8.2 CHARACTERIZATION METHODS

This section describes and evaluates methods for estimating the characteristics of solid waste. The purposes of waste characterization are identified; and methods for estimating quantity, composition, combustion characteristics, and metals concentrations are addressed.

Purposes of Solid Waste Characterization

The general purpose of solid waste characterization is to promote sound management of solid waste. Specifically, characterization can determine the following:

The size, capacity, and design of facilities to manage the waste.
The potential for recycling or composting portions of the waste stream.
The effectiveness of waste reduction programs, recycling programs, or bans on the disposal of certain materials.
Potential sources of environmental pollution in the waste.

In practice, the immediate purpose of most waste characterization studies, including many extensive studies, is to comply with specific regulatory mandates and to provide information for use by vendors in preparing bids to design, construct, and operate solid waste management facilities.

The purposes of a waste characterization program determine the design of it. If all waste is to be landfilled, the characterization program should focus on the quantity of waste, its density, and its potential for compaction. The composition of the waste and its chemical characteristics are relatively unimportant. If all waste is to be incinerated, the critical parameters are quantity, heat value, and the percentage of combustible material in the waste. If recycling and composting are planned or underway, a composition study can identify the materials targeted for recovery, estimate their abundance in the waste, and monitor compliance with source separation requirements.

Basic Characterization Methods

Environmental engineers use one of two fundamental methods to characterize solid waste. One method is to collect and analyze data on the manufacture and sale of products that become solid waste after use. The method is called material flows methodology. The second method is a direct field study of the waste itself. Combining these two fundamental methods creates hybrid methodologies (for example, see Gay, Beam, and Mar [1993]).

The direct field study of waste is superior in concept, but statistically meaningful field studies are expensive. For example, a budget of $100,000 is typically required for a detailed estimate of the composition of MSW arriving at a single disposal facility, accurate to within 10% at 90% confidence. A skilled and experienced team can often provide additional information at little additional cost, including an estimated composition for bulky waste based on visual observation.

The principal advantage of the material flows methodology is that it draws on existing data that are updated regularly by business organizations and governments. This method has several positive effects. First, the entire waste stream is measured instead of samples of the waste, as in field studies. Therefore, the results of properly conducted material flows studies tend to be more consistent than the results of field studies. Second, updates of material flows studies are relatively inexpensive once the analytical structure is established. Third, material flows studies are suited to tracking economic trends that influence the solid waste stream.

The principal disadvantages of material flows methodology follow.

Obtaining complete production data for every item discarded as solid waste is difficult.
Although data on food sales are available, food sales bear little relation to the generation of food waste. Not only is most food not discarded, but significant quantities of water are added to or removed from many food items between purchase and discard. These factors vary from one area to another based on local food preferences and eating patterns.
Material flows methodology cannot measure the generation of yard waste.
Material flows methodology does not account for the addition of nonmanufactured materials to solid waste prior to discard, including water, soil, dust, pet droppings, and the contents of used disposable diapers.
Some of the material categories used in material flows studies do not match the categories of materials targeted for recycling. For example, advertising inserts in newspapers are typically recycled with the newsprint, but in material flows studies the inserts are part of a separate commercial printing category.

In performing material flows studies for the U.S. EPA, Franklin Associates bases its estimates of food waste, yard

waste, and miscellaneous inorganic wastes on field studies in which samples of waste were sorted. Franklin Associates (1992) also adjusts its data for the production of disposable diapers to account for the materials added during use.

In general, the more local and the more detailed a waste characterization study is to be, the greater are the advantages of a direct field study of the waste.

Estimation of Waste Quantity

The best method for estimating waste quantity is to install permanent scales at disposal facilities and weigh every truck on the way in and again on the way out. An increasing number of solid waste disposal facilities are equipped with scales, but many landfills still are not.

In the United States, facilities without scales record incoming waste in cubic yards and charge tipping fees by the cubic yard. Since estimating the volume of waste in a closed or covered vehicle or container is difficult, the volume recorded is usually the capacity of the vehicle or container. Because this estimation creates an incentive to deliver waste in full vehicles, the recorded volumes tend to be close to the actual waste volumes.

For the reasons previously stated, expressing waste quantity in tons is preferable to cubic yards. This conversion is conceptually simple, as shown in the following equation:

$$M = VD/2000 \qquad 8.2(1)$$

where:

M = mass of waste in tons
V = volume of waste in cubic yards
D = density of waste in pounds per cubic yard

If the density is expressed in tons per cubic yard, dividing by 2000 is unnecessary. In the United States, however, the density of solid waste is usually expressed in pounds per cubic yard.

Although simple conceptually, converting cubic yards to tons can be difficult in practice. The density of solid waste varies from one type of waste to another, from one type of vehicle to another, and even among collection crews. In small waste streams, local conditions can cause the overall density of MSW, as received at disposal facilities, to vary from 250 to 800 lb/cu yd. A conversion factor of 3.0 to 3.3 cu yd/tn (600 to 667 lb/cu yd) is reasonable for both MSW and bulky waste in many large waste streams; however, this conversion factor may not be reasonable for a particular waste stream.

At disposal facilities without permanent scales, environmental engineers can use portable scales to develop a better estimate of the tons of waste being delivered. Selected trucks are weighed, and environmental engineers use the results to estimate the overall weight of the waste stream.

Portable truck scales are available in three basic configurations: (1) platform scales designed to accommodate entire vehicles (or trailers), (2) axle scales designed to accommodate one axle or a pair of tandem axles at a time, and (3) wheel scales designed to be used in pairs to accommodate one axle or a pair of tandem axles at a time. Axle scales can be used singly or in pairs. Similarly, either one or two pairs of wheel scales can be used. When a single axle scale or a single pair of wheel scales is used, adding the results for individual axles yields the weight of the vehicle.

Platform scales are the easiest to use, but the cost can be prohibitive. The use of wheel scales tends to be difficult and time consuming. The cost of axle scales is similar to that of wheel scales, and axle scales are easier to use than wheel scales. The use of a pair of portable axle scales is recommended in the *Municipal solid waste survey protocol* prepared for the U.S. EPA by SCS Engineers (1979). Regardless of what type of scale is used, a solid base that does not become soft in wet weather is required.

Truck weighing surveys, like other waste characterization field studies, are typically conducted during all hours that a disposal facility is open during a full operating week. A full week is used because the variation in waste characteristics is greater among the hours of a day and among the days of a week than among the weeks of a month. Also, spreading the days of field work out over several weeks is substantially more expensive.

A truck weighing survey should be conducted during at least two weeks—one week during the period of minimum waste generation and one week during the period of maximum waste generation (see Section 8.1). One week during each season of the year is preferable. Holiday weeks should be avoided.

Weighing all trucks entering the disposal facility is rarely possible, so a method of truck selection must be chosen. A conceptually simple approach is to weigh every nth truck (for example, every 5th truck) that delivers waste to the facility. This approach assumes that the trucks weighed represent all trucks arriving at the facility. The total waste tonnage can be estimated with the following equation:

$$W = T(w/t) \qquad 8.2(2)$$

where:

W = the total weight of the waste delivered to the facility
T = the total number of trucks that delivered waste to the facility
w = the total weight of the trucks that were weighed
t = the number of trucks that were weighed

This approach is suited to a facility that receives a fairly constant flow of trucks. Unfortunately, the rate at which trucks arrive at most facilities fluctuates during the operating day. A weighing crew targeting every nth truck will

miss trucks during the busy parts of the day and be idle at other times. Missing trucks during the busy parts of the day can bias the results; the trucks that arrive at these times tend to be curbside collection trucks, which have a distinctive range of weights. Also, having a crew and its equipment stand idle at slow times while waiting for the nth truck to arrive reduces the amount of data collected, which reduces the statistical value of the overall results.

A better approach is to weigh as many trucks as possible during the operating day, keeping track of the total number of trucks that deliver waste during each hour. A separate average truck weight and total weight is calculated for each hour, and the hourly totals are added to yield a total for the day. For this purpose, Equation 8.2(2) is modified as follows:

$$W = T_1(w_1/t_1) + T_2(w_2/t_2) \cdots + T_n(w_n/t_n) \qquad 8.2(3)$$

where:

W = the total weight of the waste delivered to the facility
T_1 = the number of trucks that delivered waste to the facility in the first hour
T_2 = the number of trucks that delivered waste to the facility in the second hour
T_n = the number of trucks that delivered waste to the facility in the last hour of the operating day
w_1 = the total weight of the trucks that were weighed in the first hour
w_2 = the total weight of the trucks that were weighed in the second hour
w_n = the total weight of the trucks that were weighed in the last hour of the operating day
t_1 = the number of trucks that were weighed in the first hour
t_2 = the number of trucks that were weighed in the second hour
t_n = the number of trucks that were weighed in the last hour of the operating day

Estimating the statistical precision of the results is complex when the ratio of the weighed trucks to the unweighed trucks varies from hour to hour. (Klee [1991, 1993] provides a discussion of this statistical problem.)

Sampling MSW to Estimate Composition

As in all statistical exercises based on sampling, the acquisition of samples is a critical step in estimating the composition of MSW. The principal considerations in collecting samples are the following:

Each pound of waste in the waste stream to be characterized must have an equal opportunity to be represented in the final results.
The greater the number of samples, the more precise the results.
The greater the variation between samples, the more samples must be sorted to achieve a given level of precision.
The greater the time spent collecting the samples, the less time is available to sort the samples.
The more the waste is handled prior to sorting, the more difficult and less precise the sorting.

A fundamental question is the time period(s) over which to collect the samples. One-week periods are generally used because most human activity and most refuse collection schedules repeat on a weekly basis. Sampling during a week in each season of the year is preferable. Spring sampling is particularly important because generation of yard waste, the most variable waste category, is generally least in the winter and greatest in the spring.

Another fundamental question is whether to collect the samples at the places where the waste is generated or at the solid waste facilities where the waste is taken. Sampling at solid waste facilities is generally preferred. Collecting samples at the points of generation may be necessary under the following circumstances, however:

The primary objective is to characterize the waste generated by certain sources, such as specific types of businesses.
The identity of the facilities to which the waste is taken is not known or cannot be predicted with confidence for any given week.
The facilities are widely spaced, increasing the difficulty and cost of the sampling and sorting operation.
Access to the facilities cannot be obtained.
Sufficient space to set up a sorting operation is not available at the facilities.
Appropriate loads of waste (e.g., loads from the geographic area to be characterized) do not arrive at the facilities frequently enough to support an efficient sampling and sorting operation.

Sampling at the points of generation tends to be more expensive and less valid than sampling at solid waste facilities. The added expense results from the increased effort required to design the sampling protocol and the travel time involved in collecting the samples.

The decreased validity of sampling at the points of generation has two principal causes. First, a significant portion of the waste is typically inaccessible. Waste can be inaccessible because it is on private property to which access is denied or because it is in trash compactors. Some waste is inaccessible during the day because it is not placed in outdoor trash containers until after business hours and it is picked up early in the morning. The second major cause of inaccuracy is that the relative portion of the waste stream represented by each trash receptacle is unknown because the frequency of pickup and the average quantity in the receptacle at each pickup are unknown. Random selection of receptacles to be sampled results in under-

sampling of the more active receptacles, which represent more waste.

These problems are generally less acute for residential MSW than for commercial or institutional MSW. Residential MSW is usually accessible for sampling from the curb on collection day or from dumpsters serving multifamily residences. Because households generate similar quantities of waste, random selection of households for sampling gives each pound of waste a similar probability of being included in a sample. In addition, because waste characteristics are more consistent from household to household than from business to business, flaws in a residential sampling program are generally less significant than flaws in a commercial sampling program.

A universal protocol for sampling solid waste from the points of generation is impossible to state because circumstances vary greatly from place to place and from study to study. The following are general principles to follow:

Collect samples from as many different sectors of the target area as possible without oversampling relatively insignificant sectors.

If possible, collect samples from commercial locations in proportion to the size of the waste receptacles used and the frequency of pickup.

Collect samples from single-family and multifamily residences in proportion to the number of people living in each type of residence (unless a more sophisticated basis is readily available). The required population information can be obtained from U.S. census publications.

Give field personnel no discretion in selecting locations at which to collect samples. For example, field personnel should not be told to collect a sample from Elm Street but rather to collect a sample from the east side of Elm Street, starting with the second house (or business) north from Park Street.

To the extent feasible, add all waste from each selected location to the sample before going on to the next location. This practice reduces the potential for sampling bias.

Collecting samples at solid waste facilities is less expensive than collecting them at the points of generation and is more likely to produce valid results. Sample collection at facilities is less expensive because no travel is required. Samples collected at facilities are more likely to represent the waste being characterized because they are typically selected from a single line of trucks of known size that contain the entire waste stream.

Collecting samples at solid waste facilities has two stages: selecting the truck from which to take the sample and collecting the sample from the load discharged from the selected truck.

SELECTING SAMPLES

Environmental engineers usually select individual trucks in the field to sample, but they can select trucks in advance to ensure that specific collection routes are represented in the samples. Possible methods for selecting trucks in the field include the following:

- Constant interval
- Progress of sorters
- Random number generator
- Allocation among waste sources

The American Society for Testing and Materials (1992) *Standard test method for determination of the composition of unprocessed municipal solid waste* (ASTM D 5231) states that any random method of vehicle selection that does not introduce a bias into the selection process is acceptable.

Possible constant sampling intervals include the following in which n is any set number:

- Every nth truck
- Every nth ton of waste
- Every nth cubic yard of waste
- A truck every n minutes

Collecting a sample from every nth truck is relatively simple but causes the waste in small trucks and partially full trucks to be overrepresented in the samples. Collecting a sample from the truck containing every nth ton of waste is ideal but is difficult in practice because the weight of each truck is not apparent from observation. Collecting a sample from the truck containing every nth cubic yard of waste is more feasible because the volumetric capacity of most trucks can be determined by observation. However, basing the sampling interval on volumetric capacity tends to cause uncompacted waste and waste in partially full trucks to be overrepresented in the samples.

Basing the sampling interval on either a set number of trucks or a set quantity of waste causes the pace of the sampling operation to fluctuate during each day of field work. This fluctuation can result in inefficient use of personnel and deviations from the protocol when targeted trucks are missed at times of peak activity.

Collecting a sample from a truck every n minutes is convenient for sampling personnel but causes the waste in small trucks and partially full trucks to be overrepresented and the waste in trucks that arrive at busy times to be underrepresented in the samples. This approach also causes overrepresentation of waste arriving late in the day because the time interval between trucks tends to lengthen toward the end of the day and because trucks arriving late tend to be partially full, especially if the facility charges by the ton rather than by the cubic yard.

Obtaining samples as they are needed for sorting is similar to collecting a sample every n minutes and has the same disadvantages. Regardless of the sampling protocol used, however, the sorters should be kept supplied with waste to sort even if the available loads do not fit the protocol. Having more data is better.

ASTM D 5231 specifically identifies the use of a random number generator as an acceptable method for random selection of vehicles to sample. A random number generator can provide random intervals corresponding to each of the predetermined intervals just discussed. For example, if a facility receives 120 trucks per day and 12 are to be sampled, one can either sample every 10th truck or use the random number generator to generate 12 random numbers from 1 to 120. Similarly, random intervals of waste tonnage, waste volume, or elapsed time can be generated.

Random sampling intervals have the same disadvantages as the corresponding constant sampling intervals plus the following additional disadvantages:

Random sampling intervals increase the probability that the field crew is idle from time to time.
Random sampling intervals increase the probability that the field crew has to work overtime.
Random sampling intervals increase the probability that targeted trucks are missed when too many randomly selected trucks arrive within too short a time period.

In many cases, sampling by waste source minimizes the problems associated with these types of interval sampling. Sources of waste from which samples can be selected include individual municipalities, individual waste haulers, specific collection routes, waste generation sectors such as the residential sector and the commercial sector, and specific sources such as restaurants or apartment buildings. In general, sampling by source makes sense if adequate information is available on the quantity of waste from each source to be sampled. Samples can be collected from each source in proportion to the quantity of waste from each source, or the composition results for the various sources can be weighted based on the quantity from each source.

In the best case, the solid waste facility has a scale and maintains a computer database containing the following information for each load of waste: net weight, type of waste, type of vehicle, municipality of origin, hauler, and a number identifying the individual truck that delivered the waste. This information, combined with information on the hauling contracts in effect in each municipality, is usually sufficient to estimate the quantity of household and commercial MSW from each municipality.

The municipality is often the hauler for household waste, and, in those municipalities, private haulers usually handle commercial waste. In other cases, the municipality has a contract with a private hauler to collect household waste and discourages the hauler from using the same vehicles to service private accounts. Household and commercial waste can also be distinguished by the types of vehicles in which they are delivered. Dominant vehicle types vary from one region to another.

If the solid waste facility has no scale, environmental engineers can use records of waste volumes in designing a sampling plan but must differentiate between compacted and uncompacted waste. Many facilities receive little uncompacted MSW, while others receive substantial quantities.

Because per capita generation of household waste is relatively consistent, environmental engineers can use population data to allocate samples of household waste among municipalities if the necessary quantity records are not available.

Field personnel must interview private haulers arriving at the solid waste facility to learn the origins of the load of waste. Information provided by the haulers is often incomplete. In some cases this information can be supplemented or corrected during sorting of the sample.

McCamic (1985) provides additional information.

COLLECTING SAMPLES

Most protocols, including ASTM D 5231, state that each selected truck should be directed to discharge its load in an area designated for sample collection. This provision is convenient for samplers but is not necessary if a quick and simple sampling method is used. ASTM D 5231 states that the surface on which the selected load is discharged should be clean, but in most studies preventing a sample from containing a few ounces of material from a different load of waste is unnecessary.

Understanding the issues involved in selecting a sampling method requires an appreciation of the nature of a load of MSW discharged from a standard compactor truck onto the surface of a landfill or a paved tipping floor. Rather than collapsing into a loose pile, the waste tends to retain the shape it had in the truck. The discharged load can be 7 or 8 ft high. In many loads, the trash bags are pressed together so tightly that pulling material for the sample out of the load is difficult. Some waste usually falls off the top or sides of the load, but this loose waste should not be used as the sample because it can have unrepresentative characteristics.

In general, one sample should be randomly selected from each selected truck, as specified in ASTM D 5231. If more than one sample must be taken from one load, the samples should be collected from different parts of the load.

A threshold question is the size of the sample collected from each truck. Various sample sizes have been used, ranging from 50 lb to the entire load. Large samples have the following advantages:

The variation (standard deviation) between samples is smaller, so fewer samples are required to achieve a given level of precision.
The distribution of the results of sorting the samples is closer to a normal distribution (bell-shaped curve).
The boundary area between the sample and the remainder of the load is smaller in proportion to the volume of the sample, making the sampler's decisions on

whether to include bulky items from the boundary area less significant.

Small samples have a single advantage: shorter collection and sorting time.

A consensus has developed (SCS Engineers 1979; Klee and Carruth 1970; Britton 1971) that the optimum sample size is 200 to 300 lb (91 to 136 kg). This size range is recommended in ASTM D 5231. The advantages of increasing the sample size beyond this range do not outweigh the reduced number of samples that can be sorted. If the sample size is less than 200 lb, the boundary area around the sample is too large compared to the volume of the sample, and the sampler must make too many decisions about whether to include boundary items in the sample.

Environmental engineers use several general procedures to obtain samples of 200 to 300 lb from loads of MSW, including the following:

Assembling a composite sample from material taken from predetermined points in the load (such as each corner and the middle of each side)
Coning and quartering
Collecting a grab sample from a randomly selected point using a front-end loader
Manually collecting a column of waste from a randomly selected location

Numerous variations and combinations of these general procedures can also be used.

The primary disadvantage of composite samples is the same as that for small samples: the large boundary area forces the sampler to make too many decisions about whether to include items of waste in the sample. A composite sample tends to be a judgement sample rather than a random sample. A secondary disadvantage of composite samples is that they take longer to collect than grab samples or column samples.

A variation of composite sampling is to assemble each sample from material from different loads of waste. This approach has the same disadvantages as composite sampling from a single load of waste and is even more time-consuming.

In coning and quartering, samplers mix a large quantity of waste to make its characteristics more uniform, arrange the mixed waste in a round pile (coning), and randomly select a portion—typically one quarter—of the mixed waste (quartering). The purpose is to combine the statistical advantages of large samples with the reduced sorting time of smaller samples. The coning and quartering process can begin with the entire load of waste or with a portion of the load and can be performed once or multiple times to obtain a single sample. ASTM D 5231 specifies one round of coning and quartering, beginning with approximately 1000 lb of waste, to obtain a sample of 200 to 300 lb.

Coning and quartering has the following disadvantages and potential difficulties compared to grab sampling or column sampling:

Substantially increases sampling time
Requires more space
Requires the use of a front-end loader for relatively long periods. Many solid waste facilities can make a front-end loader and an operator available for brief periods, but some cannot provide a front-end loader for the longer periods required for coning and quartering.
Tends to break trash bags, making the waste more difficult to handle
Increases sorting time by breaking up clusters of a category of waste
Reduces accuracy of sorting by increasing the percentage of food waste adhering to or absorbed into other waste items
Promotes loss of moisture from the sample
Promotes stratification of the waste by density and particle size. The biasing potential of stratification is minimized if the quarter used as the sample is a true pie slice, with its sides vertical and its point at the center of the cone. This shape is difficult to achieve in practice.

The advantage of coning and quartering is that it reduces the variation (the standard deviation) among the samples, thereby reducing the number of samples that must be sorted. Coning and quartering is justified if it reduces the standard deviation enough to make up for the disadvantages and potential difficulties. If coning and quartering is done perfectly and completely, sorting the final sample is equivalent to sorting the entire cone of waste, and the standard deviation is significantly reduced. Since the number of samples that must be sorted to achieve a given level of precision is proportional to the square of the standard deviation, coning and quartering can substantially reduce the required number of samples. Note, however, that the more thoroughly coning and quartering is performed, the more pronounced are each of the disadvantages and potential difficulties associated with this method.

A more common method of solid waste sampling is collecting a grab sample using a front-end loader. This method is relatively quick and can often be done by facility personnel without unduly disrupting normal facility operations. Sampling by front-end loader reduces the potential impact of the personal biases associated with manual sampling methods but introduces the potential for other types of bias, including the following:

Like shovel sampling, front-end loader sampling tends to favor small and dense objects over large and light objects. Large and light objects tend to be pushed away or to fall away as the front-end loader bucket is inserted, lifted, or withdrawn.

On the other hand, the breaking of trash bags as the front-end loader bucket penetrates the load of waste tends to release dense, fine material from the bags, reducing the representation of this material in the sample.

Front-end loader samples taken at ground level favor waste that falls off the top and sides of the load, which may not have the same characteristics as waste that stays in place. On dirt surfaces, front-end loader samples taken at ground level can be contaminated with dirt.

The impact of these biasing factors can be reduced if the sampling is done carefully and the sampling personnel correct clear sources of bias, such as bulky objects falling off the bucket as it is lifted.

In front-end loader sampling, sampling personnel can use different sampling points for different loads to ensure that the various horizontal and vertical strata of the loads are represented in the samples. They can vary the sampling point either randomly or in a repeating pattern. The extent of the bias that could result from using the same sampling point for each load is not known.

An inherent disadvantage of front-end loader sampling is the difficulty in estimating the weight of the samples. Weight can only be estimated based on volume, and samples of equal volume have different weights.

A less common method of solid waste sampling is manually collecting a narrow column of waste from a randomly selected location on the surface of the load, extending from the bottom to the top of the load. This method has the following advantages:

- No heavy equipment is required.
- Sampling time is relatively short.
- Because different horizontal strata of the load are sampled, the samples more broadly represent the load than grab samples collected using a front-end loader. Note, however, that loads are also stratified from front to back, and column samples do not represent different vertical strata.
- The narrowness of the target area within the load minimizes the discretion of the sampler in choosing waste to include in the sample.

The major disadvantage of column sampling is that manual extraction of waste from the side of a well-compacted load is difficult, and the risk of cuts and puncture wounds from pulling on the waste is substantial.

Of the many hybrid sampling procedures that combine features of these four general procedures, two are worthy of particular note. First, in the sampling procedure specified in ASTM D 5231, a front-end loader removes at least 1000 lb (454 kg) of material along one entire side of the load; and this waste is mixed, coned, and quartered to yield a sample of 200 to 300 lb (91 to 136 kg). Compared to grab sampling using a front-end loader, the ASTM method has the advantage of generating samples more broadly representative of the load but has the disadvantage of increasing sampling time.

In a second hybrid sampling procedure, a front-end loader loosens a small quantity of waste from a randomly selected point or column on the load, and the sample is collected manually from the loosened waste. This method is safer than manual column sampling and provides more control over the weight of the sample than sampling by front-end loader. This method largely avoids the potential biases of front-end loader sampling but tends to introduce the personal biases of the sampler.

Number of Samples Required to Estimate Composition

The number of samples required to achieve a given level of statistical confidence in the overall results is a function of the variation among the results for individual samples (standard deviation) and the pattern of the distribution of the results. Neither of these factors can be known in advance, but both can be estimated based on the results of other studies.

ASTM D 5231 prescribes the following equation from classical statistics to estimate the number of samples required:

$$n = (t^{*}s/ex)^2 \qquad 8.2(4)$$

where:

n = required number of samples
t^{*} = student t statistic corresponding to the level of confidence and a preliminary estimate of the required number of samples
s = estimated standard deviation
e = level of precision
x = estimated mean

Table 8.2.1 shows representative values of the coefficient of variation and mean for various solid waste components. The coefficient of variation is the ratio of the standard deviation to the mean, so multiplying the mean by the coefficient of variation calculates the standard deviation. Table 8.2.2 shows values of the student *t* statistic.

Table 8.2.1 shows the coefficients of variation rather than standard deviations because the standard deviation tends to increase as the mean increases, while the coefficient of variation tends to remain relatively constant. Therefore, the standard deviations for sets of means different from those in the table can be estimated from the coefficients of variation in the table.

The confidence level is the statistical probability that the true mean falls within a given interval above and below the mean, with the mean as the midpoint (the confidence interval or confidence range). A confidence level of 90% is generally used in solid waste studies. The confidence interval is calculated based on the results of the study (see Table 8.2.3 later in this section).

TABLE 8.2.1 REPRESENTATIVE MEANS AND COEFFICIENTS OF VARIATION FOR MSW COMPONENTS

Waste Category	*Mean (%)*	*Coefficient of Variation*[a] *(%)*
Organics/Combustibles	86.6	10
Paper	39.8	30
Newspaper	6.8	80
Corrugated	8.6	95
Kraft	1.5	120
Corrugated & kraft	10.1	85
Other paper[b]	22.9	40
High-grade paper	1.7	230
Other paper[b]	21.2	40
Magazines	2.1	160
Other paper[b]	19.1	40
Office paper	3.4	—
Magazines & mail	4.0	90
Other paper[b]	17.2	40
Yard waste	9.7	160
Grass clippings	4.0	300
Other yard waste	5.7	180
Food waste	12.0	70
Plastic	9.4	40
PET bottles	0.40	100
HDPE bottles	0.70	95
Other plastic	8.3	50
Polystyrene	1.0	95
PVC bottles	0.06	200
Other plastic[b]	7.2	50
Polyethylene bags & film	3.7	45
Other plastic[b]	3.5	80
Other organics	15.7	55
Wood	4.0	170
Textiles	3.5	—
Textiles/rubber/leather	4.5	110
Fines	3.3	70
Fines $<\frac{1}{2}$ inch	2.2	80
Disposable diapers	2.5	110
Other organics	1.4	160
Inorganics/Noncombustibles	13.4	60
Metal	5.8	70
Aluminum	1.0	70
Aluminum cans	0.6	95
Other aluminum	0.4	120
Tin & bimetal cans	1.5	70
Other metal[b]	3.3	130
Ferrous metal	4.5	85
Glass	4.8	70
Food & beverage containers	4.3	85
Batteries	0.1	160
Other inorganics		
With noncontainer glass	3.2	160
Without noncontainer glass	2.7	200

[a]Standard deviation divided by the mean, based on samples of 200 to 300 pounds.

[b]Each "other" category contains all material of the previous type except material in those categories.

TABLE 8.2.2 VALUES OF STUDENT *t* STATISTIC

	Student t *Statistic*	
Number of Samples (n)	*90% Confidence*	*95% Confidence*
2	6.314	12.706
3	2.920	4.303
4	2.353	3.182
5	2.132	2.776
6	2.015	2.571
7	1.943	2.447
8	1.895	2.365
9	1.860	2.306
10	1.833	2.262
12	1.796	2.201
14	1.771	2.160
17	1.746	2.120
20	1.729	2.093
25	1.711	2.064
30	1.699	2.045
41	1.684	2.021
51	1.676	2.009
61	1.671	2.000
81	1.664	1.990
101	1.660	1.984
141	1.656	1.977
201	1.653	1.972
Infinity	1.645	1.960

The desired level of precision is the maximum acceptable error, expressed as a percentage or decimal fraction of the estimated mean. Note that a lower precision level indicates greater precision. A precision level of 10% (0.1) is frequently set as a goal but is seldom achieved.

After a preliminary value for n based on a preliminary value for t^* is calculated, the calculation is repeated with the value of t^* corresponding to the preliminary value for n.

Equation 8.2(4) assumes that the values for each variable to be measured (in this case the percentages of each solid waste component in the different samples) are normally distributed (conform to the familiar bell-shaped distribution curve, with the most frequent value equaling the mean). In reality, solid waste composition data are not normally distributed but are moderately to severely skewed right, with numerous values several times higher than the mean. The most frequent value is invariably lower than the mean, and in some cases is close to zero. The greater the number of waste categories, the more skewed the distributions of individual categories are.

Klee (1991; 1993) and Klee and Carruth (1970) have suggested equations to account for the effect of this skewness phenomenon on the required number of samples. Use of these equations is problematic. Like Equation 8.2(4), they are designed for use with one waste category at a time. For waste categories for which the mean is large compared to the standard deviation, the equations yield higher

numbers of samples than Equation 8.2(4). This result is intuitively satisfying because more data should be needed to quantify a parameter whose values do not follow a predefined, normal pattern of distribution. For waste categories for which the mean is less than twice as large as the standard deviation, however, these equations tend to yield numbers of samples smaller than Equation 8.2(4). This result is counterintuitive since no reason is apparent for why an assumption of nonnormal distribution should decrease the quantity of data required to characterize a highly variable parameter.

An alternative method of accounting for skewness is to select or develop an appropriate equation for each waste category based on analysis of existing data for that category. Hilton, Rigo, and Chandler (1992) provide the results of a statistical analysis of the skewness of individual waste categories.

Equation 8.2(4) gives divergent results for different solid waste components. Based on the component means and coefficients of variation shown in Table 8.2.1 and assuming a precision of 10% at 90% confidence, the number of samples given by Equation 8.2(4) is 45 for paper other than corrugated, kraft, and high-grade; almost 700 for all yard waste; and more than 2400 for just grass clippings. The value of Equation 8.2(4) alone as a guide in designing a sampling program is therefore limited.

An alternative method is to estimate the number of samples required to achieve a weighted-average precision level equal to the required level of precision. The weighted-average precision level is the average of the precision levels for individual waste categories weighted by the means for the individual waste categories. The precision level for individual waste categories can be estimated with the following equation, which is Equation 8.2(4) solved for e:

$$e = t^{*}s/xn^{1/2} \qquad 8.2(5)$$

The precision level for each category is multiplied by the mean for that category, and the results are totaled to yield the weighted-average precision level. The number of samples (n) is adjusted by trial and error until the weighted-average precision level matches the required value.

Calculation of the weighted-average precision level is shown in Table 8.2.3 later in this section. Figure 8.2.1 shows the relationship of the weighted-average precision level to the number of samples and the number of waste categories based on the values in Table 8.2.1. Overall precision improves as the number of samples increases and as the number of waste categories decreases. This statement does not mean that studies involving greater number of categories are inferior; it simply means that determining a few things precisely is easier than determining many things precisely.

Sorting and Weighing Samples of MSW

In most cases, sorting solid waste should be viewed as an industrial operation, not as laboratory research. While accuracy is essential, the appropriate measure of accuracy is ounces rather than grams or milligrams. Insistence on an excessive level of accuracy slows down the sorting process, reducing the number of samples that can be sorted. This

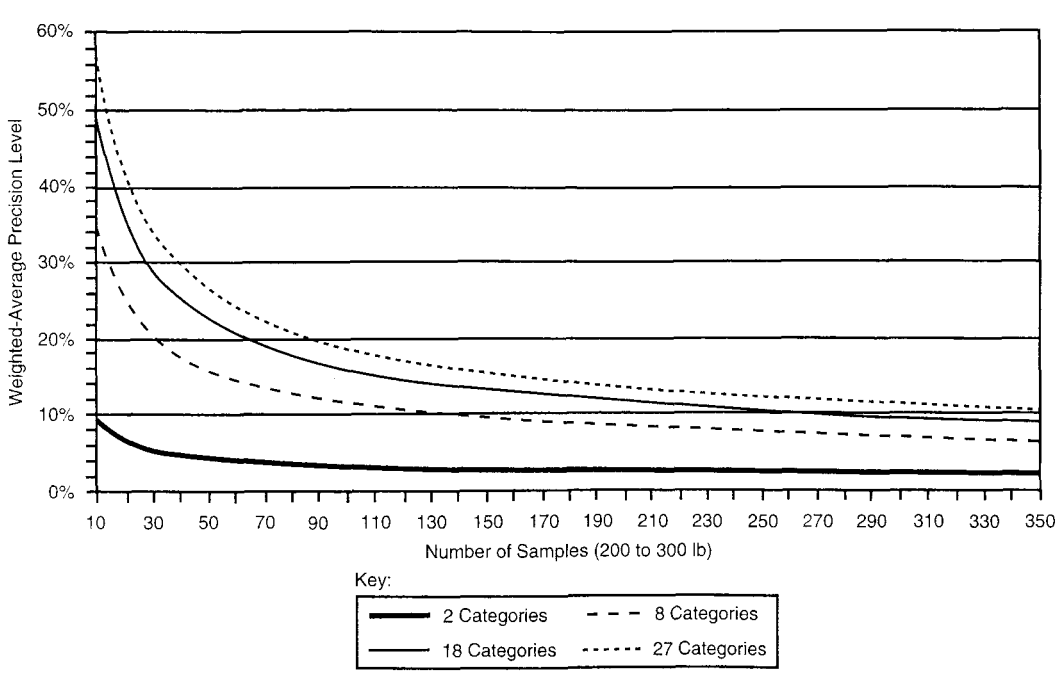

FIG. 8.2.1 Effect of the number of samples and the number of waste categories on weighted-average precision level (derived from Table 8.2.1).

reduction, in turn, reduces the statistical precision of the results. In the context of an operation in which a 10% precision level is a typical goal, inaccuracy of 1% is relatively unimportant.

The principles of industrial operations apply to solid waste sorting, including minimization of motion and maintenance of worker comfort and morale.

SORTING AREAS

A sorting area is established at the beginning of the field work and should have the following characteristics:

- A paved surface approximately 1000 sq ft in area and at least 16 ft wide
- Accessibility to vehicles
- Protection from precipitation and strong winds
- Heating in cold weather
- Separation from traffic lanes and areas where heavy equipment is used but within sight of arriving trucks

A typical sorting operation might use two sorting boxes and a crew of ten to twelve. The crew includes two sorting teams of four or five persons each, a supervisor, and a utility worker. The basic sorting sequence, starting when collection of the sample is complete, is as follows:

1. The sample is transported from the sampling point to the sorting area. A pickup truck or front-end loader can be used for this purpose.
2. The sampler gives the sorting supervisor a copy of a data form.
3. The sample is unloaded onto the surface of the sorting area.
4. Large items (e.g., corrugated cardboard and wood) and bags containing a single waste category (most often yard waste) are removed from the sample and set aside for weighing, bypassing the sorting box.
5. The remainder of the sample is transferred by increments into the sorting box, using broad-bladed shovels to transfer loose material.
6. The waste is sorted into the containers surrounding the sorting box.
7. The containers are brought to the scale, checked for accuracy of sorting, and weighed.
8. The gross weight of the waste and container and a letter symbol indicating the type of container are recorded on the data form.
9. If required, the waste in the containers is subsampled for laboratory analysis.
10. The containers are dumped in a designated receptacle or location.

The supervisor must ensure that each sample remains matched with the correct data form and that waste does not cross between samples.

SORTING CONTAINERS

Use of a counter-height sorting box speeds sorting, decreases worker fatigue, and encourages interaction among the sorters. All of these factors help build and sustain the morale of the sorters.

The following sorting box design has proven highly effective. The box is 4 ft wide, 6 ft long, 1 ft deep, and open at the top. It is constructed of $\frac{3}{8}$-in or $\frac{1}{2}$-in plywood with an internal frame of 2-by-3s or 2-by-4s. The long framing pieces extend 1 foot beyond the ends of the box at each bottom corner, like the poles of a stretcher. These framing pieces facilitate handling and extend the overall dimensions of the box to 4 ft by 8 ft by 1 ft. The box can lie flat within the bed of a full-sized pickup truck or standard cargo van.

A screen of $\frac{1}{2}$-in hardware cloth (wire mesh with $\frac{1}{2}$-in square openings) can be mounted in the bottom of the sorting box, $1\frac{1}{2}$ in from the bottom (the thickness of the internal framing pieces). If the screen is included, one end of the box must be open below the level of the screen to allow dumping of the fine material that falls through the screen. By allowing fine material to separate from the rest of the sample, the screen facilitates sorting of small items and makes dangerous items such as hypodermic needles easier to spot.

To facilitate dumping of the fines and to save space during transportation and storage, the sorting box is built without legs. During sorting, the sorting box is placed on a pair of heavy-duty sawhorses, 55-gal drums, or other supports. A support height of 32 in works well for a mixed group of male and female sorters. Fifty-five-gal drums are approximately 35 in high, approximately 3 in higher than optimum, and because of their size are inconvenient to store and transport.

The containers into which the waste is sorted should be a combination of 30-gal plastic trash containers and 5-gal plastic buckets. The 5-gal buckets are used for low-volume waste categories. Containers larger than 30 gal occupy too much space around the sorting box for efficient sorting and can be heavy when full. In a typical study with twenty-four to twenty-eight waste categories, each sorting crew should be equipped with approximately two dozen 30-gal containers and one dozen 5-gal buckets. In addition, each sorting crew should have several shallow plastic containers approximately 18 in wide, 24 in long, and 6 in deep.

For optimum use of space, the 30-gal containers should have rectangular rims. They should also have large handles to facilitate dumping. Recessed handholds in the bottom of the container are also helpful. In general, containers of heavy-duty HDPE are best. Because of their molded rims, these containers can be inverted and banged against pavement, the rim of a rolloff container, or the rim of a matching container to dislodge the material adhering to the inside of the container. The containers need not have

wheels. Plastic containers slide easily across almost any flat surface.

Substantial field time can be saved when the containers of each type have fairly uniform weights so that each type of container can be assigned a tare weight rather than each container. When container weights are recorded on the data form after sorting, recording a letter code that refers to the type of container is faster than reading an individual tare weight on the container and recording it on the data form.

Assigning individual tare weights to containers weighing 2% more or less than the average weight for the container type is unnecessary. Batches of 5-gal buckets generally meet this standard, but many 30-gal containers do not. Ensuring that tare weights are consistent requires using portable scale when shopping for containers.

CONTAINER LABELING

Most sorting protocols, including ASTM D 5231, call for labeling each container to indicate which waste category is to be placed in it. When a sorting box is used, however, unlabeled containers have the following advantages:

The sorters are encouraged to establish a customary location for each waste category and sort by location, which is faster than sorting by labels.

When sorting is done by location rather than by labels, the containers can be placed closer to the sorters, which further speeds the sorting process.

Less time is required to arrange unlabeled containers around the sorting box after the sorted material from the previous sample has been weighed and dumped.

Keeping the containers unlabeled increases the flexibility of the sorting operation.

The flexibility gained by not labeling the containers has several aspects. First, different samples require multiple 30-gal containers for different waste categories. Second, many waste categories require a 30-gal container for some samples and only a 5-gal container for others. Third, the need for another empty container arises frequently in an active sorting operation, and grabbing the nearest empty container is quicker than searching for the container with the appropriate label.

Despite the advantages of unlabeled containers, the containers for food waste should be labeled. If individual containers are not designated for food waste, all containers will eventually be coated with food residue. This residue is unpleasant and changes the tare weights of the containers.

The tare weights of the food waste containers should be checked daily. Generally, checking the tare weights of other containers at the beginning of each week of field work is sufficient unless a visible buildup of residue indicates that more frequent checking is required.

SORTING PROCESS

The actual sorting of the sample should be organized in the following basic manner:

Each waste category is assigned a general location around the perimeter of the sorting box. In one effective arrangement, paper categories are sorted to one side of the sorting box, plastic categories are sorted to the other side, other organic categories are sorted to one end, and inorganic categories are sorted to the other end.

Each sorter is assigned a group of categories. With a typical sorting crew of four, each sorter is assigned the categories on one side or at one end of the box.

The sorters place their assigned materials in the appropriate containers and place other materials within reach of the sorters to which they are assigned.

Toward the end of sorting each sample, one of the shallow containers is placed in the middle of the sorting box, and all sorters place other paper in this container (see Table 8.2.1). This process can be repeated for food waste.

When only scattered or mixed bits of waste remain, sorting is suspended.

The material remaining above the screen in the sorting box, or on the bottom of a box without a screen, is scraped or brushed together and either (1) distributed among the categories represented in it in proportion to their abundance, (2) set aside as a separate category, or (3) set aside to be combined with the fine material from below the screen. ASTM D 5231 specifies the first alternative, but it should not be selected if the waste categories are to be subsampled for laboratory testing.

If the sorting box has a screen, the box is upended to allow the fine material from below the screen to fall through the slot at one end of the box. The material that falls out is swept together and shoveled into a container—preferably a wide, shallow container—for weighing.

WEIGHING SAMPLES

ASTM D 5231 specifies the use of a mechanical or electronic scale with a capacity of at least 200 lb (91 kg) and precision of 0.1 lb (0.045 kg) or better. When 30-gal containers are used in sorting samples of 200 to 300 lb, gross weights greater than 100 lb are unusual. Even if larger containers or sample sizes are used, sorting personnel should avoid creating containers with gross weights greater than 100 lb because they are difficult and dangerous to handle. For most sorting operations, a scale capacity of 100 lb is adequate. An electronic scale with a range of 0–100 lb is generally easier to read to within 0.1 lb than a mechanical scale with a range of 0–100 lb.

A platform-type scale is preferred. The platform should be 1 ft square or larger.

The digital displays on electronic scales make data recording easier and minimize recording errors by displaying the actual number to be recorded on the data form. When recording weights from a mechanical scale, interpolation between two values marked on the dial is often required. The advantages of mechanical scales are lower cost, reliability, and durability.

Ideally, one worker places containers on the scale, the supervisor checks the containers for accuracy of sorting and records the weights and container types, and two or more workers dump the weighed containers. If the containers are subsampled for laboratory analysis prior to being dumped, the process is much slower and fewer workers are required.

DUMPING SAMPLES

On landfills, the sorting containers are dumped near the sorting area for removal or in-place burial by facility personnel. In transfer stations and waste-to-energy facilities, the containers can be dumped on the edge of the tipping floor.

When the sorting area is separated from the disposal area, use of the sampling vehicle for disposal is difficult. Loads of waste that should be sampled can be missed, and sorting delays occur because the sampling vehicle is not available for dumping full containers from the previous sample. A better procedure is to dump the sorted waste in a rolloff container provided by the disposal facility. Facility personnel transport the rolloff container to the disposal area approximately once per day. The density of sorted waste is often as low as 150 lb/cu yd, so the rolloff tends to be filled more rapidly than expected. To facilitate dumping sorted waste over the sides, the rolloff container should not be larger than 20 cu yd (15.3 cu m).

Processing the Results of Sorting

After a sample is weighed and the gross weights and container types are recorded on the data form, the net weights are calculated and recorded on the data form. Total net weights are calculated for waste categories sorted into more than one container. Field personnel should calculate net category weights and total net sample weights after each day of sorting to monitor the size of the samples. Undersize samples decrease the accuracy and statistical precision of the results and can violate the contract under which the study is conducted. Oversize samples make sorting the required number of samples more difficult.

The net weights for each waste category in each sample are usually entered into a computer spreadsheet. For each waste category in each group of samples to be analyzed (for example, residential samples and commercial samples), the following should be calculated from the data in the spreadsheet:

- The percentage by weight in each sample
- The mean percentage within the group of samples
- The standard deviation of the percentages within the group of samples
- The confidence interval around the mean

Calculating the overall composition usually involves dividing the total weight of each waste category by the total weight of the samples rather than calculating the composition of each sample and averaging the compositions. If the samples have different weights, which is usually the case, these two methods yield different results. Calculating overall composition based on total weight creates a bias in favor of dense materials, which are more abundant in the heavier samples. Averaging the compositions of the individual samples is preferable because it gives each pound of waste an equal opportunity to influence the results. ASTM D 5231 specifies averaging of sample compositions.

Table 8.2.3 shows mean percentages, standard deviations, uncertainty values, precision levels, and confidence intervals for a group of 200 MSW samples with the characteristics shown in Table 8.2.1. The confidence intervals are based on the uncertainty values (sometimes called precision values). The uncertainty values are typically calculated with the following formula:

$$U_c = t^* s/n^{1/2} \qquad 8.2(6)$$

where:

U_c = uncertainty value at a given level of confidence, typically 90%
t^* = student t statistic corresponding to the given level of confidence
s = sample standard deviation
n = number of samples

This equation is equivalent to the equation for calculating the precision level, Equation 8.2(5), with both sides multiplied by the mean, x. Dividing the uncertainty value by the mean yields the precision level. Adding the uncertainty values for all waste categories yields the weighted average precision level, weighted by the means for the individual waste categories.

Equation 8.2(6), like Equations 8.2(4) and 8.2(5), assumes that the percentage data are normally distributed. As previously discussed, this is not actually the case, and no reliable and reasonably simple method exists for estimating the effect of lack of normality on the statistical precision of the results.

Precision analysis can only be applied to groups of samples that are representative of the waste stream to be analyzed. For example, if 40% of the municipal waste stream is commercial waste but 60% of the samples sorted during a study are collected from commercial loads, statistical precision analysis of the entire body of composition data generated during the study is meaningless. Assuming that the commercial and residential samples represent the

TABLE 8.2.3 ILLUSTRATION OF WEIGHTED-AVERAGE PRECISION LEVEL AND CONFIDENCE INTERVALS[a]

Waste Category	*Mean (%) (x)*	*Standard Deviation (%) (s)*	*Student t Statistic (t^*) for 200 Samples (n) and 90% Confidence*	*Uncertainty Value (%) ($U_{90} = t^*s/n^{1/2}$)*	*Precision Level (%) (U_{90}/x)*	*90% Confidence Interval (%)*
Newspaper	6.8	5.4	1.653	0.6	9.4	6.8 ± 0.6
Corrugated & kraft	10.1	8.6	1.653	1.0	9.9	10.1 ± 1.0
Other paper	22.9	9.2	1.653	1.1	4.7	22.9 ± 1.1
Yard waste	9.7	15.5	1.653	1.8	18.7	9.7 ± 1.8
Food waste	12.0	8.4	1.653	1.0	8.2	12.0 ± 1.0
PET bottles	0.4	0.4	1.653	0.05	11.7	0.4 ± 0.05
HDPE bottles	0.7	0.7	1.653	0.1	11.1	0.7 ± 0.1
Other plastic	8.3	4.1	1.653	0.5	5.8	8.3 ± 0.5
Wood	4.0	6.8	1.653	0.8	19.9	4.0 ± 0.8
Textiles/rubber/leather	4.5	5.0	1.653	0.6	12.9	4.5 ± 0.6
Fines	3.3	2.3	1.653	0.3	8.2	3.3 ± 0.3
Disposable diapers	2.5	2.8	1.653	0.3	12.9	2.5 ± 0.3
Other organics	1.4	2.2	1.653	0.3	18.7	1.4 ± 0.3
Aluminum	1.0	0.7	1.653	0.1	8.2	1.0 ± 0.1
Tin & bimetal cans	1.5	1.1	1.653	0.1	8.2	1.5 ± 0.1
Other metal	3.3	4.3	1.653	0.5	15.2	3.3 ± 0.5
Food & beverage containers	4.3	3.7	1.653	0.4	9.9	4.3 ± 0.4
Other inorganics	3.3	5.3	1.653	0.6	18.7	3.3 ± 0.6
Total or weighted average	100.0			10.1	10.1	100.0 ± 10.1

[a]Based on 200 samples, 90% confidence, and the eighteen waste categories listed in the table. Means and standard deviations are based on Table 8.2.1.

respective fractions of the waste stream from which they were collected, separate precision analysis of the commercial and residential results is valid. Representativeness is achieved by either random selection of loads to sample or systematic selection of loads based on preexisting data.

Visual Characterization of Bulky Waste

The composition of bulky waste is typically estimated by observation rather than by sorting samples. Visual characterization of bulky waste is feasible for several reasons: (1) most bulky waste is not hidden in bags, (2) most loads of bulky waste contain few categories of waste, and (3) the categories of waste present are usually not thoroughly dispersed within the load, as they are in loads of MSW. Conversely, sorting samples of bulky waste is problematic for several reasons: (1) because the variation among loads of bulky waste is large, a large number of trucks must be sampled, (2) because the waste categories are not thoroughly dispersed within the loads, the samples must be large, (3) sorting and weighing bulky waste is difficult and dangerous if not done with specialized mechanical equipment.

Estimating the composition of bulky waste based on observation has three phases. First, field personnel prepare field notes describing each load as the load is dumped, as the load sits on the tipping floor or landfill after dumping, and as the heavy equipment operators move the load around the tipping floor or the working face of the landfill. Second, they determine or estimate the weight of each load. Third, they combine the field notes and load weights to develop an estimate of the composition of each load and of the bulky waste as a whole.

In general, the field notes should include the following elements for each load:

The date and exact time of day

The type of vehicle and its volumetric capacity (e.g., 30-cu-yd rolloff, 40-cu-yd trailer)

Any identifying markings that help match the field notes with the corresponding entry in the facility log for that day. Identifying markings that can be useful include the name of the hauler, the license plate number, and identifying numbers issued by regulatory agencies.

Either (1) a direct estimate of the by-weight composition of the load or (2) an estimate of the by-volume composition of the load combined with an indication of the amount of air space in each component.

If the facility does not have a scale, the facility log generally contains a volume for each load but no weight. If the volume of each load can be determined in the field, as it can when each truck or container is marked with its volumetric capacity, field notes do not have to be matched with log entries. Regardless of whether the facility log is used, the field notes should contain any information that

can be helpful in estimating the weight of each load, including its total volume if different from the capacity of the vehicle in which it arrived.

Field personnel should visually characterize most if not all of the loads of bulky waste arriving at the solid waste facility during the period of field work. Because the composition of bulky waste varies from load to load, a large number of loads must be characterized.

Characterized loads of bulky waste should not be regarded as samples because they contain vastly different quantities of waste. The overall composition of bulky waste is not the mean of the results for individual loads, as with MSW. Rather, the overall composition is weighted in accordance with the weights of the individual loads. An estimate of the overall percentage of each component involves calculating the total quantity of the component in all observed loads and dividing it by the total weight of all observed loads, as illustrated by the following equation:

$$p_o = (p_1w_1 + p_2w_2 \cdots + p_nw_n)/w_o \qquad 8.2(7)$$

where:

p_o = the overall percentage of the component in the observed loads
p_1 = the percentage of the component in the first observed load
w_1 = the weight of the first observed load
p_2 = the percentage of the component in the second observed load
w_2 = the weight of the second observed load
p_n = the percentage of the component in the last observed load
w_n = the weight of the last observed load
w_o = the total weight of all observed loads

Before the overall composition can be calculated in this way, the weight of each load must be estimated. If the facility has a scale, environmental engineers can determine the actual weight of the observed loads by matching the field notes for each load with the corresponding entry in the facility log, based on the time of arrival and information about the truck and the load. The time of arrival recorded in the facility log is the time when the truck was logged in rather than the time when the load was discharged. Field personnel must determine the difference between the two times.

If the facility does not have a scale, environmental engineers must estimate the weight of each component and the total weight of the load by converting from cubic yards to tons. The following procedure is suggested:

The total volume of the load is distributed among the components of the load based on the field notes.
The weight of each component is estimated based on its volume and density. Table 8.1.3 shows density ranges for certain waste components.
The estimated component weights are added yielding the estimated total weight of the load.

The cost of a study can be reduced if the same person collects MSW samples for sorting and performs visual characterization of bulky waste during the same period of field work. This technique is feasible if loads of MSW and bulky waste are dumped in the same part of the facility and if a quick method is used for collecting MSW samples.

Sampling MSW for Laboratory Analysis

Obtaining meaningful laboratory results for MSW is difficult. The primary sources of difficulty are (1) the presence of many different types of objects in MSW and (2) the large size of these objects. Collecting small but representative samples from a homogeneous pile of small objects (e.g., a pile of rice) is easier than from a heterogeneous pile of large objects. Secondary sources of difficulty in sampling MSW include the uneven distribution of moisture and inconsistent laboratory procedures.

MIXED SAMPLE VERSUS COMPONENT SAMPLE TESTING

An initial choice to be made is whether to test mixed samples or individual waste components. Testing mixed samples is preferable when:

- The only purpose of the laboratory testing is to determine the characteristics of the mixed waste stream, such as heat value.
- The statistical precision of the laboratory results must be demonstrated.
- The study does not include sorting waste samples.
- No significant changes in the composition of the waste stream are anticipated.

Testing of individual waste components is necessary, of course, when the characteristics of individual waste components must be determined. In addition, component testing makes projecting the impact of changes in the component composition of the waste, such as changes caused by recycling and composting programs, possible. Component testing also enhances quality control because laboratory errors are easier to detect in the results for individual components than in those for mixed samples.

The procedures for collecting mixed samples for laboratory testing are essentially the same as those for collecting mixed samples for sorting. The preceding evaluation of these procedures also applies to the collection of mixed samples for laboratory testing, except for the comments concerning the impacts of various sampling procedures on the sorting process.

Laboratory samples of individual waste components are usually composite subsamples of samples sorted to estimate composition. In general, each component laboratory

subsample includes material from each sorted sample. Material for the laboratory subsamples is collected from the sorting containers after the sorting and weighing are complete.

LABORATORY PROCEDURES

A fundamental question is how large should the samples sent to the laboratory be. The answer to this question depends on the procedures used by the laboratory. A state-of-the-art commercial laboratory procedure includes the following steps:

A portion of the sample material sent to the laboratory is weighed, dried, and reweighed to determine the moisture content. The limiting factor at this stage of the procedure is usually the size of the laboratory's drying oven.

A portion of the dried material is ground into particles of $\frac{1}{8}$ to $\frac{1}{4}$ in.

A portion of the $\frac{1}{8}$-to-$\frac{1}{4}$-in material is finely ground into as close to a powder as possible. For flexible plastic, dry ice must be added prior to fine grinding to make it more brittle.

The actual laboratory test is generally performed on 0.5 to 3 g of the finely ground material, depending on the type of test and the specific equipment and procedures.

Variations on this procedure include the following:

Most laboratories do not have equipment for grinding inorganic materials such as glass and metal. In combustion testing, this material is removed from the sample prior to grinding, then weighed and reported as ash. For metals testing, metal objects can be cut up by hand or drilled to create small pieces for testing. Glass and ceramics are typically crushed.

Many laboratories do not have fine grinding equipment, so they perform tests on relatively coarse material.

In addition to using different methods for preparing waste for testing, laboratories use different test methods.

The more sample material the laboratory receives, the more material they must exclude from the small quantity of material that is tested. The real question is not how large the samples should be but how field and laboratory personnel should share the task of reducing samples to a gram or two. For practical purposes, the maximum quantity sent to the laboratory should be the quantity the laboratory is prepared to spread out and mix in preparation for selecting the material to be dried. The minimum quantity should be the quantity the laboratory is prepared to dry and grind up.

Composite laboratory samples are typically accumulated in plastic trash bags, then boxed for shipment. An alternative is to accumulate the samples in 5-gal plastic buckets with lids. Plastic buckets are more expensive than plastic bags but have several advantages:

Plastic buckets (and their lids) are easier to label, and the labels are easier to read.

Adding material to plastic buckets is easier.

The lids, which are lifted only when material is added to the buckets, prevent moisture loss during the active sampling period.

Sample material can be compacted in plastic buckets if it is pushed down around the inside edge.

The buckets can be used as shipping containers.

The buckets can be reused if the laboratory ships them back.

COLLECTING MATERIAL FOR LABORATORY SUBSAMPLES

Three general methods for collecting material for laboratory subsamples from containers of sorted waste are blind grab sampling, cutting (or tearing) representative pieces from large objects, and selecting representative whole objects for inclusion in the sampling. Blind grab sampling is the preferred approach for waste that mainly consists of small objects. Cutting representative pieces is appropriate for waste consisting of large objects with potentially different characteristics. Selecting representative whole objects is appropriate for waste containing only a few different types of objects.

Blind grab samples should be collected by hand or with an analogous grasping tool. The objective is to extract the material from a randomly selected but defined volume within the container of sorted material. When scoops and shovels are used in sampling heterogeneous materials, they tend to create bias by capturing dense, small objects while pushing light, large objects away.

In collecting subsamples from containers of sorted waste, samplers must realize that because sorting progresses from larger objects to smaller, the objects at the top of the container tend to be smaller than those at the bottom. Objects of different sizes can have different characteristics, even within the same waste category. Therefore, the sampler must ensure that the objects at different levels of the containers are represented in the samples. Emptying the container onto a dry and reasonably clean surface prior to collecting the subsample may be necessary.

If the laboratory samples are tested for metals, objects with known metals content should not be represented in the samples. Instead, such objects should be weighed, and the laboratory results should be adjusted to reflect the quantities of metals they contain. For example, if 8 oz of lead weights are found in 10 tn of sorted waste, the weights represent 25 ppm of lead. The weights should be withheld from the laboratory sample, and 25 ppm should be added to the overall lead concentration indicated by the laboratory results. This procedure is more accurate than laboratory testing alone.

Review and Use of Laboratory Results

Laboratory procedures are imperfect, and errors in using the procedures and in calculating and reporting the results are common. Reviewing the results received from a laboratory to see if they make sense is important. This exercise is relatively straightforward for combustion characteristics because much is known about the combustion characteristics of solid waste and its component materials (see Section 8.1). Identification of erroneous laboratory results is more difficult for metals and toxic organic substances.

The following guidelines apply in an evaluation of reasonableness of laboratory results for combustion characteristics on a dry basis:

Dry-basis results for the paper, yard waste, plastics, wood, and disposable diapers categories should be close to those shown in Tables 8.1.4 and 8.1.5.

Greater variability must be accepted in individual results for food waste, textiles/rubber/leather, fines, and other combustibles because of the chemical variety of these categories.

The result for carbon must always be at least six times the result for hydrogen.

No oxygen result should be significantly higher than 50%.

For plant-based materials and mixed food waste, oxygen results should not be significantly less than 30% on an ash-free basis.

Among the paper categories, only those with high proportions of glossy paper, such as magazines and advertising mail, should have ash values significantly greater than 10%.

Nitrogen should be below 1% for all categories except grass clippings, other yard waste, food waste, textiles/rubber/leather, fines, and other organics (see Table 8.1.4).

Chlorine should be below 1% for all categories except for PVC bottles, other plastic, textiles/rubber/leather, and other organics.

Sulfur should be below 1% for all categories except other organics.

The laboratory should be willing to check its calculations and repeat the test if the calculations are not the source of the problem.

Estimating Combustion Characteristics Based on Limited Laboratory Testing

The combustion characteristics of individual waste categories on a dry basis are well documented and fairly consistent within categories. Moisture and component composition are more variable. One option, therefore, is to sort samples to estimate component composition and have subsamples tested for moisture only. Then, with the use of the documented values for the proximate and ultimate composition and heat value of each waste component, the overall combustion characteristics of the waste stream can be estimated.

Another potential cost-saving measure is to estimate heat value based on ultimate composition. Several equations have been proposed for this purpose (Niessen 1995):

TABLE 8.2.4 HEAT VALUE ESTIMATES BASED ON BOIE, CHANG, AND DULONG EQUATIONS

Equation	*Dry-Basis HHV (Btu/lb)*	*As-Received HHV (Btu/lb)*
Boie	7395	5310
Chang	7479	5370
DuLong	7510	5392
Average	7461	5357
Laboratory values	7446	5348

BOIE EQUATION

$$HHV = 14{,}976C + 49{,}374H - 4644O + 2700N + 4500S + 1692Cl + 11{,}700P \quad 8.2(8)$$

CHANG EQUATION

$$HHV = 15{,}410 + 32{,}350H - 11{,}500S - 20{,}010O - 16{,}200Cl - 12{,}050N \quad 8.2(9)$$

DULONG EQUATION

$$HHV = 14{,}095.8C + 64{,}678(H - O/8) + 3982S + 2136.6O + 1040.4N \quad 8.2(10)$$

where:

HHV = higher heating value in Btu/lb

Percentages for each element must be converted to decimals for use in these equations (i.e., 35% must be converted to 0.35). Using the values in Table 8.1.4 in the three equations yields the results shown in Table 8.2.4.

These values are close to the overall values in Table 8.1.5, which are based on laboratory testing of the same samples on which the ultimate composition in Table 8.1.4 is based. The laboratory-based values are closer to the average results for the three equations than to the results for any individual equation.

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