [equation (16)] by a J' given by

$$(1/J') = 1 + (\rho_o B_o/100)\ (1 + E/100) + (\rho_o B'/100) \tag{17}$$

This can be regarded as equivalent to a reduction of the true moisture content to an effective content W', given by

$$W' = (J'/J).W \tag{18}$$

Strictly, there should be a further correction to the maximum flame temperature for the dry material, T_{fo}, but the correction is small and it appears only in a small correction term.

The equations given above can be substantially simplified by evaluating the constants. Values adopted for the coefficients are as follows $c_p = 0.25$, $\rho_o = 0.05$ lb/cu ft, $E_o = 10{,}000$ Btu/lb, E% = 250. These give a value for J of 0.054.

The boiling point of water, T_b, is 672°R; the evaporation enthalpy, h_g, can be taken as 1150 Btu/lb. The flame temperature, T_{fo}, can be calculated from equation (15) by assuming 15 percent wall loss so $T_{fo} = 2300$°R. Inserting these values equation (17) can be written

$$(T_f/T_{fo}) = (1 - 0.0765W)/(1 + 0.108W) \qquad (19)$$

Substituting for W by the moisture fraction, m, then gives

$$(T_f/T_{fo}) = (1 - 1.13m)/(1 - 0.94m) \qquad (20)$$

FUNDAMENTALS OF HUMAN WASTE INCINERATION

Introduction

A number of different methods can be used for the disposal of wastes, but most of these present serious engineering problems and result in undue construction and operation costs. In general the following systems can be used:

1. Induction heating, which is similar to the dielectric type of heating used on ordinary electric ranges.
2. The Zimmerman process, which involves large scale and unnecessarily complicated equipment.
3. Biological Treatment.
4. Chemical Treatment.
5. Dumping and Burial.
6. Incineration.

Systems 3 through 6 are the most feasible for use in the majority of installations. As the physical, climatic, and other conditions characteristic of a specific area affect the choice of the method of disposal, a brief description of the different systems is presented, with the problems pertinent to each, so that conclusions can be drawn as to the most desirable method of disposal.

Biological Treatment

Fecal matter, like all forms of dead organic matter, animal or vegetable, undergoes decomposition and disintegration, when exposed to the air, eventually becoming reduced to stable inorganic compounds. Offensive putrescible matter is destroyed, and complex substances are transformed into simple ones which can be utilized by growing plants and animals. This transformation of sewage and other organic wastes is achieved by the action of bacteria and other microorganisms. Under proper environmental conditions, these microorganisms utilize organic waste as food, converting it into simpler, non-polluting compounds such as carbon dioxide, nitrates, sulphates, and water. The rate of biological activity is dependent on the temperature of the media and the surrounding atmosphere, and decreases with decreasing temperature.

Chemical Treatment

The addition of chemicals causes some organic and inorganic substances in solution to separate and then precipitate, together with the matter in suspension. The solids, or sludge, may be removed and disposed of by dumping, or may be pelletized for use as a fertilizer, while the liquids can be discharged into a body of water. The chemicals most commonly used as coagulants are alum, lime, and iron sulfate, either along or in combination. The degree of purification depends on the dosage, the types of chemicals that are used, and the temperature and characteristics of the waste.

Dumping and Burial

The waste solids from biological or chemical treatment plants can be disposed of by dumping on waste land or on land that requires fill. Some wastes mix readily with the earth to produce a soil suitable for plant growth; other wastes, which are not desirable in soil, should be buried on waste land.

Incineration

The incineration of organic wastes provides the ultimate in volume reduction, reducing them to carbon dioxide, water and highly oxygenated nitrogen and sulfur compounds. The effectiveness of the incineration process is dependent on the incinerator design and on such variables as temperature, oxygen and the time of contact. The ash remaining from incineration can usually be dumped at sea without creating a nuisance, or can be used as land fill.

It is recommended that the wastes be concentrated as much as possible before incineration in order to reduce auxiliary fuel requirements.

STUDY ON A INCINERATOR SYSTEM

Every successful incinerator in operation today has at least two distinct stages. The first stage consists of the evaporation of the liquids and the volatilization of the solids, while the second stage consists of the combustion of the volatiles in the gas.

In an incinerator system there are certain requirements that must be fulfilled in regard to the safe, efficient and complete destruction of human wastes, which are as follows:

The primary chamber must be supplied with sufficient heat to accomplish evaporation and to volatize the organic material present in the urine and the feces.

The vapors from the primary chamber must pass into the secondary chamber where the vapors must be subjected to high enough temperatures, in the presence of a sufficient amount of oxygen, to undergo complete combustion of the volatile organics in the waste gas. In addition, the time of contact of the waste gas with the oxygen must be sufficiently long, with a high degree of turbulence, to allow intimate contact between the gas and the oxygen.

The unit should warm up instantly, i.e., there should be no danger of the initial products of evaporation not being exposed to oxidizing temperatures. The primary chamber should be cooled to less than 212°F in less than two minutes to prevent flash during loading.

It is desirable to obtain exhaust gases in the form of CO_2, N_2, water vapor, and O_2 without the presence of carbon monoxide and/or products of imcomplete combustion of the organic materials originally present in the urine and feces, such as oxalic acid, hippuric acid, glucose, fats, etc., or combinations of any of these substances. A low percentage of CO in an exhaust gas analysis without a trace of odors would indicate that there is almost complete combustion.

An exhaust analysis should show that the concentrations of all toxic, odorous, or otherwise objectionable compounds are less than the Threshold Limit Values (Table 3).

The unit should be supplied with the safety features necessary to eliminate any possible danger.

Electric Incinerator

The following information applies to an electric system made by Incinemode, Inc., of Garland, Texas.

The following plot (Figure 9) shows the relationship of temperature with time at various points within the Incinemode unit during a test on the disposal of one pound of water.

The water had an initial temperature of 104°F, about 10°F higher than the normal discharge temperature of urine. With a room temperature of 66°F, the liquid cooled to 86°F before operation commenced. The first noticeable temperature rise occurred after a span of eight minutes; the liquid was fully evaporated after a period of 45 minutes. At no time during this evaporation period did the vapor temperature rise above 415°F. These temperatures were attained by the use of natural draft, i.e., no exhaust fan was used; and exhaust fan would have the effect of cooling the vapor. An effective temperature rise of 600°F to 900°F would be theoretically possible by using a catalyst; this would raise the temperature from 600°F to 1300°F, not including the air required for the complete oxidation of the waste. In essence, this suggests that the vapors cannot reach sufficient temperatures without the use of a superheater or a preheater prior to the catalyst. A catalyst must have the necessary contact surface, the proper combination of materials for the waste in question, a sufficient air supply and a preheater to provide the proper temperature prior to the catalyst in order to perform its function.

The Incinemode unit has a power rating of 2,400 watts for the main heating coils and 900 watts for the Oxycat superheater. As the superheater was inoperative, 2,400 watts was used; at this power, a time of 45 minutes was needed to evaporate one pound of water. This resulted in a thermal efficiency as shown below:

$(212 - 85) + 970 = 1{,}097$ Btu/lb water

1 watt = 3,414 Btu/hr

2,400 watts = 8,200 BTU/hr = 6,150 BTU/45 min

$$\text{Thermal eff.} = \frac{1097}{6150} = 0.178 = 17.8\%$$

The unit without the superheater had a time lag to bring the water up to boiling temperature. The lack of any superheater prevented exhaust gases from reaching the temperature necessary for combustion. This unit did not have an exhaust fan which would be necessary for complete oxidation, and which would also result in cooling the exhaust gases more thoroughly. The surface temperature of the coils was a maximum of 1060°F and the pan 1020°F after evaporation was completed. Intermediate temperatures are as shown in Figure 9.

The results of this experiment clearly demonstrate that evaporation can only be used if the evaporated vapors are then exposed to other heat sources or to a second stage process such as exposure to an oil flame.

Complete oxidation cannot be accomplished unless the waste is in intimate contact with air at 1500°F (24). Coil temperatures were never above 1100°F in this unit. Up to the present time, no electric heating coils have been found which can exceed this temperature.

The Chemistry of Combustion

Preliminary to the design of an incinerator, it is necessary to have an analysis of the waste material to be destroyed and to conduct studies on the behavior of this material in the incineration process. While it is true that incineration is used as a method of a sludge disposal from biological treatment processes, it should be noted that this sludge has undergone aerobic and/or anaerobic decomposition, hence this sludge does not have similar operational characteristics in an incinerator to that of fresh human excreta. The analysis of the waste material and a study of the chemistry of combustion follows.

Tables 4 and 5 are presented to show that the constituents of urine and feces are primarily carbon, hydrogen, and oxygen with other elements being present to a lesser extent. Compounds which have similar constituents are the hydrocarbon fuels which are composed of carbon and hydrogen with very small amounts of impurities, such as sulphur.

Because of this analogy between fuels and wastes, the analysis can be confined to the products of combustion of fuels and then relate this to the combustion of wastes.

Products of Combustion of Hydrocarbon Fuels

At the temperature of combustion, hydrocarbons rapidly dissociate into free hydrocarbon radicals. These hydrocarbon radicals are liable to oxygen attack, with highly reactive, unstable oxygenated compounds or radicals being formed which have only transitory lives. It is only through successions of these active radicals that the carbon and hydrogen of fuels and wastes are converted into carbon dioxide and water. The atoms and radicals, O, H, OH, and HO_2, involved in the oxidation of hydrogen are also active in the combustion of hydrocarbons. Aldehydes are also essential links in the combustion process.

The hydroxylation theory is of importance in considering the combustion of hydrocarbon fuels.

There is a combination of the hydrocarbon with oxygen preliminary to final combustion. Hydrocarbons combine with oxygen to form alcohols and aldehydes previous to, and as a preliminary step in, burning to CO, CO_2 or water. This holds true at all temperatures.

The initial addition of oxygen to the hydrocarbon molecule forms an alcohol with which, in turn, more oxygen reacts, forming an aldehyde. This aldehyde, in many cases, breaks down into intermediate combustible gases, CO and H_2, or the aldehyde may burn completely to CO_2 and H_2O. This process is termed hydroxylation because the first addition of oxygen to the hydrocarbon molecule gives the hydroxyl grouping (-OH) characteristic of alcohols (28).

A survey of available literature regarding odor and the measurement of odor intensities did not reveal a method suitable for evaluating the complex mixture of odors that can result from incineration. An example of a complex odor that is the result of incomplete combustion is a substance called urinoid (C_6H_8O).

The breakdown of such substances as hippurric acid, oxalic acid, uric acid, urea, indican, crectinine, phenols, indole, skatole, etc., under the influence of temperatures of 1600°F or more and excess air (air more than required for the chemical reactions) is a study requiring full scale research. A literature review failed to show any information regarding this subject at the present time.

Therefore, if sufficient oxygen is supplied and a temperature greater than the ignition temperature of all of the organic compounds present in the waste, then theoretically complete combustion should be assured.

Methods to Determine Products of Combustion

The objective of this section is to present methods for determing the concentration of the intermediate products of combustion from the burning of wastes in an incinerator. These methods are presented here very briefly while the complete experimental procedure can be found in the references cited (29).

1. Aldehydes.

Total aldehydes can be determined by a method similar to that used by Goldman and Yagoda (30) after the incinerator effluent is collected in five gallon carboys containing 100 ml of one per cent sodium bisulfite solution, drained and washed with distilled water.

2. Ammonia.

Five gallon carboys can be used here also but instead contain 100 ml of one percent H_2SO_4 as the absorb--ing solution. A modification of the Kjeldahl (31) distillation method can be used for the analysis of ammonia.

3. Oxides of Nitrogen.

Total oxides of nitrogen samples from the effluent can be drawn into carboys containing 100 ml of 0.1 N sulphuric acid and 1 to 2 ml of 30 per cent hydrogen peroxide; the phenoldisulfonic acid method (32) of analysis is used to determine the total oxides of nitrogen.

To determine the nitrogen dioxide (33) in the effluent, the Saltzman method may be used. Forty ml of effluent are drawn into a 50 ml of Saltzman's reagent. After absorption the remaining material, which is red-violet in color, is read on a Beckman Model DU spectrophotometer at a wave length of 505 millimicrons using distilled water as a reference. Standards are used to calibrate the instrument so as to permit determinations of the concentrations of nitrogen dioxide in ppm by volume.

4. Organic Acids.

Sampling for organic acids in the effluent is done by drawing about 0.7 cfm through a series of Greenbury-Smith impingers (34). The first two impingers contain 100 ml each of a 5 per cent solution of sodium hydroxide. The third impinger is used dry to separate mist. In the analysis the results are calculated as acetic acid in ppm by volume in the effluent.

5. Hydrocarbons.

The mader method (35) of the Los Angeles Air Pollution Control District can be used for the determination of hydrocarbons. This method involves the concentration of the hydrocarbons from a large gas sample by freeze-out techniques and determination of the hydrocarbons, as hexane, by infrared spectrogaphic analysis.

6. Particulate Matter.

The A.S.A. method (36) is a process by which the total weight of fly ash, smoke, and combustible tars per unit volume of gas is determined by filtering the gas through fine fiber-glass wood filter paper.

7. Smoke.

Many smoke measuring meters are available of which the Bacharach Smoke Meter is an example. Some are of the continous recording type and others only furnish spot values.

8. Odor.

Conventional odor comparison methods as used in water treatment practices can be used. The A.G.A. requires that odors present must not be more objectionable than those developed due to the burning of paper.

9. Other Methods.

The Orsat Analysis can be used to determine the amount of CO_2, CO and H_2 present in a sample of exhaust gas. The lower level of detection for the Orsat is 0.1 percent of 1000 ppm.

Comparison of Stack Emissions from Gas-Fired Incinerators and other Sources. Gas-fired domestic incinerators, minicipal incinerators, and gas and oil-fired industrial heating units do not attain complete combustion which would emit gases only in the form of CO_2, O_2, N_2 and water vapor, but instead emit gases that result from incomplete combustion, such as NO_2, SO_2, NH_3, CO, etc. The concentrations of the gases emitted from these units are presented in Table 3 along with the Treshold Limit Values of these gases. This table is presented for the following reasons:

1. To show that the concentrations of various exhaust gases vary considerably with the type of unit.

2. To show that exhaust gases from these incinerators are above the Threshold Limit Values for man and that incinerators should be designed to avoid the dangers of these gases.

3. To show what level of concentration of exhaust gases an incinerator system should achieve in comparison with other units and the Threshold Values.

Physiological effects of the products of combustion.

Carbon Monoxide.

Carbon monoxide at room temperature is a colorless, odorless, tasteless gas that is highly poisonous. It is lighter than air and diffuses readily with air. Carbon monoxide is formed in operations resulting from the oxidation of carbon-containing material. It is present in the products of combustion of gaseous, liquid or solid fuels when the conditions of combustion are not properly controlled (37).

The physiological effects of carbon monoxide are very noticeable and sudden, with only small concentrations of the gas being required.

Carbon monoxide is a blood poison since it combines with the hemoglobin in the blood forming a stable compound, carbon monoxide hemoglobin, which causes internal asphyxiation because the hemoglobin is no longer able to absorb-oxygen and deliver it to the tissues. Hemoglobin has an affinity for carbon monoxide which is 300 times greater than for oxygen, hence it will rapidly absorb the CO from any atmosphere containing even small amounts.

Table 4 shows the physiological effects when the blood contains varying percentages of carbon monoxide. Table 5 shows the physiological effects when the concentration of carbon monoxide in air varies over a given range.

Aldehydes.

The simplest molecular form of the carbonyl group (aldehyde) is formaldehyde (CH_2O) which is found by the addition of oxygen to methyl alcohol:

$$CH_3CH + 1/2O_2 \longrightarrow CH_2O \quad H_2O$$

Formaldehyde as a gas is a powerful irritant to the tissues to which it comes in contact, such as skin, conjunctiva and muccous membranes. This effect is due to the formation of an irreversible combination of formaldehyde with the protein of the surface cells. In contact with the body surface, it is changed to formic acid (carboxyl group) and methyl alcohol (38). Formic acid is a source of dermatitis and of irritation of the upper air passages.

In man the first symptom noticed is burning of the eyes and weeping, then irritation of the upper-air passages. If the gas is stronger, there is a cough, tightness in the chest, and a sense of pressure in the heat, with pneumonia occurring rarely. After inhaling a large quantity, there may be anorexia, sleeplessness, a feeling of weakness, and palpitation of the heart (40).

The danger limit for man has never been determined, although for cats it is 200 ppm. At 20 ppm the fumes become unendurable (41).

The American Standards Association has adopted a figure of 10 ppm as the maximum allowable concentration of formaldehyde.

Ammonia.

Ammonia gas is very irritating to the upper air-passages, hence smell serves as a warning of its potential danger. If avoidance of the gas is not possible the gas may be deeply inhaled and cause congestion of the lungs, followed by edema.

Table 8 shows the physiological effects of various concentrations of ammonia in the air (38).

High concentrations of ammonia, in addition to their corrosive action on mucous surfaces, which can cause permanent injury to the cornea, extensive damage to the throat and upper respiratory tract, chronic bronchial catarrh and edema, may affect heart action or cause cessation of respiration by reflex action (42). Maximum allowable concentration has been set at 100 ppm (43).

Sulphur Dioxide.

Sulphur dioxide gas causes a violent reflex action which acts as a fefense against any dangerous amount and hence allows the escape of man from the exposure to the gas and its fatal effects.

The injuries that result are frequently bronchitis, or possibly bronchial pneumonia, although edema of the larynx and lungs has been known to occur.

Acute cases of SO_2 poisoning are rare due to the intensely irritating fumes. Chronic poisoning is more prevalent and important than acute cases (41). There is no real tolerance to this gas, and the apparent tolerance is due to a chronic inflammation of the upper air passages, producing a tenacious mucus which acts as a protective coating. This protection does not extend to the lower air passages. The coating also deadens the reflex, hence this inflammation has removed one measure of protection. Table 9 shows acute effects of sulphur dioxide.

Inhalation affects chiefly the upper respiratory tract and bronchi, may cause edema of the lungs and can produce respiratory paralysis (44).

Organic Acids.

The inhalation of formic or acetic acid produces severe corrosion of the mucous membranes and pulmonary epithelium. Secondary effects are the result of hemorrhagic pneumonia due to the irritant action of the chemicals (42).

At low or tolerable levels of exposure, the amounts of the acid absorbed are readily oxidized; at higher concentrations, the discomfort is usually sufficient to force a person to leave the area.

Nitrogen Dioxide.

Nitrogen dioxide in concentrations of 100 to 1,000 ppm can cause death in animals. See Table 10.

The results of exposure of man to NO_2 are believed to be similar to that of animals based on the deaths resulting from acute exposure to this gas. Death is due to asphyxia resulting from a pulmonary edema and not due to the effects of nitrite. Asphyxia results due to the collection of fluid in the lungs which interferes with oxygen exchange. Symptoms may include weakness, nausea, abdominal pain, coughing with a foamy yellow or brownish expectorate, accelerated heart action, and severe cyanosis with convulsions. Slightest exertion under this condition may produce dysprea, cyanosis, cardiac dilitation, and collapse, with death within 8 to 48 hours.

Exposures in a range of 5 to 30 ppm with an average of 10 to 20 ppm, for periods of up to 18 months has shown no significant ill effects on man, no were there any adverse effects detected in any future examinations (42). The maximum permissible concentration has been set by various sources at from 5 to 25 ppm.

Combustion Variables.

The usual combustion process is accompanied by the bright glow or flame characteristic of fast, high temperature oxidation. The flame front or surface is an area of very rapid chemical reaction and is a boundary between burned and unburned gas that continously moves toward the unburned gas. The thickness of the flame front (or combustion wave) ranges from about a millimeter to indefinite thickness depending on local conditions. In passing through the flame front, combustion is either practically complete or consumes the locally available oxygen. The more rapid the combustion, the thinner the flame front. In the usual burner flame, ignition and combustion occur almost simultaneously and inseparably. Propagation of flame is generally a thermal process in that the flame must transfer heat to the unburned gas to cause it to ignite (50).

Solid Carbon in Flames (51).

a. Luminous flames can carbonize.

b. Tendency to smoke increases with molecular weight. Reverse is true for the olefine, diolefine, benzene, and naphthalene series. Methyl alcohol does not soot at all, but the tendency increases with molecular weight for primary alcohols. Secondary alcohols soot more readily than primary alcohols.

c. Branched chain paraffins smoke more readily than corresponding normal isomers, even though the C/H ratio is the same. The higher the branching, the greater is the smoking tendency.

d. Undersaturation increases the tendency to smoke.

e. Tendency to smoke increases with compactness.

f. In pre-mixed flames, carbon formations are not expected if there is sufficient O_2 to burn C to CO. If O_2 is insufficient to convert all the C to CO, then some C is thrown out.

g. High pressure favors carbon formation, low pressure reduces it.

h. For pre-mixed flames both SO_2 and H_2S tend to decrease carbon formation.

i. If sufficient time is available for entrance of oxygen into the hydrocarbon molecule, then hydroxylation (formation of a hydroxyl group) is favored rather than thermal decomposition into carbon and hydrogen.

Effects of Local Conditions on Combustion and Their Application (50).

Increases in temperature accelerate both the speed of ignition and the rate at which combustion is completed.

A hot refractory surface received heat from the flame and transmits it to colder portions of a burning mixture, increasing the rates both of ignition and of combustion. Refractory-tile burner ports always improve burner performance, and the role of the hot refractory lining in promoting combustion is essential to the operation of high temperature furnace. The influence of the hot refractory is so pronounced that its effect has been designated as "surface combustion". Silica, fire-clay, and other refractories catalyze combustion chain reactions at low temperatures (about 750 to 1300°F). This heat-transfer temperature effect coupled with local turbulence caused by surface roughness of refractory are of major importance in surface combustion phenomena at high temperatures.

The process of burning is controlled more by external factors such as concentrations, initial gas temperature, and the manner of mixing of the combustion air, than by differences of composition and other characteristics of the fuel.

Devices for the Complete Combustion of Gases.

Complete incineration is a two stage process. The first stage consists of drying, ignition, and volatilization. The second stage involves the total oxidation of the volatile products as they are released from the first stage.

The second stage process or the combustion of the intermediate products might be performed by any one of four different methods which are discussed below.

Catalyst.

In catalytic oxidation a combination of the molecules of the combustible gases with oxygen takes place at the surface of the catalyst. The rate at which this phenomenon occurs determines the activity of the catalyst. The physical and chemical characteristics of catalytic surfaces have an important bearing on the relative activity or rate of reaction. Keeping in mind these basic principles, it can be seen that to realize a successful catalytic oxidation reaction, the following factors must be considered:

Precautions must be taken to minimize deposits on the catalytic surface or clogging, in order to maintain contact with the molecules of combustible gases and the oxygen.

The catalytic agent must be extremely active and applied uniformly to the carrier. A deposit or coating is less apt to hinder the reaction on a very active catalyst surface than on one which is less active.

The catalytic element must be designed in such a way as to permit an even and equal flow over the catalyst surface.

Waste gases should be relatively free of catalyst poisons such as metallic oxides and other non-combustible contaminants.

As stated above, a very active and stable catalyst is able to withstand the presence of contaminating agents far more efficiently than one which is less active. Experiments in commercial installations have shown that one catalyst will function satisfactorily for several thousand hours, whereas another form of catalyst may be poisoned in a matter of a few hours under the same conditions. This difference in the behavior of catalysts can exist when the catalysts are composed of the same basic elements but of different preparation and configuration. The correct proportion of the chemicals and metals which enter into the preparation of the catalytic agent is vital to obtain catalytic activity; equally important is the design of the catalyst carrier (52).

Catalysts are generally limited to gases which are essentially a mixture of air and pure hydrocarbons or other gases which can be oxidized completely to CO_2 and H_2O. The use of appropriate catalysts can extend the use of catalytic oxidation beyond these simple applications.

The effect of the gases resulting from the evaporation of urine and feces on the catalyst has not been determined.

The gases must be preheated to a temperature of approximately 600°F for the catalytic reaction to occur (this temperature varies somewhat with the catalyst). As the gases are deficient in oxygen, air must be added to supply the oxygen for complete combustion of the CO and the hydrocarbons. The catalytic oxidation reaction results in a temperature rise of 600 to 900°F bringing the final temperature of the gas stream to 1200 to 1500°F.

The constituents of urine and feces vary, hence the products of combustion are CO_2 and water vapor, the composition of the other compounds will be variable in nature. A situation such as this would affect the usefulness or life of the catalyst.

Direct Fuel-Fired After-Burner.

The first method (Figure 10) utilized natural gas as the fuel source.

In this device, the products of combustion and free of excess air from the incinerator, plus additional excess air for the second stage process, are mixed in the throat of a venturi with the after-burner fuel gas for theoretically complete combustion within the venturi. The admission of secondary air for the after-burner should be made between the primary-burning chamber and the after-burner chamber as a deficiency of combustion air often exists with a common entrance for primary and secondary combustion air.

This is one of many techniques that can be used in the after-burner chamber and is probably one of the most effective with regard to the thoroughness of mixing of the volatile gases ,oxygen, and the flame.

The second method utilizes fuel oil as the heat source. Two general variations can be used with this heat source. The first method brings the flame in direct contact with the volatile gases, while the second method uses the heat from the oil flame to heat chips of firebrick placed in the secondary chamber. These chips of firebrick are maintained at temperatures above 1600°F and provide sufficient contact surface and obstructions to create turbulent conditions between the volatile gases, the oxygen, and the radiant heat.

EXPERIMENTS ON A FUEL-FIRED INCINERATOR

Odor Elimination.

The possibility of destroying odors completely or reducing them below the level of perception was determined experimentally. The test apparatus consisted of two separate units, the first for evaporation of the liquids (primary chamber), while the second (secondary-chamber) used an oil burner whose function was to destroy the odors in the gases. Two separate experiments were conducted, since the two primary units in our possession had radically different mass flow rates for the exhaust gases.

The first experiment consisted of a natural gas primary unit with an oil burner in the exhaust stack.

The second experiment consisted of an electric unit (previously tested) with an oil burner in the exhaust stack. Figure 10 shows the equipment layout used in the experiments. The exhaust arrangement shown applies to the experiments.

This oil burner was the type used in the 1960 Corvair Automobile. This burner was operated at a flow rate of 0.435 gph at a line pressure of 25 psig. Initial tests using both the gas and the oil unit have shown that odor reduction is possible. The test procedure consisted of evaporating a sample of urine in the gas unit and then passing the vapors thru the flame of the oil unit. The blower at point C (Figure 11) was not operating during this test. One of the products developed as a result of evaporating urine is urinoid (C_6H_8O). This substance is toxic and has a very objectionable odor. The initial vapors had an odor index between 3 and 4 which was reduced to a value of 2 after passage of these vapors through the oil flame. The following table explains this odor index.

TABLE 12

Degree of Odor	Odor Index
Too little to smell	0
Threshold (just perceptible)	1
Definite	2
Strong	3
Overpowering	4
Toxic (process only)	5

Further reduction in odor is believed possible with proper control of excess air and the rate of evaporation in the primary gas unit. A quantitative study could not be made, since the gas unit had to be returned to the manufacturer. On the basis of the gas flame temperature and the temperature in the lower exhaust stack a rough computation of the amount of air that was supplied can be calculated. The heat balance equation is as follows:

$$m_1 c_p \Delta T + m_2 c_p \Delta T = m_3 c_p \Delta T$$

$$m_1 \Delta T + m_2 \Delta T = m_3 \Delta T$$

$$m_1 (T_1 - T_2) + m_2 (T_2 - T_2) = m_3 (T_3 - T_2)$$

where:

T_1 = 3450°F theoretical flame temperature

T_2 = 100°F assumed inlet air temperature

T_3 = 700°F measured temperature in the lower exhaust stack for gas unit

m_1 = 1 assume 1 pound of air required for combustion

m_2 = x excess air supplied to unit

m_3 = 1 - x total air supplied

then $(1)\ (3450-100) + (x)\ (100-100) = (1 + x)\ (700-100)$

and $x = 4.5$ pounds or 450% excess air

A reduction in the amount of excess air to 150 per cent would be about the lower limit to assure safe operation of the unit. This reduction in air has a further effect of increasing the temperature T_3 above 700°F, hence more complete combustion and a greater reduction in odor is attained. The heat balance equation for 150 per cent excess air is as follows:

$$1\ (3450-100) + 1.5(100-100) = (1 + 1.5)\ (T_3 - 100)$$

$$T_3 = 1440°F$$

In addition there are other factors which play an important part in determining the completeness of combustion of the waste gas:

The time of contact of the oxygen molecules with the volatile organics. The relative capacity of the secondary burner with respect to the primary burner (i.e., slower evaporation with the same after-burner would result in more complete combustion). This experiment has shown that it is possible to reduce the odor level, if not destroy it, if proper design procedures are followed and complete combustion is attained. With this background experimental work and the theoretical information regarding incineration, it is possible to devise a number of schemes for use in incinerator systems.

The second experiment consisted of the Incinemode electric system as the primary unit with an oil fired secondary unit. Prior tests on the Incinemode (without an Oxycat superheater) showed that objectionable odors were emitted from this unit. Subsequent tests with the Oxycat superheater failed to reduce the intensity of the odor below its previous level. The electric unit had a very low mass-flow rate; 45 minutes is required to evaporate one pound of water and the unit depends on natural draft for the air movement through the unit. The rate of heat supplied to the electric unit was 3,300 BTU/hr, while the oil unit operated at 54,000 BTU/hr (0.75 gph nozzle at 25 psig; see Figure 12).

The test procedure was as follows:

1. A sample of urine was placed in pan of electric unit (Figure 11).

2. After evaporation had begun, sniff tests were conducted on the products from the exhaust stack.

3. The oil burner unit in stack was put in operation with subsequent sniffing of the products leaving the exhaust.

4. The oil burner was then taken out of operation and the sniff tests repeated.

5. On-off procedure with the sniffing of the exhaust products was repeated a number of times.

The result of this simple experiment has shown the following:

TABLE 13

ODOR TEST RESULTS

Units Operating; Cycle Repeated	Odor Index
Electric unit	3
Electric and oil units	0 - 1
Electric unit	3
Electric and oil units	0 - 1

The odor index may have been zero after the oil unit was in operation. This is difficult to tell, as one of the characteristic odors of urine (urinoid) has the property of retaining its odor for some time on surfaces it comes in contact with; which in this case is the olfactory organ in the nose.

With a high mass flow rate in the gas-oil experiment, the odor index was reduced from 3 to 2. With the lower mass flow rate in the electric-oil experiment, this index was reduced to less than 1.

Mass Flow Rate Determination.

This flow rate can be determined by using the following procedure:

1. Operate the oil burner located in the stack (Figure 11).

2. Measure the temperatures at points 1 through 4 (Figure 11 and Table 14).

3. Measure the concentrations of CO_2 and O_2 with a Fyrite absorption apparatus at a point A downstream of the burner under conditions of induced and no-induced draft. The air-fuel ratio associated with these concentrations of CO_2 and O_2 are obtained from Figure 13 and summarized in Table 15.

TABLE 14

TEMPERATURE VARIATIONS

Location (See Figure 10)	Temperature °F	
	Induced Draft Blower at C Operating	No Induced Draft Blower at C Not Operating
1	270	310
2	1900	2150
3	1450	1600
4	410	430
Ambient	75	75

TABLE 15

EXHAUST GAS CONCENTRATIONS

	Induced Draft Blower at C Operating				No Induced Draft Blower at C Not Operating			
	Pipe open at Point B		Pipe closed at Point B		Pipe open at Point B		Pipe Closed at Point B	
	CO_2	O_2	CO_2	O_2	CO_2	O_2	CO_2	O_2
Per cent of constituent	10.5	6.5	14.5	1.0	14.5	1.0	14.5	1.0
Air-fuel Ratio at this percentage (see Figure 13)	21	21	14.5	14.5	14.5	14.5	14.5	14.5

Note: For Locations of Points B & C, see Figure 11.

4. Utilizing the above information, the gas law equation and equation of continuity; the mass flow rate, flow velocity and time of contact of the gases can be calculated.

The unit was operated with a 0.75 gph nozzle at 25 psig; this is equivalent to 0.435 gph (Figure 12). A sample calculation for no-induced draft conditions at an air-fuel ratio of 14.5 is as follows:

Notation:

Subscript for the quantities refers to the point in the stack as shown in Figure 11.

Distance from 2 to 3 = d = 1.0 ft

T_2 = 2150°F = 2610°R

T_3 = 1600°F + 2060 R

Data:

Air-Fuel ratio = A/F = 14.5

Fuel rate = 0.435 gal/hr = $8.1(10^{-4})$ lbs/sec

Air rate = 14.5 (Fuel rate) = $1.175\ (10^{-2})$ lbs/sec

Pipe diameter = 4 inches

Pipe area = $8.72\ (10-^{2})$ ft^2

Equations:

Perfect gas law: $PV = WRT$

or: $\rho = \frac{P}{RT}$

Equation of continuity: $Q = av$

Calculations:

For a flame temperature, T_2 = 2150°F = 2610°R

$$\text{or} \quad \rho_2 = \frac{P}{RT_2} = \frac{(14.7)(144)}{(53.3)(2610)} = 1.52(10^{-2})\ \text{lbs/ft}^3$$

$$Q_2 = \frac{\text{Air Rate}}{\rho_2} = 0.773\ \text{ft}^3/\text{sec}$$

$$v_2 = \frac{Q_2}{a} = 8.87\ \text{ft/sec}$$

For a flame temperature, T_3 = 1600°F = 2060°R

$\rho_3 = 1.75(10^{-2})$ lbs/ft^3

$Q_3 = 0.672$ ft^3/sec

$v_3 = 7.71$ ft/sec

Average velocity from points 2 to 3

$v_{avg.} = 8.29$ ft/sec

Time for gases to travel from points 2 to 3

$$t_{2-3} = \frac{d}{v_{avg.}} = \frac{1.0}{8.29} = 0.121 \text{ sec}$$

hence time of contact of vapors to temperatures above 1600°F is 0.121 seconds.

The effect of the quantity of air on the temperatures and velocities of gases is apparent from the results summarized in Table 16. The no-induced draft condition applies to the odor elimination tests performed which were successful in eliminating odors at temperatures between 1600°F and 2150°F for a contact time of 0.12 seconds.

To determine with greater accuracy the magnitude of the parameters involved in this process requires more extensive and refined studies. This would necessitate the control of the following factors:

1. The rate of evaporation and the temperature and the quantity of the air and waste gases leaving the primary unit.
2. The secondary burner fuel and air rate.

3. The heat losses through the unit.

In addition protected thermocouple wires and a more accurate CO_2 and O_2 measuring device would be necessary.

TABLE 16

FLOW PARAMETERS AND THEIR VARIATIONS WITH DRAFT

Air-Fuel Ratio	Mass Flow Rate of Air lb/sec	Temperature 0_F	Velocity of vapors ft/sec	Temperature 0_F	Velocity of vapors ft/sec	Average Velocity from ptl to pt. 2 ft/sec	Time of contact Pt. 1 to Pt. 2 seconds
14.5*	$1.175(10)^2$*	2150*	8.87*	1600*	7.71*	8.29*	.121*
		*-No Induced Draft					
21.0**	$1.7(10)^2$**	1900**	11.6**	1450**	9.38**	10.49**	.095**
		**-Induced Draft					

Air Requirements for the Combustion of the Waste and Fuel.

The chemical analysis of urine and feces presented in tables 4 and 5 shows the approximate composition of the various substances found in these compounds. The approximate daily loadings for one man are as follows:

TABLE 17

QUANTITY OF WASTES

Substance	Average Weight per day per man		
Urine	1300 gms	or	2.9 pounds
Feces	135 gms	or	0.3 pounds
Water present in the Urine and Feces	1265 gms	or	2.8 pounds

Water makes up a major portion (about 90%) of the waste to be burned with the remainder being the organic compounds in the waste. The distribution of these compounds is quite variable, thus making it difficult to determine with accuracy the exact air requirements. An approximation of 0.5 to 1.0 pounds of air per pound of liquid and/or solid waste can be made using the values in table 18.

From Figure 13, it can be seen that the theoretical amount of air required is in the proportion of 14.5 pounds of air per pound of diesel fuel oil. With a given flow rate for the fuel, the air requirement can be determined with accuracy. Any additional air is termed an excess, but is necessary for safety reasons, that is, to assure complete combustion of the fuels and wastes which may vary in quantity. A reasonable excess is 100 to 150%. This excess (as shown before in table 16) can result in a temperature and contact time decrease, and also assures more intimate and complete contact of the fuel and wastes with the oxygen.

DESIGN OF A FUEL-FIRED INCINERATOR SYSTEM

Design requirements for Incinerator Systems.

The primary chamber must be supplied with sufficient heat to accomplish evaporation, volatilize the organic material present in the dry urine and feces, and raise the temperature of all of the vapors to over 1000°F.

The vapors from the primary chamber must pass into the secondary chamber where the vapors must be subjected to temperatures above 1600°F in the presence of a sufficient amount of oxygen in order to undergo complete combustion of the volatile organics in the waste gas. In addition, the time of contact of the waste gas with the oxygen must be sufficiently long with a high degree of turbulence to allow intimate contact between the gas and oxygen molecules.

The secondary chamber should warm up instantly or be designed to retain heat and not cool below 1600°F, so that the initial products of evaporation would be exposed to oxidizing temperatures. The primary chamber should be cooled to less than 212°F in less than two minutes to prevent flash during loading and the unit should contain a blower to create an air movement into the unit and not into the room.

If the unit is of the type that can be used during the evaporation and incineration process, then the exterior of the unit should not reach temperatures in excess of 100°F. If the unit is of the type that cannot be used during the incineration process, then the exterior of the unit must reach a temperature of less than 100°F less than two minutes after the shutdown of the unit.

The fuel burners should have sufficient capacity to dispose of 1 pint of liquids and 1/4 pound of solids in less than 6 minutes.

The machinery necessary for operation should be accessible by the removal of appropriate panels, be protected from the hot combustion chambers, and not be exposed in any manner so as to endanger the personnel using the unit.

The material used in the construction of the incinerator chambers and the exhaust stack must be able to resist the corrosive action of the waste and be able to withstand the extreme temperature variations to which the unit will be subjected. In addition these chambers must be designed so that they can be removed and replaced. The chambers must also be able to burn clean (i.e., they must not retain materials and odors on their surface).

The design of the unit must be such that it can be maintained in perfect working order by using a simple operating manual. Materials used in construction must be readily available and capable of resisting corrosive atmospheres.

The organic volatiles present in urine and feces should be reduced to simple, odorless, harmless, unobjectionable compounds such as CO_2, O_2, N_2, and water vapor. The products of incomplete combustion of the organic materials originally present in the urine and feces (such as oxalic acid, hippuric acid, glucose, fats, etc., or combinations of these and other substances) are usually in the form of aldehydes, nitrogen oxides ,organic acids, ammonia, hydrocarbons, sulfur oxides, carbon monoxide, etc. If any of these or similar substances are present which can have a harmful effect or are objectionable, their concentrations should be well below the Threshold Limit Values (see Table 3 for examples).

Fuel is composed primarily of carbon and hydrogen with small traces of sulfur. Urine and feces are composed primarily of water and organic compounds. These are mainly carbon, hydrogen and oxygen, with smaller quantities of sulfur and nitrogen, being present. Theoretically, in complete combustion all of the carbon, hydrogen, oxygen, sulfur, and nitrogen will be emitted in the exhaust gas; the ash will contain the inorganic materials originally present in the urine and feces, with small amounts of unburned carbon being allowable.

The piping and other equipment required to carry the fuel should be able to withstand pressures at least twice the designed carring capacity of the unit without any dangers of deformation, leakage, or bursting. The pipe at the inlet to the burner shall be provided with a shut-off valve which will close if there is an electrical power failure in the system.

The electrical system should be interlocked with the mechanical system, thus closing the fuel valves if there is a power failure.

A locking switch should be provided to prevent the opening of the charging door if temperatures are above 212°F and if the blower cooling the primary chamber is inoperative.

A heat sensing device must be placed in the stack and in other strategic locations in the unit and serve to shut off the fuel supply if temperatures become excessive.

All electrical equipment should be protected from the flame source with all motors being of explosion-proof design.

In the event of an electric failure, the air blowers would stop before the fuel supply was shut off. There would therefore be come incomplete combustion continuing in the hot chamber until the temperature had been reduced. For this reason it is necessary that a natural draft into the unit and out the exhaust stack should always be present.

Suggested Incinerator Plans.

Three methods of meeting the design requirements are presented, two of these very briefly, since they require automatic devices which are subject to breakdown. The third scheme is by far the most favorable in terms of ability to satisfy the design requirements with a minimum of danger.

The first scheme consists of a system and incinerator separated by a building wall with the incinerator on the exterior side. This system requires a transport mechanism to move the pan below the systems into the incinerator (Figure 14).

The incinerator consists of a burner designed to heat the firebrick to over 1600°F and retain this temperature until the unit is shut off. A heat sensing device located in the firebrick actuates a butterfly valve at the top of the pan to open when the firebrick temperature is over 1600°F and close when it is below this temperature. Therefore, it is possible utilizing one burner, to evaporate and burn the solids and liquids and then pass the vapors through a hot multi-surface combustion chamber thus theoretically accomplishing complete combustion. This system, however, has basic disadvantages, namely, reliance on automatic devices to control the conveyor and the butterfly valve at the top of the pan and the excessive heat loss through the exhaust stack.

The second scheme consists of a layer of insulating material separating the heated chips of firebrick from the pan containing the wastes (Figure 15). The unit operates in the following manner: the burner first heats the firebrick chips until they are above 1600°f, whereby a heat sensing device is actuated, starts a motor and through appropriate drive linkages moves the layer of insulating material from above the chips of firebrick. Heat is then transmitted to the pan where-by the solids and liquids are evaporated and burned. The vapors are then cycled back through the flame and through the hot firebrick and out the exhaust stack. This system also has the basic disadvantages of the previous unit, namely, reliance on automatic devices and the excessive heat loss through the exhaust stack.

The third scheme consists of two separate burners and chambers (Figure 16). The primary burner is of the gun type with a capacity of 0.95 gph at 100 psi, while the secondary burner is a gun type with a capacity of 0.40 gph at 100 psi.

In operation the secondary burner is turned on first to heat the secondary chamber. After a temperature of 2000°F is reached, the automatic controls turn on the primary burner and evaporation commences. With this method the vapors are always assured of being exposed to oxidizing temperatures. The heat sensing device in this case is only required to actuate a relay so as to turn on the primary burner and generally does not result in any of the complications present when conveyors or doors must be moved.

Based upon the information obtained in the preceding experiments, heat calculations will be performed to determine the economics of this odor destruction process. The heat calculations apply to a unit which has the following configuration (Figure 16).

1. Primary burner and chamber to evaporate and raise vapors to 2000°F.

2. Secondary burner and chamber to increase the contact time of the wastes and the oxygen at 2000°F and to preheat the primary air.

3. Heat exchanger in exhaust stack to preheat the primary air to 700°F and reduce the stack temperature from 2000°F to 400°F.

The physical model used for these calculations does not necessarily imply than an incinerator system should follow this configuration, but instead serves to illustrate that this type of unit could satisfy the design requirements and be reasonably economical.

The primary stage receives combustion air at 700°F heated by means of a heat exchanger located in the exhaust stack (Figure 16). Gases leaving the primary stage are at 2000°F.

In the computation of table 19 the following assumptions were made.

1. The waste is composed of water ($c_p = 1.0$); the small amount of organic substances (tables 4 and 5) with a lower heat capacity ($c_p = 0.30$) and its effect on lowering the total heat requirement of the process is neglected.

2. The air requirement for the wastes is 1 pound of air per pound of wastes.

3. All computations based on a burning cycle of 6 minutes per pound of wastes.

4. The primary oil burner has a capacity of 0.95 gph.

Based upon the above assumptions the air requirement for combustion of the fuel is:

Weight of diesel oil = 6.7 lbs/gal (Figure 12)
Theoretical air requirement = 14.5 lbs air/lb fuel (Figure 13)
Excess air (150%) = 21.8 lbs air/lb fuel
(0.95 gal/hr)(6.7 lbs/gal)(36.3 lbs air/lb fuel) = 227 lbs air/hour
= 22.7 lbs air/cycle

The heat requirements are computed according to the following equation:

$$Q = Mc_p (T_2 - T_1)$$

where:

Q is the heat required in BTU/pound of waste
c_p is the heat capacity in BTU/pound mass - degree Rankine
T_2 is the final temperature in degree Rankine
T_1 is the initial temperature in degree Rankine
M is the mass of waste in pounds mass

At 0.95 gph the heat delivery for diesel fuel oil is 119,000 BTU/hour or 11,900 BTU/cycle which is more than the 10,300 BTU required for the process.

The function of the secondary stage is:

1. To provide more thorough heating, increased time of contact, and mixing of the vapors in this high temperature region before they pass to the exhaust stack.

2. To preheat the primary air by utilizing a heat exchanger located in the exhaust stack (Figure 16), to cool the exhaust products through an exchange of heat to the combustion air.

TABLE 19

PRIMARY HEAT REQUIREMENTS

Process Performed in the System	c_p BTU/lb °R	Q BTU/lb waste
Heat water from 90°F to 212°F	1	122
Vaporize water at 212°F; latent heat of varporization		970
Heat water vapor from 212°F to 700°F	0.46(from fig.17)	230
Heat water vapor from 700°F to 2000°F	0.545(from fig.17)	710
Heat combustion air for wastes from 700°F to 2000°F (1.0 lb)	0.269(from fig.18)	350
Heat combustion air for fuel from 700°F to 2000°F (22.7 lbs)	0.269(from fig.18)	7,900
Total Heat required for Primary stage		10,282

In computing the secondary burner's capacity, the following assumptions are made.

1. The exhaust stack will exchange heat to the combustion air in cooling from 2000°F to 7000°F and provide 3,400 BTU/lb of air in contact with the exhaust stack.

2. Additional air of an amount of 0.5 lbs/lb of waste is necessary for assurance of complete combustion.

3. Air for combustion of the fuel in the secondary burner is required at the rate of 29.0 lbs/lb of fuel (a 100% excess).

4. All computations based on a burning cycle of 6 minutes per pound of waste.

5. The secondary oil burner has a capacity of 0.40 gph.

Based upon the above assumptions the air requirements for the secondary burner are:

Theoretical air requirement = 14.5 lbs air/lb fuel (Figure 12)

Excess Air (100%) = 14.5 lbs air/lb fuel

(0.40 gal/hr)(6.7 lbs/gal)(29.0 lbs air/lb fuel) = 77.7 lbs air/hour

= 7.77 lbs air/cycle

Total air flowing through exhaust stack per lb. waste.

Total primary Air	24.7
Total secondary air	8.3
Total Air	33.0

Heat value of this air if cooled from 2000°F to 700°F

$$Q = Mc_p(T_2 - T_1)$$

$$Q = (33.0)(0.26)(1300) = 11,200 \text{ BTU}$$

Heat required to heat 33.0 lbs of combustion air from 80°F to 700°F

$$Q = Mc_p(T_2 - T_1)$$

$$Q = 33.0(0.25)(620) = 5,100 \text{ BTU}$$

If heat transfer efficiency is $\frac{5,100}{11,200}$ 0.45 or 45%, then the 33.0 lbs of combustion air will be heated to 700°F.

At 0.40 gph the heat delivery for diesel fuel oil is 50,000 BTU/hour or 5,000 BTU/cycle which is more than the 4,975 BTU required for the process.

The operational costs are as follows:

Primary unit	119,000 Btuh
Secondary unit	50,000 Btuh
Total	169,000 Btuh

or 16,900 BTU/6 minute burning cycle for a 1 pound load of wastes.

With a daily load of 3 pounds per man, the heat required is 49,700 BTU which can be attained from 0.40 gallons of diesel oil at a cost of \$0.30 per gallon.

Fuel cost per man-day is:

$$0.40(0.30) = \$0.12$$

excluding electrical costs, maintenance, and amortization.

TABLE 20

SECONDARY HEAT REQUIREMENTS

Process Performed in System	c_p BTU/lb °R	Q BTU/lb waste
Heat combustion air for wastes from 700°F to 2000°F (0.5 lbs)	0.269 (from fig.18)	175
Heat combustion air for fuel from 700°F to 2000°F (7.8 lbs)	0.269 (from fig.18)	2,730
Provide 300°F of additional heating for the 24.7 lbs of primary gases flowing to the secondary chamber	0.28 (from fig.18)	2,070
Total		4,975

THERMAL DECOMPOSITION OF HUMAN WASTE

Introduction

The volatile matter and carbon remaining as a function of time was determined for different operating conditions of the volatilization chamber. An equation is proposed to describe the volatilization process, and the dependence of the constants in the volatility equation on temperature and on the rate of air supply to the volatilization chamber was determined. Volatilization temperatures as low as 300^0C may be feasible for some incinerator designs that provide a reactor for the oxidation of the material volatilized.

One of the primary reasons for the inadequacies of the available incinerator systems 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 used in the design of incinerators are based solely on heat release and heat transfer considerations patterned after the design of industrial furnaces, (56, 57). 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 on the type of fuel used, (58, 59), and on ehe "completeness" of oxidation, (60). 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 on 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 was investigated with particular emphasis on providing information for developing rational design parameters for processes depending on 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.

Experimental Methods.

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 min to assure uniformity of characteristics throughout the mixtures. The percentage of solids in the samples was determined by drying at 103°C and weighing, (61). A semi-micro carbon and hydrogen apparatus was used to determine the fraction of ash, volatile matter, carbon, and hydrogen in the dried samples, (62). Approximately 20 mg samples were used. The weight remaining after ignition at 850°C for a period of 30 min in the carbon and hydrogen apparatus was taken as the weight of ash;

the weight loss as the weight of volatile matter; the quantity of carbon dioxide produced on ignition as the carbon content; and the quantity of hydrogen in the water produced on ignition as the hydrogen content in the sample. Samples dried at 103°C, kept in a dessicator, and refrigerated may be stored for a period of a month without significant changes in the gross characteristics. Analysis were made periodically on the dried raw samples.

The volatilization chamber used was a gas-tight retort approximately 12 cm I.D. and 13cm deep with a total effective volume of 1.4 l. The temperature within the retort was measured with a shielded Chromed-Alumel thermocouple with air flow through the retort at the desired rate. The temperature within the retort can be controlled to within 5°C. The rate of air supplied to the volatilization chamber was metered with rotameters calibrated for 2% accuracy.

The change in weight and other characteristics of the human waste with respect to time for a given rate of air supply and temperature was 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. On 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 .1mg.

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

It was observed that the weight, carbon, and volatile matter content of dried human waste change slowly at temperatures less then 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°C to 400°C. The rate of air supply ranged from 1 l. per min per gram sample to 7.5 l. per min per gram sample, reported at 21°C to 760mm Hg.

Analysis

The characteristics of the five raw samples used to study the volatilization of human wastes are presented in Table 21.

TABLE 21

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
1	48.8	- - -	5.53	.535	.912
2	32.5	6.50	1.43	.419	.773
3	42.1	3.89	2.53	.506	.833
4	45.1	3.80	4.27	.504	.894
5	41.8	3.81	2.77	.493	.849

Each tabulated value represents the arithmetic average of three determinations. Variations were usually less then one unit in the third significant figure. The variation 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 are typical. (63) 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 fourfold variation. The percentage of carbon and volatile matter in the samples are approximately 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 that are preceded by grit removal.

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 on the imbalance between the number or molecules escaping from and condensing onto the bulk phase. According to classical physical chemistry, (64) 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, or

$$N = FSe^{-E/kT} \qquad (21)$$

in which N represents the fraction of molecules escaping per time, S is the frequency factor, F is the proportionality constant, E represents the minimum energy possessed by an escaping molecule, k is the Boltzmann constant, and T is the 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 the concentration of molecules in the gas phase. The process of condensation is considered to require no energy of activation. Following the preceding concept, the fraction of material loss per time is proportional to the Boltzmann factor. The quantity of material condensing is small for large air flows or flushing rates. From Eq. 21, the fraction of material loss with respect to time is a constant for a given temperature and material. However, the waste material undergoes decomposition at increased temperatures and the value of the Boltzmann factor and 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, therefore, large as compared with 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,

$$\frac{dX}{Xdt} = -F\ S\ e^{-E/kt} = K\ X^{(n-1)} \qquad (22)$$

in which X denotes the fraction of material remaining measured either by volatile matter or carbon; n, K are constants, and t denotes time. Separating variables and integrating yields

$$\frac{1}{K(1-n)}\left(1^{(1-n)} - X^{(1-n)}\right) = t \qquad (23)$$

Rearranging,

$$X^{(1-n)} = (1-n)\ Kt + 1 \qquad (24)$$

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

$$\log X = \frac{1}{(1-n)} \log t + \frac{1}{(1-n)} \log (n-1)K \qquad (25)$$

Eq. 22 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 on both temperature and oxygen supply, as 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 observation made at 400^{0}C is shown in table 22 and presented graphically in Figs. 19 & 20 in accordance with Eq. 25. 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. Correlation studies indicate that Eq. 25 is a reasonable representation of the volatilization process. Values of correlation coeffients for the observation, summarized in Table 23, are greater than .98. The values of correlation coefficients for observations summarized in Table 24 are .78 for runs 1 & 2 and greater than .95 for the remaining runs.

TABLE 22

WEIGHT OF RESIDUAL MATERIAL VERSUS TIME

Time, in minutes	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

The volatility of the feces and urine mixtures as measured by volatile matter and by carbon are presented in Tables 23 & 24 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 using Eq. 25. Figs. 21-28 are graphical presentations of selected information contained in Tables 23 & 24.

The fraction of material remaining at time zero is one. At time zero, according to Eq. 22, 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 nonlinear relationship between K and 1/T for an air supply of 7.5 l. per min per gram sample, shown in Figs. 21 & 22 reflects the influence of two factors: (1) the proportionality constant in Eq. 21, F, is a function of temperature for complicated molecules, and (2) the average critical energy E, required for a molecule to be volatilized 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 indicate that the initial time rate of change in the fraction of material remaining increases markedly for temperatures greater than 350°C. The dependence of the initial rate of decrease in X on the rate of air or oxygen supply with the temperature at 400°C is represented by figures 25 and 26. The initial rate of decrease for the fraction of volatile matter remaining, K_V, was found to be highest for an oxygen supply of 0.56 l per min per gram to 1.0 l per min per gram of volatile matter (liters per minute per gram of V_O), decreased slightly with an increasing oxygen supply, and decreased sharply for a 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 Eq. 22.

Values of K_V for an oxygen supply greater than 0.56 l per min per gram of 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 ration of V_o/C_o is two (table 21). 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 fraction of carbon. The ratio of K_V/K_c at 400°C for an air supply greater than 2 l per min per gram 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, $d\dot{V}/dt$ must be greater than dC/dt at all times, in which 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 Eq. 22, the lower the rate of loss of material, indicating lower volatility. The slight dependence of n on oxygen supply at 400°C is shown in figures 23 and 24. Figures 27 and 28 indicates that n_c increases rapidly for temperature less than 400°C; n_V appears to increase linearly with decreases in temperature. From figure 25, it is noted that variations in the value of n influence the rate of material loss more than corresponding variations in the value of K. The rate of volatilization is thus primarily temperature dependent, incluenced only slightly by air supply, provided it be greater than 3.8 l per min per gram of material.

The intercept tabulated in tables 22 and 23 represents the value of log X for time equal to 1 min. The fraction of material remaining after 1 min is essentially 100% for temperatures less than 300°C or air supply not exceeding 1 l per min per gram of material. A significant quantity of material is volatilized in 1 min only for temperatures greater than 350°C. The time required for 90% volatilization of the material was computed from Eq. 25 with the experimentally determined constants and the values tabulated in tables 22 and 23. These values indicate that temperatures less than 400°C are impractical and air rates of less than 2 l. per min per gram of material are not desirable if one is interested in obtaining a 90% reduction of volatile matter by thermal decomposition in less than 1 hr.

From the data presented and Eq. 25, it is possible to calculate the time temperature required for any desired percentage reduction in volatile matter. A temperature of 400°C and an air supply rate of 3.8 l per min per gram of material appear to be the minimum practical conditions for volatilization if greater than 80% of the volatile matter is to be volatilized in a short time, for example, less than 1 hour. If volatile matter reduction of 50% to 70% is acceptable, then a temperature as low as 300°C may be used. It was observed that, when at least 50% reduction in volatile matter was achieved, the residue appeared black and had only a slight odor. The selection of the desired percentage reduction in volatile matter will depend on the method of final disposal.

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 disign 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 over-all 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. per min per gram of material-air supply, which reduces the volatile content to less than 50% of the original value in 10 min to 15 min. 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 of volatilization can be provided by transferring the residue from the first stage of volatilization to the oxidation where a high temperature is provided for another purpose. Other schemes may be conceived, using the information presented.

CONCLUSIONS

1. The time required for pyrolysis is approximately the time required for heating, and the time required for combustion is the time required to burn the solid pieces for both non-pyrolyzing materials and residues of pyrolyzing materials.

2. Specimen size, and therefore comminution, has a striking effect on residence time, since heating time is approximately proportional to the square of specimen size, and burning time is proportional of either the first or second power of size, depending upon the shape of the specimen and the relative rates of mass transfer and the chemical reactions.

3. Burning time is inversely proportional to the mole fraction of oxygen in the ambient gas, provided that the burning rate is note significantly influenced by chemical reactions that are not first-order in oxygen.

4. 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 extremely well. Values of the correlation coefficients generally were above 0.95. The exponent and proportional constant were found to be

dependent on both temperature and the rate of air supply to the volatilization chamber.

5. 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 2 liters per minute per gram of material. The initial rate of change in the fraction of material remaining, K_C, based on carbon measurements, 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.

6. The ratio of maximum to minimum initial rate of volatilization was approximately three to one for air supply rates corresponding to constant initial time rate of change in the fraction of volatile matter.

7. The time required for a given percentage of reduction of volatile matter or carbon depends more on the exponent n in the rate equation than on the proportionality constant K. The exponent n was found to be primarily dependent on temperature for air supply rates exceeding 3.8 liters per minute per gram of material; for air rates less than 3.8, a small increase in n (lower volatility) was observed.

TABLE ONE. BASIC DATA CONSIDERATIONS

Type(s) of waste	Liquid, solid, gas, or mixtures.
Ultimate analysis	Carbon, hydrogen, oxygen and nitrogen, water, sulfur and ash on an "as-received" basis.
Ash characteristics	If appreciable and significant.
Metals	Calcium, sodium, copper, vanadium, etc.
Halogens	Bromides, chlorides, fluorides.
Heating value	Btu/lb on an "as-received" basis.
Solids	Size, form and quantity to be received.
Liquids	Viscosity versus temperature, specific gravity and impurities.
Gases	Density and impurities.
Special characteristics	Toxicity and corrosiveness, other unusual features.
Disposal rates	Peak, average, minimum (present and future).
Supply conditions	Temperature and pressure available.

TABLE TWO. FURNACE TEMPERATURE VERSUS FIRING RATE

Fraction[a] Cold (%)	Firing Rate Btu/hr sq ft[b]	Furnace Temperature (°F)[c]		
		0% Excess Air	50% Excess Air	100% Excess Air
0	Any	3677	2790	2230
10	10,000	2021	1839	1668
	40,000	2680	2303	1984
	80,000	2992	2482	2083
	120,000	3137	2563	2124
20	10,000	1709	1587	1470
	40,000	2349	2083	1844
	80,000	2680	2303	1984
	120,000	2866	2413	2047
30	10,000	1538	1442	1350
	40,000	2156	1942	1745
	80,000	2487	2178	1907
	120,000	2680	2303	1984
40	10,000	1422	1342	1265
	40,000	2021	1839	1668
	80,000	2349	2083	1844
	120,000	2544	2216	1930
50	10,000	1336	1266	1199
	40,000	1918	1758	1606
	80,000	2243	2004	1791
	120,000	2437	2144	1884
60	10,000	1268	1206	1146
	40,000	1836	1691	1554
	80,000	2156	1942	1745
	120,000	2349	2083	1844
80	10,000	1165	1114	1064
	40,000	1709	1587	1470
	80,000	2021	1839	1668
	120,000	2212	1984	1775
100	10,000	1089	1045	1001
	40,000	1613	1507	1404
	80,000	1918	1758	1606
	120,000	2106	1904	1717

a. Fraction Cold is the ratio of the surface of the furnace enclosure that received heat divided by the total furnace surface.

b. Firing rate is the ratio of the heat release in Btu/hr divided by the sum of all enclosing surfaces.

c. Table is theoretical for conditions given and is computed with No. 6 fuel oil.

TABLE THREE. COMPARISON OF STACK EMISSIONS

Source	Aldehydes as Formaldehyde	Nitrogen Oxide as NO_2	Organic Acid as Acetic Acid	Ammonia	Hydrocarbons as Hexane	Carbon Monoxide
	ppm	ppm	ppm	ppm	ppm	ppm
Gas-fired; AGA prototype; domestic wastes	8	15	7	5	0.7	200-400
Municipal incinerator; with scrubber	1-9	24-58	---	---	---	1000
Other incinerators; backyard	760	1.5	---	65	---	5,500 27,000
Gas & oil-fired heating units						
Large gas-fired Industrial	49	215	30	0.6	---	---
Large oil-fired Industrial	61	390	365	0.6	---	---

TABLE THREE. (CONTINUED)

Source	Aldehydes as Formaldehyde	Nitrogen Oxide as NO_2	Organic Acid as Acetic Acid	Ammonia	Hydrocarbons As Hexane	Carbon Monoxide
	ppm	ppm	ppm	ppm	ppm	ppm
Automobile exhaust						
Idling	88	8	---	---	1,275	36,000
Acceleration	1,369	4,180	---	---	410	100
Cruising	264	1,606	---	---	354	4,000
Deceleration	193	18	---	---	5,125	15,000
Threshold Limit Values	5	5	10	100	---	100

TABLE 4

URINE ANALYSIS (25)(26)

Organic Compound		Amount in Urine (gm/day/cap)	Per cent of Total
Name	Formula		
Urea	NH_2CONH_2	30	2.3
Oxalic Acid	$(COOH)_2\ 2H_2)$	0.02	---
Hippuric Acid	$C_6H_5CONHHCH_2COOH$	0.7	0.05
Crectinine	$C_4H_7N_3O$	1.2	0.09
Allantoin	$NHCONHCOCHNHCONH_2$	0.04	---
Phenols	C_6H_5OH	0.2	0.015
Glucose	$C_6H_{12}O_6$	0.05	---
Uric Acid	NHCONHC:C(CO)NHCONH	Unknown	Unknown
Indican	*	0.01	---
Purine Basis	*	0.01	---
Protein	*		
Fats	*	0.05	---
Other Colloids	*		
Amino Acid Nitrogen	*	0.20	0.015

---

* Formula was omitted because of the complicated structure of its carbon, hydrogen, nitrogen and oxygen molecules.

TABLE 5

FECES ANALYSIS (26)(27)

Chemical Compounds			
Name	Formula	Amount in Feces (gm/day/cap)	Per cent of Total
Indole	$C_6H_4NHCH:CH$		
Skatole	$C_6H_4NHCH:CCH_3$		
Methylmercaptan	CH_3SH	33.3	25
Ammonia	NH_3		
Amino acids	$H_2NCHRCOOH$		
Fats	*		
Water	H_2O	100	75

* See note Table 1

Organisms	
Name	Amount in Feces per day
Escherichia coli	200 billion/capita
Pathogenic bacteria as:	
1) Salmonella typhosa	200 billion/carrier
2) Endamoeba histolytica	10 million cysts/carrier

TABLE 6

CARBON MONOXIDE IN THE BLOOD (38)(39)

Physiological Effects	Per cent CO Hemoglobin
No appreciable effect, except shortness of breath on vigorous muscular exertion.	10
No appreciable effect in most instances, except shortness of breath, even on moderate exertion; occasionally slight headache.	20
Decided headache; irritable; easily fatigued; judgement dustrubed, weakness, dizziness, nausea; vomiting.	30
Headache; slight confusion; collapse and fainting on exertion; increased respiration and pulse.	40 to 50
Unconsciousness; intermittent convulsions; respiratory failure; depressed heart action; and possibly death.	60 to 70
Weak pulse, slow respiration, respiratory failure, possible death.	70 to 80
Immediately fatal.	Over 80

TABLE 7

CARBON MONOXIDE IN THE AIR (38)

Physiological Effects	Parts of Carbon Monoxide per million parts of air
Concentration allowable for an exposure of 8 hours without appreciable effect.	100
Concentration which can be inhaled for 1 hour without appreciable effect.	400 to 500
Concentration causing an appreciable effect after exposure of 1 hour.	600 to 700
Concentration causing unpleasant but not dangerous symptoms after exposure of 1 hour.	1,000 to 1,200
Dangerous concentration for exposure for 1 hour.	1,500 to 2,000
Concentrations which are fatal in exposures of less than 1 hour.	4,000 and above

TABLE 8

CONCENTRATIONS AND EFFECTS OF AMMONIA GAS

Physiological Effects	Concentration in ppm
Least detectable odor.	53
Least amount causing irritation to the eye.	698
Least amount causing immediate irritation to the throat.	408
Least amount causing coughing.	1,720
Maximum concentration allowable for prolonged exposure.	100
Maximum allowable concentration for short exposures (1/2 to 1 hour).	300 to 500
Dangerous for even short exposure.(1/2 hr)	2,500 to 4,500
Rapidly fatal for short exposure.	5,000 to 10,000

TABLE 9

ACUTE EFFECTS OF SULPHUR DIOXIDE

Effects	Concentration
Immediate irritation to nose and throat	6 to 12 ppm
Detection by taste rather than odor	0.3 to 1 ppm
Noticeable odor	3 ppm
Least amount irritating to the eyes	20 ppm
Irritating to moist areas of the skin within a few minutes.	1 per cent

TABLE 10

CONCENTRATIONS OF NO_2 AND AVERAGE TIME TO PRODUCE DEATH IN ANIMALS (33)

Concentration in ppm	Time in min
30	No deaths
100	318
150	90
400	58
600	32
800	29
1,000	19

TABLE 11

IGNITION TEMPERATURES OF VARIOUS GASES AND LIQUIDS

Mixture with Air	Air -% in Gas-Air Mixture	Temperature °F	Investigator (49)
Hydrogen	-----	1376	(45)
	13.5	1283	(45)
	-----	1076	(46)
Carbon monoxide	-----	1708	(45)
	Moist Air	1180	(46)
Methane	25	1832	(45)
	-----	1616	(45)
	13.5	1628	(45)
	-----	1202	
		1382	(46)
Ethane	-----	1832	(45)
	-----	960 1160	(46)
Ethyl Alcohol	-----	932	(47)
Acetone	-----	932	(47)
Aldehyde	-----	716	(48)
Hydrogen sulphide	-----	687	(46)
Propane	-----	986	(46)
Ammonia	-----	1436	(46)
Ether	50	1892	(45)

TABLE 18

COMBUSTION CONSTANTS (49)

Part I

1	2	3	4	5	6	7	8	9
No.	Substance	Formula	lbs per ft^3	Sp.Gr. Air 1.000	Heat of Combustion			
					BTU/ft		BTU/lb	
					Gross	Net	Gross	Net
1	Carbon	C	----	----	----	----	14093	14093
2	Hydrogen	H_2	0.005327	0.0696	325.0	275.0	61000	51623
3	Oxygen	O_2	0.08461	1.1053	----	----	----	----
4	Nitrogen (Atmos)	N_2	0.07439	0.9718	----	----	----	----
5	Carbon monoxide	CO	0.07404	0.9672	321.8	321.5	4347	4347
6	Carbon dioxide	CO_2	0.1170	1.5282	----	----	----	----
	Paraffin Series	$C_nH_{2n}2$						
7	Methane	CH_4	0.424	0.5543	1013.2	913.1	23879	21520
8	Ethane	C_2H_6	0.0803	1.0488	1792	1641	22320	20432
9	Propane	C_3H_8	0.1196	1.5617	2590	2385	21661	19944

TABLE 18 - Part 1 - COMBUSTION CONSTANTS (Cont.)

1	2	3	4	5	6	7	8	9
No.	Substance	Formula	lbs per ft^3	Sp.Gr. Air 1,000	Heat of Combustion			
					BTU/ft		BTU/lb	
					Gross	Net	Gross	Net
Miscellaneous Gases								
10	Methyl alcohol	CH_3OH	0.0846	1.1052	867.9	768.0	10259	9078
11	Ethyl Alcohol	C_2H_5OH	0.1216	1.5890	1600.3	1450.5	13161	11929
12	Ammonia	NH_3	0.0456	0.5961	441.1	365.1	9668	8001
13	Sulphur	S	----	----	----	----	3983	3983
14	Hydrogen Sulphide	H_2S	0.0911	1.1898	647	596	7100	6545
15	Sulphur dioxide	SO_2	0.1733	2.264	----	----	----	----
16	Water vapor	H_2O	0.0476	0.6215	----	----	----	----
17	Air	----	0.0766	1,0000	----	----	----	----

TABLE 18 - Part II - COMBUSTION CONSTANTS (Cont.)

10	11	12	13	14	15	16
No.	Required for Combustion			Flue Products		
	O_2	N_2	Air	CO_2	H_2O	N_2
1	----	----	----	----	----	----
2	0.5	1.882	2.382	----	1.0	1.882
3	----	----	----	----	----	----
4	----	----	----	----	----	----
5	0.5	1.882	2.382	1.0	----	1.882
6	----	----	----	----	----	----
7	2.0	7.528	9.528	1.0	2.0	7.528
8	3.5	13.175	16.675	2.0	3.0	13.175
9	5.0	18.821	23.821	3.0	4.0	18.821
10	1.5	5.646	7.146	1.0	2.0	5.646
11	3.0	11.293	14.293	2.0	3.0	11.293

TABLE 18 - Part II - COMBUSTION CONSTANTS (Cont.)

10	11	12	13	14	15	16
No.	Required for Combustion			Flue Products		
	O_2	N_2	Air	CO_2	H_2O	N_2
12	0.75	2.823	3.573	----	1.5	3.323
13	----	----	----	----	----	----
				SO_2		
14	1.5	5.646	7.146	1.0	1.0	5.646
15	----	----	----	----	----	----
16	----	----	----	----	----	----
17	----	----	----	----	----	----

TABLE 18 - Part III - COMBUSTION CONSTANTS (Cont.)

17	18	19	20	21	22	23	24
No.	Pounds per pound of combustible						Experimental Error in Heat of Combustion Per cent (or -)
	Required for Combustion			Flue Products			
	O_2	N_2	Air	CO_2	H_2O	N_2	
1	2.664	8.863	11.527	3.664	----	8.863	0.012
2	7.937	26.407	34.344	----	8.937	26.407	0.015
3	----	----	----	----	----	----	----
4	----	----	----	----	----	----	----
5	0.571	1.900	2.471	1.571	----	1.900	0.045
6	----	----	----	----	----	----	----
7	3.990	13.275	17.265	2.744	2.246	13.275	0.033
8	3.725	12.394	16.119	2.927	1.798	12.394	0.030
9	3.629	12.074	15.703	2.994	1.634	12.074	0.023
10	1.498	4.984	6.482	1.374	1.125	4.984	0.027
11	2.084	6.934	9.018	1.922	1.170	6.934	0.030
12	1.409	4.688	6.097	----	1.587	5.511	0.088
				SO_2			

TABLE 18 - Part III - COMBUSTION CONSTANTS (Cont.)

17	18	19	20	21	22	23	24
No.	Pounds per pound of combustible						Experimental Error in Heat of Combustion Per Cent (or -)
	Required for Combustion			Flue Products			
	O_2	N_2	Air	CO_2	H_2O	N_2	
13	0.998	3.287	4.285	1.998	----	3.287	0.071
				SO_2			
14	1.409	4.688	6.097	1.880	0.529	4.688	0.030
15	----	----	----	----	----	----	----
16	----	----	----	----	----	----	----
17	----	----	----	----	----	----	----

TABLE 23

VOLATILITY OF HUMAN WASTE BASED ON VOLATILE MATTER

	Constants for Volatility Equation					Air Supply		
Raw Sample	Slope	Intercept	n_v	K_c	Temperature, in$^{\circ}$C	Rate, in liters per min	Oxygen in liters per min per gram of V_o	Time for 90% Volatilization, in minutes
1	-0.358	-0.0388	3.79	0.459	400	2.03	0.256	480
2	-0.443	-0.283	3.26	1.92	400	4.26	0.565	42
2	-0.528	-0.300	2.89	1.95	400	7.56	0.973	21
2	-0.692	-0.224	2.45	1.46	400	15.13	2.06	13
2	-0.707	-0.149	2.42	1.15	400	15.13	2.06	16
3	-0.175	-0.134	6.71 (5.79)	1.02 (0.686)	350	4.16	0.515	a
1	-0.281	0	4.56	0.281	300	15.13	1.91	a
1	-0.272	0	4.68	0.272	300	15.13	1.91	a
4	-0.0764	0	14.1	0.076	200	7.56	0.890	a
1	-0.0899	0	12.1	0.090	200	15.13	1.91	a

[a] Time greater than 10 days.

Notes: Values in parenthesis are corrected to air supply rate of 15.13 l per min. Volumetric rates of air supply reported at 21°C, 760 mm Hg.

TABLE 24

VOLATILITY OF HUMAN WASTE BASED ON CARBON

Raw Sample	Constants for Volatility Equation				Temperature in °C	Rate in liters per min	Oxygen in liters per min per gram of C_o	Time for 90% Volatilization, in minutes
	Slope	Intercept	n_c	K_c				
5	-.400	0	3.50	.400	400	2.03	.436	317
1	-.353	0	3.83	.353	400	2.03	.506	677
2	-.445	-.218	3.25	1.37	400	4.16	1.33	57
2	-.587	-.0858	2.70	.822	400	7.56	2.44	36
2	-.501	-.397	3.00	3.12	400	15.13	4.89	16
2	-.485	-.319	3.06	2.21	400	15.13	4.89	25
3	-.214	0	5.66 (4.84)	.137 (.418)	350	4.16	1.05	a
1	-.168	0	6.95	.168	300	15.13	3.78	a
1	-.173	0	6.78	.173	300	15.13	3.78	a
4	-.0492	0	21.4	.0490	200	7.56	1.76	a
1	-.154	0	7.50	.154	200	15.13	3.78	a

[a] Time greater than 10 days.

Notes: Parenthesis value corrected to air supply rate of 15.13 l. per min. Volumetric rates of air supply reported at 21°C, 760 mm Hg

FIGURE 1

ADIABATIC TEMPERATURÉ OF A CELLULOSE FUEL VERSUS EXCESS AIR.

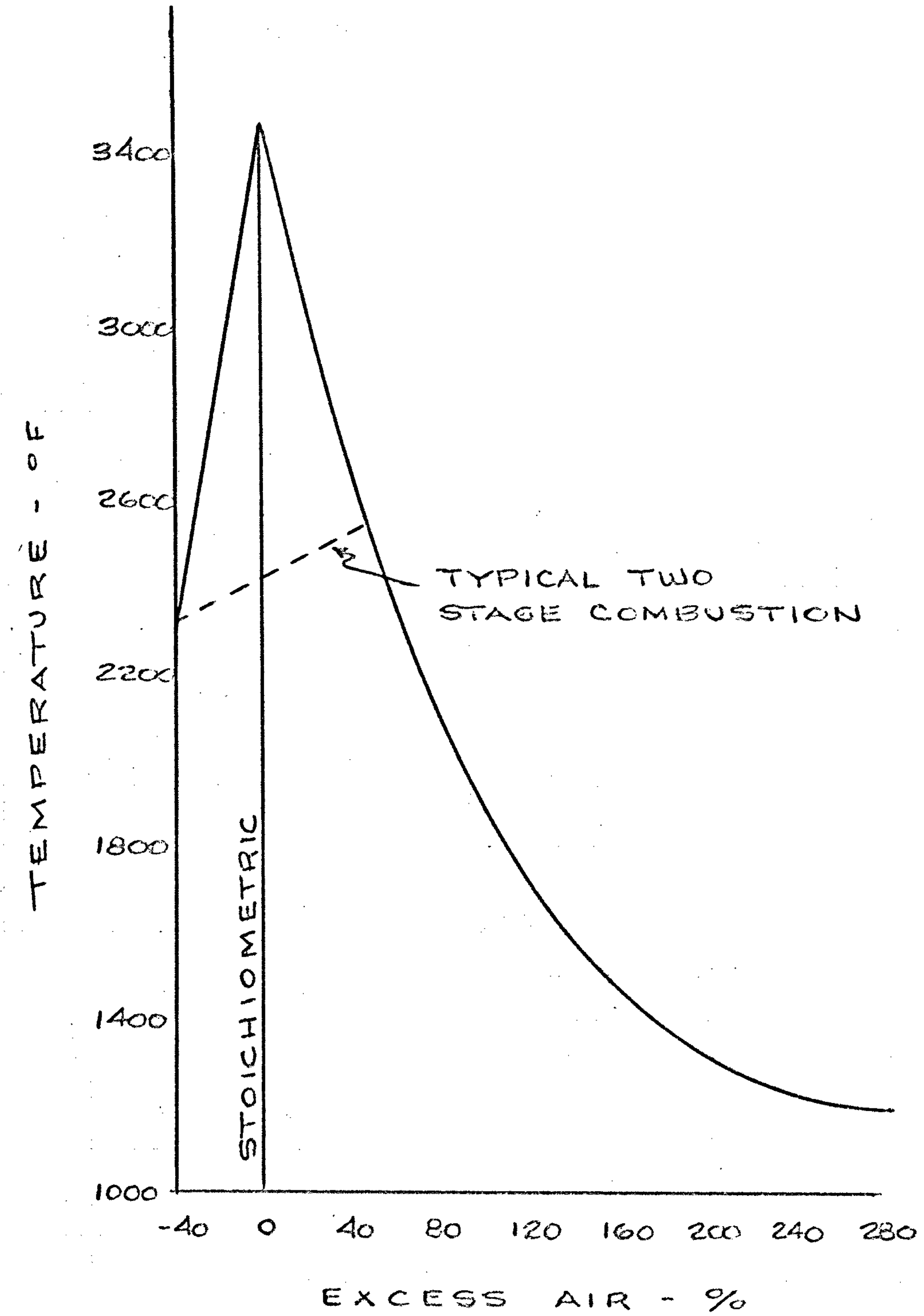


FIGURE 2

AVAILABILITY OF HEAT FROM AUXILIARY FUEL FIRING VS. COMBUSTION TEMPERATURE

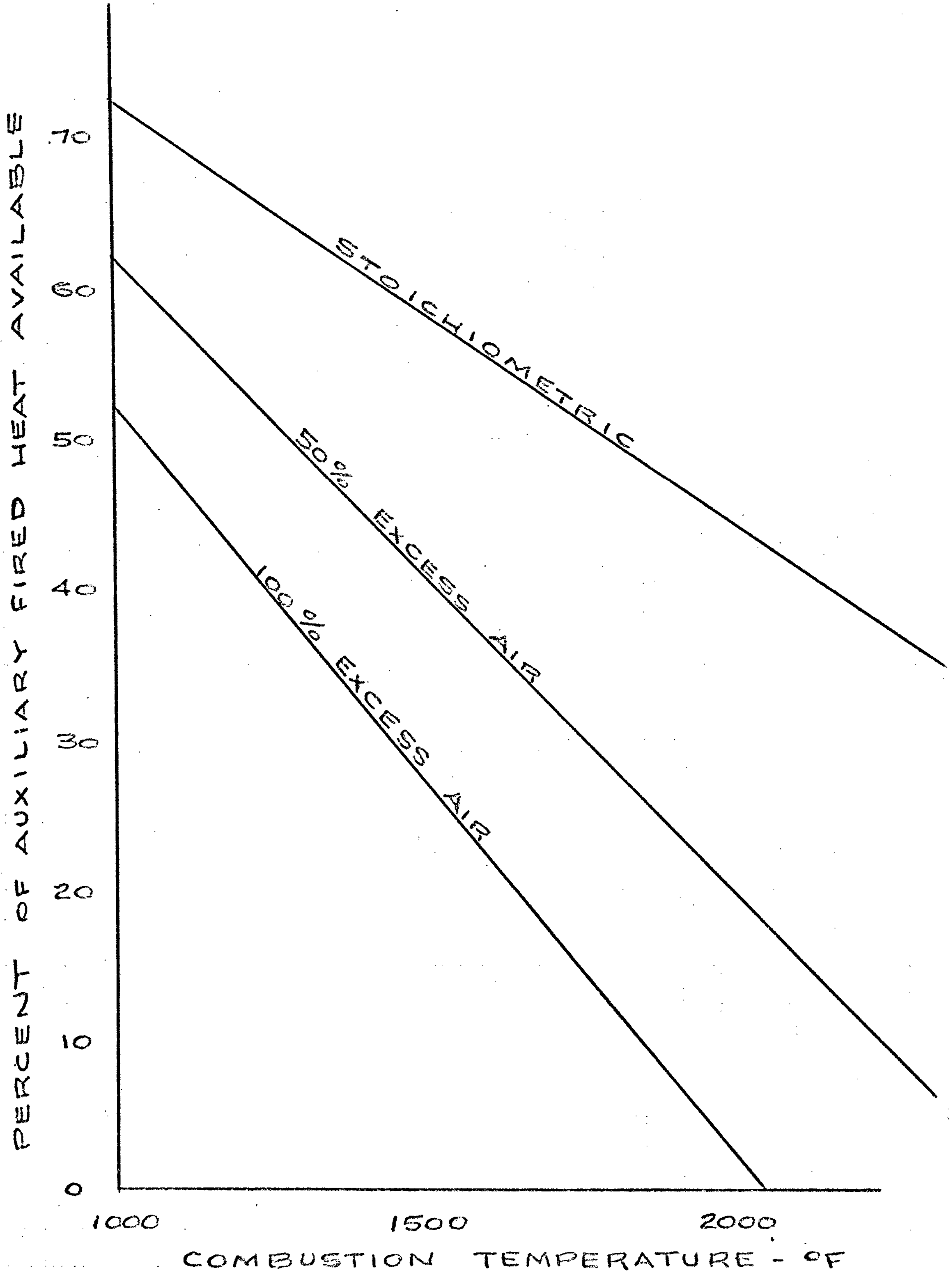
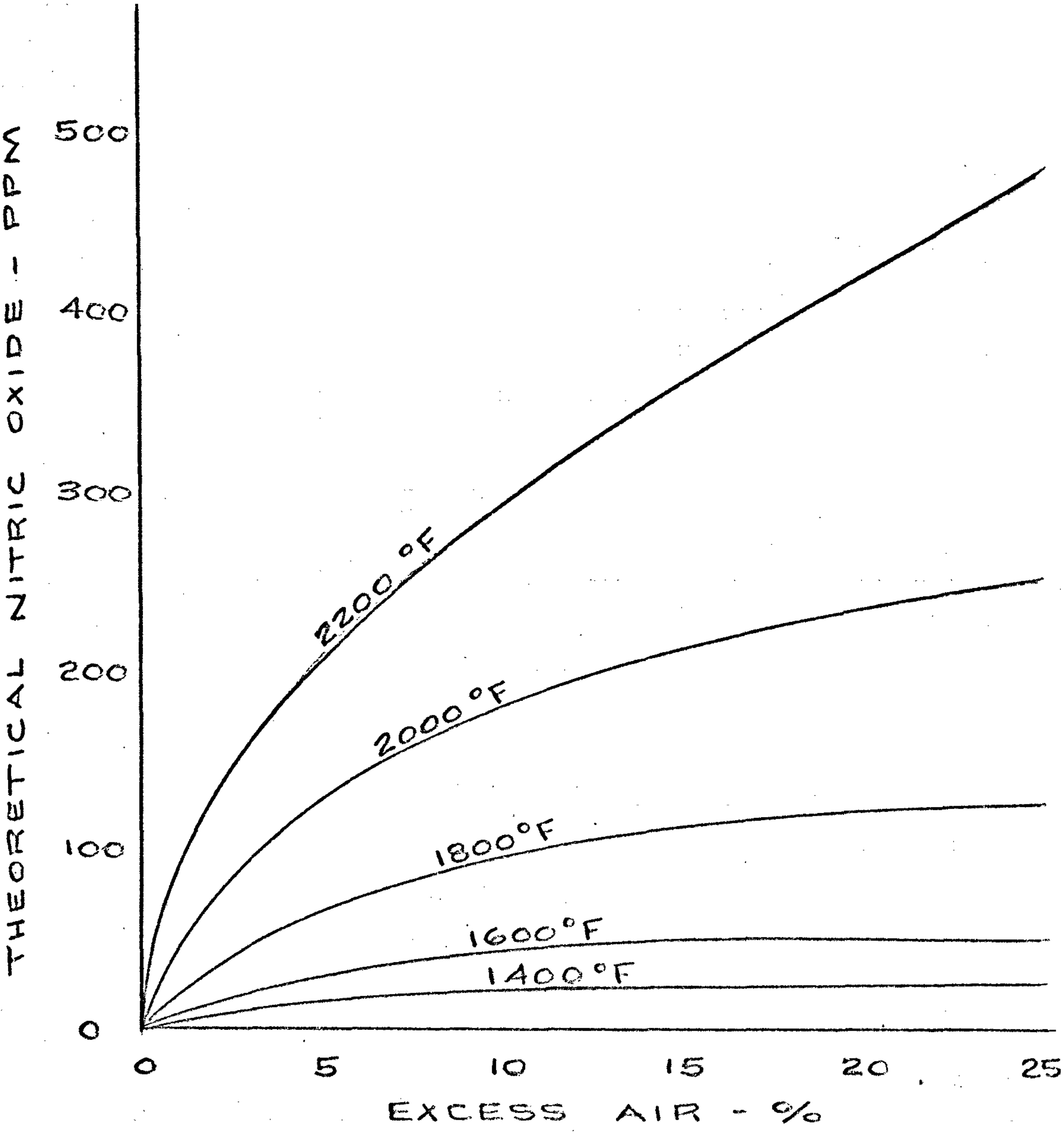


FIGURE 3

EQUILIBRIUM NITRIC OXIDE PRODUCED IN FLAMES



21

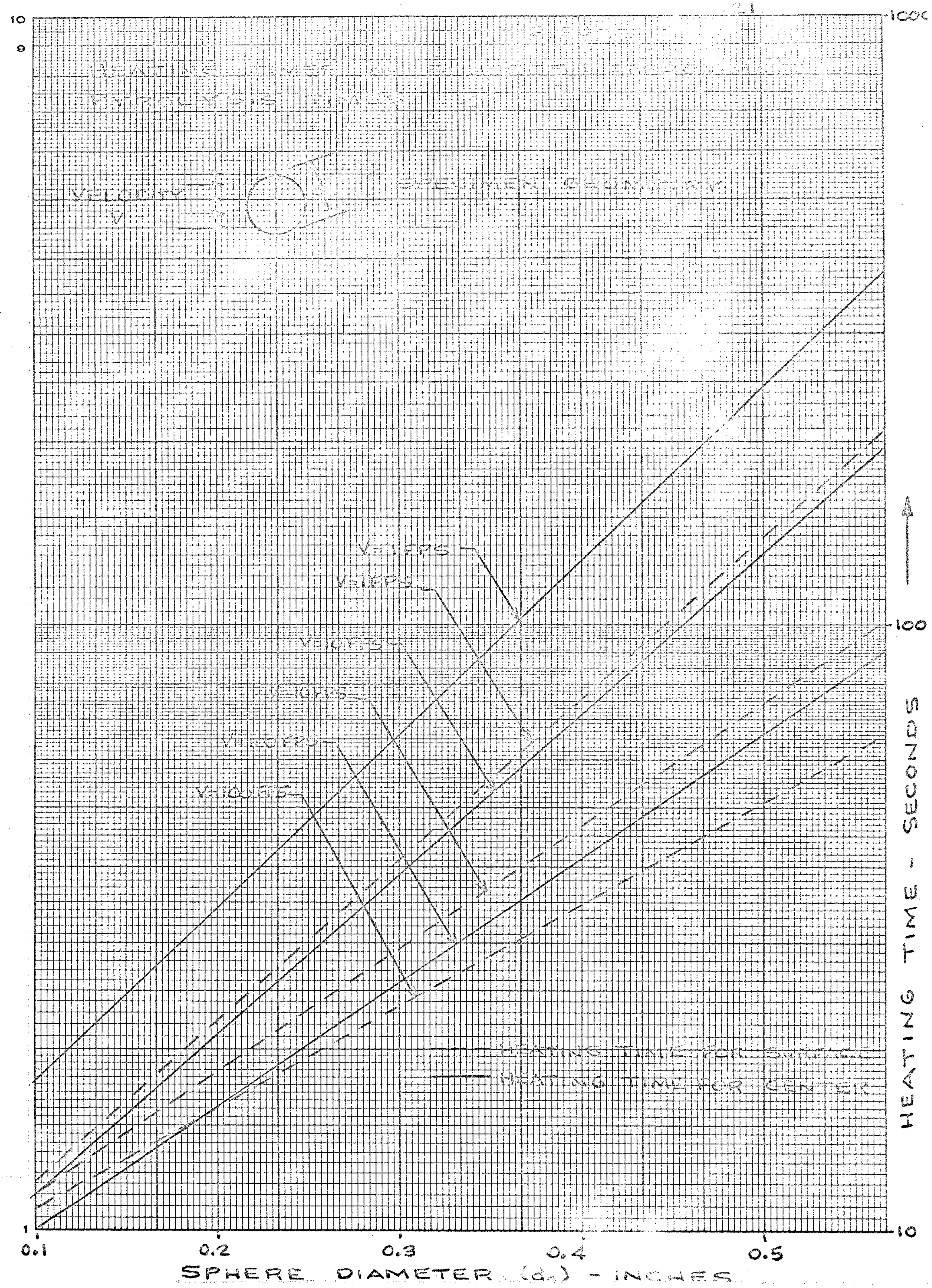
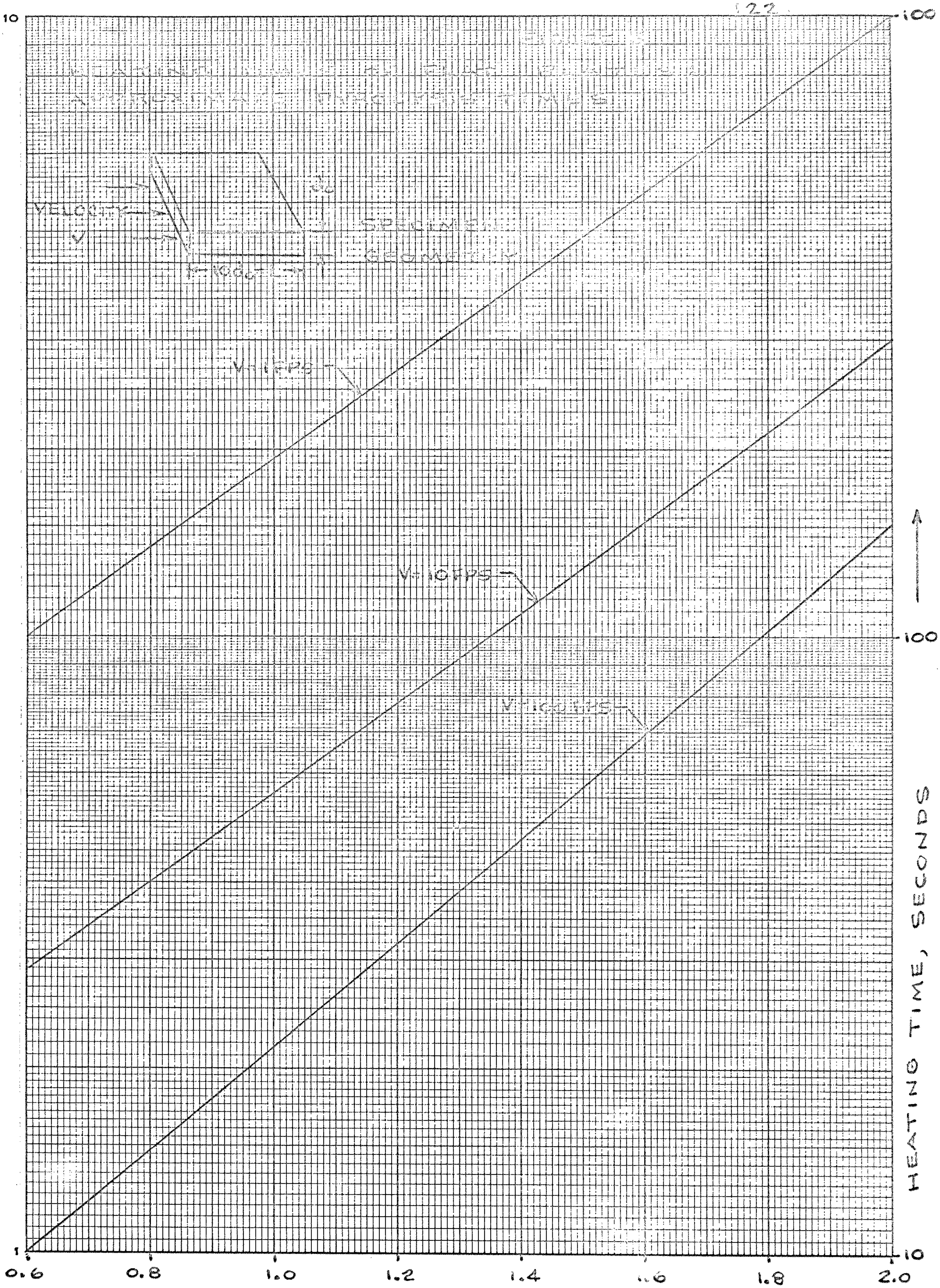


FIGURE
HEATING TIMES FOR SPHERICAL SPECIMENS
PYROLYSIS STUDY
VELOCITY
V
SPECIMEN GEOMETRY
V=1FPS
V=1FPS
V=10FPS
V=10FPS
V=100FPS
V=100FPS
HEATING TIME FOR SURFACE
HEATING TIME FOR CENTER
HEATING TIME - SECONDS
1
10
100
1000
9
SPHERE DIAMETER (d.) - INCHES
0.1
0.2
0.3
0.4
0.5


VELOCITY
V
3c
100c
SPECIMEN
GEOMETRY
V=1FPS
V=10FPS
V=100FPS
HEATING TIME, SECONDS
10
100
1000
1
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

[illegible]

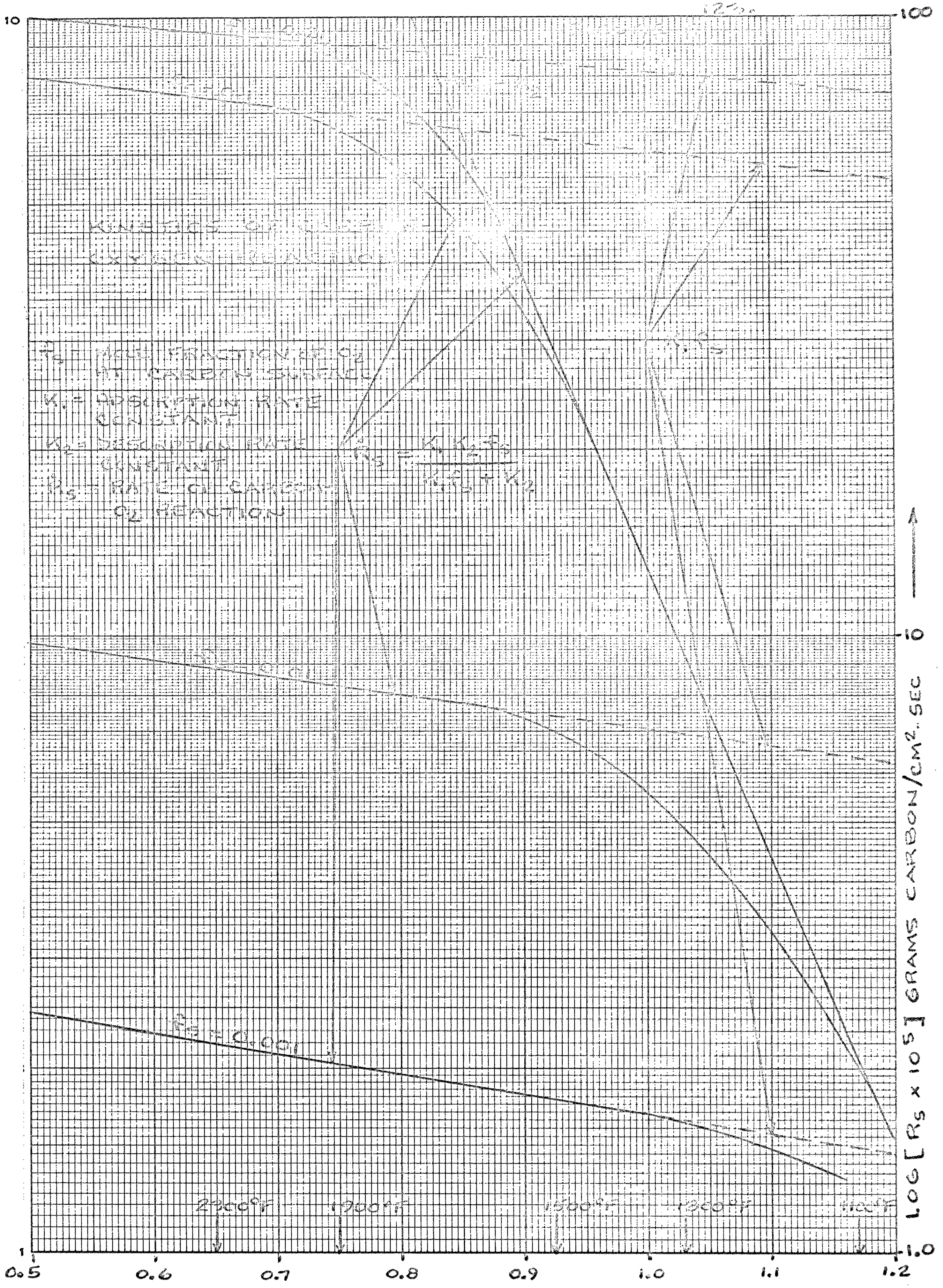

KINETICS OF CARBON OXYGEN REACTION
F_s = MOLE FRACTION OF O_2 AT CARBON SURFACE
K_1 = ADSORPTION RATE CONSTANT
K_2 = DESORPTION RATE CONSTANT
R_s = RATE OF CARBON-O_2 REACTION
$R_s = \frac{K_1 K_2 F_s}{K_1 F_s + K_2}$
F_s = 0.001
F_s = 0.01
1250
2300°F
1900°F
1500°F
1300°F
1100°F
10
100
1
10
1.0
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
LOG [$R_s \times 10^5$] GRAMS CARBON/CM². SEC →

FIGURE 7
IDENTIFICATION OF
RATE-CONTROLLING
STEP IN CARBON
COMBUSTION

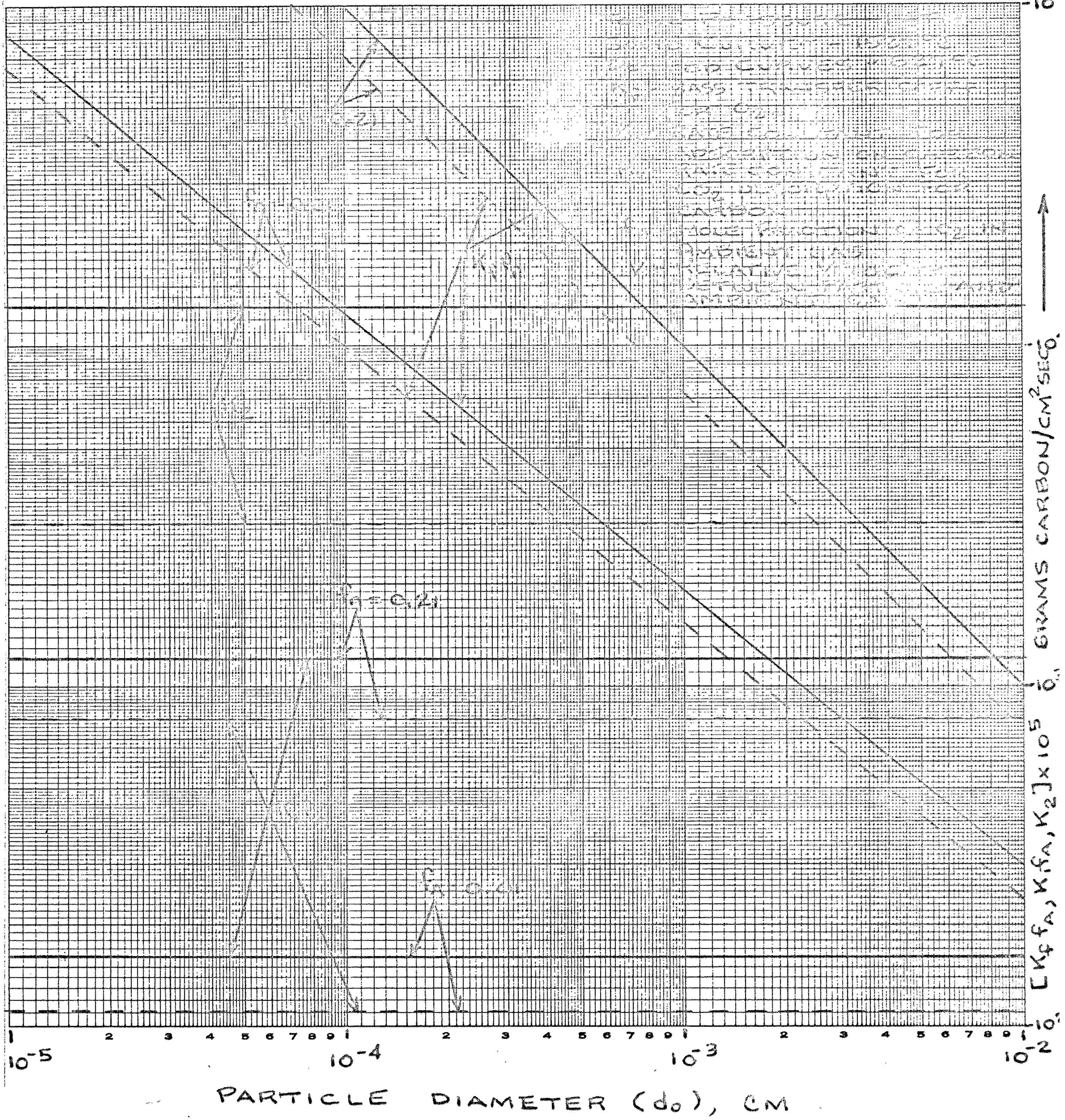
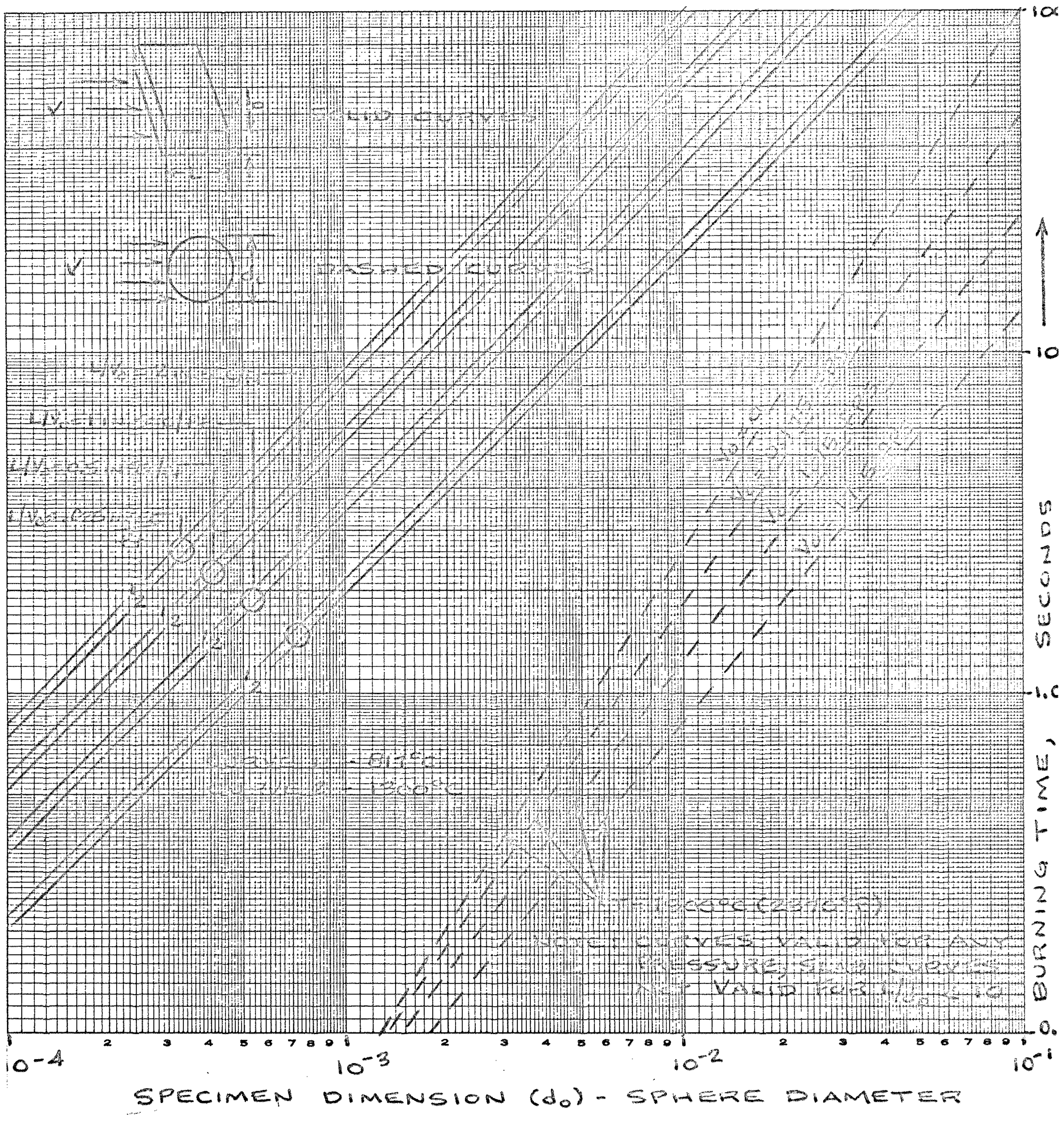


FIGURE 8
BURNING TIMES OF
SOLID SPECIMENS



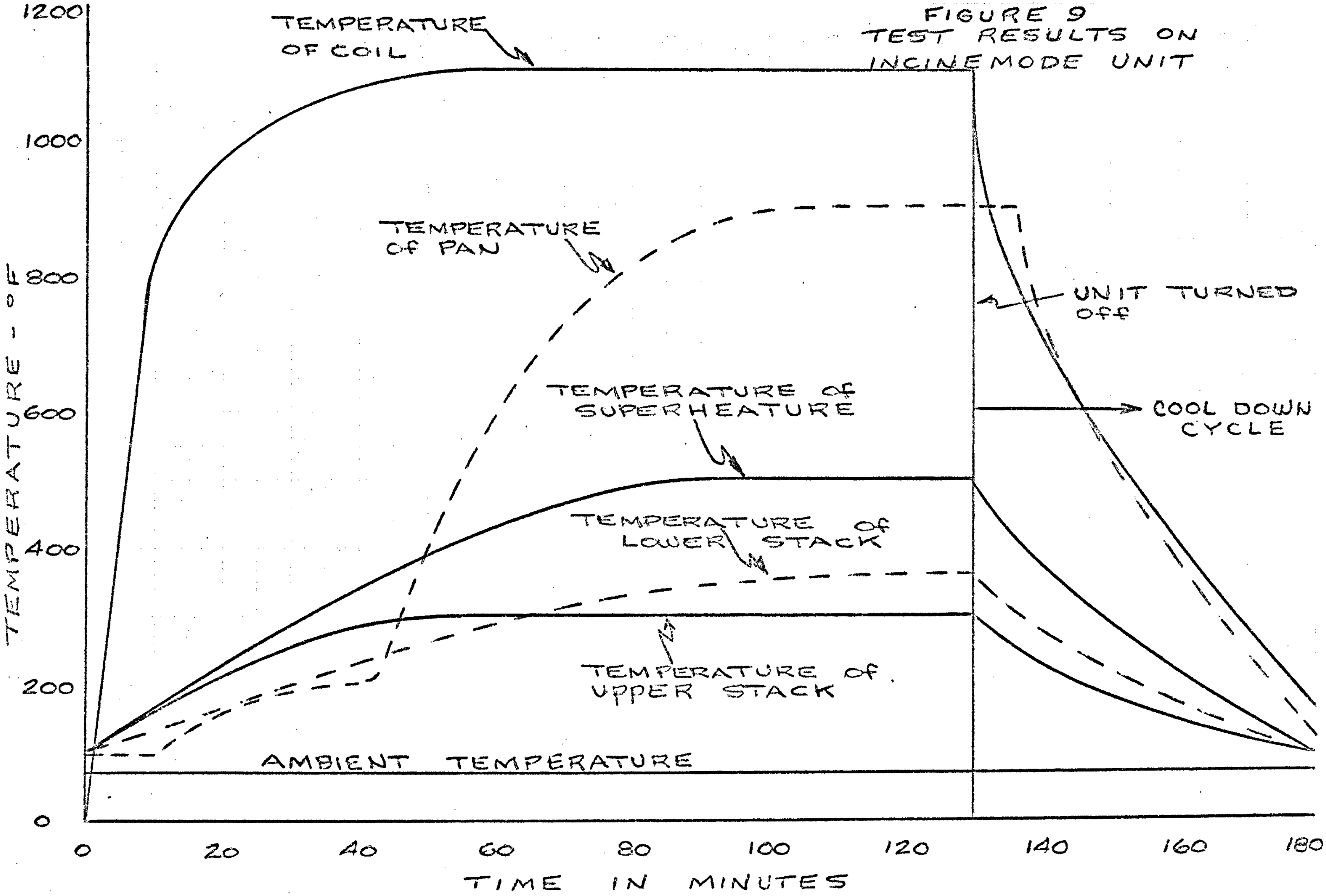


FIGURE 9
TEST RESULTS ON
INCINEMODE UNIT

FIGURE 10

VENTURI TYPE AFTER-BURNER
USING A TARGET AND A
MULTIPORT BURNER (24)

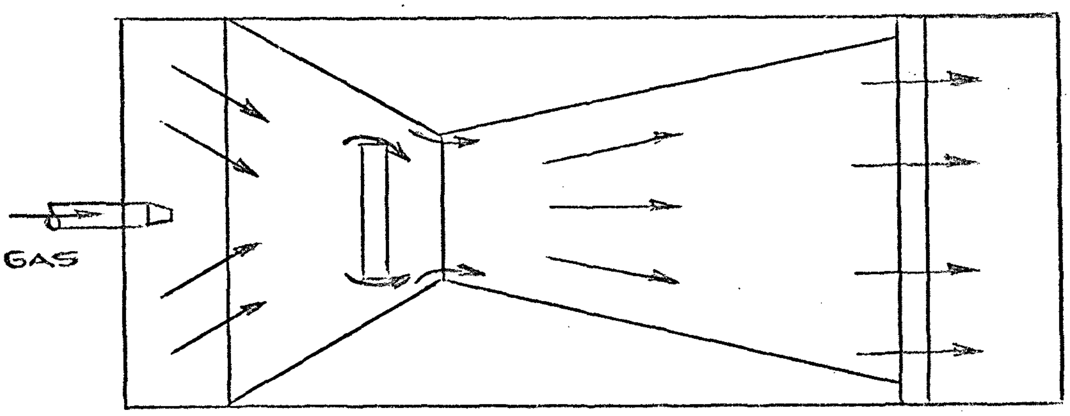
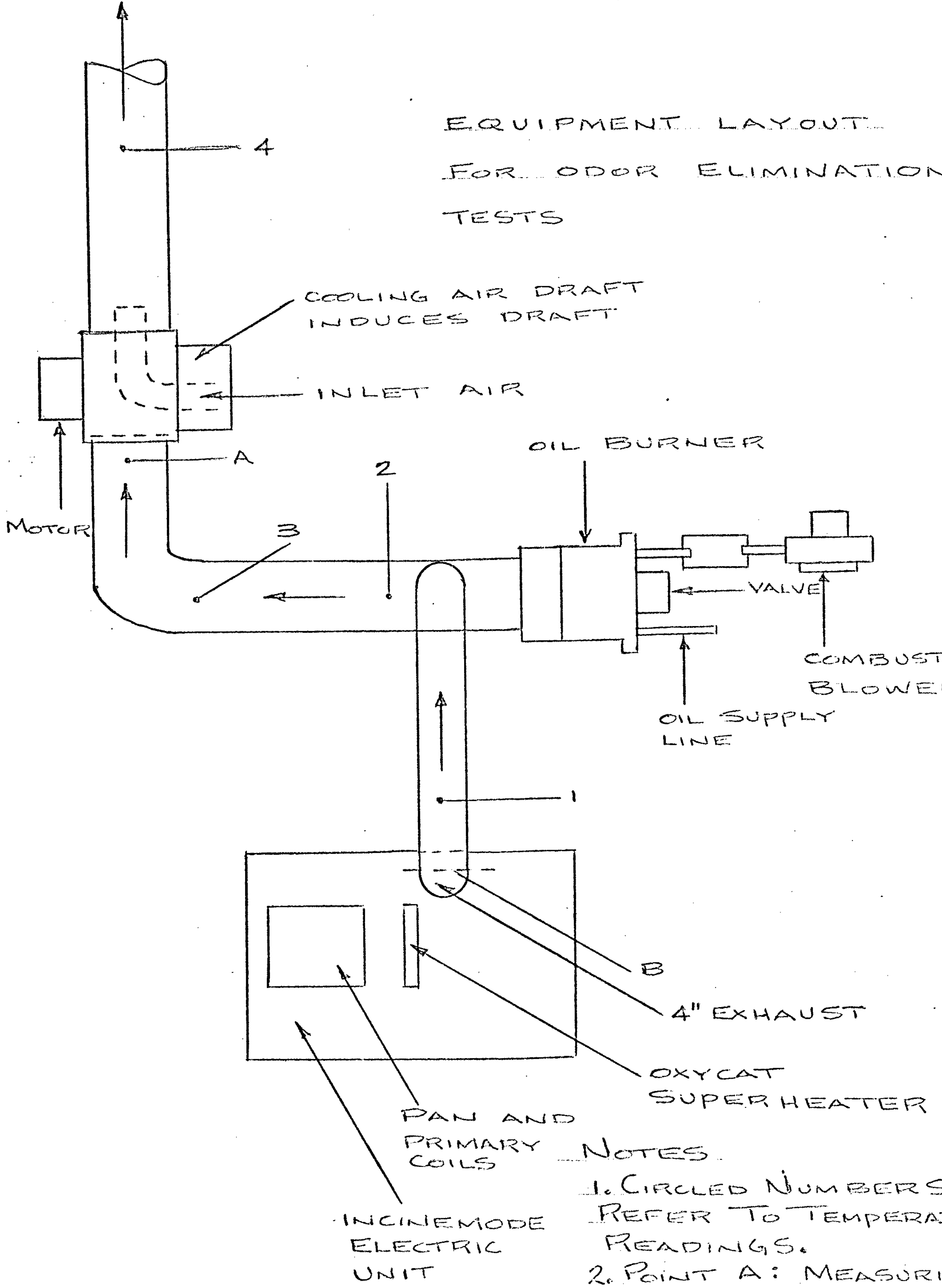


FIGURE 11

EQUIPMENT LAYOUT FOR ODOR ELIMINATION TESTS



NOTES

1. CIRCLED NUMBERS REFER TO TEMPERATURE READINGS.
2. POINT A: MEASURING POINT FOR GAS CONCENTRATIONS.

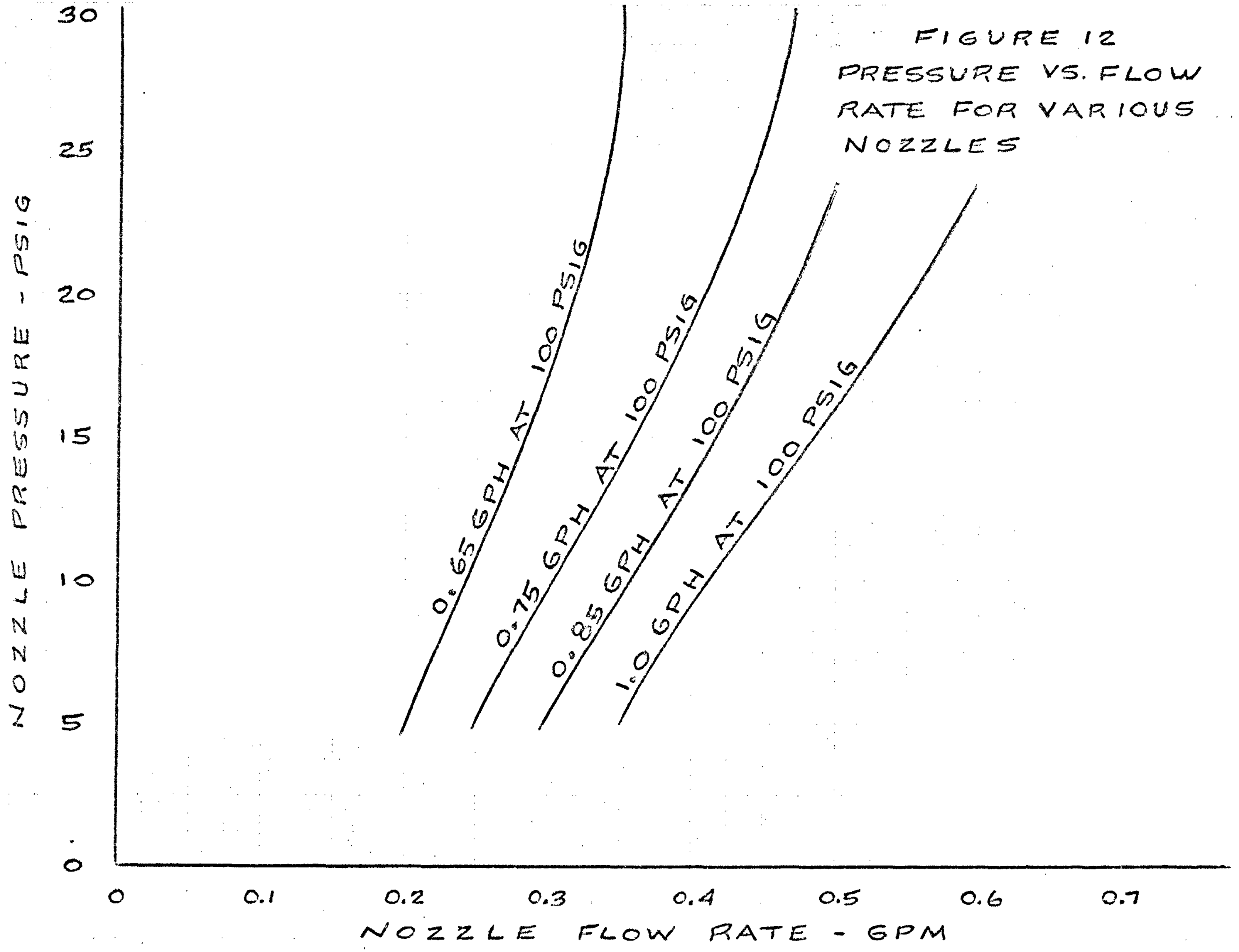


FIGURE 12
PRESSURE VS. FLOW RATE FOR VARIOUS NOZZLES

FIGURE 13

EXHAUST GAS CONSTITUENTS

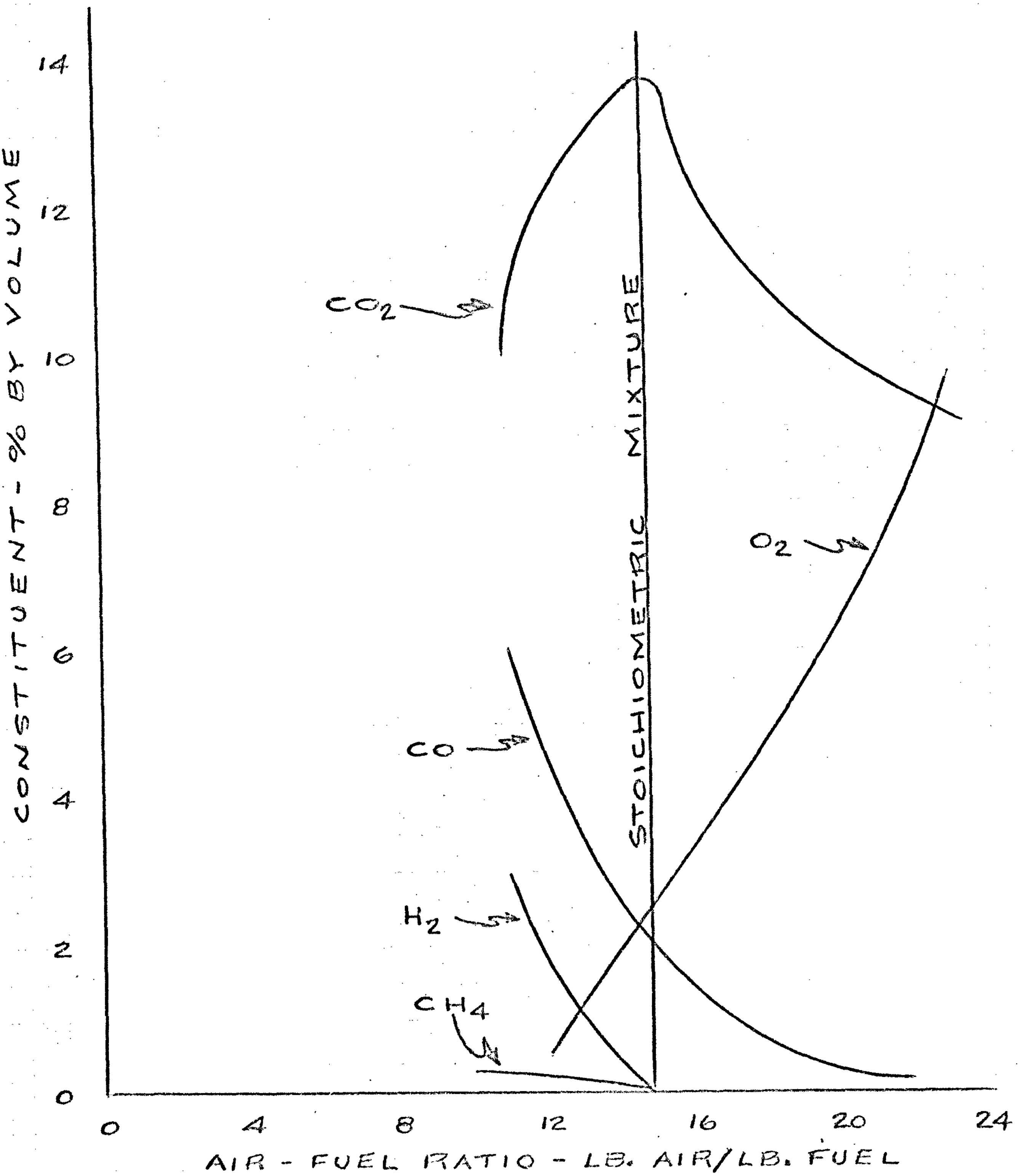


FIGURE 14

CONVEYOR WITH

REMOTE INCINERATOR

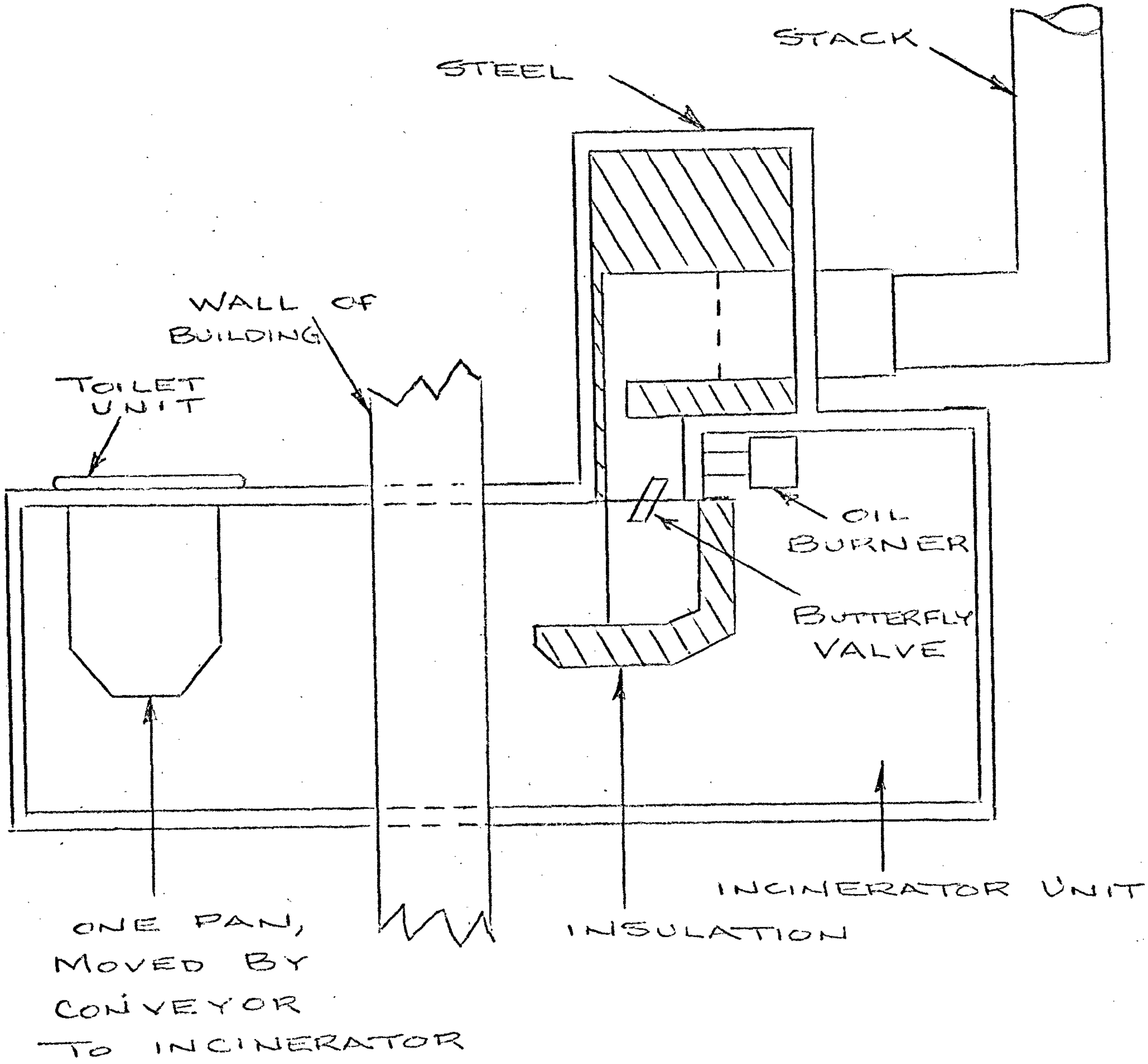
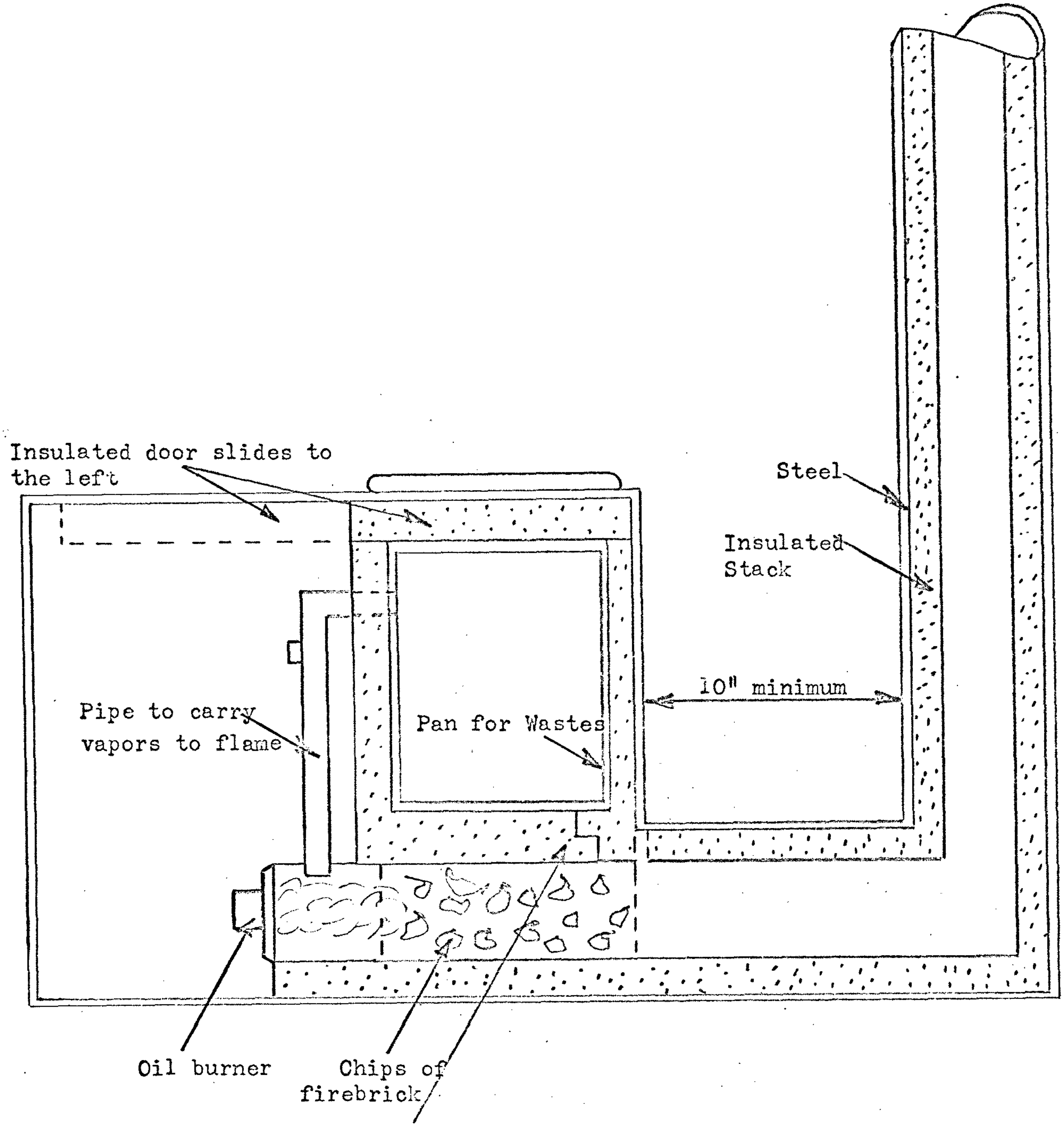


FIGURE 15

ONE BURNER UNIT
WITHOUT BAGS OR CONVEYORS



Insulating layer moves in a direction out of the paper when chips of firebrick are over 1600^{0}F

FIGURE 16

SUGGESTED DESIG
FOR INCINERATO
SYSTEM

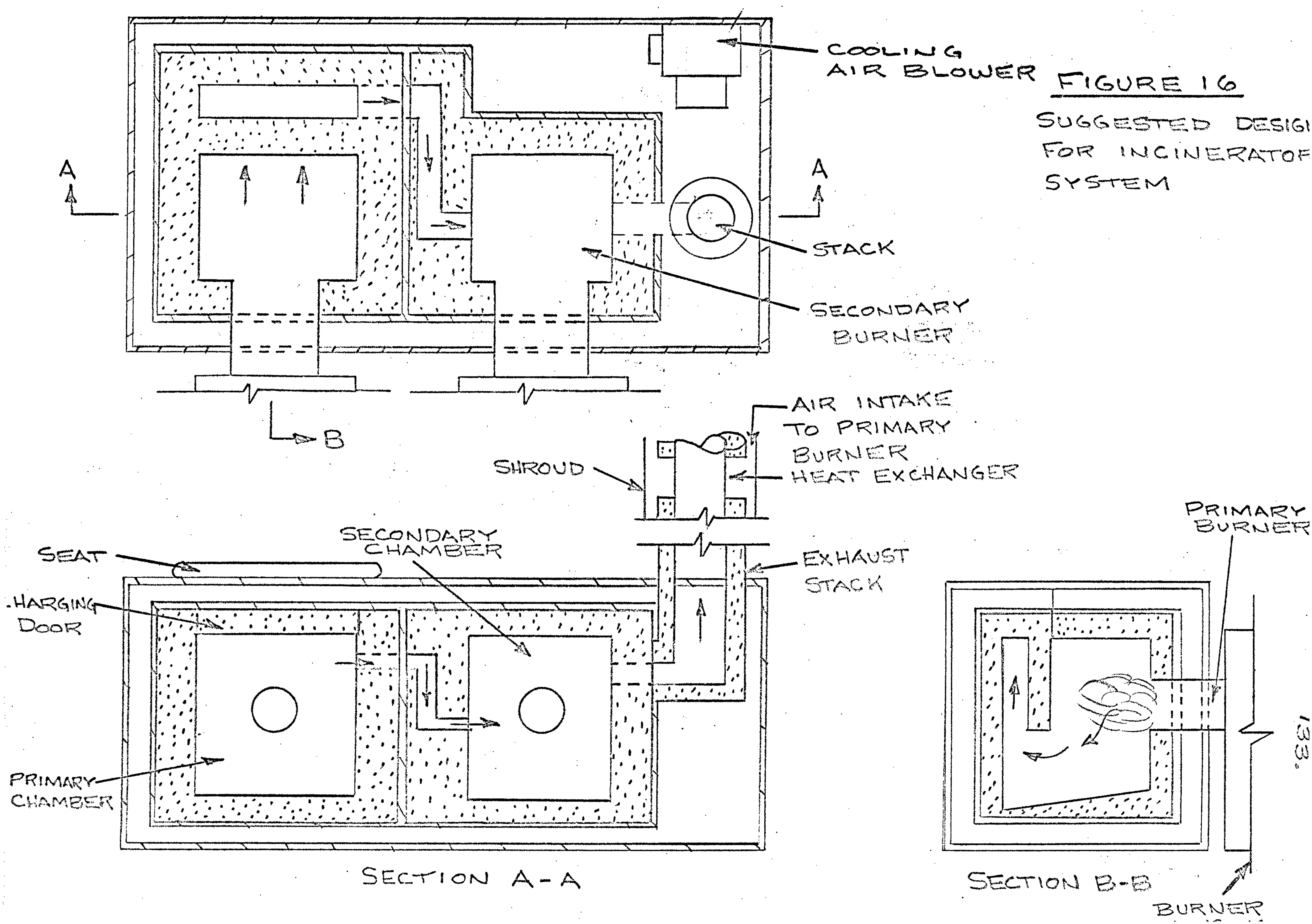
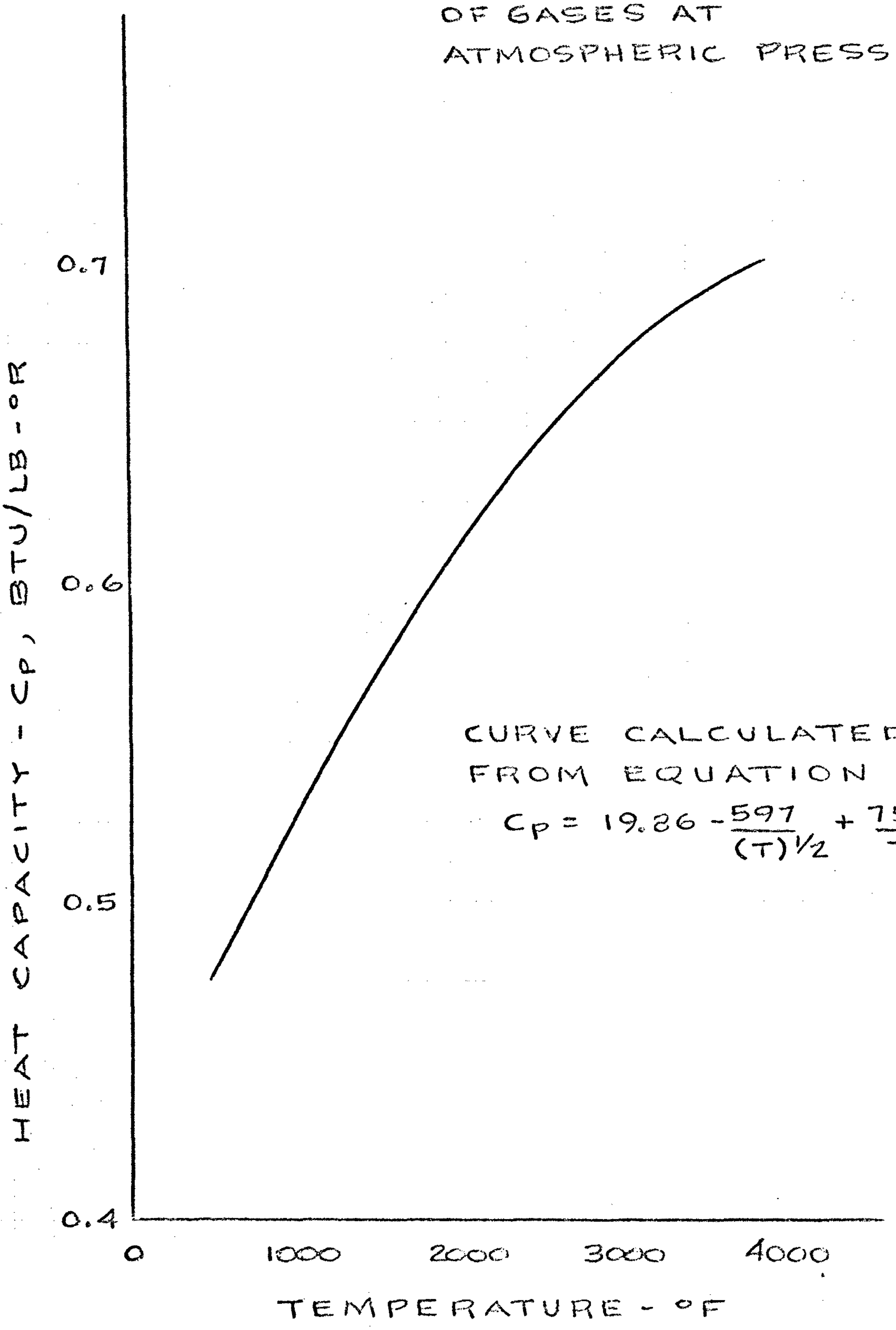


FIGURE 17
THE SPECIFIC HEAT
OF GASES AT
ATMOSPHERIC PRESSURE



CURVE CALCULATED
FROM EQUATION

$$C_p = 19.86 - \frac{597}{(T)^{1/2}} + \frac{7500}{T}$$

FIGURE 18
SPECIFIC HEAT OF GASES
AT ATMOSPHERIC
PRESSURE (54) (55)

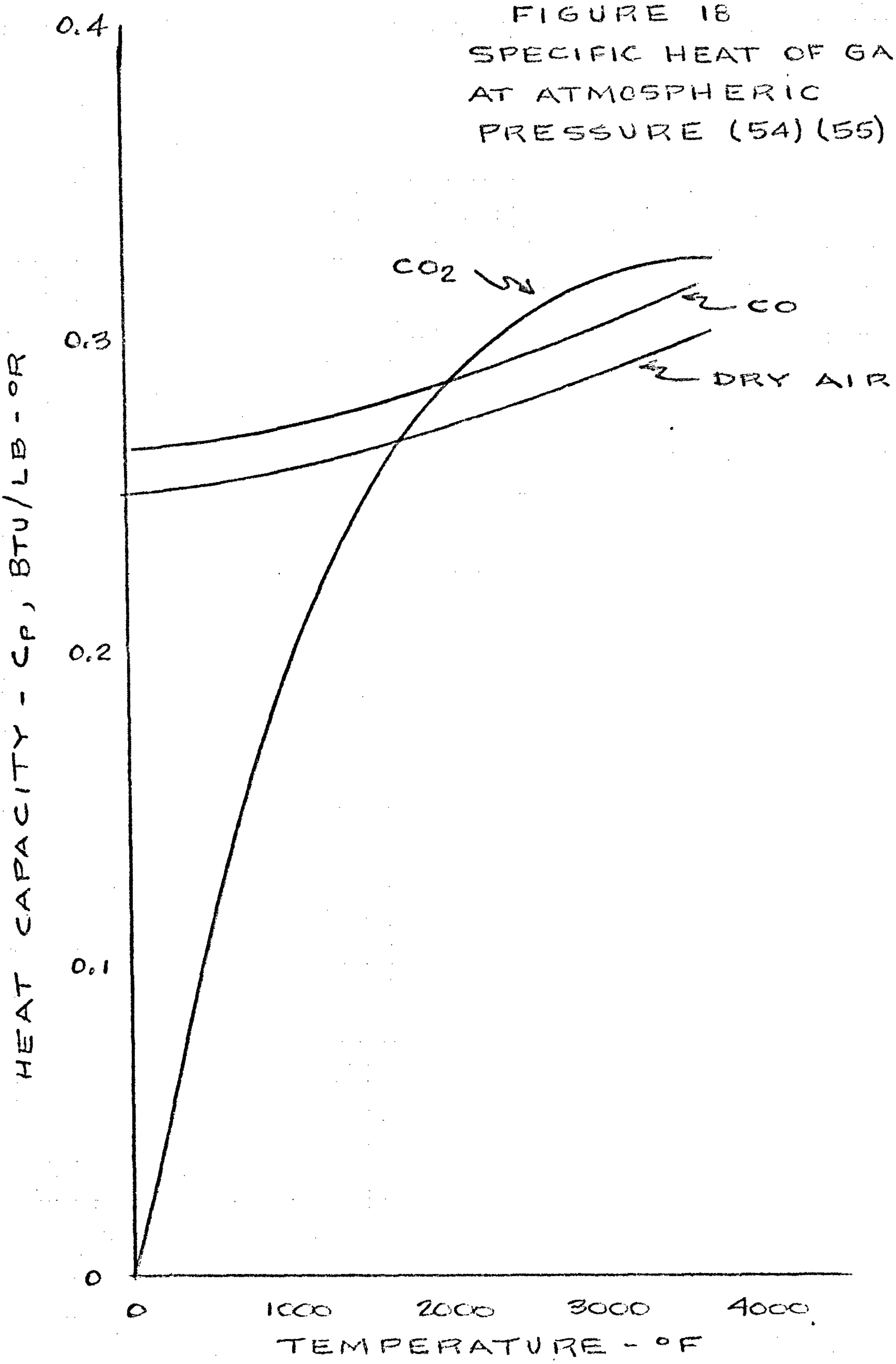


FIGURE 19
RESIDUAL VOLATILE
MATTER VS. TIME
AT 400°C

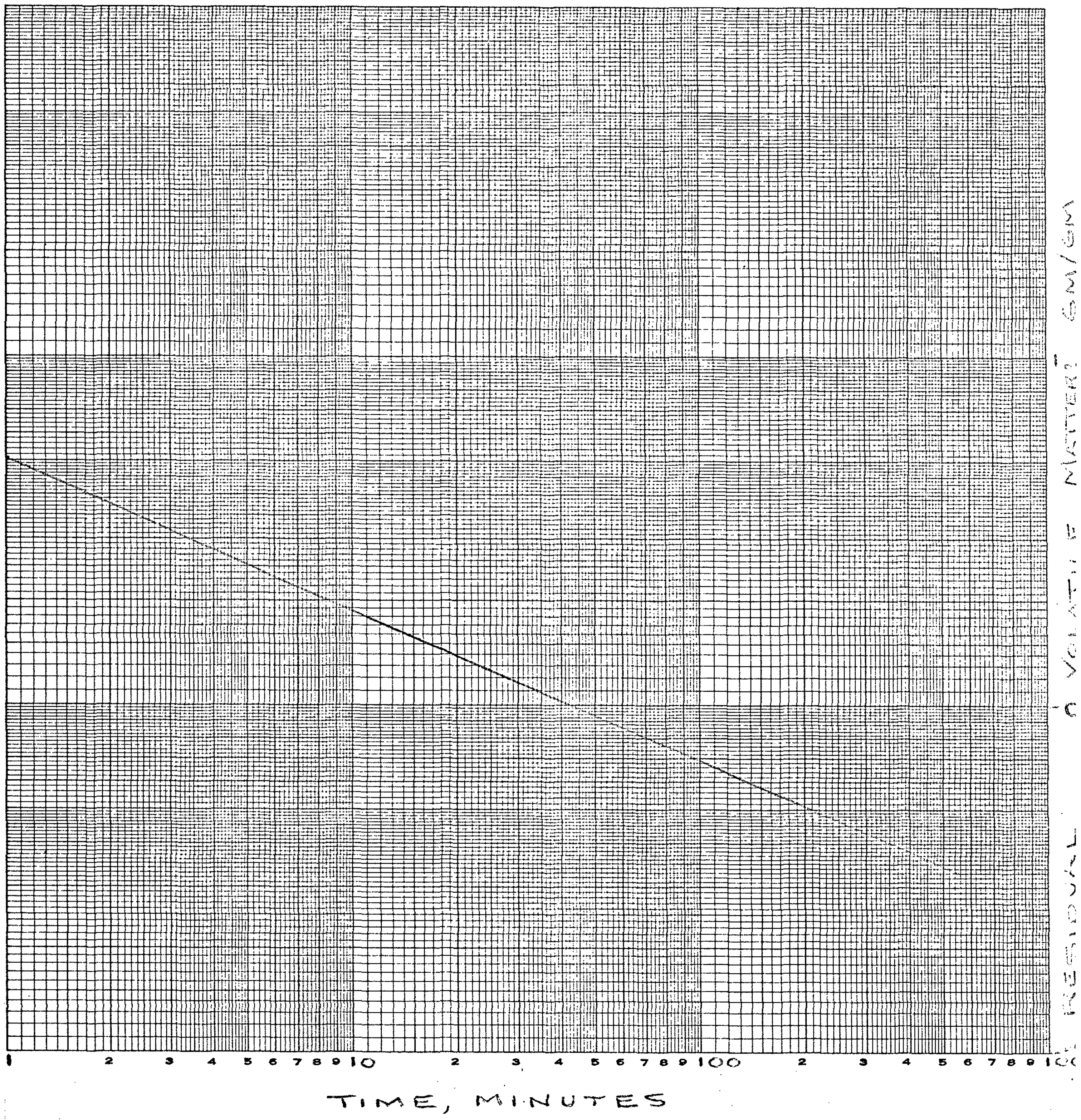


FIGURE 20
RESIDUAL CARBON
VS. TIME AT 400°C

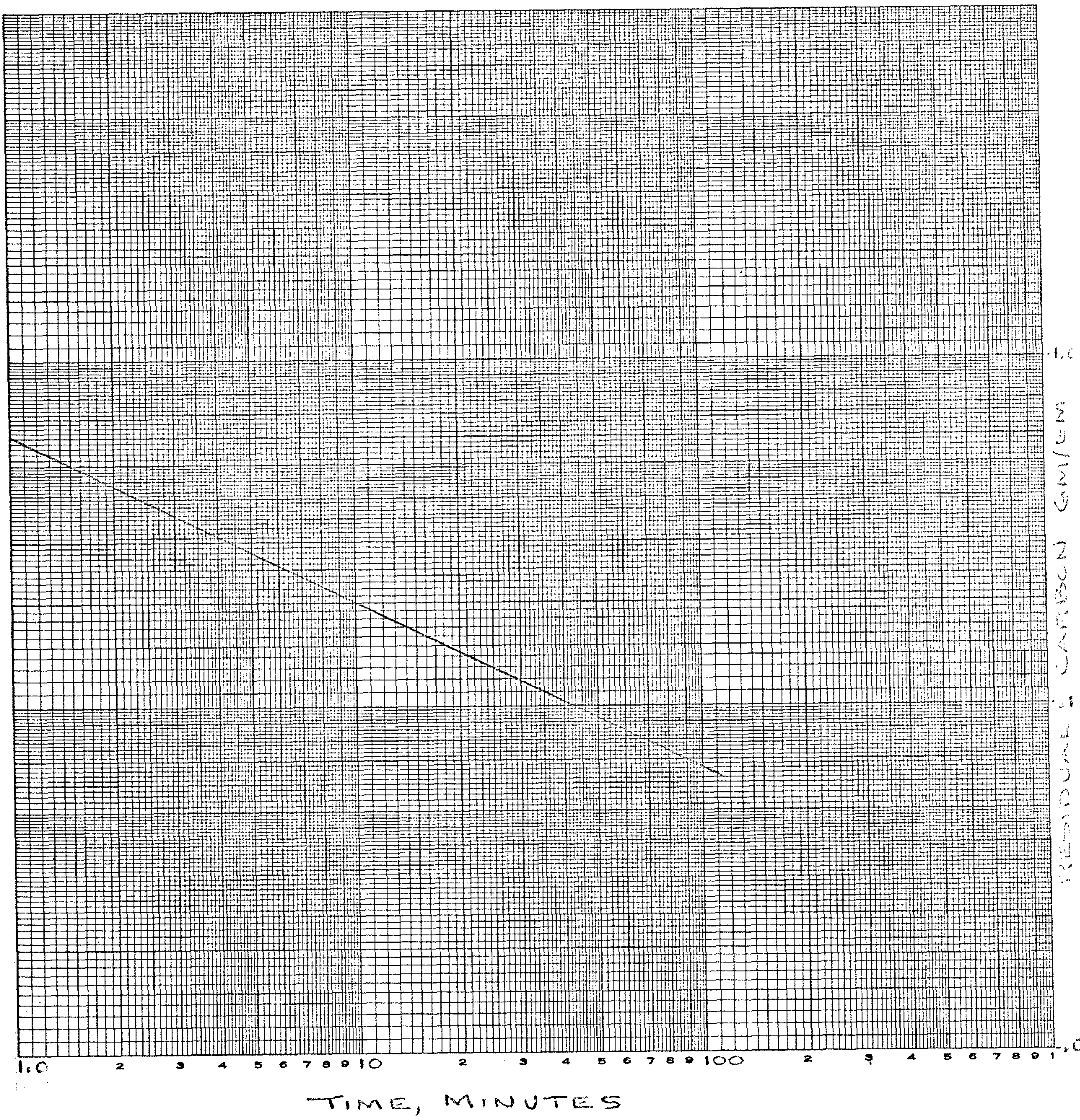


FIGURE 21
INITIAL RATE CONSTANT
K_v VS. TEMPERATURE
AIR SUPPLY = 7.5 L/M/GM

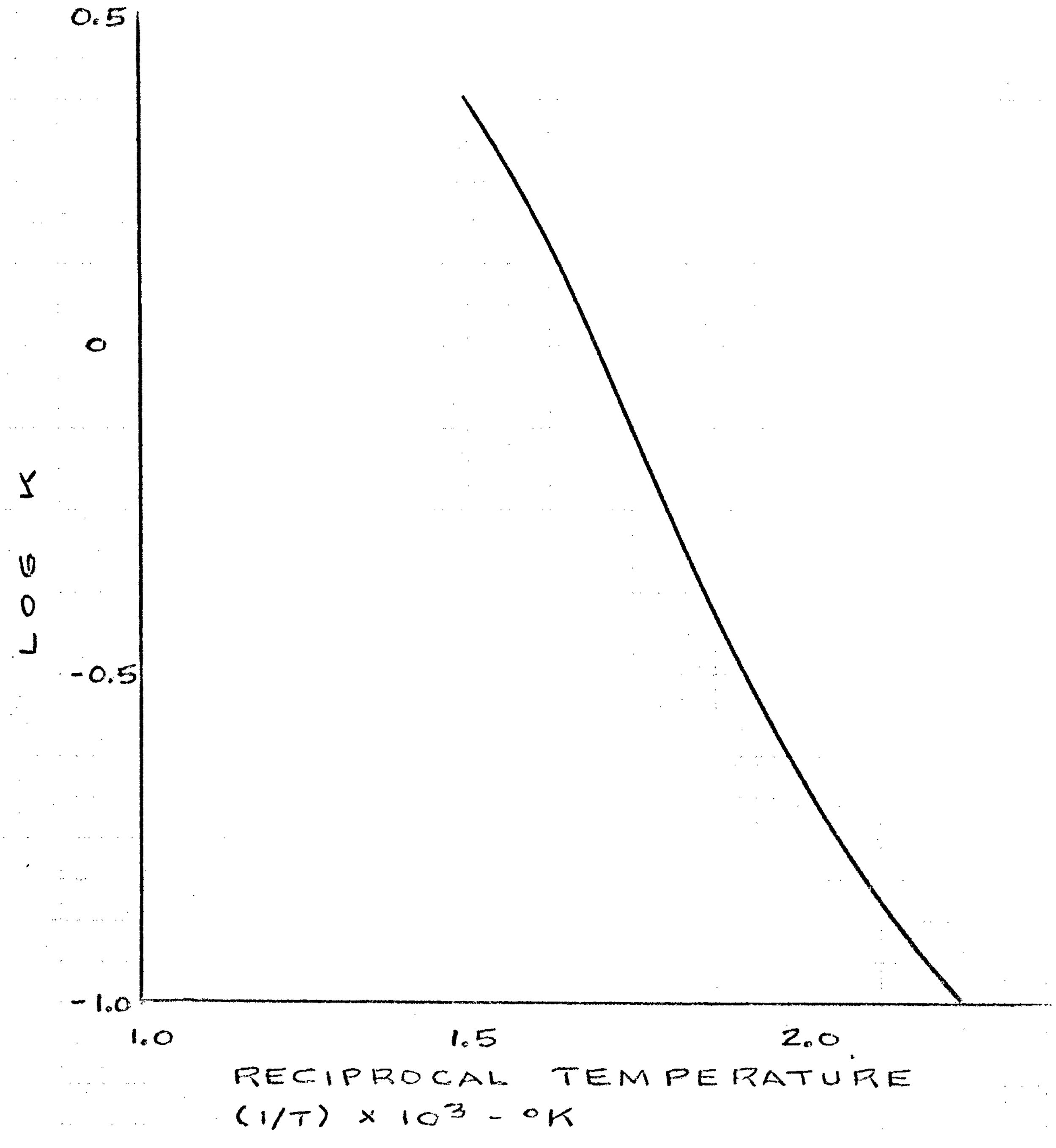
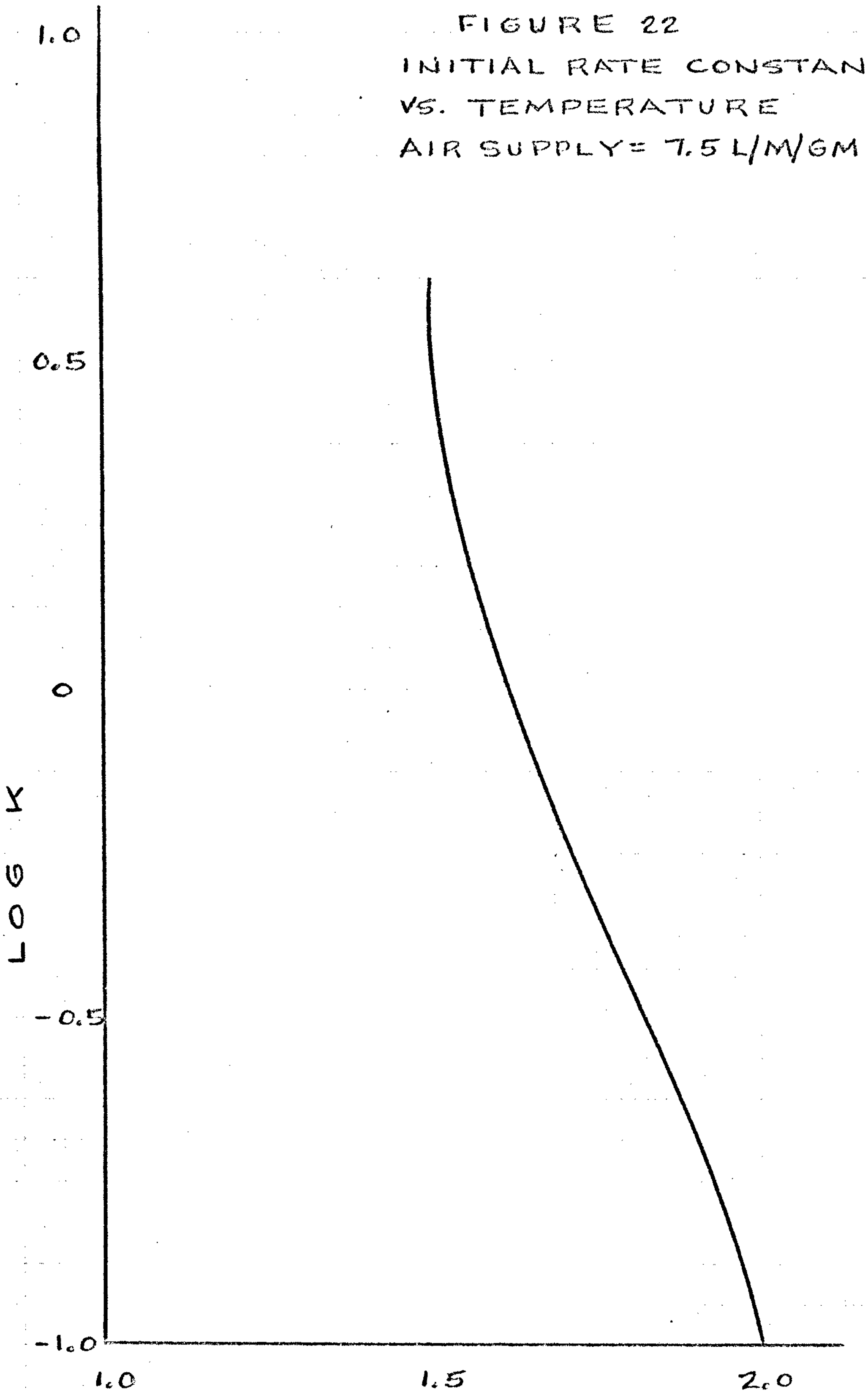


FIGURE 22

INITIAL RATE CONSTANT, K_C

VS. TEMPERATURE

AIR SUPPLY = 7.5 L/M/GM



RECIPROCAL TEMPERATURE

(1/T) × 10³ - °K

FIGURE 23
PARAMETER OF
VOLATILITY VS.
OXYGEN SUPPLY AT 400°C

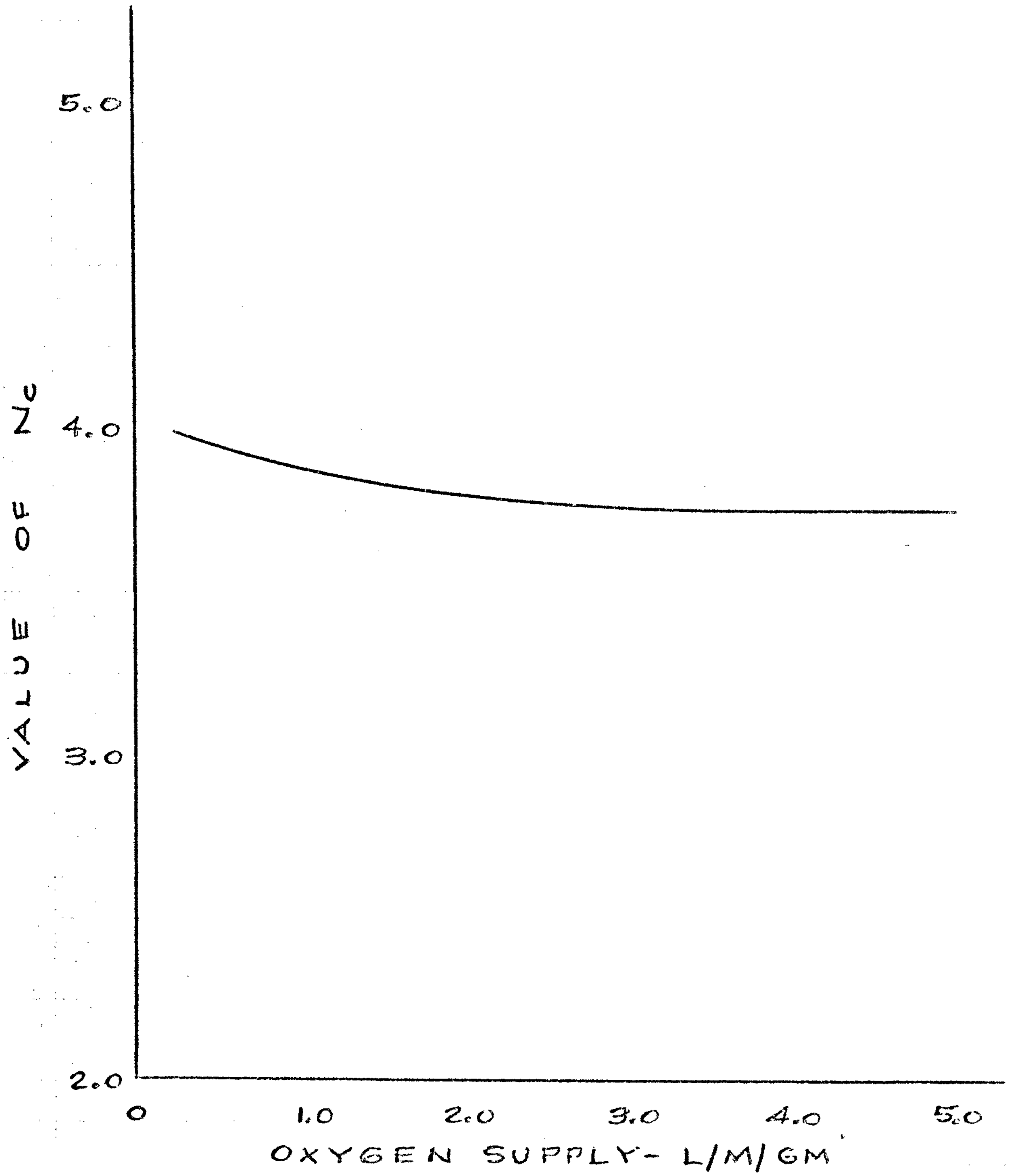


FIGURE 24
PARAMETER OF
VOLATILITY VS.
OXYGEN SUPPLY AT 400°C

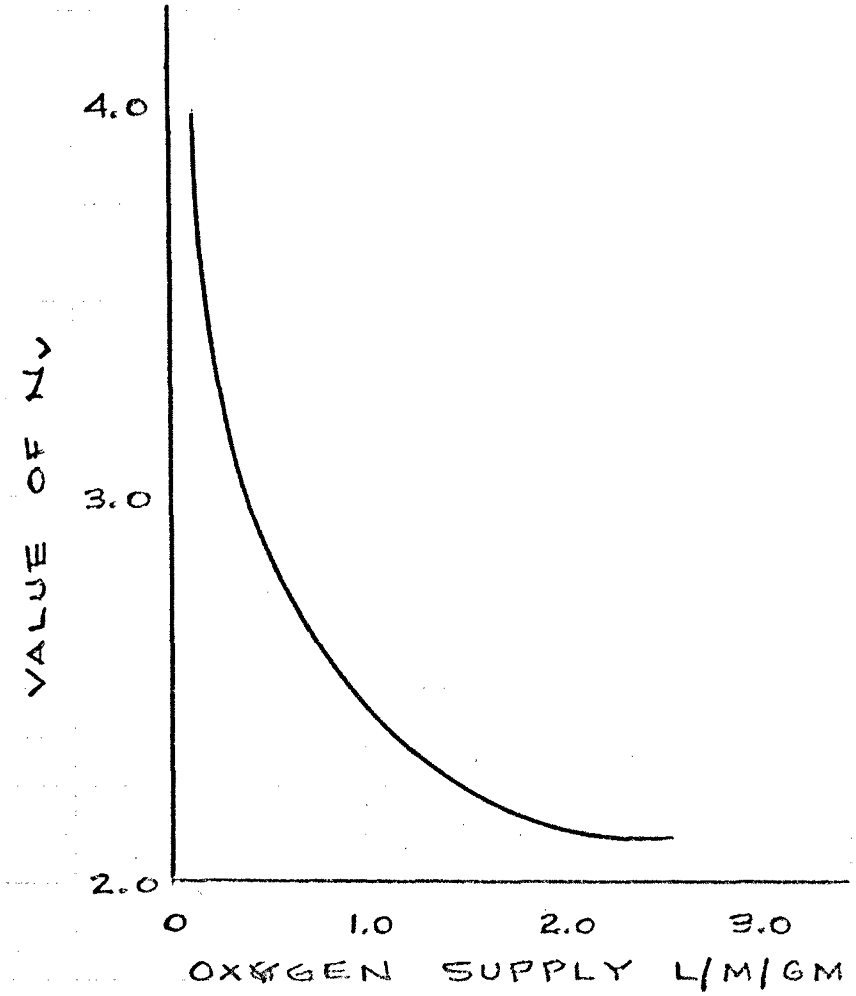


FIGURE 25
PARAMETER OF
VOLATILITY, K_c VS.
OXYGEN SUPPLY AT 400°C

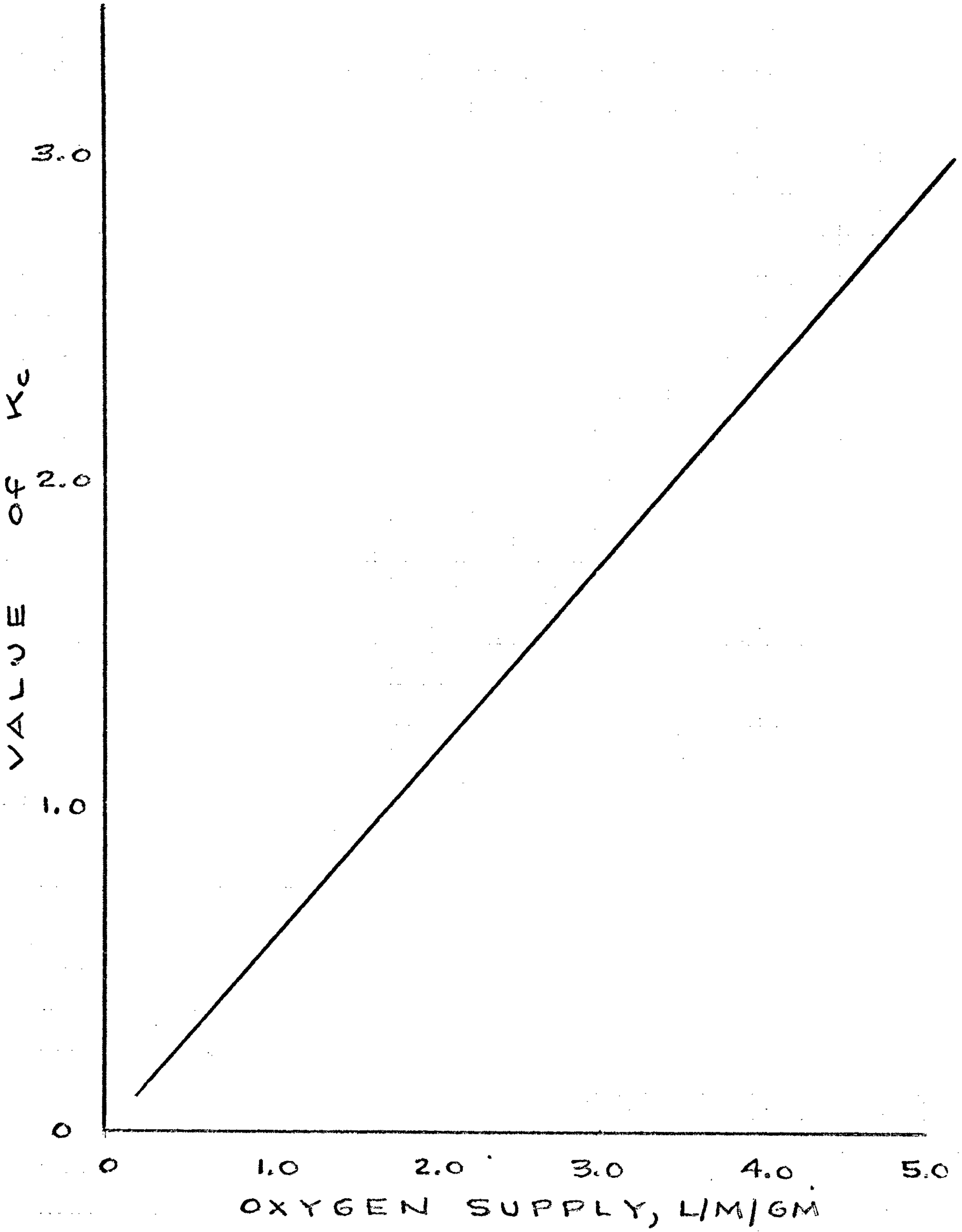


FIGURE 26
PARAMETER OF
VOLATILITY, K_v VS
OXYGEN SUPPLY AT 400°C

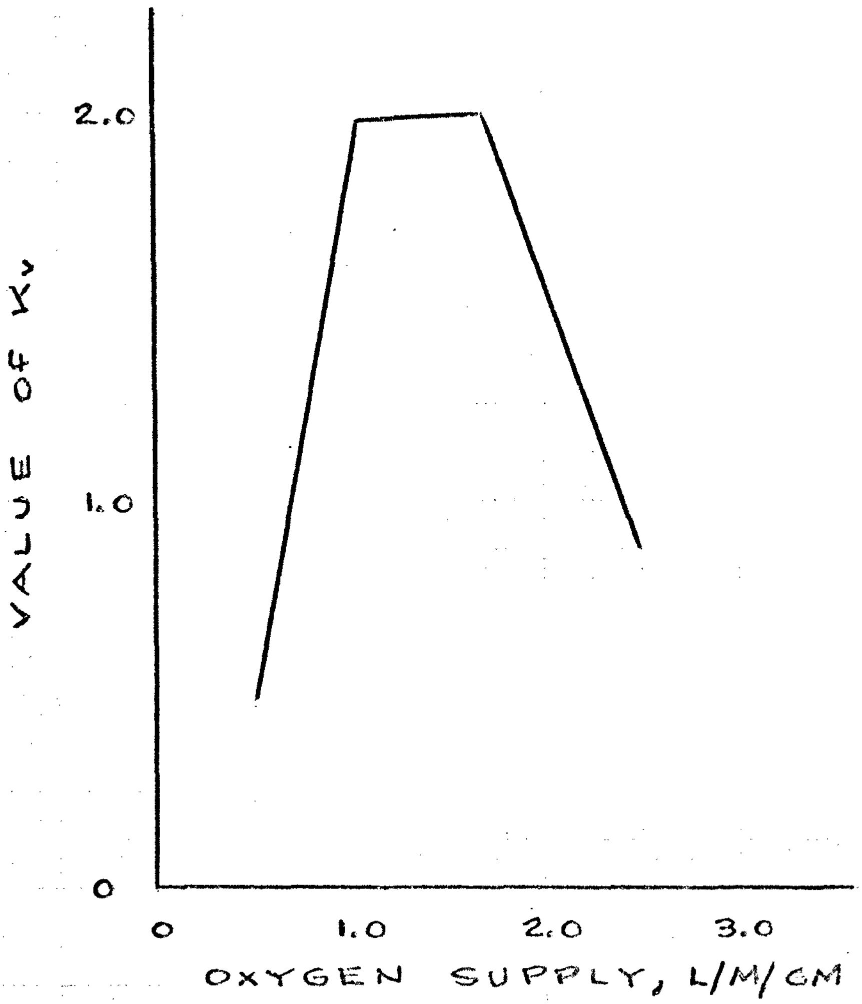


FIGURE 27
PARAMETER OF
VOLATILITY, N_v VS.
TEMPERATURE

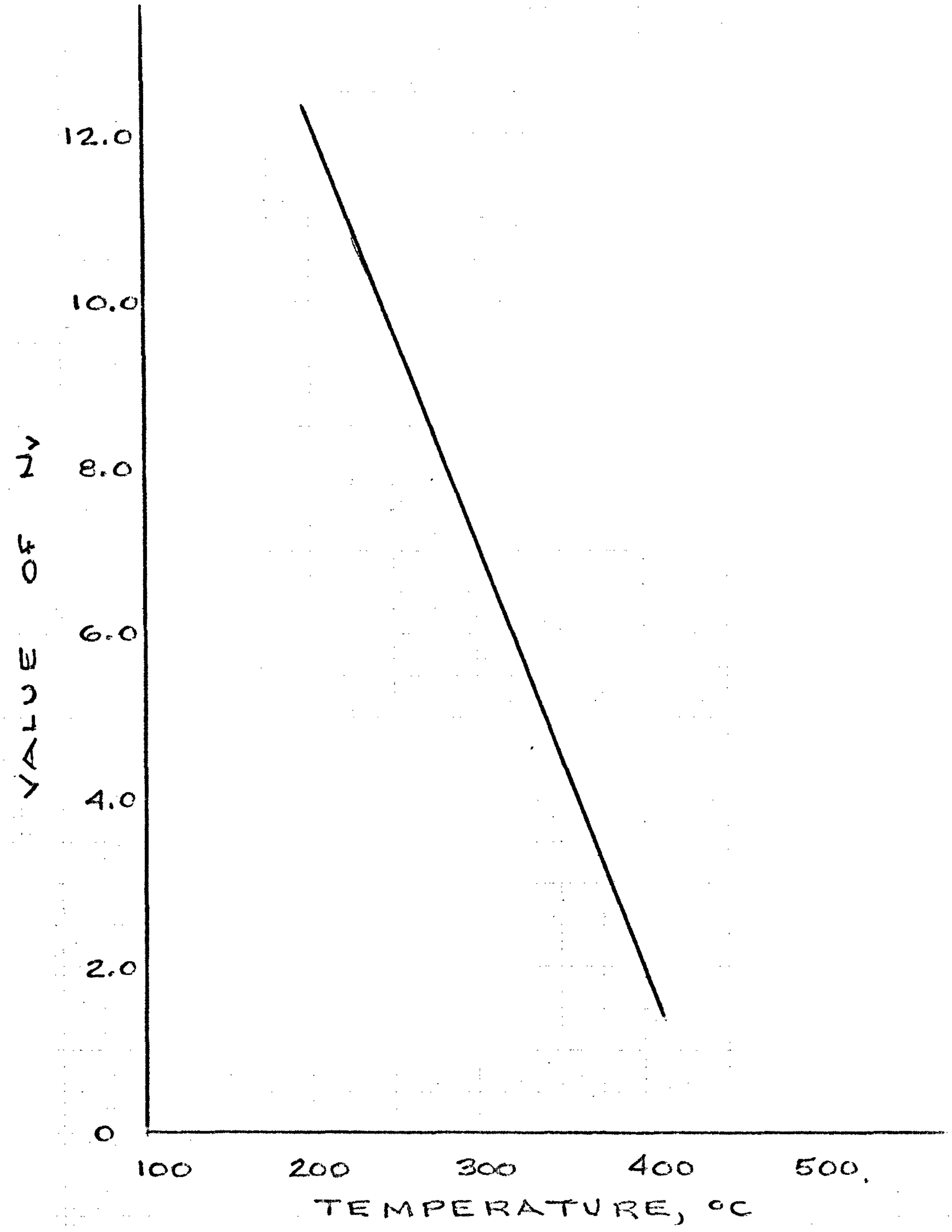
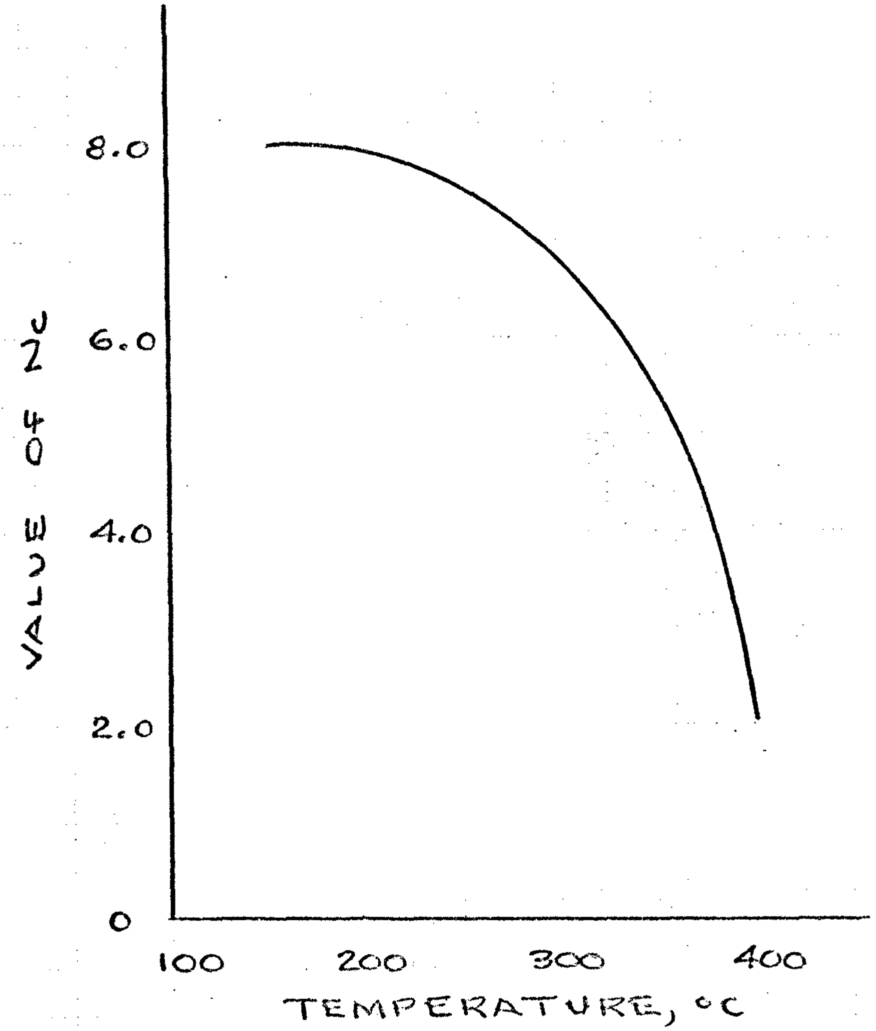


FIGURE 28
PARAMETER OF
VOLATILITY, N_c VS.
TEMPERATURE



APPENDIX

Appendix A

Heating times of solid specimens. The heating of dry pieces of solid waste in an incinerator is a problem in unsteady state heat transfer which is complicated by both endothermic and exothermic pyrolysis reactions. The time required for heating is estimated in the following analysis by considering simplified, but still meaningful, conditions.

Energy absorption and liberation within the pieces of waste is neglected. The error introducted by this simplification is decreased by the fact that the endothermic reactions, which are more energetic than the exothermic reactions, occur at a temperature which is low in comparison with that of the ambient gas, so that heat transfer to the energy-absorbing zone within a specimen tends to be rapid.

The pieces of waste are assumed to be suddenly plunged into a hot chamber whose temperature remains constant. This is, in effect, assuming well-mixed, steady conditions in the heating chamber.

Heat transfer by radiation and by particle-particle contact is neglected. The error thus introduced depends on the design of the incinerator. Furthermore, the particles are assumed to be either thin, flat slabs or spheres, the heating times of which should bracke the times for the actual shapes.

The heating time is defined as the time required for the temperature of a specimen to rise 95 percent of the initial temperature difference between the specimen and the surroundings. Each of the following criteria of hotness is employed: surface, center, and in the case of flat plates, space-mean temperatures.

The time defined in the foregoing is given in terms of the Fourier number (Fo), which is expressed as a function of the independent variables of the system by using the Nusselt number (Nu) and the Biot number (Bi).

Thus, we have

$$F_o = f\left(Bi, Nu, x/d_o\right) \qquad (1)$$

where d_o is the dimension of the specimen (sphere diameter or plate thickness), and x is distance from the specimen to the material whose heating time is referred to in Fo. This relationship, representing the solution of the differential equation describing the heat-transfer process, is given in graphical form in the literature (16). Therefore, for a given specimen of known thermal diffusivity, the heating time for material at a given position within a specimen is obtained by first calculating the Biot and Nusselt numbers.

Calculation of Nusselt Number

The nusselt number, which is a measure of the rate of heat transfer from the ambient gas to the surface of the specimen, is given by Nu $hd_o/\lambda g$ for spheres and Nu $= hL/\lambda g$ for flat plates, where d_o is the sphere diameter, L is the plate length, h is the heat-transfer coefficient for convection from the ambient gas to the surface of the specimen, and λg is the thermal conductivity of the ambient gas. The following semi-empirical relationships are known:

For sphere (14):

$$Nu = 2\left[1 + .3 Re^{1/2} Pr^{1/3}\right] \quad (2)$$

For flat plate (17):

$$Nu = .664\, Re^{1/2} Pr^{1/3} \quad (3)$$

Pr is the Prandtl number of the ambient gas, and Re is Reynolds number gased on the relative velocity between the specimen and the ambient gas. Equation (3) is limited to laminar flow over the surface of the slab, a condition which is expected to be satisfied in most all incinerators.

Prandtl number, which is essentially independent of both temperature and pressure, has a value of about 0.7 for air. Pr 1/3 is approximated by unity in this calculation.

In calculating Reynolds number, the dimension of the specimen is taken to be the diameter of spheres and the length of plates. The length and width of the plate are assumed to be much larger than the thickness, and the plate is assumed to be oriented with its length parallel to the velocity of the ambient gas. Specific values of width are of no consequence in this calculation. The properties of the ambient gas are assumed to be identical to those of dry air.

Calculation of Biot Number

The Biot number is a measure of the relative rates of surface and internal heat transfer and is given by Bi = hr_o/λ_s, where λ_s is the thermal conductivity of the solid material, and r_o is the radius of spheres and the half-thickness of flat plates. Bi is expressed in the following in terms of Nu. In the case of flat plates, the length has been assumed to be 10 times the thickness.

For sphere:

$$\mathrm{Bi} = (1/2)(\lambda_A/\lambda_S)\,\mathrm{Nu} \qquad (4)$$

For flat plate:

$$\mathrm{Bi} = (1/20)(\lambda_A/\lambda_S)\,\mathrm{Nu} \qquad (5)$$

The thermal conductivity of a wide range of carbonaceous materials, including various woods, plastics, rubber, and coal, is within the range 2.8 X 10^{-4} to 3.8 x 10^{-4} cal/cm-deg C-sec (18,19). It is assumed here that a value of

$$\lambda_S = 2.5 \times 10^{-4}\ \mathrm{CAL/CM\,^\circ C\text{-}SEC}\ (0.06\ \mathrm{BTU/HR\,^\circ F\text{-}Ft}$$

is representative of solid waste.

Biot number is calculated using the values of Nu calculated in the foregoing and assuming the ambient gas to be air.

Calculation of Fourier Number

The Fourier number is given by $\mathrm{Fo} = \alpha\, t_h/r_o^2$, where a is the thermal diffusivity of the solid material, and t_h is the heating time. Fo is calculated using the values of Bi obtained in the foregoing and graphs of equation (1) found in reference (16).

Calculation of Heating Time

The heating time of a specimen of given dimension is obtained from the Fourier number and the thermal diffusivity of the material.

This analysis uses the value $\alpha = 1.0 \times 10^{-3}$ sq cm/sec (3.9×10^{-3} sq ft/hr) which should be appropriate for waste, since it is approximately valid for coal, wood, and many other carbonaceous materials (18,19).

The extreme case, where surface heat transfer is infinitely faster than heat transfer within the specimen (i.e., $\lambda_s/hr_o = 0$), represents an upper limit to the heating rate obtained by increasing without bonds the relative velocity between the specimen and the ambient gas. Heating times for this case are found in a similar manner to that described in the foregoing.

Appendix B

Derivation of burning time equations. As was done in the analysis of heating time in Appendix A, two extreme specimen geometries are considered here: flat plates and spheres. In the case of each geometry, the equations for burning time are derived for cases of complete mass-transfer control and complete chemical control.

Flat plate: mass-transfer controlled burning rate. The plate is assumed to be oriented with its length parallel to the velocity of the ambient gas. Combustion of the edges of the specimen is assumed to be negligible with respect to both total burning rate and changes in the dimensions of the specimen.

The molar flux of oxygen reaching the burning surface is

$$\dot{N} = k_f(f_a - f_s)$$

where kf is the mass transfer coefficient (g-moles/sq cm-sec), and f_a and f_s are the mole fractions of oxygen in the ambient gas and at the solid surface. Owing to the assumption that burning rate is mass-transfer controlled, $f_s = 0$. Therefore,

$$\dot{N} = k_f f_a \qquad (6)$$

For the case of laminar flow at the surface of the specimen, which will almost always be the case, k_f is given by the following semi-empirical equation (20):

$$k_f = 0.664\ (PD/RTL)\ Re^{\frac{1}{2}} Sc^{1/3} \qquad (7)$$

where P is absolute pressure, D and Sc are the coefficient of diffusion and Schmidt number for oxygen in the ambient gas, R is the ideal gas constant, and T is absolute temperature.

The Schmidt number is essentially independent of both temperature and pressure and has a value of about 0.9 for oxygen in air. Since the ambient gas of the waste has properties similar to air, $S_c{}^{1/3}$ is assumed to be unity. Therefore,

$$\dot{R}_s = FM_s\dot{N} \tag{8}$$

where F is the moles of solid material consumed per mole of oxygen used, and M_s is the molecular weight of the solid material.

Combining equations (6), (7), and (8) gives

$$\dot{R}_s = (0.664)\ FM_s\ (D/L)\ (Pf_a/RT)\ Re^{\frac{1}{2}} \tag{9}$$

The specific burning rate is also given as follows in terms of the density of the solid material (ρ_s) and the rate of decrease of specimen thickness (dr/dt):

$$\dot{R}_s = \rho_s dr/dt$$

Assuming temperature pressure, oxygen concentration, and ambient velocity to be independent of time, $\dot{R}_s$ is constant, and integration of the foregoing gives:

$$t_b = (\rho_s/\dot{R}_s)\ r_o \tag{10}$$

The desired burning-time is obtained by replacing $\dot{R}_s$ in equation (10) with equation (9). In making this substitution, it is convenient to express D and Re in terms of temperature and pressure as follows:

$$D = D_o\ (T/T_o)^{3/2}\ (P_o/P) \tag{11}$$

$$Re = (Vl/\nu_o)\ (T_o/T)^{3/2}\ (P/P_o) \tag{12}$$

where V is the relative velocity between the ambient gas and the specimen, ν is the kinematic viscosity of the ambient gas, and the subscript o denotes STP conditions (0^0C and 1atm).

The temperature and pressure dependence of the relative velocity is not clearly known, If we express V as

$$V = V_o\ (T/T_o)^m (P/P_o)^n$$

then values of m ranging from 1/2 to 1 and values of n ranging from 0 to -1 are obtained depending upon the conditions chosen with regard to: 1) the size of the specimen, 2) whether the specimen is stationary with respect to the combustion chamber or suspended in the flow, 3) the extent to which the suspended specimen interacts with other specimens, and 4) the fractions of the time that the suspended plate is oriented parellel with and perpendicular to the main flow. The velocity of the ambient gas relative to the specimen will be treated as though it is the average linear flow rate through the chamber. Hence,

$$V = V_o(T/T_o)\ (P_o/P) \qquad (13)$$

Since this equation is not necessarily correct, it should be remembered that the burning-time equation resulting from this analysis may not reveal the actual influence of pressure and temperature on burning time.

Substituting equations (11) to (13) into equation (10) gives

Flat plates; mass-transfer control:

$$t_b = \left[K_3 K_4 (T_o/T)^{1/4} (L/V_o)^{1/2} (1/f_a)\right] d_o \qquad (14)$$

where

$$K_3 = \rho_s/FM_s, \qquad K_4 = RT_o \nu_o{}^{1/2}/1.328 D_o P_o$$

and d_o is the initial thickness of the plate.

For combustion in air, $K_4 = 3.19 \times 10^4$ sp cm-sec$^{1/2}$/g-mole. The value of K_3 depends upon the material being burned.

Sphere: mass-transfer controlled burning rate. The sphere is assumed to burn uniformly over its surface, and the ambient gas is assumed to remain constant with respect to temperature, pressure, oxygen concentration, and velocity relative to the burning specimen. The following analysis is very similar to that performed in the following in the foregoing for flat plates, except that Re changes during burnout for the case of spheres.

Assuming that Schmidt number is unity, the mass-transfer coefficient for a sphere may be written (20)

$$k_f = (DP/RTr)\left[1 + 0.276Re^{1/2}\right]$$

where r is the radius of the sphere at any time t. Using this equation and equating the rate of oxygen transport to the surface of the sphere to the equivalent rate of decrease of the sphere radius, we have

$$-\rho_s dr/dt = (DP/RTr)$$
$$\left[1 + .276Re_o^{1/2}(r/r_o)^{1/2}(T_o/T)^{1/2}\right] f_a FM_s$$

where Re has been expressed in terms of its initial, STP value with velocity assumed to be $V = V_o(T/T_o)(P_o/P)$. This equation is arranged for integration in the following manner:

$$DPf_A/RTK_3 \int_0^{(t_b)_{M.T.}} dT = \int_{R_o}^{0} \left[R/(1+zR^{1/2})\right] dR$$

where $z = 0.276\ (Re_o T_o/r_o T)^{1/2}$, r_o is the initial sphere radius and (t_b) m.t. is the burning time under mass-transfer controlled conditions. The substitution $zr^{1/2} = y-1$ allows this equation to be integrated to give

Sphere; mass-transfer control:

$$(t_b)_{m.t.} = \left[K_1 K_2 K_3 (T_o/T)^{1/2} (1/f_a) \right] d_o^2 \qquad (15)$$

where d_o is the initial sphere diameter and

$$K_1 = RT_o/8D_oP_o$$

$$K_2 = \left[(4/3)U^3 - 2U^2 + 4U - 4\ln\ (1\ U) \right] /U^4$$

$$U = 0.276 Re_o^{1/2} (T_o/T)^{1/2}$$

$$K_3 = \rho_s/FM_s$$

The value of K_1 is 1.273×10^4 cm-sec/g-mole for combustion in air. The value of K_2 is unity for the case of no convection (i.e., for $V = 0$), and decreases as Re_o increases. For values of Re_o greater than about 1500, K_2 becomes inversely proportional to $Re_o^{1/2}$, so that burning time becomes proportional to $d_o^{3/2}$ and inversely proportional to $V^{1/2}$. The stoichiometric constant K_3 is evaluated in the analysis of flat-plate combustion.

Chemically Controlled Burning of Carbon: Spheres and Flat Plates

Combustion is assumed to occur only on the outer surface of specimens, thus neglecting reaction in pores. Assuming that oxygen concentration and temperature are constant, the specific burning rate $\dot{R}_s$, is also constant, and the burning times of a spherical or flat-plate specimen is obtained by integrating the quation $\dot{R}_s = -\rho_c\, dr/dt$, where ρ_c is the density of carbon, and r is either the sphere radius or the plate half-thickness. The burning time under conditions of chemical rate control is found to be

$$(t_b)_{c.c.} = (\rho_c/2\dot{R}_s)d_o \qquad (16)$$

From the chemistry of the carbon-oxygen reaction, $\dot{R}_s$ is given as follows:

Adsorption control:

$$\dot{R}_s = M_c \eta f_a P (1/2\pi M_o RT)^{1/2} \exp(-E_1/RT)$$

Desorption control:

$$\dot{R}_s = M_c A_2 \exp(-E_2/RT)$$

where E_1 and E_2 are the activation energies for oxygen adsorption on carbon and desorption of carbon oxides (assumed to be solely CO_2), M_c and M_o are the molecular weights of carbon and oxygen, η is the steric factor of the adsorption process, and A_2 is the frequency factor of the desorption process. Substitution of these expressions into equation (16) gives the following results:

Carbon sphere or flat plate; adsorption control:

$$(t_b)_a = K_5(P_o P)(1/f_a) \left[1/(T_o/T)^{1/2} \exp(-E_1/RT)\right] d_o \qquad (17)$$

Carbon sphere or flat plate; desorption control:

$$(t_b)_d = K_6 \left[1/\exp(-E_2/RT)\right] d_o \qquad (18)$$

where

$$K_5 = \rho_c (2\pi M_o R T_o)^{1/2}/2 M_c \eta P_o$$

$$K_6 = \rho_c/2 M_c A_2$$

APPENDIX C

DEFINITION OF MEDICAL TERMS

Anorexia -- loss of appetite.

Asphyxia -- unconsciousness due to suffocation or interference of any kind with oxygenation of the blood.

Cardiac dilatation -- enlarging of the heart, occuring pathologically or made artificially.

Catarrh -- simple inflamation of a mucous membrane.

Conjunctiva -- the mucous membrane covering the anterior surface of the eyeball and lining the lids.

Cyanosis -- a dark bluish or purplish coloration of the skin and mucous membrane due to deficient oxygenation of the blood.

Dyspnea -- difficult respiration.

Edema -- an abnormal accumulation of clear watery fluid in the lymph spaces of the tissues.

Hemoglobin -- the coloring matter of the blood.

Pulmonary epithelium -- the purely cellular, nonvascular layer covering all the free surfaces of the lungs.

LIST OF REFERENCES

1. Perry, Chemical Engineer's Handbook, Ed. 4, New York, McGraw-Hill, 1963.

2. Williams and Johnson, Stoichiometry for Chemical Engineers, New York, McGraw-Hill, 1958.

3. JANAF Thermochemical Tables Report, OTS PB-168370, U. S. Government Printing Office, 1965.

4. Basic Considerations in the Combustion of Hydrocarbon Fuels in Air, NACA Report 1300, U. S. Government Printing Office, 1959.

5. Limits of Flammability of Gases and Vapors, Bureau of Mines, Bulletin 503, U.S. Government Printing Office, 1952.

6. Physics of Combustion and Explosion, Khitrin, L.N., OTS61-31205, National Science Foundation.

7. Howard, J.B. and Essenhigh, R.H., Eleventh Symposium (International) on Combustion, The Combustion Institute, 1967, pg. 399.

8. Pitt, G.J., Fuel, vol. 41, 1962 pg. 267.

9. Van Krevelen, D. W. and Schuyer, J., Coal Science, Elsevier, 1957 pg. 295.

10. Berkowitz, N., Fuel, vol. 39, 1960, pg. 47.

11. Essenhigh, R. H., Froberg, R., and Howard, J.G., Ind. Eng. Chem., vol. 57 No. 9, 1965, pg. 32.

12. Essenhigh, R. H., and Howard, J.B., Ind. Eng. Chem., vol. 58, No. 1, 1966, pg. 14.

13. Tu, C. M., Davis, H., and Hottel, H.C., Ind. Eng. Chem., vol. 26, 1934, pg. 749.

14. Ranz, W. E. and Marshall, W. R., Chem, Eng. Prog., vol. 48, 1952, pgs. 141, 173.

15. Essenhigh, R. H., and Fells, I., Discussion Faraday Soc. No., vol. 31. 1961, pg. 208.

16. McAdams, W. H., Heat Transmission, 3rd edition, McGraw-Hill, 1954, pgs. 36-40.

17. Rohsenow, W. M. and Choi, H. Y., Heat, Mass and Momentum Transfer, Prentice-Hall, 1961, pg. 148.

18. Ibid.: pgs. 516, 517.

19. Schaffer, E. L., Pyrodynamics, vol. 2, 1965, pg. 117.

20. Rohsenow, W. M. and Choi, H. Y., Heat, Mass and Momentum Transfer, Prentice-Hall, 1961, pgs. 416, 418.

21. Essenhigh, R. H., Colliery Engineering, vol. 38, 1961, pg. 534; vol. 39, 1962, pgs. 23, 65, 103.

22. Thring, M. W., Science of Flames and Furnaces, 2nd ed., John Wiley, N.Y., 1962.

23. MacLellan, D. E., Thermal Efficiency of Industrial Furnaces: A study of the effect of Firing Rate and Output, M. S. Thesis, Department of Fuel Science, The Pennsylvania State University, September, 1965.

24. Skipworth, D. W., G.M. Hein and H. W. Nelson, Design of Domestic Gas-Fired Incinerators for Elimination of Smoke, Odors, and Fly Ash, Amer. Gas Assoc., Inc., Research Bull. 78, (April 1958), pgs. 45-7.

25. Cushny, A. R. The Secretion of Urine, Monographs of Physiology, 2nd ed., 1926.

26. Best, C. H. and N. B. Taylor, The Physiological Basis of Medical Practice, Williams and Wilkins Co., Baltimore, 5th ed., 1950.

27. Fair, G. M. and J. C. Geyer, Water supply and Waste Water Disposal, John Wiley and Sons, Inc., New York, 1st ed., 1956, pgs. 512-13.

28. Haslem, R. T. and R. P. Russell, Fuels and Their Combustion, McGraw-Hill Book Co., New York, 1st ed., 1926, pg. 181.

29. Hein, G. M. and R. B. Engdahl, A Study of Effluents from Domestic Gas-Fired Incinerators, A report Conducted at Batelle Memorial Institute, Project DG-3M, (Amer. Gas Assoc., June 1959, pgs. 9-11.

30. Goldman, F. H. and H. Yogada, Collection and Estimation of Traces of Formaldehyde in Air, Ind. Eng. Chem., Anal. Ed., XV (Fune 15, 1943), pgs. 377-78

31. Steyermark, A. Quantitative Organic Microanalysis, The Blakiston Co., New York, 1st ed., 1951, pg. 134.

32. Jacobs, M. B., The Analytical Chemistry of Industrial Poisons, Hazards, and Solvents, Interscience Publishers, New York, 2nd ed., 1949, pg 354.

33. Saltzman, M. B. Colorimetric Microdetermination of Nitrogen Dioxide in the Atmosphere, Anal. Chem., XXVI, December 1954, pgs. 1949-55.

34. Kanter, C. V., R. G. Lunche and A. P. Fudurich, Techniques of Testing for Air Contaminants from Combustion Sources, Jour. APCA, Feb., 1957, pgs. 191-99.

35. Mader, P. P., M. W. Heddon, R. T. Lofberg and R. H. Liehler, Determination of Small Amounts of Hydrocarbons in the Atmosphere, Anal. Chem., Dec., 1952, pgs. 1899-902.

36. Anon, American Standard Approval Requirements for Domestic Gas-Fired Incinerators, Amer. Gas Assoc., Inc., ASA Z 21.6-1957, Jan. 1, 1957.

37. Shnidman, L. Improved Apparatus for the Rapid Determination of Carbon Monoxide, Amer. Gas Assoc., Oct. 1943, pgs. 405-08, 428.

38. Henderson, Y. and H. W. Haggard, Noxious Gases, Reinhold Publishing Co., New York, 2nd ed., 1943, pgs. 130-31, 195.

39. Sayers, R. R. and W. P. Yant, U.S. Bur. Mines Depts. Investigations No. 2476, 1923.

40. Hamilton, A. and H. L. Hardy, Industrial Toxicology, P. B. Hoeber Inc., New York, 2nd ed., 1949, pgs. 29, 225.

41. Haggard, H. W., Action of Irritants on the Respiratory Tract, Jour. Indust. Hyg. & Toxicol, 1923, pg. 390.

42. Patty, F. A. Editor, Industrial Hygiene and Toxicology, II Interscience Publishers, New York, 1st ed., 1949 pgs. 559, 585, 607-09, 884.

43. Anon, Threshold Limit Values, Adopted at the Meeting of the American Conference of Government Industrial Hygienists in Philadelphia, Pa., April, 1956.

44. Johnstone, R. T. Occupational Diseases, Saunders Co., Philadelphia, 1942.

45. McDavid, J. W. The Temperature of Ignition of Gaseous Mixtures, Trans. Chem. Soc. of London Jour., 1917, pgs. 1003-015.

46. Dixon, H. B. and H. F. Coward, The Ignition of Gaseous Mixtures, Trans. Chem. Soc. of London Four., 1917, pgs. 514-40.

47. Anon, Combustion, American Gas Association, New York, 3rd ed., 1938, pg. 86.

48. Washburn, E. W., Editor-in-Chief for the National Research Council, International Critical Tables II, McGraw-Hill Book Co., New York, 1st ed., 1926, pgs. 150, 161, 172.

49. Shnidman, L., Gaseous Fuels, American Gas Association, New York, 1st ed., pgs. 76, 116, 118, 123, 124, 126-27.

50. Griswold, J. Fuels Combustion and Furnaces, McGraw-Hill Book Co., New York, 1st ed., 1946, pgs. 122, 130, 181, 182-84, 210.

51. Gaydon, A. G. and H. G. Wolfhand, Flames, their Structure, Radiation, and Temperature, Chapman & Hall Ltd., London, 1st ed., 1953 pgs. 177-209.

52. Houdry, J. H. and C. T. Hayes, Versatility of Oxidation Catalysts for Industrial Air Pollution Control, Jour. APCA, Nov., 1957 pgs. 182-83.

53. Sweigert, R. L. and M. W. Beardsley, Experimental Specific Heat Equations Based upon Spectroscopic Data, Georgia School Technol. Bull., June, 1938.

54. Obert, E. F. Concepts of Thermodynamics, McGraw-Hill Book Co., New York, 1st ed., 1960, pgs. 372-73, 514-15.

55. Ellenwood, F. O., N. Kulik and N. R. Gay, The Specific Heat of Certain Gases over Wide Ranges of Pressures and Temperature, Cornell Univ. Bull. 30, Oct., 1942.

56. Meissner, H. G. Municipal Incinerator Selection, Public Works, Vol. 90, 1959, pg. 99.

57. Blanke, J. H. D., The Design and Operation of Big City Incinerator Furnaces, Power Engineering, Vol. 63, 1959, pg. 96.

58. Schalla, T. P., Formation and Combustion Smoke in Laminar Flames, Annual Reports, Natl. Advisory Comm. for Aeronautics, Washington, D. C. Report 1186-1954.

59. Quon, J. E., B. D. Tebbens, and J. F. Thomas, Combustion Nuclei An Index for Classifying Gaseous Hydrocarbon Fuels, Industrial and Engineering Chemistry, Vol. 53, 1961, pg. 235.

60. Tebbens, B. D., J. F. Thomas, and M. Mukai, Aromatic Hydrocarbon Production related to Incomplete Combustion, Archives of Industrial Health, Amer. Medical Ass., Vol. 14, 1956, pg. 413.

61. Standard Methods for the Examination of Water and Wastewater, Amer. Pub. Health Assn., New York, N.Y., 11th ed., 1960.

62. Niederl, J. B., Niederl, V., Micro-methods of Quantitative Organic Analysis, John Wiley and Sons, Inc., New York, 2nd ed., 1942.

63. Sewage Treatment Plant Design, Manual of Engineering Practice No. 36, ASCE, New York, 1959.

64. Moelwyn-Hughes, E. A., Physical Chemistry, Pergamon Press, New York, 2nd ed., 1961.