Residue Characterization According to Furnace Design

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INTRODUCTION

Incineration has been employed since about 1874 [6] as a method of solid waste treatment and disposal. The first incinerators were constructed in England to burn "mixed refuse" and the combustion process was initially called either "destruction" or "cremation". A prime consideration in the early development of refuse incinerators was that the heat released could be recovered for steam production, and also that the public health nuisance and hazard conditions could be eliminated or substantially reduced if the furnace were operated at sufficiently high temperatures.

Refuse incineration in the United States did not follow the early leadership of England and continental Europe, but rather, the United States developed its own goals and proceeded to experiment with its own processes. While in Europe, the original intent of refuse incineration was to render innocuous the potentially hazardous or odorous material, very little attention was given as to how efficient the process actually was. This paper will report some of the findings on the characterization of residue as well as attempt to interpret this character relative to process efficiency. Hopefully, some day this character can be related to overall environmental effect, and limitations on the use and handling of residue can be specifically outlined.

It was apparent in early attempts at refuse incineration that there were virtues of the process which could be of benefit to the general population. It soon became apparent also that the volume reduction of solid by-product resulting from combustion was a very important consideration. When the economics of refuse incineration are discussed today, volume reduction remains one of the primary justifications.

However, the economic factors of land availability, etc., which necessitated the construction of incinerators, now are dictating that the characteristics of residue must also meet a certain quality or else special handling and approved disposal of the residue must be practiced. These few factors represent, of course, only a portion of the problem confronting the solid waste environmental engineer. Increased quantities of solid waste, both on a per capita and total population basis, and decreased land availability in the more densely populated areas all assist in complicating any decision-making as to method of waste disposal.

While the methods for properly handling solid waste in sanitary landfill operations were recognized and defined almost 30 years ago, [12] it has been

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only a recent decision to assess the possible public health significance of incinerator residue. Several manuals and operating procedures have been developed for sanitary landfills, [3, 5, 11] but the absence of similar guidelines for incinerators is quite noticeable.

Very little attention has been given to either the quality or character of the resulting residue or to the exploitation of residue or unprocessed refuse as a potential resource. [1, 4, 8] Recently, there has been an upsurge in the possible use of refuse for heat recovery and other uses, but the character of the residue remains undefined.[9]

NOMENCLATURE

P = Percent combustible matter remaining in the incinerator residue, expressed in terms of dry residue.

A_f = Fraction of ash in dry residue, expressed as weight fraction.

V_f = Fraction of volatile matter (combustible) in dry residue, expressed as weight fraction.

A_o = Fraction of ash in dry unburned refuse, expressed as weight fraction.

V_o = Fraction of volatile matter in dry unburned refuse, expressed as weight fraction.

A'_o = Amount of ash in dry residue resulting from combustion of one unit of refuse.

V'_o = Amount of volatile (unburned matter) in dry residue resulting from the combustion of one unit of raw refuse.

K = The weight reduction equal to the amount of V_o which has been burned from one unit of raw refuse.

B = Percent of burnout of combustible matter.

METHODS OF CHARACTERIZING SOLID WASTE

Characterization of residue can be performed according to several widely different criteria. Briefly stated, residue can be described according to its relation to one of the following: water quality, air quality, or as a general environmental nuisance or potential health hazard. The most obvious way of determining the character of residue is not by any single method, but rather by a complex comparison of the raw refuse input character against the residue ash output character. Such a comparison permits evaluation of the overall efficiency of the combustion process by giving a quantitative measure of the process's ability to destroy, modify or utilize all combustible fuel.

In order to determine the properties of residue or any solid waste, several approaches can be used. Researchers, such as Kaiser [7] have attempted to adapt to residue and solid waste the techniques relating to coal analysis of the American Society for Testing Materials. [2] The pertinent ASTM techniques can be subdivided into the proximate and ultimate analyses. Both the proximate analysis and ultimate analysis are useful in establishing the fuel properties of coal, but they are not entirely applicable in determining the properties of a solid waste material or incinerator residue.

The proximate analysis includes the quantification of moisture content, ash, volatile matter, and fixed carbon; with the sum of these four fractions equalling 100%. The ultimate analysis includes moisture, carbon, hydrogen, oxygen, nitrogen, sulfur and ash, with the sum of these materials also being 100%. There are several basic reasons why neither of these approaches is totally suitable for the analysis of incinerator residue.

SIGNIFICANCE OF RESIDUE — REFUSE COMPARISON

Incinerator residue can have characteristics similar to raw refuse if the combustion process is not as efficient as is technically possible, so the residue contains sizable quantities of burnable carry-over. Depending upon its chemical composition, this unburned matter can undergo microbial decomposition which results in the release of malodors to the atmosphere and presents a potential health hazard to workers, animals or children who come in contact with the improperly handled solid waste. The amount of unburned material present in the residue may be a measure of this potential health hazard.

The unburned combustible material ("volatile matter" or sometimes called "loss on ignition") is not the only valid indicator of potential activity, but simply represents one necessary condition for biological activity. A second, and equally necessary requirement is that the elements necessary for bacterial metabolism and nutrition also be present in sufficient quantities. Foremost among the elements and compounds in this category are the nitrogen compounds such as proteins and amino acids, sulfur compounds, and fats, lipids and carbohydrates. Chemical analysis of these compounds is not an easy task because the concentration levels could be very low, even in the raw refuse, and the number of different compounds is very large, making the identification of the individual compounds almost impossible.

Since the ways of determining the characteristics of refuse are not always indicative of the ultimate goal behind a classification scheme, this paper will only discuss two main tests used in the classification of any solid waste matter. These two tests are the volatile content (or, as previously stated, the loss on ignition) and the quantity of material which is soluble in petroleum ether or a similar organic solvent.

VOLATILE MATTER AND ASH

The term volatile matter as applied to residue is an indicator of the quantity of combustible material which remains in the residue after incineration. The term volatile matter as applied to raw refuse is that fraction which can be burned. If either the raw refuse or incinerated residue is analyzed for the volatile fraction, the matter which is unburnable is called residue (ash). The term residue or ash as applied to the chemical analyses of a solid waste should not be confused with the similar terminology applied to incineration. [10]

The term, "ash," when applied to incineration, has a slightly different meaning. If the quantification of volatile matter and ash is done on a dry weight of residue basis, then much possible confusion is eliminated.

While the actual analysis of volatile matter and ash is not too complicated, the chemical significance of the two terms could vary with analytical technique. The ASTM method [2] uses a closed crucible for the determination of ash and volatile percentages in coal. The closed crucible is used to prevent oxidation of elemental carbon and pyritic compounds and to expel only the volatile hydrocarbons. In refuse testing, the term, "volatile matter" has been defined to include all the combustible material, free carbon as well as any combined carbon. Thus, in performing the test for volatile matter in refuse, it is desirable to encourage carbonaceous oxidation keeping the crucible uncovered. Obviously, the volatile matter reported using this method is not analogous to the volatile matter of coal. Perhaps a separate terminology such as "percent combustible" should be used.

ETHER-SOLUBLE FRACTIONS

Material which is soluble in anhydrous diethyl ether has been defined as the lipid content. [10] This soluble classification contains the bulk of the organic material, but, in addition, some inorganic compounds are also slightly soluble in the ether.

The lipids are a very important classification of compounds in refuse or residue analysis since many of these ether-soluble products are capable of undergoing microbial decomposition. The ether-soluble compounds do not contain all the substances which are classified in the "putrescible group," but certainly the majority of ether-soluble compounds are putrescible or fermentable.

Anhydrous diethyl ether is a most volatile and explosive solvent. If an extraction of soluble compounds in a Soxhlet extractor is undertaken, extreme caution should be exercised. Comparative studies on the extraction of organic materials using a Soxhlet apparatus and several organic solvents showed very little difference between diethyl ether and petroleum ether. The results which appear in this paper are obtained using petroleum ether as the solvent in the extraction.

The volatile fraction and ether-soluble fraction are by no means exhaustive tests used in characterizing solid waste material. The two tests are fast, safe and easy to perform and can be adapted readily to a quality control program. A more complete list of analyses is suggested in Table 1.

TABLE 1. COMPARATIVE TESTS FOR SOLID WASTE CHARACTERIZATION

1. Volatile Fraction
2. Ash Fraction
3. Ether-Soluble Fraction
4. Water-Soluble Fraction
5. Nitrogen
6. Calorific Value
7. Sulfur
8. Chemically Bound Carbon
9. Iron
10. Protein
11. Carbohydrate
12. Carbon
13. Hydrogen
14. Moisture

Before leaving the subject of chemical analysis, the effect of moisture should be discussed.

Moisture Content:

The moisture content of raw refuse is quite variable and ranges between 10% and 50% by weight as received, with the median being somewhere about 25%. The wide variability in the moisture content is caused by variation in a number of parameters such as the type of refuse (separate or combined) which is collected, the season of the year, the geographical location, the amount of precipitation and other factors. It is best to correct for moisture in both the volatile and ether-soluble analyses unless "as received" conditions are specified. The determination of moisture content in refuse and residue is a study in itself, and the average moisture content for any given set of climatological, geographical and socio-economic conditions could be of value in furnace design. Because the moisture content is not constant, it is recommended that all analytical tests performed on any solid waste should be reported on a dry weight basis, thereby eliminating the necessity to correct for moisture content.

The moisture content in solid refuse is very important in handling and disposal. The design of some furnace components, the extent of refuse compaction, rate of microbial decomposition, and the total weight of material which is collected are all related to the moisture content. Any analysis of solid waste material should contain the moisture content, but all other analyses should be reported on a dry weight basis.

Test Results

Table 1 lists the tests which are recommended if a complete characterization of the solid waste is to be undertaken. Actually these tests represent only the chemical phase of the characterization, and if physical properties or radiological data are required, additional tests must be added. The results which will be discussed in this paper are items 1 and 3 of Table 1.

The respective Tables 2, 3 and 4 each give data on residue from three basic incinerator designs. Table 5 gives the same data for composite samples of unburned refuse. Briefly described, the incinerators are as follows:

a). Table 2 gives data on residue sample quality obtained from three continuous feed incinerators, each from a different location. Each plant has one inclined stoker for drying and ignition and one horizontal burning stoker. Two of the plants have supplemental I.D. fans for draft control, while the third relies upon natural draft. The design capacity of all three plants is similar. All results have been arithmetically averaged.

b). Table 3 gives the same data for three municipal incinerators, also geographically separated, which have a rotary kiln as part of the furnace equipment. All plants are identical in configuration and design capacity, and all plants have two stages of reciprocating gates prior to the kiln portion of the furnace. While the terminology is not universally accepted, this type of incinerator will be referred to as a three burning stage furnace with a rotary kiln. Each grate represents one stage of burning and the kiln represents the third stage. Again all results were numerically averaged.

c). Table 4 gives data from two plants which have circular furnaces and are batch feed operations. All furnances listed under A and B have a rectangular configuration. Both plants are manually stoked and equipped with supplementary I.D. fans.

In addition to the three basic furnace designs discussed in this paper, several other grate designs are being studied. These include a batch-feed, reciprocating grate and a continuous-feed, rocker grate furnace. Data on these plants are not presented since the results are not statistically valid due to an insufficient number of samples.

DISCUSSION OF RESULTS

In Table 5 the average value for combustible material in unburned refuse is 58.16 percent and the ether-soluble fraction is 4.02 percent. All results are reported as percent of dry weight of material and the results in Table 5 will be used as a basis for evaluating the results listed in Tables 2, 3 and 4.

Table 2 lists the results of analyses for the two-stage traveling grate furnace. Reference to this table shows the volatile or combustible fraction to be 10.75 percent and the ether soluble fraction to be 0.60 percent. The efficiency of this furnace, based solely upon combustion of the burnable fraction as measured by the volatile matter in the residue, is given by:

$$\text{Efficiency} = (1 - V_f/(A_f + V_f)) \qquad (1)$$
$$100 = (A_f/(A_f + V_f))\,100$$

$$P = (V_f/(A_f + V_f))\,100 \qquad (2)$$

Where P is the percent volatile remaining in the residue, V_f is the weight of volatile per given weight of residue and A_f is the weight of ash or inert fraction per given weight of residue.

Using equation (2) and the mean values of Table 2 it is seen that the value of P for the traveling grate incinerator is:

$$P = \frac{(10.75)}{100}\ 100 = 10.75$$

The actual percent of combustible matter which has been destroyed cannot be directly calculated

TABLE 2. ANALYSIS OF DATA FOR TWO-STAGE TRAVELING GRATE INCINERATOR

Analysis (1)	Percent Volatile Fraction[a] (2)	Percent Ether soluble (3)
Mean %	10.75	0.60
Range High %	19.29	2.59
Range Low %	4.37	0.03
Standard Deviation within sample	2.22	0.214
Standard Deviation among samples	3.88	0.57
Standard Deviation among incinerators (of means for each incinerator)	2.74	0.12
Percent Reduction from Raw Refuse	91.3	

a-All results reported as percent by dry weight

TABLE 3. ANALYSIS OF DATA FOR ROTARY KILN INCINERATOR

Analysis (1)	Percent Volatile Fraction[a] (2)	Percent Ether Soluble (3)
Mean	10.95	*
Range High	15.92	*
Range Low	6.08	*
Standard Deviation Within Sample	1.225	*
Standard Deviation Among Samples	3.057	*
Standard Deviation Between Incinerators	*	*
Percent Reduction from Raw Refuse	91.16	

[a] All results reported as percent by dry weight
*Insufficient data.

TABLE 4. ANALYSIS OF DATA FOR BATCH FEED CIRCULAR FURNACE

Analysis (1)	Percent Volatile Fraction[a] (2)	Percent Ether Soluble (3)
Mean	39.51	1.356
Range High	66.72	1.870
Range Low	10.80	0.78
Standard Deviation Within Sample	3.591	0.328
Standard Deviation Among Samples	15.779	0.396
Percent Reduction from Raw Refuse	53.0	

[a] All results reported as percent by dry weight

TABLE 5. ANALYSIS OF DATA FOR UNBURNED REFUSE

Analysis (1)	Percent Volatile Fraction[a] (2)	Percent Ether Soluble (3)
Mean	58.16	4.02
Range High	94.31	7.32
Range Low	21.84	0.870
Standard Deviation Within Sample	1.31	1.26
Standard Deviation Among Samples	3.08	1.90

[a] All results reported as percent by dry weight

from the original weight of refuse since one pound of residue is obtained from more than one pound of raw refuse. In order to calculate the true P it will be necessary to determine the weight relationship between the raw refuse and residue, and to put this relationship into equation 2.

If reference is made to Figure No. 1, the relationships between unburned refuse, residue and the ash remaining after combustion of one unit of refuse are depicted.

It can be seen that V'_o and A'_o are related to A_f and V_f by direct proportion so that it follows:

$$\frac{V'_o}{V_f} = \frac{A'_o}{A_f} \qquad (3)$$

Where V'_o and A'_o are respectively the ash and volatile percentage remaining after combustion of one unit weight of refuse.

The weight reduction is K. Thus,

$$A'_o + V'_o + K = A_o + V_o \qquad (4)$$

Rearranging (3), we have:

$$V'_o = A'_o \frac{V_f}{A_f} \qquad (3A)$$

But the weight of ash per unit weight of refuse remains unchanged upon combustion (by definition) so that A_o must equal A'_o.
Therefore, (3A) becomes:

$$V'_o = A_o V_f/A_f \qquad (3B)$$

Equation (3B) is an expression of the weight of volatile remaining after combustion of a unit weight of raw refuse in terms of feasible analytical determination of ash and volatile in the refuse and residue.

Recognizing the identity of A_o and A_o' equation (4) becomes:

$$V_o = V_o' + K \qquad (4A)$$

Solving for V_o' we obtain

$$V_o' = V_o - K \qquad (4B)$$

Combining (4B) and (3B) yields:

$$V_o - K = \frac{A_o V_f}{A_f} \qquad (5)$$

At this point the term, "percent of burnout," must be defined. Burnout is that quantity of combustible matter which has been destroyed in the process of combustion. The definition of burnout can be given by:

$$B = \frac{K}{V_o} \times 100 \qquad (6)$$

Where B is the percentage of burnout of combustible matter. The burnout is 100% when K is equal to V_o. Since B is the function which is indicative of the efficiency of incineration, this is the term which must have a solution. Equation (5), when solved for K has the following form.

$$K = V_o - A_o V_f/A_f \qquad (5A)$$

Substituting into Equation (6), we can obtain an expression for burnout in terms of quantities which may be measured in the laboratory.

$$B = 1 - A_o V_f/A_f V_o \ 100 \qquad (7)$$

The factor A_o/V_o is the weight ratio of the ash percent to volatile percent for dry raw refuse. Since this ratio will vary with the type and character of refuse, it may be advantageous to determine an acceptable range for this ratio. Based upon separation of refuse into ash and volatile components, a figure of 0.60 to 0.75 seems acceptable. A factor of 0.667 represents a concentration of 40 percent ash and 60 percent combustible, which is a good approximation of the respective fractions.

If tests on the character of residue are performed, but the tester does not have satisfactory data for raw refuse composition, then the suggested A_o/V_o factor of 0.67 can be used. With this ratio taken as a constant percent, Equation (7) can be rewritten as shown in Equation (8).

$$B = (1 - 0.67 \ V_f/A_f) \ 100 \qquad (8)$$

Since the ratio A_o/V_o is available from Table 5 and equals 0.72, the degree of burnout can be estimated for the data shown in Table 2.

When the degree of burnout is recalculated using the modification as developed the burnout for a traveling grate incinerator becomes:

$$B = 1 - [0.72 \, (10.75/89.25)] \ 100 = 91.3$$

It can be seen in Tables 3 and 4 that the percent of volatile matter remaining from the rotary kiln and circular batch feed furnaces is 10.95 and 39.51, respectively. The resulting reductions of combustible matter are 91.1 and 53.0 percent respectively. These analyses on the percent reductions of the volatile fraction are very significant since there does appear to be a wide disparity in the residue quality from incinerators of different basic designs.

In addition to the average volatile percent and the combustible reduction estimate, Tables 2 - 5 contain information on the range and standard deviation of the analyses. "Range High" and "Range Low" are of course self-explanatory and represent the extremes of the values obtained in chemical analysis of the samples. "Standard Deviation Within the Sample" is a measure of the analytical error and the homogeneity of the sample. In most cases the analytical technique is replicated five times on each sample in order to obtain the sample average.

The "Standard Deviation Among Samples" is a measure of the total deviation and includes not only the deviation within the sample, but also the deviation between average sample means. The deviation between samples and the total deviation are estimates of the variability of refuse and residue and help to substantiate the critical sampling problems encountered in any analytical system.

Effect of Operation on Residue Quality

The results of Tables 2-5 clearly indicate that a significant difference does exist in the character of residue from incinerators. There appears to be a definite trend in the character of residue from units having different basic design configurations. The operation of an incinerator could also have a marked effect on the overall character of residue, and in some instances, will give equally dispersive results. The extent to which operation does effect residue quality has not been established at the present time, but when statistical validity has been obtained, the results will be released.

CONCLUSIONS

The operation and design of municipal incinerators can exert substantial influence on the character of residue resulting from an incinerator. One large problem in discerning these differences is the relationship between the refuse charged to the furnace and the ash residue resulting after combustion.

One method which can be used to establish a criteria for the character of residue is to analytically determine its volatile fraction. A knowledge of the volatile fraction of both the raw refuse and incinerated residue allows an estimate of the amount of burnout of the combustible fraction.

The percent volatile is a simple test which can be performed routinely by laboratory assistants. If incinerator plants were monitored by a simple test, such as the percent volatile, the character of the residue produced could be more uniform.

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