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THE ANAEROBIC DIGESTION OF ORGANIC SOLID WASTES

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ABSTRACT

Anaerobic digestion offers many advantages in the processing of organic solid wastes, using a closed system to convert the waste to combustible gas and a stabilized organic residue. Odors are contained while digestion removes their source and gas is collected for energy recovery as heat or electricity. The stabilized residue is less than the starting waste by the mass of gas produced, and it can be disposed of by land application, land filling, incineration or composting.

The stimulation of digesters and the phenomenon of co-digestion are two ways the performance of anaerobic digesters can be enhanced. Data from farm digesters and municipal wastewater treatment plants illustrate the present venue of the process; laboratory studies of the anaerobic digestion of a variety of solid wastes show that the process can be applied to these materials as well. About two thirds of municipal solid waste is shown to be amenable to anaerobic digestion in a substrate from an active municipal sewage plant digester.

BACKGROUND

Anaerobic digestion is a process which converts organic matter into a gas and a stabilized residue, by microorganisms in the absence of oxygen. Many microorganisms thrive in anaerobic environments such as swamps, peat bogs, soils, aquatic deposits, forest litter, the digestive tracts of animals, for example. Anaerobic digestion was an essential step in laying down fossil fuels like coal, oil, lignite and natural gas. The process occurs inadvertently in many places where organic matter is kept in a way that generally excludes oxygen, such as land fills, sewer lines, etc; gas is evolved and undesirable components which are odorous or toxic may be released to the environment from these uncontrolled sources.

The largest intentional application of anaerobic digestion by man has been in the stabilization of municipal wastewater sludges. From here, the practice has begun to spread to the treatment of animal wastes [Robinson, 1980], waste streams from food processing plants [Price and Cheremisinoff, 1981a] and to the digestion of organic wastes from chemical plants [Torpy, 1988]. For these applications, digesters are built which exclude air so that anaerobic processes can take place. Most digesters also provide temperature control [commonly 95-100F], and at least enough mixing to distribute the raw feed and to release the gas generated so that the biochemical reactions may continue.

Digesters vary in construction from the simplest rectangular pits used on farms to sophisticated, engineered structures that minimize retention time to achieve the desired digestion. In municipal sewage plants digesters are generally vertical cylinders, often with floating roofs to provide some gas storage space and a pressurizing mechanism; this is especially useful when the gas, which is combustible, is used onsite with a varying demand for digester heating, hot water, electricity generation, etc. In all cases, provision is made to feed periodically, to exclude air, to capture the gas generated, to contain odors while digesting the materials that produce them, and to provide for the withdrawal of stabilized sludge. In some designs, clear supernatant liquor can also be drawn from the digester, effectively increasing its capacity, and reducing the sludge volume for disposal [Price and Cheremisinoff, 1981b].

The gas produced by anaerobic digestion is typically about 70% methane by volume and 30% carbon dioxide. Such a gas undergoes self-sustained combustion in air with a release of energy of about 700 Btu per cubic foot. This energy can be recovered in furnaces which are often used to heat digesters to the desired operating temperature, and also to provide hot water for domestic or process use. Gas of this composition can fuel reciprocating gas engines, to generate electricity for example, with only a simple knock-out pot for cleaning. Differences in feed materials and in operating conditions may affect the gas composition somewhat; the introduction of air into the digester results in a rapid loss of methane content, and hence combustibility, and this condition should be carefully avoided.

The other product of anaerobic digestion is the stabilized organic residue or sludge. The term "stabilization" means reduction or elimination of microorganism activity. In the case of raw sludge that is treated with lime, stabilization is achieved by creating conditions in which the microorganisms cannot live or reproduce; no organic material is lost in the process. In the case of digestion, stabilization occurs by removal of the organic substrates on which the microorganisms subsist; organic material is lost, and the microorganisms slow down or stop their activity. If anaerobic sludge is to be spread on the ground, regulations require that at least 38% of its volatile solids be removed by digestion; this level of stabilization is found to guard against nuisance odors.

The destruction of volatile solids, or VSD, is the common and convenient way to monitor the performance of an anaerobic digester. Volatile solids are defined as those driven off by heating a sample to 550c in air. In practice, representative samples of the feed into the digester and the sludge out are obtained; these are dried, then heated to determine the volatile solids, VS_i and VS_o, respectively. These values are then used to calculate VSD according to this relation:

$$VSD = 100[1 - \frac{VS_o}{VS_i} \times \frac{100 - VS_i}{100 - VS_o}] \quad [1]$$

The 38% - VSD requirement should apply to all anaerobic sludge for land application; sludge digested to a lesser degree will have odor problems, which usually cannot be blended away by combining with more highly digested sludge. In much of the data to be cited here a higher standard of digestion, 60% VSD, has been imposed, because it was desired to produce a stabilized residue that would not emit any more gas when placed in a land-fill.

PLANT SCALE DIGESTION DATA

The anaerobic digestion data included in this paper come from two kinds of test work. The first was conducted in full-scale municipal wastewater plants, and also full-scale farm digesters for handling animal manures. These projects were undertaken to study the effect of peat humic substance [PHS] as a stimulant for anaerobic digestion. Peat humic substance is a recognized stimulant for many living systems, including soil microorganisms, and the work referenced here showed it to be effective in anaerobic dig-

TABLE 1

SUMMARY OF SIX ANAEROBIC WWT PLANTS TREATED WITH PHS

Plant	A	B	C	D	E	F
Flow, mgd	2	4	2	3	1.5	5
Sludge removal	Wet	Beds	Wet	Land	Wet	Belt
Treatment, years	1	1	2	8	4	4
PHS conc.*	0.25	0.2	0.2	0.4	0.3	0.25
Sludge red., %**	50	15	70	20	50	35
Notes	-	Added PHS scum box ***	Started methane	Red. odor	Red. odor	Started methane

* Active peat humic substance [PHS] in digester, ppm on total contents.
** B,D,F: Due to better digestion; A,C,E: Better digestion and supernating.
*** PHS added to digester feed in all other cases.

estion as well. PHS is a general stimulant for conglomerate populations which is able to increase the activity of microorganisms which cannot metabolize it directly. However, it works by being metabolized by some of the higher members of the complex populations; the enzymes and metabolites released are believed to be responsible for the observed general increase in activity throughout the system. Because it is metabolized it must be replaced regularly [usually daily] to sustain its effect in digesters. Very low concentrations are effective; in anaerobic digesters less than 1 ppm active PHS based on total digester contents is typical.

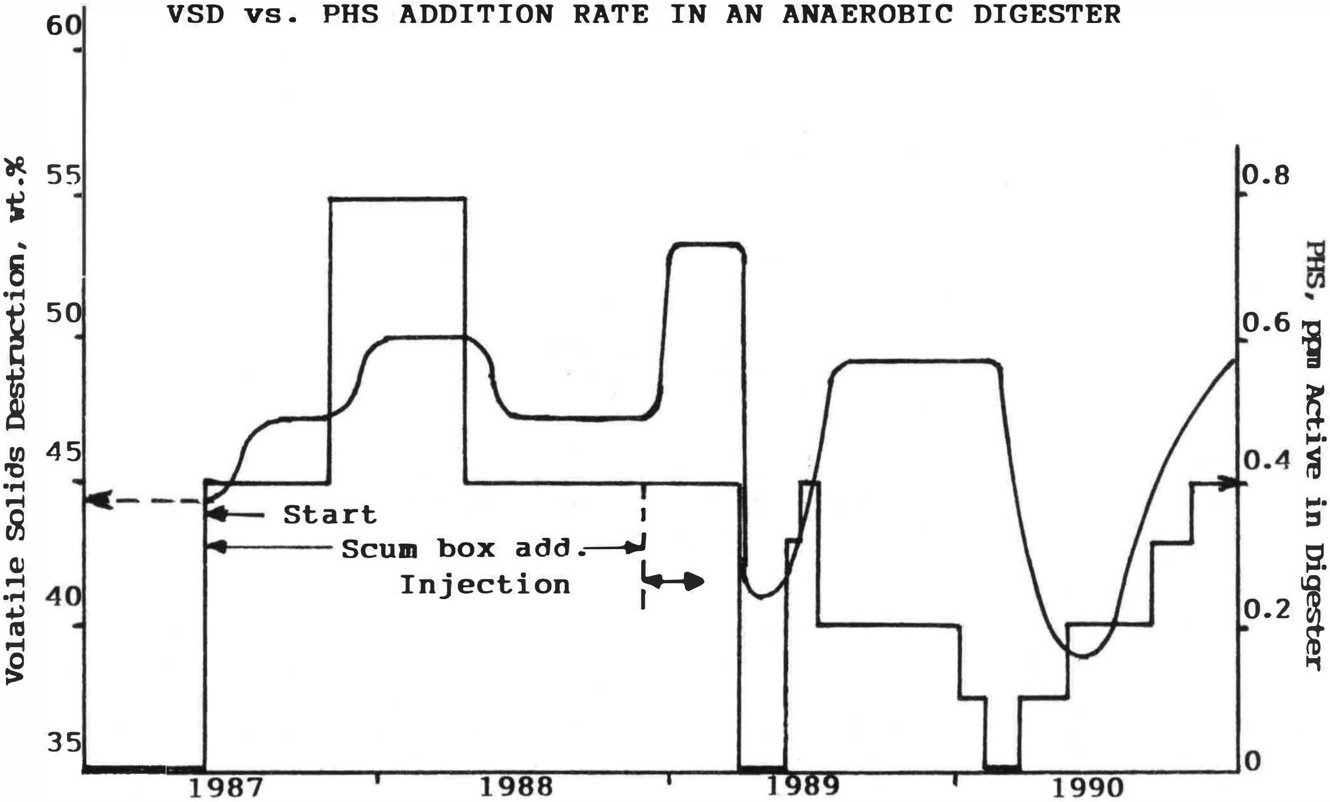
MUNICIPAL PLANTS

In Table 1 a review of six plants with anaerobic digesters provides some interesting and useful operating background [Hartung, 1990]. Digesters in two of the plants [C and F] were not producing combustible gas, a condition which stimulation was able to correct. Plant D was occasionally marginal in performance; stimulation raised VSD to a degree where land application of its sludge could be practiced with confidence. The other three plants [A, B and E] were operating well; in all cases stimulation increased the activity of the anaerobic digesters significantly. In all these plants operators had different views of what problems they wished to overcome; in each case, digester activity was the key to the solution. A more detailed description of the operation of one of the plants [C] provides more data on digester and general plant performance, and the degree of reduction in sludge and odor from PHS stimulation [Hartung, 1992].

Plant D in this group has been treated for eight years. Recently plant operating data were studied to try to relate VSD to the level of PHS treatment. Figure 1 is the result of this analysis over a four-year period in which treatment was started and varied over a wide range, including two intervals when no treatment occurred. It is quite apparent that there is a relation between treatment level and resulting VSD, and that direct injection into the digester is more effective than scum-box addition. After several months of injection, in 1990, the substrate is so active that interruption of treatment causes a slow, rather than precipitous, decline in activity; this high activity persists today. This plant is an award-winner for its beneficial use of sludge it produces.

FIGURE 1

VSD vs. PHS ADDITION RATE IN AN ANAEROBIC DIGESTER



FARM DIGESTERS

The use of farm digesters to stabilize animal manures is known; it has received added attention recently [Lusk,1995]. Two stimulation tests have been run in farm digesters where the gas has been used to generate electricity [Hartung,1991]; one of these processed dairy cow manure, the other hog manure. Table 2 summarizes the data in these operations and Figures 2 & 3 show the levels of digestion in these units before, during and after stimulation. In both cases VSD increased during treatment and declined when the treatment stopped. Both anaerobic units were farm-built digesters, lined excavations covered with flexible plastic sheets to capture the evolved gas. In both cases digester gas went directly to the engines, with only casual knock - out of suspended droplets; in both cases, hot jacket water was used in the farm operations.

While the data in all these full-scale studies were obtained to illustrate stimulation, they also provide case studies of the use of anaerobic digestion to process human and animal wastes. That stimulation improved the operation should not deflect attention from the fact that anaerobic digestion is an excellent way to stabilize these wastes.

LABORATORY TESTS

Laboratory anaerobic digestion tests, developed in conjunction with the plant work described above, and with which excellent correlation is found, constitute the second source for data reported here. These tests are conducted in calibrated

TABLE 2

DIGESTION OF ANIMAL WASTES

	VSD, weight percent	
	Untreated	PHS Treated
1000 dairy cows	21	36
11000 hogs	41	63

FIGURE 2

DAIRY COW MANURE DIGESTION WITH PHS STIMULATION

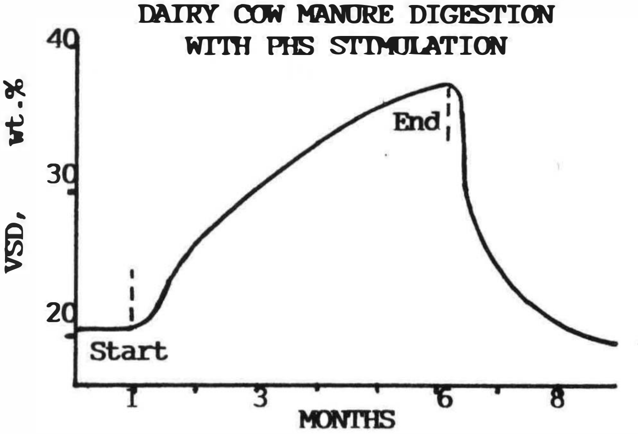
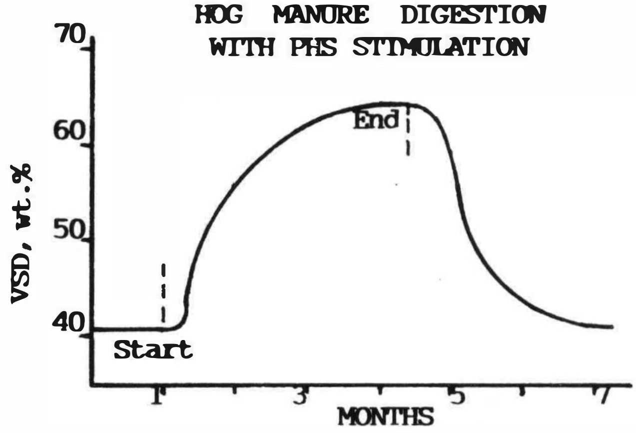


FIGURE 3

HOG MANURE DIGESTION WITH PHS STIMULATION



transparent flexible plastic pint bottles about 2/3 full with a substrate to which materials under test are added. The bottle is squeezed to expel air, then tightly sealed to retain the anaerobic condition and placed in a constant-temperature enclosure. The bottles are periodically shaken to break out gas, the level of which can be read from the outside. As gas is generated the squeezed bottle inflates to regain its original shape. When sufficient gas is generated [25cc or more] the bottle can be opened to check for combustibility by applying a flame to the neck as the bottle is squeezed to eject the gas. If desired, the gas can be sampled for analysis. It is recommended for safety that test bottles be vented before they become highly pressurized, although no instances of rupture have ever been experienced in the many hundreds of tests that have been run by this method; gas permeates the substrate as pressure builds, and the biochemical reaction slows down and stops, as the laws of equilibrium require.

After each opening, the bottle is sealed again after voiding the gas. The object of the test is to obtain data on the time rate of gas generation. Figure 4 illustrates a typical result; this is from a test in which the feed stock was green needles from an Eastern white pine tree, and the cumulative gas evolution is plotted versus time. Curves of this shape are encountered regularly, and in this case it has been fitted to calculated first-order kinetics, with a small induction period. This is a significant result as it shows that the substrate is populated with many highly active organisms so that the rate of reaction is governed only by the amount of food available from the pine needles. Substrates used in all of these tests are from a stimulated anaerobic digester in a municipal sewage plant; the substrate is kept at test temperature under anaerobic condition for several weeks until all gas formation ceases. In this way, substrates well-populated with potentially active microorganisms are used and any activity demonstrated in the test must come from test feed rather than substrate.

The earliest laboratory tests in this program to study the anaerobic digestion of solid waste materials focused on yard type wastes: Dry and green leaves, sawdust to simulate wood waste, hedge clippings, and lawn mowings both dry and green. Volatile solids were determined on each feed material and the digestion test was conducted long enough to allow calculations of the retention time needed to achieve 60% VSD, which was taken as an index of digestibility. It was found that materials digested much more rapidly when green than when dried, and that green grasses in particular are especially digestible. Data on a number of these materials are shown in Table 3. The 60% VSD criterion was chosen from laboratory experience to represent a degree of VSD where landfill material would not produce further gas;

TABLE 3

LABORATORY ANAEROBIC DIGESTION RATES FOR COMMON WASTES

Material		Days for 60% VSD
Red and yellow maple leaves	Acer rubrum	50-60
Brown Norway maple leaves	A. platanoides	"
Sawdust	Mixed source	"
Hedge clippings, privet	Lingustrum vulgare	25-30
Honeysuckle leaves, green	Lonerica tatarica	"
Lawn clippings, dry	?	"
Pine needles, green	Pinus strobis	"
Red cedar, green	Juniperus virg. juv.	"
Crab waste, meat and shell	?	"
Strip newspaper		23-28
Pulped newspaper		11-13
Rye grass, dry	Lolium perenne	14
50/50 pulped paper/dry rye grass		10
Mixed garbage		5
Rye grass, green	Lolium perenne	4

this has **not** been verified by field experiment.

Another line of study arose from some different work in which the anaerobic digestion of news - print was contemplated. Tests were run with feed of different particle size, and it was found that appreciable advantage exists for smaller size, down to the level of pulp. At this time, some other tests were in progress on dry rye grass which was thought to be a potential source of the enzyme cellulase; if this were to be true, the enzyme might make more cellulose from the newspaper available for digestion and a mixture of the two feeds would be more digestible than either alone. This turned out to be the case as is seen in Table 3 where the data are also included. What this result did was to direct attention to other mixtures, and to a phenomenon known as co-digestion.

CO-DIGESTION

Table 3 contains two other entries for materials which are by their nature mixtures: Garbage and crab waste. The first of these, garbage, was a synthetic mixture made up of ten components judged to be most common in the average household food detritus. Some of these, lettuce, potato peels and bread, for instance, are known to digest with great ease, while others, like egg shells, chicken bones and steak bones are much more refractory. The mix, however, digests at a rate which is surprisingly fast, reaching 60% destruction of its organic matter in less than five days, and more than 90% in ten days. The organic matter destroyed includes that in bones and shells, and examination of the digested material shows these structures to be highly degraded. Taken alone, these components are quite refractory, so they must be benefiting from co-digestion with the other components in the mix.

The second example is crab waste from a commercial sea-food packing plant. Shell content was well over 50%, but enough meat and other body parts were present to make it a composite material. Crab shells are rich in chitin which is a relatively inert material; alone, these external body parts are very resistant to degradation. In the digestion test, however, with appreciable amounts of more active internal parts, degradation was striking; shells were softened and dissolved to a high degree, again, presumably, by co-digestion.

These anecdotal results seem to be logical but they lack authority. Two other lines of investigation are in progress to try to quantify this phenomenon better.

FIGURE 4

PINE NEEDLE DIGESTION

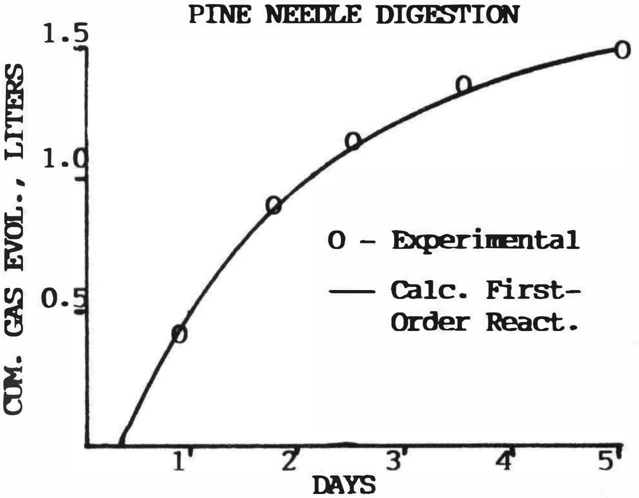


TABLE 4

DIGESTION OF TROPICAL GRASSES

	Days for 60% VSD	
	As Is	Stim/PHS
Sorghum, S.vulgare	5.5	4.0
Corn, Zea maize	3.5	2.0
Mature cane, S.offic.	5.5	2.5
Cane shoots, "	5.5	3.0
Sugars, various *	2.5	1.0

* In this test five different sugars were run sequentially in the same substrate. Corn and maple syrups, sucrose, brown sugar and molasses all gave the same rate.

In one, a specific organic chemical is being added to a laboratory digester at a rate which permits sustained operation; co-digestion can be demonstrated here. In the other study tropical grasses like corn, sorghum and sugarcane, which digest very easily [Table 4], are involved. The sugars, including sucrose, brown sugar, molasses, corn syrup and maple syrup, digest still more readily. This suggests that it should be possible to separate juice from fiber, digest both and compare the calculated composite of the separate rates with the actual rate of the whole plant. If co-digestion exists here, then the whole plant should digest better than the calculated sum of its parts. Table 5 indicates that this is indeed happening with corn, where the whole plant digests at about three times the rate calculated for the composite of its parts.

DISCUSSION

Anaerobic digestion is shown to be an effective way to stabilize sludges from municipal wastewater treatment plants and from animal husbandry operations. The data cited show that anaerobic units can digest these wastes efficiently and in socially acceptable ways; of the six plants listed in Table 1, four were located immediately adjacent to residential areas, and the other two were not far removed, and all operated for many years in these environments. These plants were studied to evaluate stimulation by PHS, and all benefited economically and socially from treatment, but stimulation was not necessary to justify their existence and location. Two plants [C and F] were not producing methane; stimulation with PHS provided a way to start the methane generating process. Containment of odors was a matter of importance to all plants, and odor reductions from stimulation were an added benefit. Additional gas from increased digestion and more consistent flow from the digesters reduced or eliminated dependence on purchased fuel; this was a further benefit of stimulation. The most important result of stimulation, though, was the reduction of sludge for disposal.

Gas from the farm digesters operating on animal manures was burned in engine-generator sets to provide electricity, using the hot jacket water for building heat, equipment wash-up, etc. These generators were tied into the local power grid as a sink for excess power generation. The value of power produced in this way varies with the arrangements that can be made with the local utilities; one of the farmers cited here reduced his power bill from over $600 per month, at 5¢ per kwh, to essentially zero. Stimulation improved the economics here, but these installations were justified without it.

TABLE 5

CO-DIGESTION WITH CORN

	Days for 60% VSD	
	As Is	Stim/PHS
Corn Juice	1.5	1
Corn Bagasse	15	10
Whole Corn, calc.	12	8
Whole Corn, actual	3.5	2.5

Application of anaerobic digestion on a laboratory scale to various components of municipal solid waste shows that all the organic materials digest in an acceptable retention time. Green biomass is digested more rapidly than dried, and in many instances fine grinding is advantageous. A typical gas evolution curve shows that an active substrate provides an abundance of methane-forming microorganisms [Figure 4] and the reaction has first-order kinetics. Starting with a depleted substrate from an active dugester, these organic feeds quickly bring the system to life and gas production with the tropical grass feeds of Table 4 is rapid and copious. The data shown were obtained from sequential tests [as many as 17] over periods up to seven months without changing the substrate or adding more. A new substrate has emerged which the new active feeds sustain. This has not been done to this degree with the less active materials, such as the higher entries in Table 3. It is anticipated that all active feeds and mixtures that contain them in appreciable amounts will behave this way. The practical significance of this is that the mixed feeds can keep the substrate active without periodic infusions of fresh substrate and the mixed feeds cam accommodate the less active components efficiently.

While stimulation and co-digestion will affect the economics of anaerobic digestion positively, the ecological benefits of the process may be of even greater importance. The overall reduction in organic sludge while capturing energy from it in a form that can be used without great controversies, coupled with the inherent containment of odors, merits serious attention by municipal officials and engineers. There is much engineering and other planning to be done, but it appears that a basis exists for implementing this approach to the management of the municipal solid waste problem.

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