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Waste Isolation Pilot Plant Simulated Waste Compositions and Mechanical Properties

Barry M. Butcher

Prepared by
Sandia National Laboratories
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WASTE ISOLATION PILOT PLANT SIMULATED WASTE COMPOSITIONS AND MECHANICAL PROPERTIES

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ABSTRACT

Analyses of the final state of collapse of various types of contact-handled waste drums are required to assess of the performance of the waste storage areas in the Waste Isolation Pilot Plant. To provide data for calculations, tests must use simulated, instead of actual waste. Data on the contents of the principal categories of contact-handled transuranic waste from the Idaho National Engineering Laboratory were used to define standard compositions of simulated waste. Categories of baseline waste will be created by mixing appropriate amounts of the simulants together. Selection of materials is discussed. Methods for estimating the consolidation characteristics of simulated waste are also described. Theoretical solid densities, theoretical solid compressibilities, and initial void volumes of various waste components are estimated, and a method for estimating consolidation curves in the absence of experimental data is described.

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WASTE ISOLATION PILOT PLANT SIMULATED WASTE COMPOSITIONS AND MECHANICAL PROPERTIES

1. INTRODUCTION

Dispersal of radioactive material from its storage location is a fundamental issue in evaluating the performance of the Waste Isolation Pilot Plant (WIPP). Migration of radioactive material is most likely to occur by the flow of groundwater. As time passes, some of the waste may dissolve in brine, which can then transport radioactive material out of the disposal rooms. Although the solubility of waste radionuclides in brine is still being evaluated, current performance assessment predictions are that natural leaching processes will occur over thousands of years and in such dilute amounts as to be harmless.

The rate of brine flow into or out of the room depends, in part, on the permeability of its contents. Some waste, particularly the older material, will be loosely packed to a 0.70 to 0.80 void fraction[1] when emplaced. As room boundaries converge, the waste will be compacted until the backstress exerted by the waste and pressure of the fluids within its pores (brine or trapped gas from corrosion or bacterial decomposition) equals the lithostatic stress (approximately 15 MPa). The final density of the waste must be predicted to determine its permeability.

The amount of water in the rooms at a given time is also important. Although room contents are initially highly permeable because of the high void fraction, little brine will have had time to enter. Water from bacterial decomposition of the waste may be present, and water is also available from the sludges. Later, more brine will flow into the rooms and more decomposition water may be available, but the void fraction, and hence the permeability of the waste, will have been greatly reduced. A competition exists, therefore, between how rapidly the waste consolidates and how rapidly brine gets into the void space, which must be resolved to determine the final state of the waste.

Analyses of the rate of collapse of various types of contact-handled (CH) waste drums are needed to estimate final porosities of the waste for performance assessment. In many cases, numerical calculations will require a model defining the compaction of various categories of waste.

Input for the compaction model will be experimentally determined compaction curves, in part obtained from straightforward laboratory tests. Testing of actual radioactive waste is not feasible at present because CH transuranic (TRU) waste containers may rupture during the tests. Instead, nonradioactive "simulated" waste with the same mechanical characteristics as real

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1. The void fraction is the part of the waste volume occupied by air or other gases.

waste will be tested. Chemical additives may also be used to simulate various chemical aspects of the waste.

This report explains how simulated waste will be defined, how it will be made, and how its consolidation properties will be determined. First, the approach to defining simulant materials will be justified. Second, Idaho National Engineering Laboratory (INEL) waste form categories will be reviewed. Third, simulated waste compositions for the dominant waste form categories will be described. Fourth, compositions of the various simulated wastes will be discussed. Finally, some consolidation properties for the various waste forms will be presented.

2. APPROACH

Two approaches were considered. The direct sampling approach would ask suppliers of the waste to set aside nonradioactive trash for use as simulated waste, ensuring that the nonradioactive waste is from the same environment as the real waste. However, as Clements and Kudera (1985) showed, INEL waste from the same category varies greatly from drum to drum. The authors of other waste characterization studies (Shefelbine, 1978; Kosiewicz et al., 1978) also caution that waste compositions continually vary in response to changing programs and improved waste management techniques. With direct sampling, there is no way of assuring that the nonradioactive waste acquired typifies actual stored waste, or that it is representative of future waste. In addition, a large number of tests would be required to obtain statistically meaningful results.

A second, more structured approach, is to use the detailed inventory of actual contents of drums of INEL waste, provided by Clements and Kudera, to define "standard" drum contents for each waste form category.[2] Simulated waste with the prescribed compositions is assembled from generic materials (shredded paper, pieces of polyethylene, chopped-up metals, and synthetic sludge, etc.) and placed in full-scale and scaled-down containers for compaction testing. Because much of the waste will come from the INEL, its compaction characteristics will dominate closure of the disposal rooms. Also, no other inventory study has examined the contents of individual drums in the detail provided by Clements and Kudera.

In defining standard drum contents or mixtures for each waste form category, exact duplication of the various categories of waste is impossible because of its variability. Instead, prescribed "average" contents will provide a basis for extrapolation of compaction results to different waste contents. Such extrapolation entails: (1) defining the approximate compressibilities for each component of a given waste form; (2) using the data to estimate compaction characteristics of the baseline mixture (standard contents or average composition) of a given waste form; (3) determining the accuracy of predictions by comparing them with compaction test results on drums containing the baseline mixture; and (4) using the results to predict overall compaction characteristics of real waste. This approach provides a means for extrapolation and minimizes the number of tests in the program because test results are less variable and the samples need not be selected by a statistical process. Even though prescribed waste mixtures may not be exactly representative of future waste, this second approach can correct results for future changes in waste composition.

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2. The distinction between the waste form category, which is the descriptive class to which each drum is assigned, and the components of a drum are its contents is important. For example, a drum in the category of metals waste may contain some combustible components such as cellulosic materials or plastics.

3. WASTE FORMS

The INEL CH TRU waste drums examined by Clements and Kudera encompassed the 14 major waste form categories listed in Table 1. Each waste form category had a number of subcategories. Clements and Kudera examined 37 different waste forms, choosing the number of drums of each form to be inventoried in part on the basis of prevalence in storage at the INEL. A comparison with the categories used to describe the general retrievable waste inventory listed in Table 2 shows that the INEL categories have greater detail.

The significant difference between the Clements and Kudera study and most previous inventories of CH TRU waste was that the contents of each drum were actually inventoried by separating the waste into various components and weighing them, as shown in the abbreviated description of a typical combustible waste drum given in Table 3. Other studies, excepting those on the characteristics of waste at Los Alamos (Kosiewicz et al. 1978), tabulated types and weights of drums without evaluating actual contents.

Using the INEL combustible waste form category as an example, a total of 40 drums involving six subcategories (cf. Table 1) was selected for examination. Eighteen drums had been stored for 6 months, three had been stored for 3 years, and 18 for 12 years. Ten of the drums were code content 330, 10 were code content 337, and the remaining three subcategories each had three drums. One drum was mislabeled, leaving 39 drums. The contents of each drum of combustibles were then separated into 6 basic components: surgeons' gloves, paper, cloth, plastic, rubber, and "other" (such as wood filter frames). Other components present in lesser amounts were various types of glass, metal (usually lead, or metallic objects), leaded rubber, and sorbents such as vermiculite or commercial oil-absorbing materials. Typical components are described in Tables 4 and 5.

A reasonable approach to quantitatively defining the compaction characteristics of various types of waste is to concentrate on categories that make up the largest portion of INEL waste. Waste at other sites can be treated similarly as more information becomes available. Figure 1 shows that the principal amounts of INEL waste fell into the three categories of combustibles, metals, and sludges, which comprised about 83% of the stored waste at the time of the investigation. Another category called filters represented 10% of the waste;[3] 2.8% of the waste was categorized as glass, and the remaining 4.2% represented a number of other categories (Figure 2). This report concentrates on the combustible, metallic, and uncemented sludge categories because of their dominance. The compaction characteristics of the other categories are expected to be quite similar to one of the major categories. Those present in trace amounts will probably have little effect on the overall compaction response of the disposal rooms.

3. Clements and Kudera examined only one drum of this type of waste.

Table 1. INEL Waste Form Categories and Content Code Descriptions (from Clements and Kudera 1985).

Category	Code	Content Description
Combustibles	328	Filters, Ful-Flo from incinerator
	330	Combustibles, dry
	336	Combustibles, wet
	337	Plastic and nonleaded rubber
	900	Low specific activity (LSA) plastics, paper, etc.
	970	Wood
Metals	320	Heavy non-stainless steel (SS) metal
	480	Light non-SS metal
	481	Leached light non-SS metal
Glass	440	Glass
	441	Unleached Raschig rings
	442	Leached Raschig rings
Nonmetal molds and crucibles	300	Graphite molds
	301	Graphite cores
	312	Graphite, coarse
Uncemented sludges	1	First stage (741) or combined
	2	Sludge (7412)
	3	Second stage sludge
	7	Grease (organic setups)
	292	Cemented sludge (cement added as an absorbent only)
Cemented sludges and solutions	4	Special setups
Concrete, brick	371	Brick
	960	Concrete, asphalt
Salts	409	Molten salt (30% unpulverized)
	414	Direct oxide reduction salt
Leaded rubber	339	Leaded drybox gloves and other, leaded rubber
Benelex, plexiglas	302	Benelex and Plexiglas
	464	Benelex and Plexiglas

Table 1 - Continued

Resins	432	Resin, cemented
Mixed waste-paper, metal, glass	241	Americium process residue
	950	LSA metal, glass, etc.
Filters	335	Absolute filters (8" by 8")
	338	Insulation and filter media
	360	Insulation
	490	Filters
Particulate wastes	374	Blacktop, concrete, dirt, and sand
	376	Cemented insulation and filter media

Table 2. Retrievably Stored Contact-Handled Waste Composition at DOE/Defense Sites Through 1985, Vol% (from DOE/RW-0006, Rev 4).

Waste Type	Site					
	Hanford	INEL	Los Alamos	Nevada Test Site	Oak Ridge	Savannah River Plant
Absorbed liquids or sludges	1.2	14.5	21	2	-	3.5
Combustibles	39.4	25.8	20	57	57	70
Concreted or cemented sludges	-	2.7	8	-	-	-
Dirt, gravel, or asphalt	4.4	2.6	2	-	5	-
Filters or filter media	1.1	7.1	2	-	5	5
Metal, glass, or similar noncombustibles	53.8	35.2	47	41	33	21.5
Other	0.1	12.1	-	-	-	-
% of Total Waste	18	61	12	1	3	5

Table 3

Synopsis of a Typical INEL Waste Drum Inventory
(from Clements and Kudera, 1985).

Combustible Waste Form 336

Container ID: 23-01599

Time Period: 6 Month

Component	Weight	Visual Identification
Surgeons' Gloves	5.75 lb	
Paper	34.0	Kimwipes
Cloth	8.5	Booties
Plastic	17.0	Polyethylene and PVC bags
Other Combustibles	3.0	PVC pipe
Vermiculite	3.5	
Other Metals	1.5	Nails
Total	73.25	
Container Weight	140 lb	

Packaging Description: Ranges from loose waste to triple-bagged waste.

Liquids: Wet Kimwipes - a total of 188 ml of free liquid with a pH of 7. The major composition is Freon TF and an unidentified oil.

WIPP-certifiable - No

Table 4. Typical Contents of Combustible Category Drums.

Items	Constituents
Filters	Ful-Flo filters (with grease coating) High-efficiency particulate air (HEPA) filters
Plastic and Rubber	Polyethylene and polyvinyl chloride (PVC) bags Polyethylene and PVC plastic bottles, tubing Plastic buckets, hose Tygon Plastic air suits Surgeons' gloves Rubber gloves Rubber gaskets and hose Rubber mats
Paper, Cloth, and Wood	Cloth rags Booties, overalls Kimwipes, smear paper Paper Cardboard Wood filter frames and nails Wood and wood chips, sawdust
Metal	Steel Aluminum Scissors Nails, rod, and tape Lead sheeting and paint cans
Other	Extension cords Cellulosics-paks Raschig rings Paint brushes Leaded gloves
Sorbents	Vermiculite Cement Oil dry

Table 5. Typical Contents of Metal Category Drums.

Cast iron conduit
Light fixtures, wiring
Aluminum light guards
Mild steel instrument panel
Tools
Furnace and components
Wire brushes
Copper tubing
Aluminum foil
Lead sheeting and tape
Batteries
Welding rod
Pumps
Tantalum funnels, crucibles, and chips
Canisters, motors, oil filters
Electrical hardware
Cables, cord, wire, circuit boards
Metal fixtures, bearings, parts
Copper strips, gaskets
Tin cans
Carbon steel
Stainless steel
Aluminum
Lead
Copper

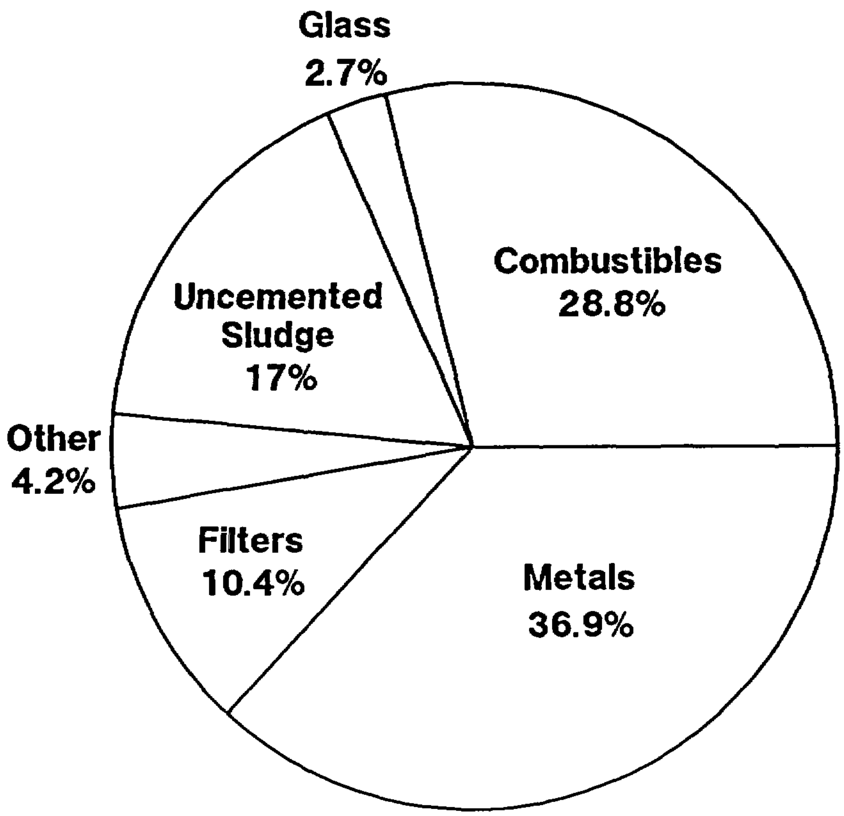

Figure 1. Primary INEL CH TRU waste categories.

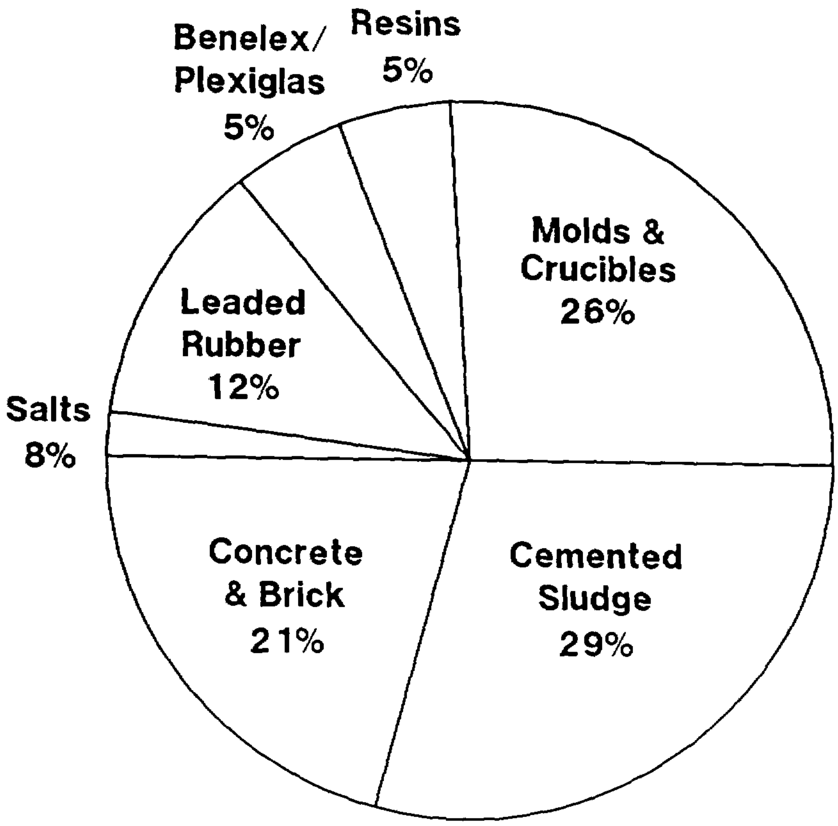

Figure 2. Other INEL CH TRU waste categories (4.2% of total).

The relative amounts of different waste forms in storage raises another issue concerning the final consolidated state of the disposal rooms. The mode of operation of the WIPP will probably be to store waste forms randomly. Thus, a number of drums of a relatively incompressible waste category that represents a small portion of the total amount of waste could be shipped at the same time. Such waste would be localized within a disposal room rather than dispersed throughout the repository, a factor that might be considered in predicting compaction response. A statistical model of waste emplacement within the disposal rooms may be needed, but such a model is beyond the limits of the present investigation.

3.1. Standard Contents of Combustible, Metal, and Uncemented Sludge Waste Forms

Clements and Kudera characterized each drum in a given waste form by separating the contents into components and weighing them. Several simplifications were possible in analyzing their results. First, Clements and Kudera's six combustible wastes (surgeons' gloves, paper, cloth, plastic, rubber, and "other") were combined into two components: a cellulosic component containing paper, cloth, and wood, and a plastics component containing surgeons' gloves, plastic, and rubber.[4] This simplification is possible because components of generically similar material are expected to have about the same compressibility.

Second, Clements and Kudera's four types of metal waste (tantalum, steel, stainless steel, and "other" metals) were lumped into a single category[5] because the collapse of metallic waste depends more on the form of the waste (e.g., hard-to-collapse, thick-walled pipe vs. easy-to-collapse, thin-gauge lighting fixtures) than on its composition. In addition, the metal components are expected to occupy the smallest volume of any of the waste constituents because of their high solid density. Thus, large uncertainties in the solid density of metallic waste produce volume changes that are small in terms of the initial volume of the waste.[6] Near-solid volumes

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4. Inventory averages by weight were 15% gloves, 24% paper, 4% cloth, 38% plastic, 2% rubber, and 17% "other combustibles."

5. The actual inventory by weight was 4% tantalum, 64% steel, 7% lead, and 25% other metals such as aluminum and copper.

6. For metallic waste near solid density ρ_s, with volume V, the change in volume related to uncertainty in ρ_s is $\Delta V \sim - V_m \Delta\rho_s/\rho_s$, where V_m is the solid volume of the metal. In comparison to other waste materials with much smaller densities, V_m is small, so that a larger uncertainty in solid density, $\Delta\rho_s/\rho_s$, can be tolerated for the same dV. For example, in the metallic waste form category, the average volume V_m for all steel waste with $\rho_s = 7800$ kg/m^3 (Marks' Handbook, Eighth Edition) would be about 0.007 m^3 or 3.3% of the volume of a 55-gallon (0.21 m^3) drum. A change in V of 2% of the original drum volume would correspond to an uncertainty of about 40% in ρ_s.

of the minor components of the metals waste, such as combustibles and sorbents, are comparable to the final volume of the metallic component, as will be shown in analysis of the initial void volumes in the drums.

Third, vermiculite, portland cement, and other absorbing materials added in minor amounts to drums containing combustible and metallic waste forms to eliminate free liquids were lumped together as single component.

Because interest is focused on the final stages of compaction of the waste, the possibility that simulated waste may respond differently than real waste during the initial stages of its compaction is not considered a problem. By the time simulated waste has consolidated to low void volumes, most of the influence of the initial state of the waste should have disappeared and the waste will have been compacted to a simpler structure of densified material interspersed with a wide distribution of void sizes. Residual void structure is important because large voids may eventually become brine pockets and the interconnectivity of the smaller voids will determine the permeability of the room contents.

3.1.1. Combustible Waste

The state of an average drum of combustibles was estimated by summing the weight of each component and finding its average value, as shown in Table 6. The amount of each component in combustible waste is shown in Figure 3. To create simulated combustible waste components, materials representative of the items listed in Table 4 will be mixed until their combined weight is equal to the average weight of the drums. If the average weight of a collection of drums containing combustible waste differs from the average gross weight quoted above, the weights of the various components will be adjusted in proportion to the difference between drum weights.

In the results for combustible waste, the uncertainty of ±50.0 lbs in the average weight of the drum contents is large. In addition, a histogram of how this weight is distributed among the various drums (Figure 4) shows that the cause of the discrepancy is a wide variation of weights from drum to drum. Part of the scatter occurs because all the subcategories of the combustible waste form have been lumped into a single category. Another source, as stated previously, is variation in waste compositions and amounts as suppliers' programs change.

Although the uncertainty given in the previous paragraph is large, it is not as significant as a first examination suggests. Although the analysis defines a "standard" drum of waste, the results, as ultimately applied to WIPP performance assessment, will always be used to define the response of an assemblage of drums. For combustible waste, the size of these units is assumed to be about 39 drums, the number of drums inventoried by Clements and Kudera. Therefore, results are interpreted in the sense that on the average, an assemblage of 39 drums of retrievable, combustible waste will

Table 6. Average Drum of Combustibles: Weights.

Item	Weight
Container (DOT-17C with 90 mil liner)[a]	
Drum contents (liner not included)	88.1 ± 50.0 lbs
Metals	9% (by weight)
Paper, cloth, and wood	37% (by weight)
Plastics, surgeons' gloves, rubber	45% (by weight)
Sorbents	9% (by weight)
Drum	64.5 lbs
Liners + other components	17.0 lbs[b]
Average gross	169.6 lbs[c]

a. Rocky Flats Plant Standard SX-200, "Standards for DOT-17C 55 Gal. Drum."

b. Normally this quantity should be the difference between the weight of the drum contents plus the weight of the drum and the measured gross weight of the drum. Estimation in this manner was not possible for combustibles because of several obvious discrepancies in gross drum weights, so this value is assumed to be the weight of the 90 mil polyethylene liner.

c. The value of average gross weight calculated from the data was 162.2 lbs.

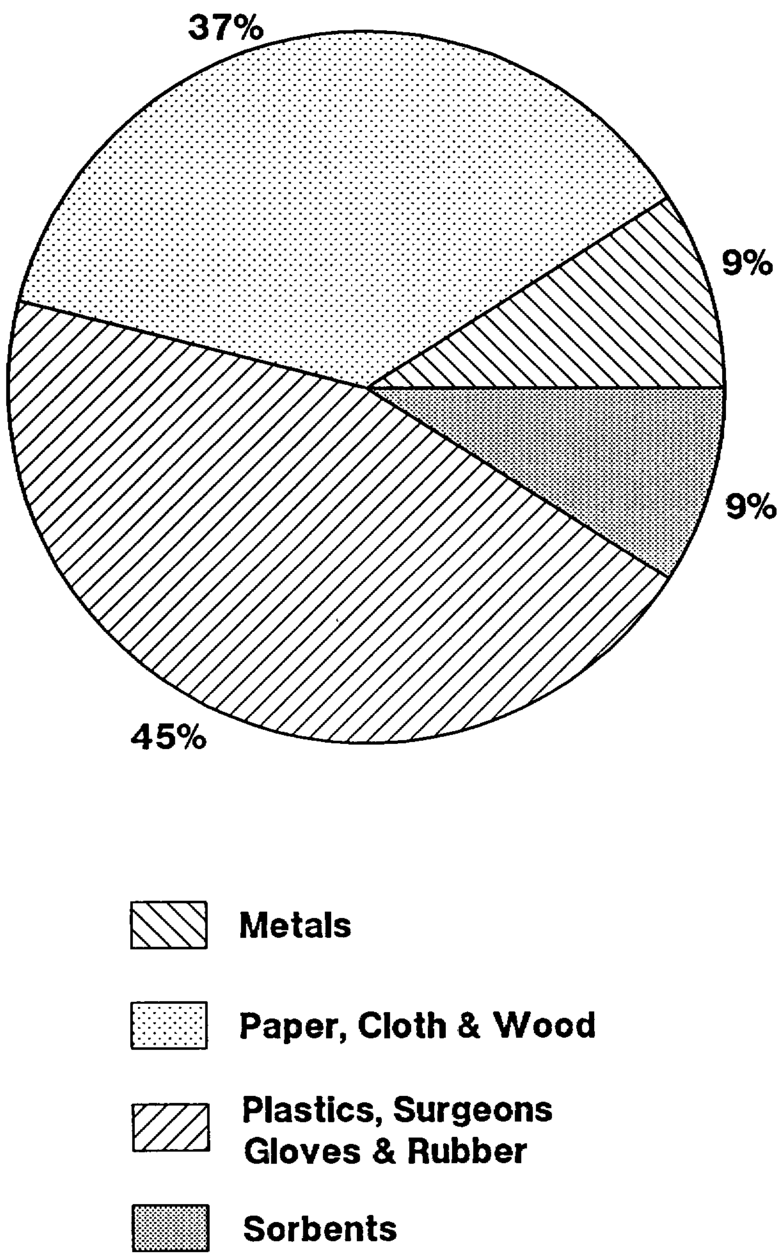

Figure 3. INEL CH TRU combustible waste components.

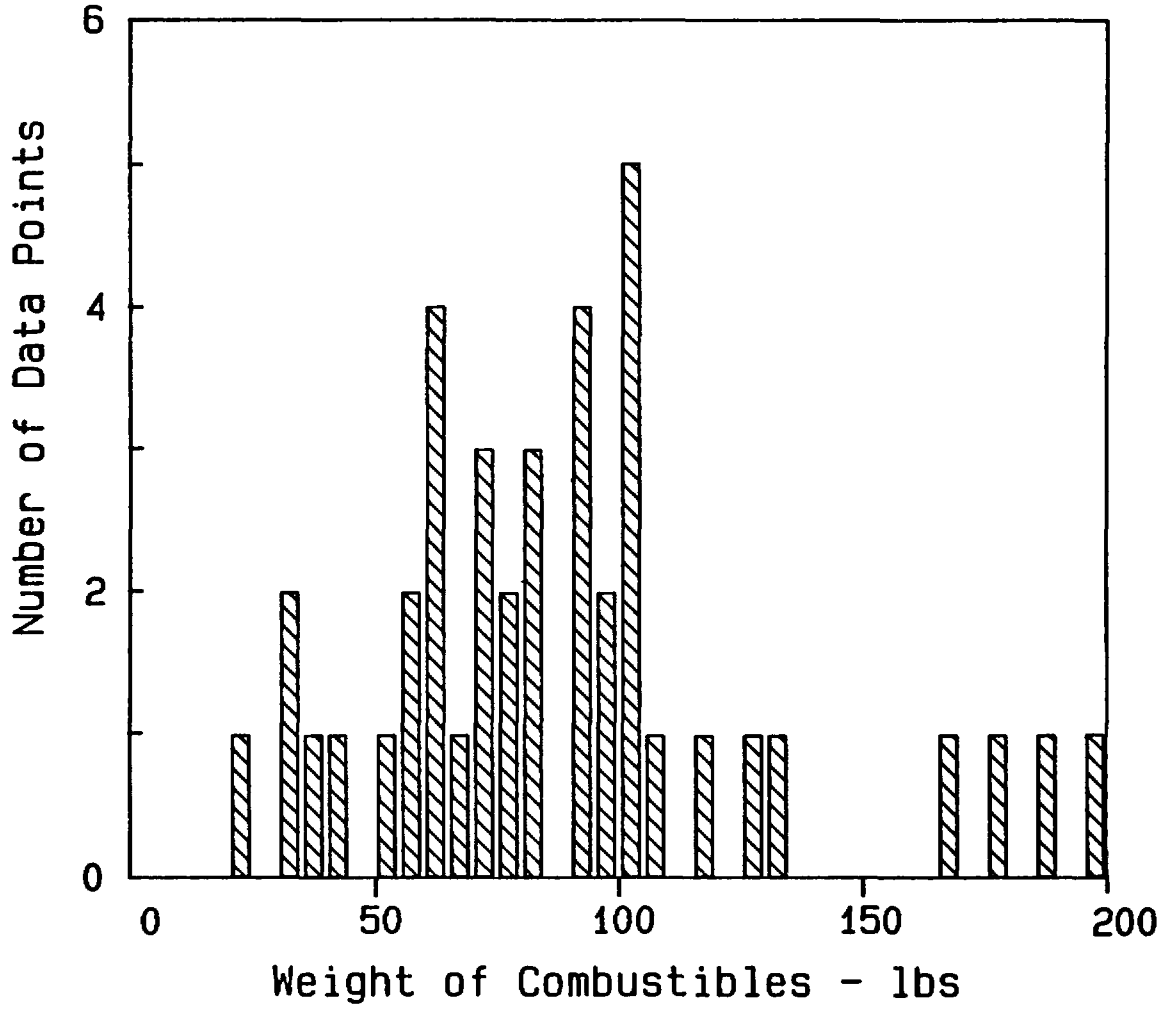

Figure 4. The weight distribution of the contents of drums containing INEL combustible waste.

have the composition and properties that are being derived. Unfortunately, there is no present way to decide how representative the 39 drums that Clements and Kudera selected were in regard to all of the stored waste, but the results in Figure 4 suggest that enough drums were selected to begin to have the appearance of some sort of distribution function.

3.1.2. Metallic Waste

The state of an average drum of metallic waste was estimated by summing the weight of each component and finding its average value as shown in Table 7. The amount of each component in metallic waste is shown in Figure 5. To create this waste, components will be mixed together until their combined weight is equal to the total weight of the recommended contents, adjusting each component in proportion to compensate for any differences in total drum weight. The 29 drums of metallic waste investigated by Clements and Kudera were found to have the weight distribution shown in Figure 6.

3.1.3. Uncemented Sludge

Uncemented sludge was divided into an inorganic component and an organic component, a mixture of grease and sorbents. Other components within these drums were plastics and sorbents. An average drum of sludge was estimated by summing the weight of each component and finding its average value, as shown in Table 8.

The amounts of each component in the two types of sludge waste are shown in Figures 7 and 8. Simulation of the sludge components is discussed later. Forty-four drums of sludge waste were investigated by Clements and Kudera. Weight distributions for sludge drums are shown in Figure 9.

Table 7. Average Drum of Metallic Waste: Weights.

Item	Weight
Container (DOT-17C with 90 mil liner)	55 gallons
Drum contents (liner not included)	142 ± 74.7 lbs
Metals	83% (by weight)
Paper, cloth, and wood	2% (by weight)
Plastics, surgeons' gloves, rubber	10% (by weight)
Sorbents	5% (by weight)
Drum	64.5 lbs
Liners + other components	17.0 lbs[a]
Average gross	223.5 lbs[b]

a. This quantity should be the difference between the weight of the drum contents plus the weight of the drum and the measured gross weight of the drum. As for combustibles, estimation in this manner was not possible for metallic waste because of obvious discrepancies in gross drum weights, so that this value is assumed to be the weight of the 90 mil polyethylene liner.

b. The value of average gross weight calculated from the data was 216 lbs.

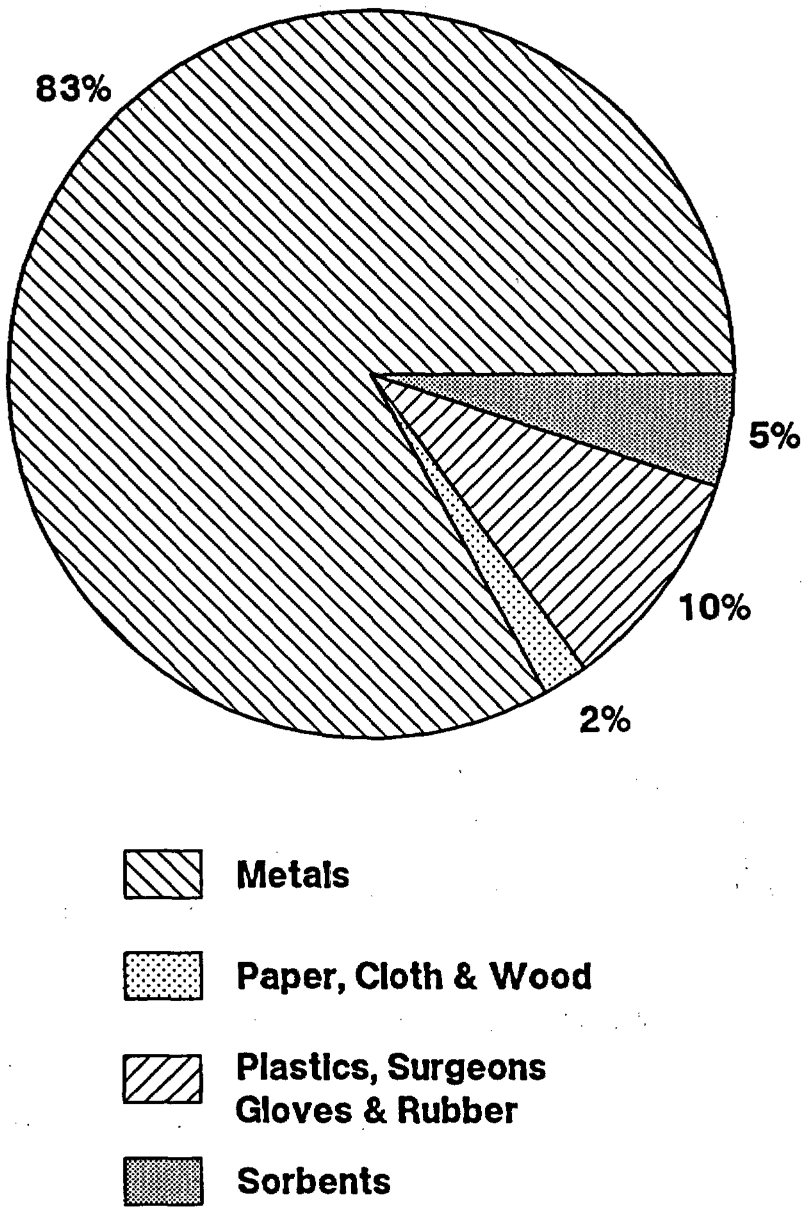

Figure 5. INEL CH TRU metallic waste components.

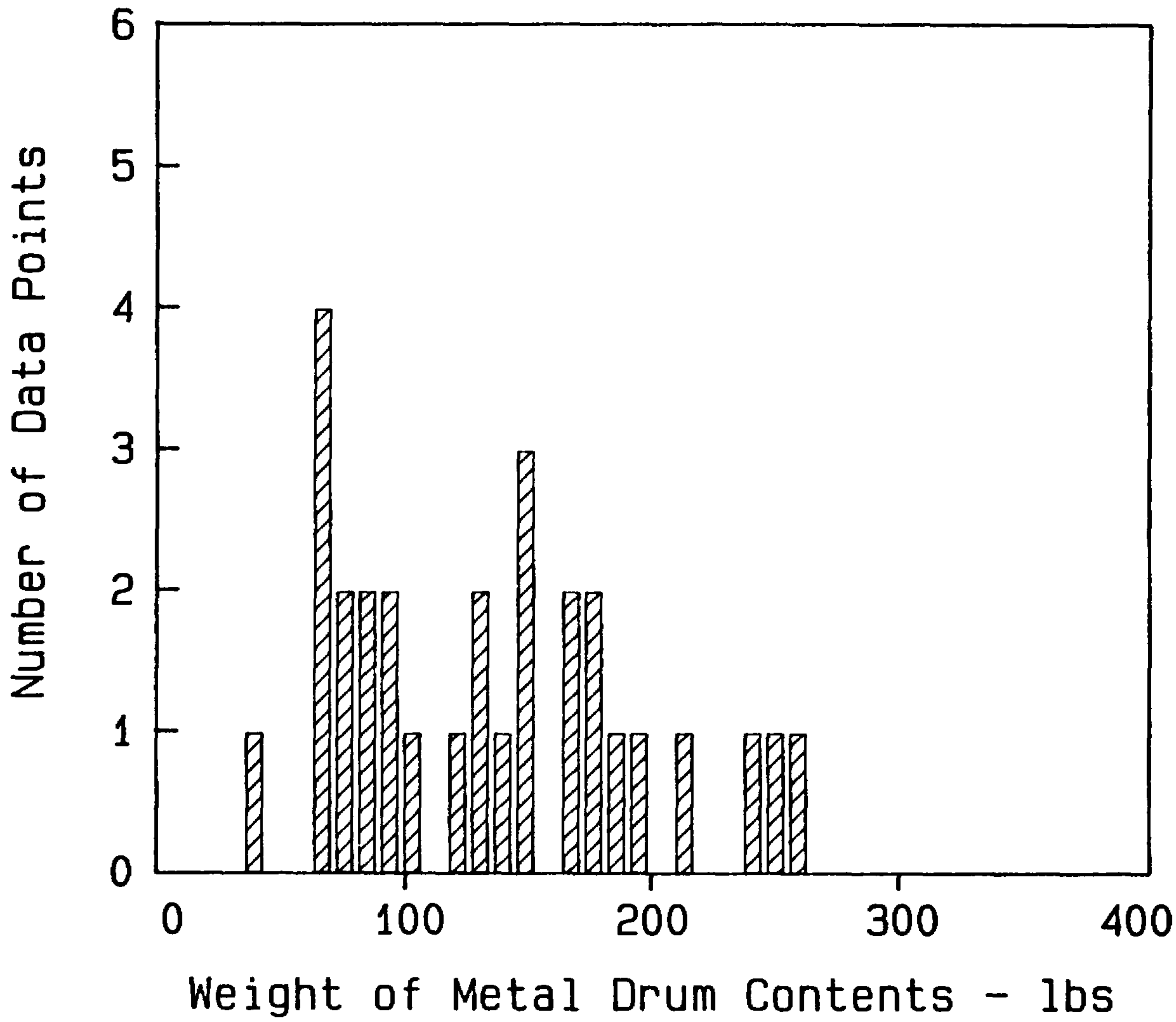

Figure 6. The weight distribution of the contents of drums containing INEL metallic waste.

Table 8. Average Drum of Uncemented Sludge: Weights.

Item	Weight
Drum (DOT-17C with 90 mil liner	55 gallons
Drum contents (liner not included)	375 ± 60 lbs
Inorganic	
Sludge[a]	92% (by weight)
Plastics	1% (by weight)
Sorbents	7% (by weight)
Drum	64.5 lbs.
Liners + other components	19.3 lbs
Average gross	459 lbs
Organic	
Sludge[a]	89% (by weight)
Plastics	1% (by weight)
Sorbents	10% (by weight)
Drum	64.5 lbs
Liners + other components	17.5 lbs
Average gross	499 lbs

a. The solid density of this sludge is estimated to be 1476 kg/m^3 using methods for estimating initial void volumes described in this report.

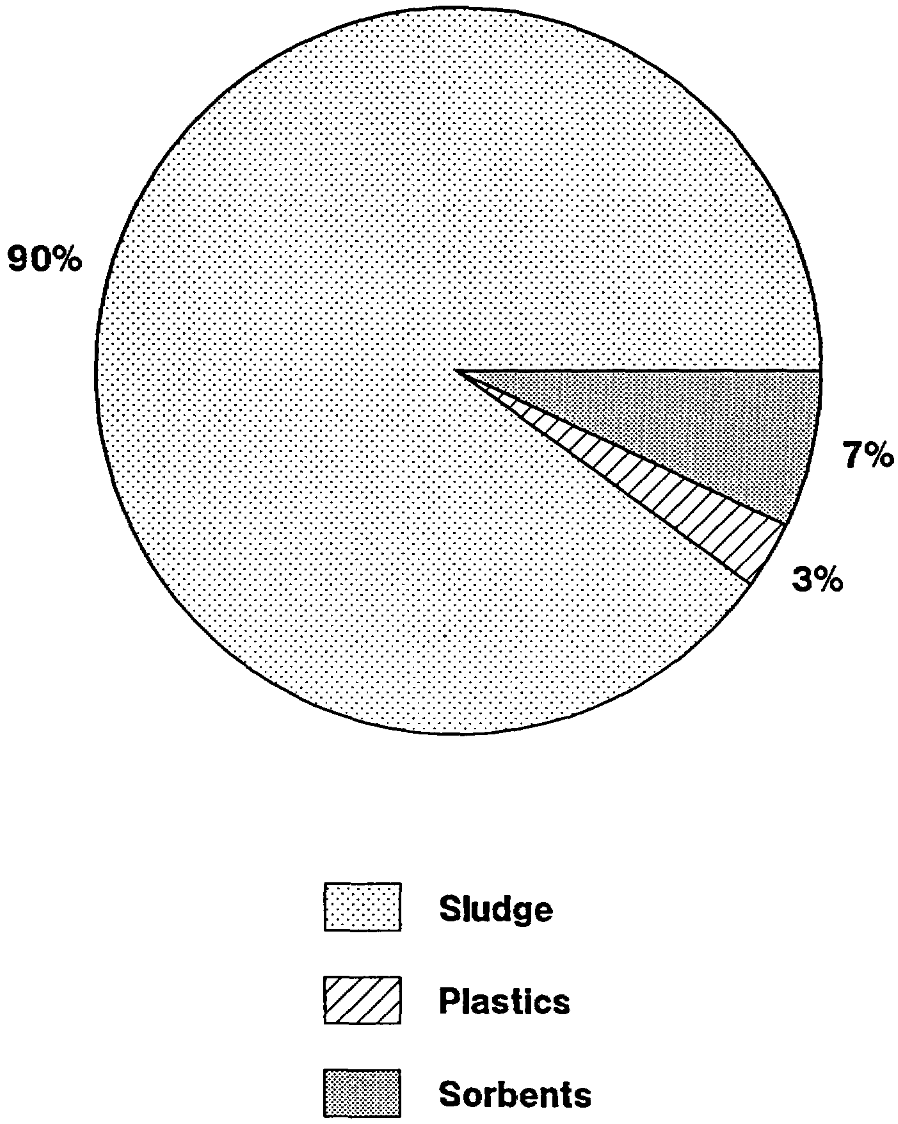

Figure 7. INEL CH TRU uncemented inorganic sludge waste components.

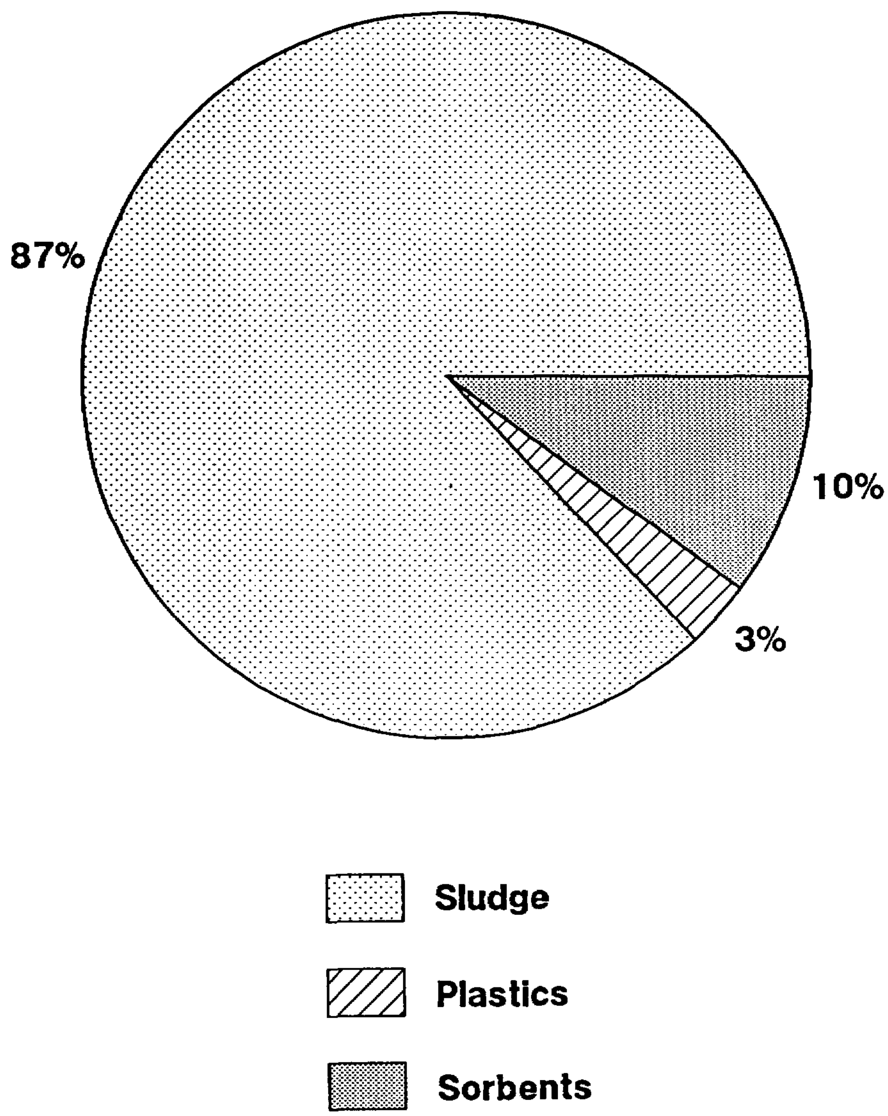

Figure 8. INEL CH TRU uncemented organic sludge waste components.

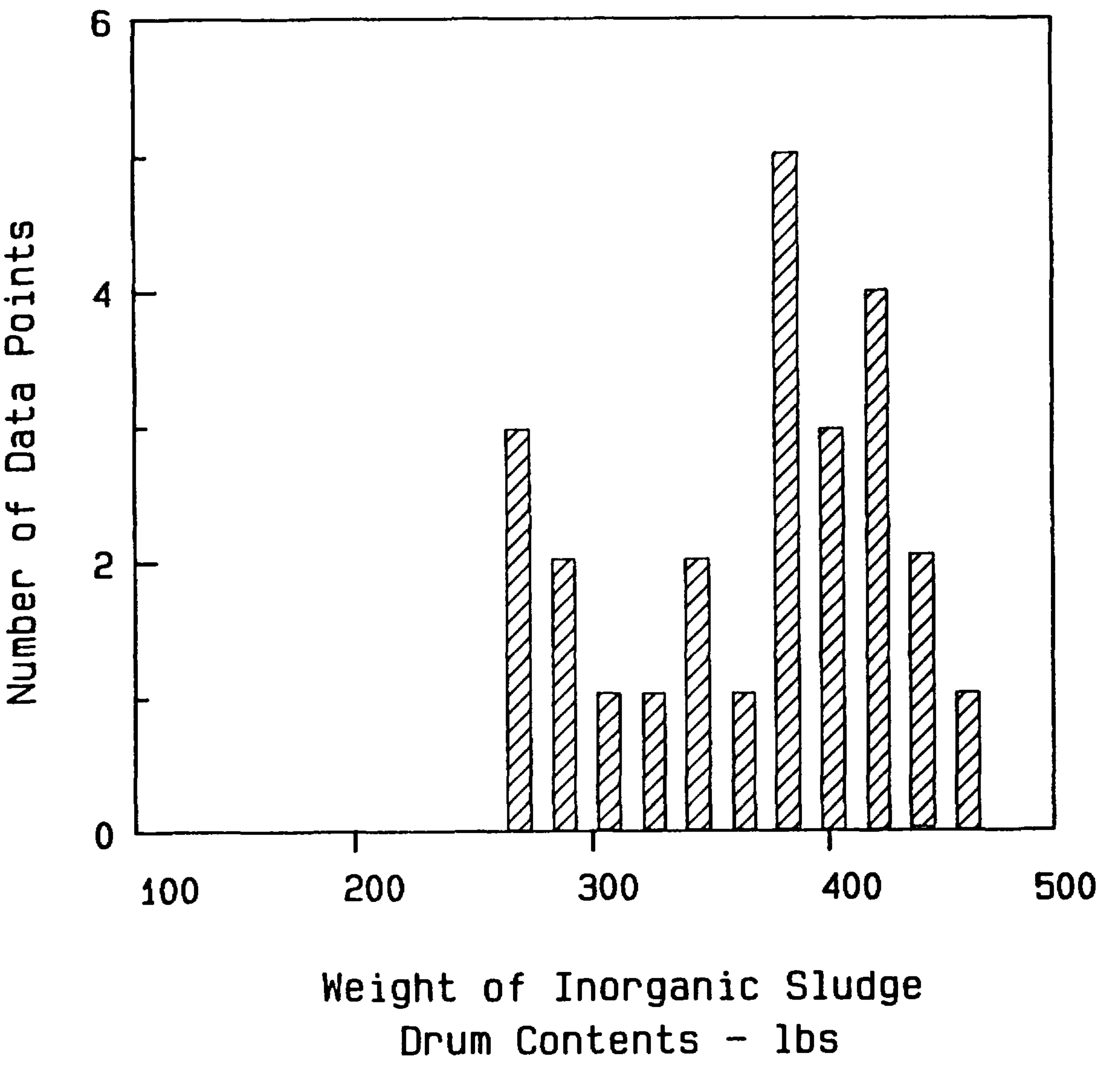

Figure 9. The weight distribution of the contents of drums containing INEL uncemented inorganic sludge waste.

4. COMPACTION PROPERTIES OF SIMULATED WASTE

The maximum density achieved during compaction of a porous medium depends upon the amount of external stress. For the WIPP, this stress corresponds to the lithostatic pressure (15 MPa), which should be sufficient to compact the waste to a fairly dense state. The theoretical solid density of the waste[7] is important because densities at the upper end of the compaction curve must approach it in value. The purpose of this section is to estimate near-solid densities of the waste components for use in predicting the final compaction of various waste categories.

Three methods exist for estimating the theoretical solid density of simulated waste. The most obvious is to compact the waste and measure its density. This information will be obtained for WIPP experimentally. In a second approach, Clements and Kudera measured initial void volumes within different waste categories by removing a known volume of gas from each drum and measuring changes in internal gas pressure. The density of the solid material inside the drums can be determined from this data, the internal volume of the drums, and their tare weights, which are easily measured quantities. The disadvantage of this method is that only the average volume corresponding to the solid material and closed voids is resolvable. In addition, something must be known about the individual components of the drums to extrapolate results to new mixtures in the future.

A third method is to estimate reasonable solid densities for the generic waste components and use these values and the weights of the various components of each category to compute average solid densities for the waste. The validity of these estimates is checked by estimating the initial void volumes of "standard" drums of each category of waste for comparison with averages of values measured by Clements and Kudera.

Two sets of values for the "solid density" of the waste components were selected. The first set represents the density that would be observed for the material under enough stress to eliminate almost all porosity. These values, referred to as the theoretical solid densities of the components, are given in Table 9. To illustrate the basis for their selection, the density for cellulosics corresponds to a value for pine wood of 685 MPa, measured using shock wave loading techniques (LASL Shock Hugoniot Data, 1980). The density for metals is the weighted average of the densities of the major constituents of metal waste, and the density of the sorbents was assumed to be 2000 kg/m^3 (typical of hard brick).

The second set of values for the solid density of the waste is proposed because the theoretical values are considered too severe to use in estimates of compaction properties. Using metallic waste components as an

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7. The state in which no voids are present.

example, a load many times the lithostatic pressure at the WIPP horizon would have to be applied to eliminate all closed voids in these waste forms. This is due to the fact that very large stresses are required for plastic deformation of steel and other metals. Substantial residual porosity in the form of unconnected voids may exist in waste under more modest stresses. The presence of this component of porosity should be recognized in estimates of compaction properties and is the basis for a second set of values.

Densities based on the total volume of both solids and closed voids may be more appropriate for estimating compaction properties. For example, the solid density of cellulosic materials[8] was assumed to be about 500 kg/m^3, typical of unpressurized pine wood; metals and other high-density components were assumed to have solid densities of about 3000 kg/m^3. Later analysis showed that a "solid" density of 1500 kg/m^3 for the less compressible sorbents and metals appeared to give greater consistency with Clements and Kudera's experimental results. Void fraction comparisons based upon solid plus closed-void densities (Table 10) compare favorably with average void volumes reported by Clements and Kudera. These values and the values computed using theoretical solid densities comprise a range within which the experimentally determined values (work in progress) should fall.

Another variation of this analysis can be used to examine how the initial void fraction (or volume of the solids) within individual drums might be estimated from the weight of their contents. Figure 10 shows a correlation between weight and pore fraction of combustible category waste drums. This prediction assumes that the portion of the drum volume that is not void, according to Clements and Kudera's measurements, is occupied by waste at near theoretical solid density. Similar results for metallic waste (Figure 11) show that the void fraction appears nearly independent of the weight of the drums, a correlation expected because the solid volume of the metals is such a small fraction of the drum volume. Finally, a correlation is observed between the initial void fraction and the weight of drums of inorganic sludge (Figure 12), but the data for organic sludge (Figure 13) are too scattered to show a similar correspondence. These results can be used to adjust the theoretical solid volume of the waste when the weight of a drum is quite different from the average weight of the drums in its waste form category.

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8. Densities expected under consolidation pressures on the order of lithostatic pressure

Table 9. Recommended Theoretical Solid Densities for Simulated Waste Components.

Component	Solid Density (kg/m³)	Solid + Closed-Void Density (kg/m³)	Closed-Void Porosity (%)
Cellulosics (paper, cloth, wood, etc.)	940	500	47
Plastics	1200	1000	17
Sorbents	2000	1500	25
Metals, metals components	6500	1500	77
Sludge	--	1400	--

Table 10. Waste Void Volume Ratios.

Category	Measured by Clements and Kudera	Estimated from Solid + Closed-Void Densities	Estimated from Theoretical Solid Densities
Combustibles	0.75 ± 0.136	0.76	0.82
Metals	0.77 ± 0.14	0.79	0.89
Sludge[a]	0.435	-	-

a. The value for sludge represents the average for all sludges. Organic sludge void fractions are less, with average values as low as 0.3.

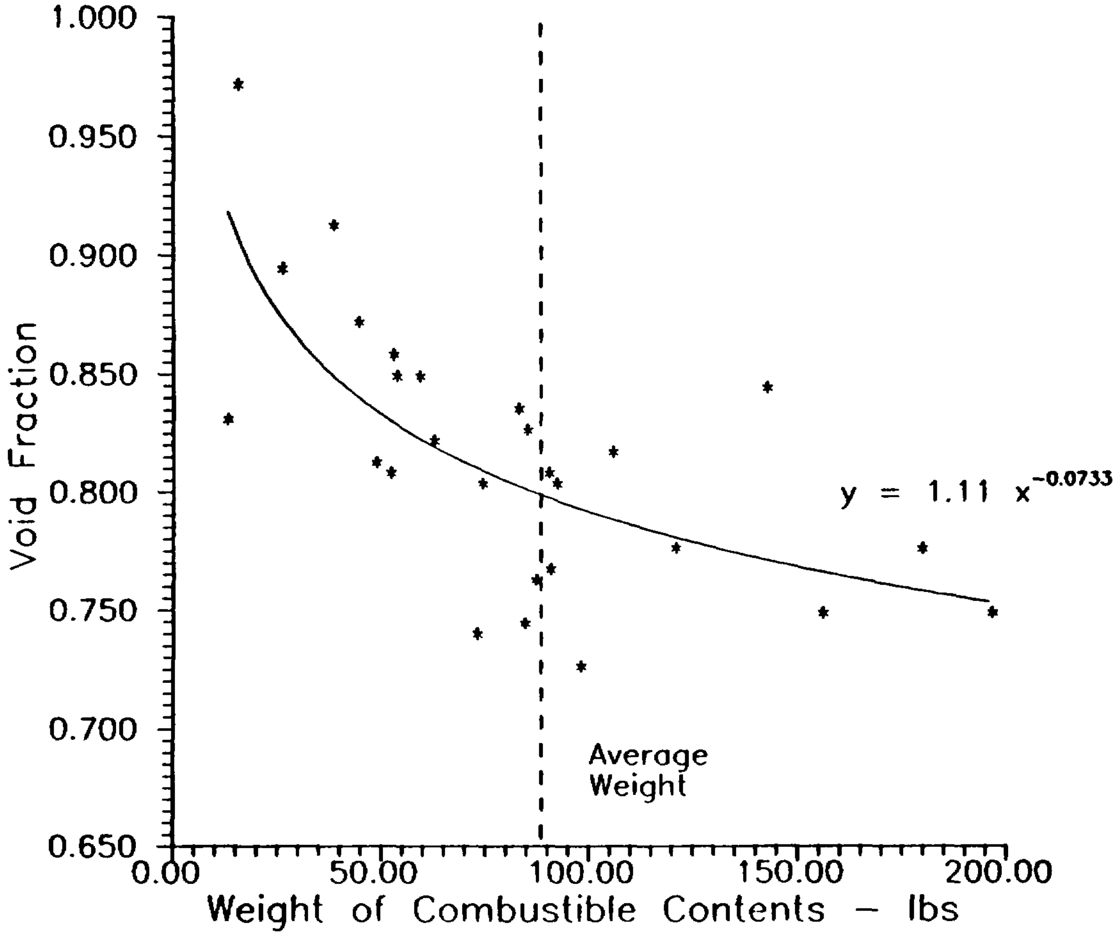

Figure 10. The initial void fraction variation of drums containing INEL combustible waste.

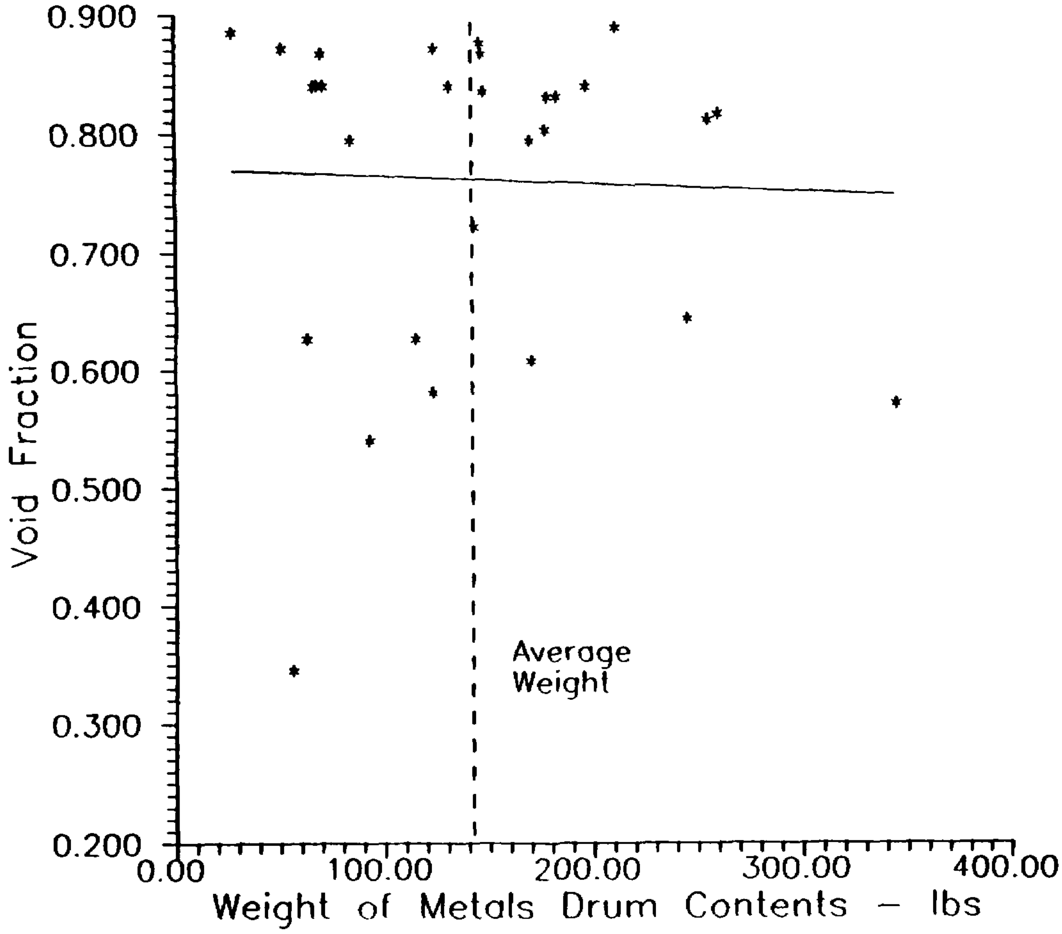

Figure 11. The initial void fraction variation of drums containing INEL metallic waste.

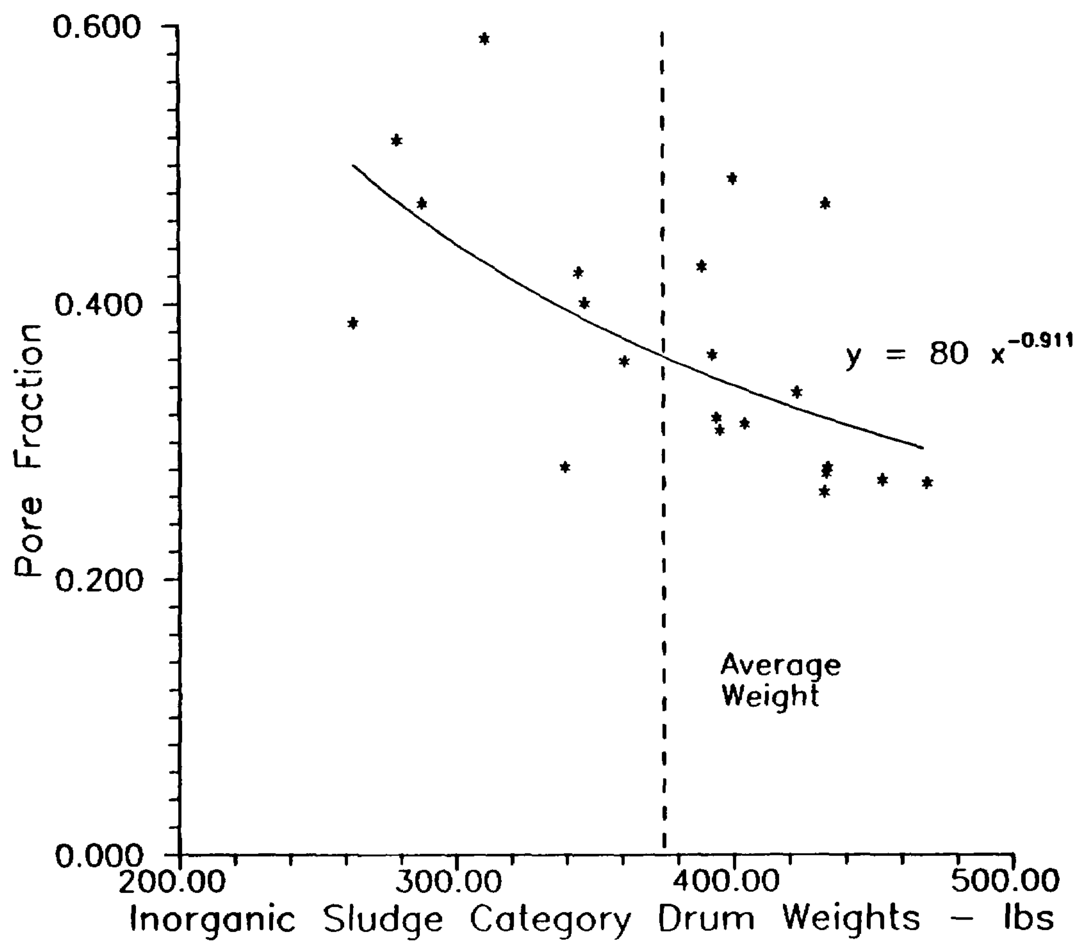

Figure 12. The initial void fraction variation of drums containing INEL uncemented inorganic sludge waste.

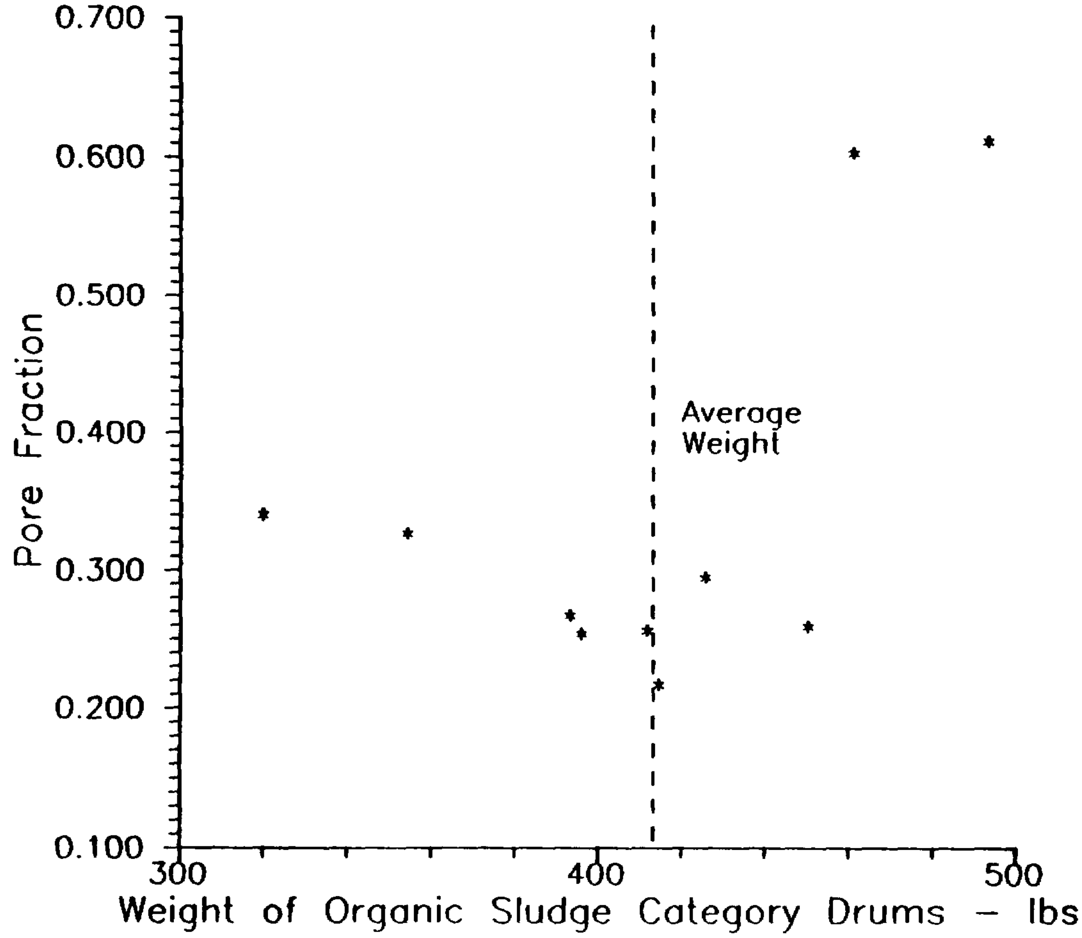

Figure 13. The initial void fraction variation of drums containing INEL uncemented organic sludge waste.

5. SELECTION OF SIMULATED WASTE MATERIALS

Selection of materials for simulated waste entails a trade-off between what can be reasonably acquired and what is thought representative of real waste (Tables 4 & 5). For example, in considering materials suitable for making simulated combustible waste, lunch-room garbage and waste paper do not seem appropriate because the composition of this garbage is hard to define. A better approach is to use well-defined mixtures of materials, because the reproducibility of test results increases confidence in extrapolations to new compositions. Similar considerations apply to metallic waste and sludges.

The desired simplicity of simulated waste can be accomplished by analyzing the generic nature of each component. For example, Table 4 implies that polyethylene and PVC represent a major portion of the plastics component in combustible waste. Though lesser amounts of other plastics are often present, according to Clements and Kudera's study, these materials are unlikely to have much influence on compaction. Furthermore, the bulk response of polyethylene near theoretical solid density is not likely to be much different from PVC. Therefore, a mixture of polyethylene and PVC, although not an exact representation of the plastics in combustible waste, is thought to be suitable for representing the plastics in simulated waste. A ratio of approximately 2 parts by weight of polyethylene to 1 part PVC has been proposed in past investigations (Kosiewicz et al., 1979).

Once a generic material has been selected for simulated waste, its form must be considered. Using combustible waste again as an example, it is difficult to imagine how any cellulosic would have sufficient strength to resist compaction to near theoretical solid density. Therefore, shredded paper and rags should be suitable for simulating cellulosic materials in combustible waste.

As another example, while polyethylene bottles are more representative of real waste, polyethylene in pellet form would be much cheaper and easier to handle. Unlike cellulosics, however, certain types of PVC products might be rigid enough to initially withstand compaction at lithostatic pressure. Although the chances of plastics retaining their shapes under high stress over long periods of time is slight, large voids could remain in uncollapsed waste, eventually filling with brine.

The problem of incomplete compaction is even more complex for metal junk and is of concern because migration of soluble radionuclide species might be enhanced by interconnectivity between large brine pockets. To investigate the likelihood of large voids being retained in the waste, part of the material can be composed of easily identified, hollow, difficult-to-compress objects of known shape and void space (for example, pipe, pipe elbows, and pipe tees). After compaction testing, these objects would be recovered and examined to determine their extent of collapse and the amount of surrounding material that has flowed into them. Other objects in the waste that could reduce compaction can be identified. If these objects prove to be a critical part of compaction, radiographs taken to certify drums' suitability for storage at the WIPP could be examined to identify incompressible objects.

Characterization of sludges is more difficult. Sludges come from a number of sources and may have highly variable compositions. One type of sludge is created when aqueous wastes from the plutonium recovery area at Rocky Flats Plant are treated in a hydroxide precipitation process to remove heavy metallic elements. The resultant slurry is passed through a rotary drum vacuum filter and precoated with diatomaceous earth filter media to remove solids from the waste stream. A thin layer of filter cake is continuously cut from the drum filter, producing a wet sludge with a water content up to 60%. The wet sludge does not meet the WIPP Waste Acceptance Criteria, which prohibit free liquids, so operational practice has been to add a 1:1 portland cement/diatomaceous earth mixture to the waste container to absorb free liquids. The average waste loading for the process is approximately 40% sludge.

Other less well-defined sludges are the solid residues recovered from water-filled storage and holding tanks, catch basins, and other accumulators of extraneous solids and organic residues. Since a part of these residues is composed of air-borne dust and dirt, Huerta (1983) used pea-sized fragments of crushed rock, sand, and oil dry (a light-weight clay particle material) to simulate a light-weight sludge, and Rocky Flats soil to simulate a dense sludge. Small amounts of water were added to both mixtures to adjust package weights. The theoretical solid density of about 1500 kg/m^3 estimated for the sludges in a previous section is comparable to average densities reported for packed earth materials (Marks' Handbook, Eighth Edition).

In general, earth materials such as sands become quite difficult to compress once initial compaction has packed the grains together. Consequently, if sludges are largely composed of earth materials, they will not exhibit the large changes in void volume during compaction expected for the more compressible cellulosics and plastic materials.

Organic sludges, which are loosely described as grease-setups of organic fluids in calcium silicate (Clements and Kudera, 1985), are denser and are expected to have little rigidity, a property that will permit them to flow and eliminate void volume when under low external pressures. Most of the void volume in organic sludge waste is therefore likely to be a consequence of lesser packaging efficiency and the presence of other materials such as sorbents. Because of lesser void volume in the grease-setup, it is believed to be relatively incompressible, with the consequence that simple estimates of its compaction response will probably be adequate for disposal room closure analyses.

Huerta's study, which represents the only measurements of the compaction of simulated waste materials, is further discussed in the next section. Drums containing his simulated sludge were the only drums that showed resistance to compaction.

6. COMPACTION CHARACTERISTICS OF WASTE MATERIALS

6.1. Background

Two previous studies of the collapse of CH waste drums provide insight into compaction response. The first (Huerta et al., 1983) was directed toward determination of the crush environments during a hypothetical transportation accident. Tests were conducted on full-scale, quarter-scale, and one-eighth-scale drums containing simulated combustibles and sludge. The objective of the second study, by VandeKraats (1987), was to determine when horizontal room convergence in the WIPP would load waste surrounded by backfill to the point where breaching would occur. This information was required to estimate operational conditions, if retrieval of the waste becomes necessary. These tests were conducted on quarter-scale drums.

In Huerta's study, loads were applied either along the axis of symmetry or laterally to the drums, until they collapsed to about two-thirds of their initial dimension. For combustible waste, this displacement eliminated only about 40% of the initial void volume, whereas the state of collapse of interest requires squeezing the drums to less than 25% of their original volume. Considering the high void content of combustible waste, the results of the tests on combustible materials were not surprising. The applied force increased rapidly until buckling of the drum occurred, after which collapse proceeded with little or no increase in force until the test was terminated. In contrast, drums containing simulated sludge were the only drums that showed resistance to compaction during later stages of the tests. Stiffening of sludge waste probably occurred because of lower initial void volumes and less compressible porous matrix.

Another conclusion of Huerta's study was that his quarter-scale experimental results compared favorably with full-scale data, but the scaled pressures to collapse one-eighth-scale containers were observed to be somewhat greater than expected. VandeKraats' study imposed an additional complication of surrounding the drums with backfill, which is beyond the scope of this report.

6.2. Construction of Compaction Relationships

For the present, individual components of a given waste category are assumed to compress independently of each other, and to have compaction relationships that can be represented by pressure, volumetric-strain relationships. These assumptions are discussed in Appendix A, which describes a method for deriving an empirical relationship for estimating the compaction response of simulated waste. Using these assumptions, the state of compaction of a drum exposed to an externally applied pressure, p, can be estimated from the compaction curves of its individual components by summing volumes. For V_i, the volume of component i at pressure p, the volume of the drum, V, will be:

$$V = \Sigma V_i \qquad i = 1 \text{ to } n$$

where n is the number of components. The method has been used to estimate bulk moduli of waste at theoretical solid density as described in Appendix A. For combustible waste, the equivalent bulk modulus is estimated to be about 150 MPa, and for metallic waste a value about ten times greater, or 1500 MPa is predicted.

Unfortunately, derivation of curves for the various waste forms is not possible until more is known about compaction of their components. A program to provide experimental information is in progress. Once the compaction response of a given component is available, it can be added in proportion to its volume to similar information for other components to arrive at a curve for the response of the mixture. Although baseline curves for the standard mixes of waste described in this report are of primary interest, the method should be applicable to other combinations of waste, as they become important.

7. SUMMARY

Analyses of the final state of collapse of various types of CH waste drums are required for the disposal room models used to examine the performance of the WIPP over long periods of time. To provide input information for these calculations, tests will involve simulated waste. Data on the contents of the principal categories of CH TRU INEL waste, reported by Clements and Kudera, were used to define standard compositions of simulated waste. These compositions were obtained by determining the average weights of different components of the drums. To create a baseline waste, the appropriate amount of the simulant of each component will be mixed together and placed in DOT-17C drums. Selection of simulant materials was discussed, as was the need for including hard-to-collapse items to investigate situations where consolidation pressures may be insufficient to eliminate certain types of voids.

Methods for estimating the compaction characteristics of simulated waste were also explored. Theoretical solid densities for the major waste components were estimated to obtain an upper bound for the densities of fully consolidated material. These results were used to estimate initial void volumes, which compared favorably with initial void volume measurements made by Clements and Kudera, and the end-point compressibility of the waste near the theoretical solid state. Information about initial compaction from measurements by Huerta et al., was also reviewed. If components of a given waste category compress independently, and if the response of the waste at the beginning and end points of compaction can be bounded, a first approximation of compaction curves is possible by interpolating between these two limits. A method for estimating compaction curves is described in Appendix A.

REFERENCES

Clements, T. L. Jr., and D. E. Kudera, "TRU Waste Sampling Program: Volume 1--Waste Characterization," EG&G report EGG-WM-6503-Vol.1, September 1985.

DOE/RW-0006, Rev 4, "Integrated Data Base for 1988: Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics," Prepared by Oak Ridge National Laboratory, September 1988.

Huerta, M., G. H. Lamoreaux, L. E. Romesberg, H. R. Yoshimura, B. J. Joseph, and R. A. May, "Analysis, Scale Modeling and Full-Scale Tests of Low-Level Nuclear Waste Drum Response to Accident Environments," Sandia National Laboratories, SAND80-2517, January 1983.

Kosiewicz, S., B. Barraclough, and Zerwekh, "Studies of Waste Storage Under Conditions Expected in the Waste Isolation Pilot Plant (WIPP), An Interim Summary Report," Los Alamos Scientific Laboratory, LA-7931-PR, October 1977-June 1979.

LASL Shock Hugoniot Data, Stanley P. March, Editor, University of California Press, Berkeley, 1980.

Marks' Handbook, 8th Ed.

Rocky Flats Plant Standard SX-200.

Shefelbine, H. C., "Preliminary Evaluation of the Characteristics of Defense Transuranic Wastes," Sandia National Laboratories, SAND78-1850, November 1978.

VandeKraats, J., "Quarter-Scale Modeling of Room Convergence Effects on CH TRU Drum Waste Emplacements Using WIPP Reference Design Geometries," Westinghouse Electric Corporation, DOE/WIPP 87-012, November 1987.

APPENDIX A:

AN EMPIRICAL RELATIONSHIP FOR THE COMPACTION OF SIMULATED WASTE COMPONENTS

A.1 Initial Considerations

The relationship for the compaction of combustible waste is based upon several observations. First, according to unconfined compression measurements by Huerta et al. (1983), little increase in strength is observed during initial compaction of the dominant waste forms (combustibles, metals, and sludge) once the drum crush strength of 0.1 MPa is exceeded. The reason is probably that the waste is loosely packed, so the first stage of compaction simply collapses air space in the top of the drums. Although Huerta's results were on drums laterally unconfined in the direction of loading, the observed lateral expansion was limited. Thus, as a first approximation, changes can be neglected in the cross-sectional area of the drums during the early stages of the tests and it can be assumed that pressure-volume strain data would be similar to the observed results, because the axial deformation would reflect the change in volume.[9] In constructing a bilinear material model for drum collapse, Huerta used a value of 0.1 MPa for the initiation of irreversible drum collapse, with subsequent collapse defined by a stress-strain curve with slope 0.31 MPa to a maximum strain of 0.4. It is assumed initially that these parameters apply to the initial part of our pressure-volume relationship.

A second observation in constructing a relationship for the compaction of combustible waste is that compressibility, as the waste approaches solid density, can be related to the compressibilities of the solid forms of its constituents. For example, an assumption made in estimation of the void content of combustible waste drums was that the near-solid state of paper, cloth, and wood was comparable in density to pine wood. Pine wood, when compacted to a high pressure has a maximum bulk modulus of about 90 MPa (LASL Shock Hugoniot Data, 1980), which should also be an order of magnitude value for the bulk modulus exhibited by highly compacted paper,

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9. If no lateral expansion occurred and the waste had little shear strength, which is likely at such large void contents, the axial strain would be the same as the volume strain. In actual compaction processes, the lateral stresses acting on the waste are expected to differ from the axial stress, introducing deviatoric stress components into the three-dimensional stress field. However, following traditional continuum mechanics, compaction response can be defined from a pressure-volume relationship because the deviatoric stresses are usually not associated with changes in volume.

cloth, and wood. The bulk moduli of other components of the waste can be estimated in a similar manner, as shown in Table A1. The equivalent bulk modulus for the mixture is computed from:

$$1/K = f_1/K_1 + f_2/K_2 \ldots,$$

where f_1, f_2, etc., are the volume fractions of each component in the fully crushed waste[10] and K_1, K_2, etc., are the respective bulk moduli. The value for the equivalent bulk modulus is clearly dominated by the bulk modulus of the most compressible component: for combustible waste, the equivalent bulk modulus is estimated to be about 150 MPa and for metallic waste about ten times greater, or 1500 MPa.

Compaction analysis is in most cases attempting to define how much void volume can exist at a given compaction pressure. Therefore, the void fraction, f_v, is more useful as the independent variable than the volume strain. Whereas the volume strain is defined as

$$\varepsilon_v = (V_0 - V)/V_0 = 1 - \rho_0/\rho,$$

the void fraction is defined as

$$f_v = (V - V_s)/V = 1 - \rho/\rho_s,$$

and

$$f_v = (f_{v0} - \varepsilon_v)/(1 - \varepsilon_v), \quad \varepsilon_v = (f_{v0} - f_v)/(1 - f_v),$$

where V_0 is the original volume of the waste, V is the volume at pressure p, and V_s is the theoretical solid volume of the waste.

This definition shows that when the waste is compacted to near-solid density, the volume fraction approaches zero, which is often desired in compaction. Since bulk moduli values are to be defined near theoretical solid density, a relationship between the bulk modulus and the void fraction is required. For

$$K = \rho \, dp/d\rho$$

$$K = (1 - \varepsilon_v)dp/d\varepsilon_v = -(1 - f_v)\, dp/df_v$$

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10. To determine volume fractions f_i from weight fractions w_i, for unit thickness $l_i = f_i/\rho_i$, where ρ_i is the density of the ith component. The total thickness l is therefore the sum of the l_i's, $l = \Sigma\, l_i$, $i = 1$ to N, the number of components, and $f_i = l_i/l$.

Table A1. Crushed Volume Bulk Modulus Values for Combustibles.

Component	Bulk Modulus at Theoretical Solid Density	Crushed Volume[a] per Drum
Cellulosic materials	0.090 GPa (Pine Wood)	0.0300 m^3
Plastics	5.70 GPa (Polyethylene)	0.0179 m^3
Sorbents	1.60 GPa (Powdered Tuff)	0.0018 m^3
Metallic	32.0 GPa (2.6 g/cm^3 Aluminum)	0.0012 m^3
Total		0.0509 m^3

a. The solid + closed-void density values listed in Table 9 were used to compute these volumes.

A.2 Construction of the Compaction Relationship

The information available for constructing a relationship for the compaction of combustible waste giving f_v as a function of p is:

(1) A linear relationship between p and $0<\epsilon_v<0.4$ with slope $K_0 = 0.3$ MPa (from Huerta's data). The pore volume measured by Clements and Kudera is 0.75, so that a range from 0 to 0.4 in ϵ_v corresponds to a range from 0.75 to 0.58 in f_v.

(2) The constraint that as the pressure becomes very large, the slope of the compaction curve for the waste approaches a value consistent with the equivalent bulk modulus of its solid components; $K_s = 150$ MPa.

A function that satisfies these conditions is:

$$f_v = a_0 + a_1 \cdot p \qquad 0.75>f_v>0.58$$

$$f_v = b_0 + b_1 \cdot p + b_2 \cdot \exp(-b_3 \cdot p) \qquad 0.58>f_v$$

with a_0, a_1, b_0, b_1, b_2, and b_3 constants. The first equation is an approximation of the linear relation between p and ϵ_v observed during early stages of the collapse process;[11] the term involving constant b_1 in the second equation (for $f_v<0.58$) assures a constant bulk modulus value as the pressure becomes very large, as can be seen from its derivative.

$$df_v/dp = b_1 - b_3 \cdot b_2 \cdot \exp(-b_3 \cdot p) = -(1 - f_v)/K \qquad 0.58>f_v$$

In addition, because total elimination of all voids in a material is extremely unlikely, the constant b_0 is used to limit the value of the bulk modulus at some residual porosity level, say $f_v = 0.02$ (2%).

Using the information in the previous paragraph, values of the constants were determined for combustible waste:

$a_0 = 0.89$
$a_1 = -1.39$
$b_0 = 0.02$
$b_1 = -0.006533\ \text{MPa}^{-1}$

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11. A relationship completely consistent with a linear relationship between p and ϵ_v would have the form:

$$f_v = (p + a_0)/(p + a_1) \qquad 0.75>f_v>0.58$$

However, data scatter in Huerta's study was enough to make a linear relationship between p and f_v, matching the end points of the p-ϵ_v relationship equally acceptable.

$b_2 = 0.969$
$b_3 = 2.46\ MPa^{-1}$

Constant b_0 is assumed, b_1 is computed from K_s, a_0 and a_1 are from Huerta's data,

$$b_3 = (b_1 - a_1)/(0.58 - b_0 - b_1*(0.58 - a_0)/a_1)$$

and

$$b2 = (b_1 - a_1)/b_3* \exp(b_3/a_1*(0.58 - a_0)).$$

These constants were used to compute the baseline compaction curve for combustible waste shown in Figure A1. Although the empirical relationship for compaction is physically consistent at the upper and lower ends of the range of void fractions, it is unlikely to agree with experimental results at intermediate points of compaction. To force agreement with experimental data, the curve will probably have to be scaled up or down with pressure (the easiest variable to adjust). The data can be scaled by augmenting it by the difference between the measured compaction pressure and the pressure computed from the uncorrected compaction relation at a given void fraction f_v. A second way of obtaining better correspondence of the curve with experimental observations is to adjust its initial slope. While this procedure may cause the compaction curve to differ from experimental observation of the initial stages of compaction, it will improve representation of the final stages, a region that is of greater interest.

An example of the application of scaling procedures to improve compaction curves is illustrated by a preliminary curve for inorganic sludge, shown in Figure A1. Sludge drums are estimated to have an initial void fraction of about 0.435. In constructing a compaction curve for sludge, the initial slope of the curve has been adjusted upward from the experimental observations by Huerta et al., (1983) to make the curve rise more sharply at low values of the void fraction. Making the waste stiffer than the data implies is necessary because Huerta's tests were laterally unrestrained, a factor that would make the computed void fraction appear too small.

To make these curves more credible, therefore, two types of information must be obtained. First, the approximate density of the waste at lithostatic pressure must be measured, and second, experimental definition of the void fraction where easy collapse ceases and the waste begins to stiffen is required.

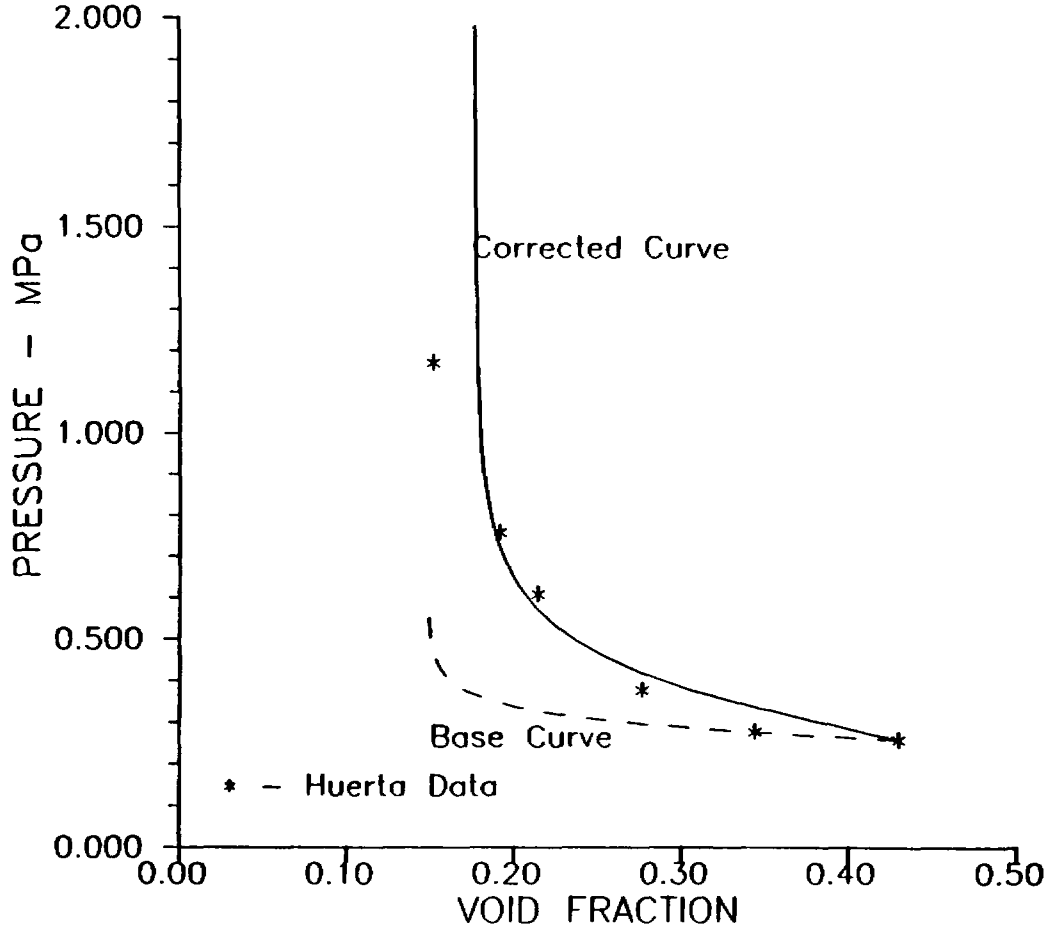

Figure A1. A compaction curve for uncemented inorganic sludge.

A.3 Nomenclature

V, ρ	-	The volume and density of the backfill at time t.
V_0, ρ_0	-	The initial backfill volume and density (voids + solid)
V_v	-	The void volume in the backfill
V_{v0}	-	The initial void volume in the backfill
V_s, ρ_s	-	The volume and density of the fully compacted state of the backfill (all voids eliminated).
ε_v	-	The volume strain; $\varepsilon_v = (V_0 - V)/V_0 = 1 - \rho_0/\rho$
f_v	-	The void fraction; $f_v = (V - Vs)/V = 1 - \rho/\rho_s$
f_{v0}	-	The initial void fraction; $f_{v0} = (V_0 - V_s)/V_0$;

$$V_{v0} = f_{v0}V_0, \quad V_v = f_vV;$$

$$f_v = (f_{v0} - \varepsilon_v)/(1 - \varepsilon_v), \quad \varepsilon_v = (f_{v0} - f_v)/(1 - f_v);$$

$$d\varepsilon_v/df_v = -(1 - f_{v0})/(1 - f_v)^2;$$

$$df_v/d\varepsilon_v = -(1 - f_{v0})/(1 - \varepsilon_v)^2;$$

K	-	Bulk modulus; $K = \rho\, dp/d\rho = (1 - \varepsilon_v)dp/d\varepsilon_v$;

$$K = -(1 - f_v)\, dp/df_v$$

K_s	-	Bulk modulus at the waste theoretical solid density

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