

Experimental Studies on High-Rate Digestion of Nightsoil

By

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The basic mechanism of nightsoil digestion was investigated, in order to develop a better and faster method of treatment. This is a very important sanitary engineering problem which we have to face in South-East Asia. Some useful experimental results of the thermophilic digestion, and the prethickening and the anaerobic contact process, which seem to be applicable to high-rate nightsoil treatment but have not been applied yet to actual plant design, are reported in this paper.

Characteristics of Nightsoil and Basic Mechanism of its Digestion

In Japan, as a rule, the nightsoil, of which the discharge rate is estimated at 1.0–1.1 liters per capita per day, is temporarily stored in a cesspool, constructed near each house, and later transported, once or twice a month, from the cesspool to a nightsoil treatment plant, of which the total number has barely managed to reach about two hundred in the past ten years. When the nightsoil arrives at the plant, therefore, it is a mixture of faece and urine, and some stage of putrefaction has been carried out in it during the storing period. The main constituents of the nightsoil are, as shown in Table 1, BOD, suspended solids, nitrogen-ammonia, chloride, general bacteria and coliform, of which MPN is usually 10^5 – 10^7 per milliliter. If this is discharged directly into the environment, it is apparent that the receiving water body will be strongly contaminated by these germs, constituents of the nightsoil and their unpleasant by-products: hydrogen sulfide, ammonia, indole, scatole, mercaptan, butyric acid, etc.¹⁾ The BOD and other harmful constituents of the nightsoil should be decomposed and removed before it can be safely discharged into our environment. The anaerobic digestion method followed by further treatment and disinfection could be successfully and practically used for this purpose. However, since the majority of such digesters are constructed irrespectively of the development of sewage treatment plants, the effluent from the digester must be treated apart by some proper method, which will not be discussed extensively in this paper.

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Table 1. Main Constituents of The Collected Nightsoil (ppm).

Sample No.	1	2	3	4	5	6	7	8	9	10	Average
pH	7.8	8.5	8.2	8.0	8.8	8.0	8.3	9.4	8.7	8.8	8.5
Total Solids	25,200	42,600	30,100	34,000	20,600	32,810	43,050	21,710	31,560	19,450	30,110
Suspended Solids	9,020	13,300	11,120	8,780	10,660	18,170	12,500	11,460	15,620	9,560	12,020
Volatile Solids	14,420	27,151	17,880	19,820	10,330	21,920	29,250	10,200	16,570	8,650	17,620
COD	18,220	18,150	18,300	17,100	4,489	7,300	8,560	3,588	4,956	3,452	10,410
BOD ₅	9,570	10,590	10,550	10,300	9,370	9,760	10,280	10,930	11,320	9,210	10,190
Nitrogen-Organic	473	672	1,225	1,088	1,320	480	628	1,148	2,352	1,232	1,062
Nitrogen-Albuminoid	192	352	325	310	1,077	269	437	571	868	459	486
Nitrogen-Ammonia	2,538	3,628	3,771	3,544	2,624	3,295	4,136	3,416	4,508	3,248	3,471
Iodine Demand	511	1,047	1,827	656	1,075	1,755	1,531	—	—	—	1,200
Cl ⁻	3,684	5,322	3,078	5,824	4,222	4,785	5,570	4,082	5,708	4,432	4,671

Table 2. Example of The Analysis of The Collected Nightsoil after Two Hours Settling.

Item		Mixture	Upper Layer	Lower Layer	Ratio of Movement of Constituents to Lower Layer
Ratio of Separation	%	100.0	73.3	26.7	—
Colour		Yellowish Brown	"	"	—
pH		8.62	8.62	8.64	—
Total Solids	%	2.361	1.885	3.667	41.5
Suspended Solids	%	0.981	0.515	2.262	61.5
Soluble Matter	%	1.380	1.370	1.408	27.2
Ash	%	1.375	1.111	2.101	40.8
Volatile Matter	%	0.986	0.774	1.569	42.5
COD	ppm	2,682	1,734	5,286	52.6
BOD ₅	ppm	16,070	11,960	27,360	45.5
Nitrogen-Organic	ppm	1,743	665	4,703	47.0
Ammonia-Organic	ppm	2,912	3,010	2,642	24.2
Nitrogen-Albuminoid	ppm	896	644	1,587	47.3
S ⁻	ppm	177	56	511	77.0
Cl ⁻	ppm	5,953	5,962	5,928	26.6
Nitrogen-Total	%	0.466	0.427	0.571	32.8
Nitrogen-Water Soluble	%	0.359	0.368	0.335	24.9
P ₂ O ₅ -Total	%	0.113	0.065	0.243	57.8
P ₂ O ₅ -Water Soluble	%	0.074	0.060	0.112	40.6
P ₂ O ₅ -Citric Acid Soluble	%	0.098	0.060	0.202	55.1
K ₂ O-Total	%	0.172	0.217	0.048	7.4
Total Bacteria	per ml	12 × 10 ⁶	11 × 10 ⁶	15 × 10 ⁶	34.0
Coliform Bacteria	MPN per ml	35 × 10 ⁵	11 × 10 ⁵	101 × 10 ⁵	77.0

In the process of the digestion, separation of the suspended solids by settling, liquefaction and gasification are taking place in the digester. Only particles of suspended solids which have a diameter of more than 0.063 mm settle in the digester and the average diameter is about 0.2 mm. The average specific gravity of the settling particles and the nightsoil are about 1.21 and 1.02 respectively.²⁾ Table 2 shows the analytical results of the samples taken from the upper and the lower layers of nightsoil which had settled for two hours under quiescent conditions. Sulfide, bacteria, carbon- and nitrogen-organic and suspended solids have been transferred to the lower layer by settling, but the soluble matter does not move as expected.²⁾

Table 3. Analysis of Fatty Acid of The Nightsoil, Collected and after Digestion at 30°C for 30 days (By elution-chromatography).

Acid	Item	Nightsoil	Digested Supernatant *	Digested Supernatant **	Digested Sludge
Butylic Acid	Acidity —eq.	4.5	18.3	4.8	1.2
	Concentration ppm	329.6	245.8	211.2	17.6
	% in Fatty Acid	6.19	27.20	24.09	3.03
Propionic Acid	Acidity —eq.	15.1	22.9	5.4	5.5
	Concentration ppm	929.8	258.6	229.6	84.6
	% in Fatty Acid	19.33	28.62	26.19	14.56
Acetic Acid	Acidity —eq.	77.5	41.3	12.4	38.5
	Concentration ppm	3,868.0	378.1	371.7	285.3
	% in Fatty Acid	72.61	43.95	42.48	49.13
Pyruvic Acid	Acidity —eq.	0.0	0.0	0.0	2.1
	Concentration ppm	0.0	0.0	0.0	30.8
	% in Fatty Acid	0.00	0.00	0.00	5.31
Formic Acid	Acidity —eq.	2.4	0.3	2.8	2.6
	Concentration ppm	99.5	2.1	64.4	19.9
	% in Fatty Acid	1.87	0.23	7.34	3.43
Lactic Acid	Acidity —eq.	0.0	0.0	0.0	1.7
	Concentration ppm	0.0	0.0	0.0	25.5
	% in Fatty Acid	0.00	0.00	0.00	4.40
l-Malic Acid	Acidity —eq.	0.0	0.0	0.0	4.3
	Concentration ppm	0.0	0.0	0.0	48.1
	% in Fatty Acid	0.00	0.00	0.00	8.28
Citric Acid	Acidity —eq.	0.0	0.0	0.0	5.9
	Concentration ppm	0.0	0.0	0.0	68.9
	% in Fatty Acid	0.00	0.00	0.00	11.68

* Sample is made at the laboratory.

** Sample is taken from the actual digester.

The collected nightsoil, having been partly putrefied in a cesspool, will not go through the period of acid production, which is the usual process for the digestion of sewage sludge, and its low oxidation-reduction potential verifies this fact.^{3,4)} According to the authors' analysis of its constituents as a BOD-source, 50% is volatile acid, 20% is suspended solids, and the rest is fat-soluble, fatty acid and nonsaponificative matter.⁵⁾ Therefore, the nightsoil received at the treatment plant is in the same condition as the half digested sewage sludge which has almost finished the period of liquefaction. The results of the analysis of the volatile acid, contained in each of the supernatant and the sludge which has been obtained after 30 days digestion of nightsoil at 30°C, are shown in Table 3. Among the volatile acids, acetic acid has the highest percentage of abundance, followed by propionic and butyric acids. By the digestion, acetic acid is remarkably decomposed into a gaseous phase while propionic and butyric acids are less so.⁶⁾ Gases produced by the digestion contain 60–80% methane and 10–30% of a mixture of carbon dioxide, nitrogen, hydrogen and hydrogen sulfide.

The particles settled once will refloat to the surface as part of the scum, being gradually solubilized by the action of anaerobic bacteria. Citric, *l*-malic, pyruvic and other organic acids which are shown in Table 3 are the products of the intermediate period of this liquefaction stage. Those acids decompose further into acetic, propionic and butyric acids and finally go into the methane fermentation stage. Ammonia which is the main source of nitrogen of the nightsoil is not affected by the digestion. However, the higher molecular nitrogen compounds, such as albuminoid and organic nitrogens, are gradually decomposed into ammonia and organic acids which will be gasified later. The analytical data of the nightsoil before and after 30 days digestion at 30°C in an actual digester are tabulated in Table 4.

Table 4. An Example of Constituents Change Caused by Digestion.

Item		Collected Nightsoil	Digested Supernatant
pH		7.8	7.6
Total Solids	ppm	28,210	11,260
Volatile Solids	ppm	17,200	3,554
Ash	ppm	11,010	7,706
BOD ₅	ppm	10,620	1,815
COD	ppm	3,420	1,032
Cl ⁻	ppm	5,880	5,620
Total Bacteria	per ml	27×10^6	58×10^5
Coliform Bacteria	MPN per ml	27×10^4	68×10^2
Ascaris lumbricoides, Ova	per 100 ml	8,200	220

Thermophilic Digestion⁷⁻¹³⁾

In Japan, because of the gradual abandonment of the utilization of collected nightsoil as fertilizer, it is often disposed of in the ocean or a sanitary sewer, being connected to a sewage treatment plant, due to the shortage of nightsoil treatment plants. As reported in our previous papers,^{14,15)} the heating process, prior to any such utilization and disposal, seems very effective to pasteurize germs and to destroy parasite ova, contained in it. In the meantime, the thermophilic digestion of nightsoil is regarded as the method to secure a higher rate of digestion with a sufficient effect of thermal disinfection.^{16,17)} Combining these two, a field experiment was carried out in which the nightsoil was first treated by a heating process to kill pathogens, then digested thermophilically without applying more heat. This digestion method produces methane at a faster rate than the conventional mesophilic method.

In this experiment, a steam ejector was used to transfer the nightsoil from the storage tank to the digester. By this procedure the nightsoil is well mixed with steam and the heating process completed. When the nightsoil is kept at 60–80°C by this method, the parasite ova are destroyed completely within 26–29 minutes and the reduction rate of the total bacteria is more than 95%. This initial heat enables the nightsoil to be digested at 55°C without adding any more extraneous heat to the digester.

On the other hand, a basic experiment has been performed on four cases of thermophilic digestion at 55°C and on a case of mesophilic digestion at 30°C as a control, each by a batch-test in a constant temperature tank.¹⁸⁾ Fig. 1 shows the apparatus of this experiment, for which conditions are as follows:

- Case (1) Seeded with the digested nightsoil sludge, being increased up to 50% by weight of the volatile matter content of the nightsoil and agitated.
- Case (2) No seeding and no agitation.
- Case (3) The same as case (1) but no agitation.
- Case (4) No seeding but with agitation.
- Case (5) Control; mesophilic digestion seeded as in case (1); (a) with or (b) without agitation.

The rates of gas production are represented in Fig. 2. The rate in cases (1)–(4) reaches about 500 c.c. per gram of the volatile matter after 12–15 days, while, in case (5), such a rate occurs after 21–23 days. The curves in Fig. 2 have an S-shape with a lag at the beginning of the digestion. Hereafter, however, they essentially follow the mono-molecular reaction model.¹⁹⁾ The constituents of gas are shown in Table 5 and do not much differ from that of the mesophilic digestion,

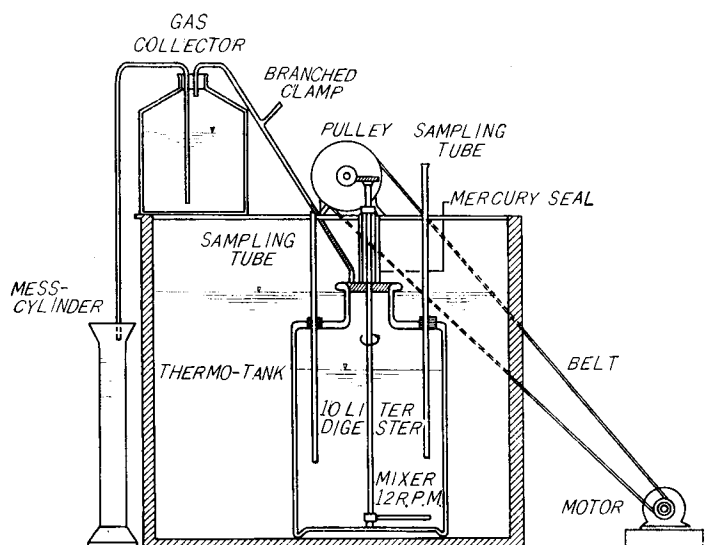


Figure 1. Bench scale digester.

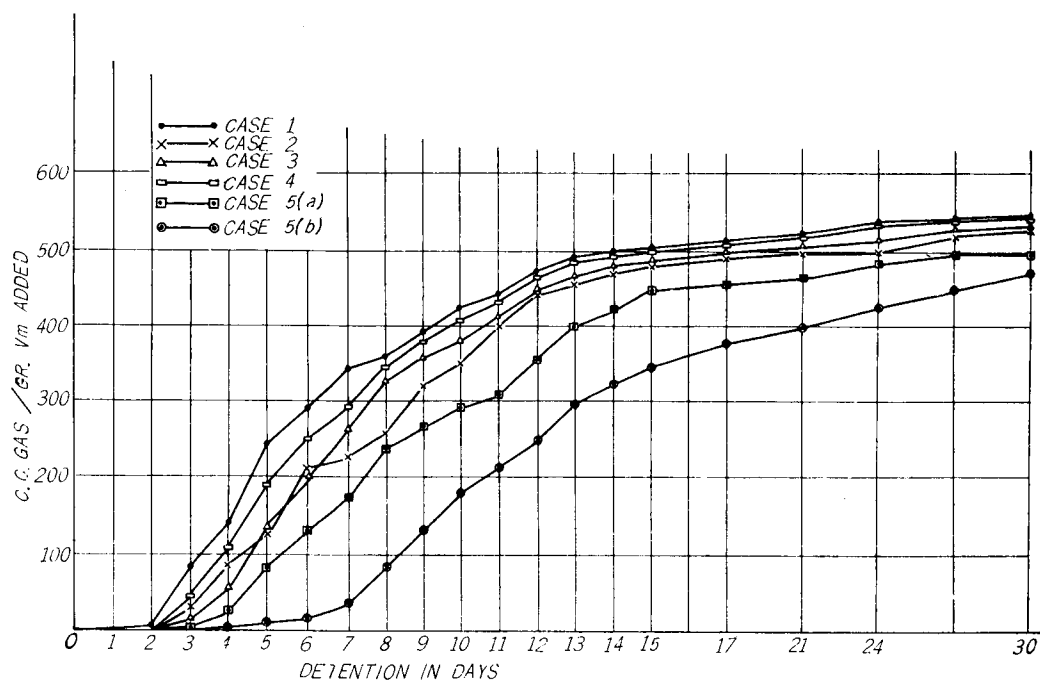


Figure 2. Gas volume in c.c. at 25°C, produced by thermophilic batch digestion of nightsoil, per gram of volatile matter added.

Table 5. Average Constituents of Digestion Gas.

Method	CO ₂ %	CH ₄ %	H ₂ %	O ₂ %	N etc. %
Thermophilic Digestion	29.2	21.0	2.8	1.0	6.0
Mesophilic Digestion	28.0	62.0	2.9	2.0	5.1

Fig. 3 shows BOD₅-curves which decrease exponentially with time and their anaerobic decomposition velocity constants, k_D , are shown in Table 6 which reveals that the velocity of the thermophilic digestion is about twice as fast as that of the conventional mesophilic digestion. After 12 days of the thermophilic digestion, BOD₅ decreases to 2,200–2,700 p.p.m. which can be obtained after 25–30 days with the conventional mesophilic digestion. Such a decrease corresponds to the first stage of the general behavior of BOD degradation and after this period its velocity becomes considerably slower. The volatile matter also behaves in the same way as BOD and about 56% of it is decomposed in the same

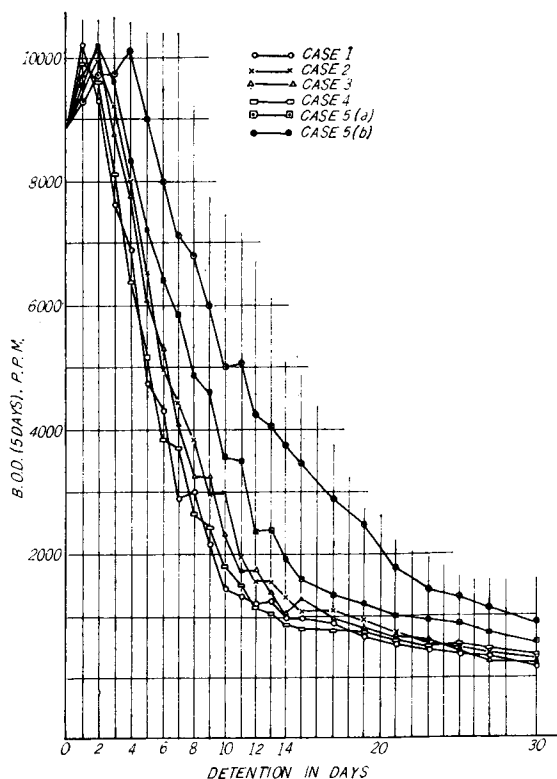


Figure 3. Five days BOD remaining in thermophilic batch digestion of nightsoil.

Table 6. Anaerobic Decomposition Velocity Constant, k_D , per day, based on 10.

Sample	Case	k_D
Thermophilic Digestion	1	0.077
Thermophilic Digestion	2	0.061
Thermophilic Digestion	3	0.064
Thermophilic Digestion	4	0.072
Mesophilic Digestion	{ 5-(a)	{ 0.050
	{ 5-(b)	{ 0.037

period. From these results, it can be concluded that agitation and seeding are favourable for promoting the thermophilic digestion and agitation is more effective than seeding.

The next problem in regard to thermophilic digestion is the characteristics of the digested sludge, among which dewaterability governs the relative difficulty of its final disposal. Therefore, filtration experiments were carefully performed on the sludges, having been produced from our experiment. As shown in Table 7, both of the specific resistances of filtration, which are derived from Cerman's and Ruth's equations,^{21,22)} do not show any significant difference between the two sorts of sludge, thermophilically and mesophilically digested.

The last and important problem in regard to thermophilic digestion is the

Table 7. Filtration Resistance and Production of Sludge Cake.

Item	Case (1)	Case (2)	Case (3)	Case (4)	Case (5)	
					(a)	(b)
Filtration Pressure (mm Hg)	450	450	450	450	450	450
Period of Digestion (day)	30	30	30	30	30	30
Solids Concentration (%)	6.7	6.7	6.7	6.7	6.7	6.7
Specific Resistance of Filtration (sec ² /g)	1.0×10^8	1.2×10^8	1.1×10^8	1.0×10^8	8.1×10^7	8.1×10^7
Production of Dry Cake (lb/ft ² /hr, Dry Basis)	5.4-6.8	4.9-6.1	5.1-6.4	5.4-6.8	6.0-7.5	5.9-7.4

Table 8. Cost of Digester Construction.

Plant Capacity		30 m ³ /day		50 m ³ /day		100 m ³ /day	
Item		Meso-philic Digester	Thermo-philic Digester	Meso-philic Digester	Thermo-philic Digester	Meso-philic Digester	Thermo-philic Digester
Effective Volume of Digester	m ³	900	450	1,500	750	3,000	1,500
Diameter and Depth of Digester	m	17φ × 5	12φ × 5	19φ × 6	15φ × 5	25φ × 7	19φ × 6
Total Volume of Concrete (1:2:4, R.C.)	m ³	290	130	470	240	920	470
Wall Thickness of Digester	m	0.4	0.3	0.5	0.4	0.6	0.5
Construction Cost of Digester	US \$	14,500	6,500	23,500	12,000	46,000	23,500
Total Power	Hp	10	7.5	15	10	30	20
Construction Cost of Power Plant	US \$	3,000	2,250	4,500	3,000	9,000	6,000
Total Surface Area of Digester	m ²	730	420	930	590	1,540	930
Heat Transfer Surface of Heat Exchanger*	m ²	6.1	17.0	10.0	28.0	19.7	56.0
Construction Cost of Heating System	US \$	4,270	11,900	7,000	19,600	13,790	39,200
Total Cost of Digester	US \$	21,770	29,650	35,000	34,600	68,790	68,700

* 8 hours operation per day.

construction cost and the fuel expense. The construction cost of the thermophilic digester, designed for 15 days digestion and held at 55°C by the ordinary heating system, is compared with that of the conventional digester, for 30 days at 30°C. The results are shown in Table 8, where the bases of the cost calculation are as follows:

- a) The cost of the heating system is based on 700 US dollars per sq. m. of the heat transfer surface of the heat exchanger.
- b) The area of the heat transfer surface, A_E , is computed from the following equation.²²⁾

$$(T_w - T_t) A_E U_E = (T_t - T_a)(A_e U_e + A_t U_r + W_n S_n),$$

where A_E = heat transfer surface area (m²),

T_w = average temperature of heating water (95 or 80°C),

T_t = digester temperature (55 or 30°C),

T_a = atmospheric temperature (15°C),

A_e = surface area of bare pipes of heating systems (3m²),

A_t = total surface area of digester (m²),

U_e = overall heat transfer coefficient of bare pipes of heating system (18 or 7 kcal/m²hr°C),

U_r = overall heat transfer coefficient of digester wall
(0.25 or 0.35 kcal/m²hr°C),

U_E = overall heat transfer coefficient of heating system
(230 or 200 kcal/m²hr°C),

W_n = feed rate of nightsoil (kg/hr),

S_n = specific heat of nightsoil (1 kcal/kg°C).

While the construction cost of the thermophilic digester is about one half of that of the conventional digester, the total construction cost which covers the heating system does not show any difference between the two methods. If the nightsoil can be preliminarily processed by some cheap heat source which may eliminate the expensive heat exchanger and boiler, however, the total construction cost of the thermophilic digester becomes 40-45% of that of the conventional one. The total heat requirements for both cases of the thermophilic and the conventional digestions are computed from the above equation and are shown in Table 9. It is seen from this table that the thermophilic digestion needs more heat of 25,000-30,000 kcal per cub. m. of nightsoil than the conventional digestion. Assuming 50% heat transfer efficiency of the heating system, it requires 50,000-60,000 kcal of fuel which corresponds to 5-6 kg of heavy oil. The operation cost of the conventional digestion is about 0.40 US dollars per cub. m. of nightsoil in which

Table 9. Heat Required for Digestion.

Plant Capacity	Item	Mesophilic Digester	Thermophilic Digester
30 m ³ /day	Required Heat Rate (kcal/day)	550,000	1,360,000
	Required Heat (kcal/m ³)	18,300	44,000
	Difference (kcal/m ³)	25,700	
50 m ³ /day	Required Heat Rate (kcal/day)	875,000	290,000
	Required Heat (kcal/m ³)	17,500	43,800
	Difference (kcal/m ³)	26,300	
100 m ³ /day	Required Heat Rate (kcal/day)	1,700,000	4,270,000
	Required Heat (kcal/m ³)	17,000	42,000
	Difference (kcal/m ³)	25,700	

the fuel cost occupies about 26%, even by utilizing the digestion gas. Since the amount and the constituents of such an available gas do not change, the fuel cost for the thermophilic digestion with the ordinary heating system is more than that of the conventional digestion, by about 0.15–0.18 US dollars per cub. m. of nightsoil.

As investigated above, thermophilic digestion considerably shortens the period of digestion, makes the nightsoil very safe and forms less scum in the digester, but requires much more heat. Therefore, this method must be recommended merely when a cheap surplus heat source is available.

Pre-Thickening Method²³⁻²⁷⁾

Pre-thickening of nightsoil can easily be done by settling it in a tank, where sludge deposits in the lower one quarter of its total volume, as shown in Table 2. The digestion of the thus pre-thickened nightsoil sludge was studied by using the apparatus sketched in Fig. 4.

Three samples are taken and prepared for such batch digesters; one from each of the upper and lower layers of the nightsoil after 2 hours of static settling and a third, a mixture of those two with a mixing ratio of 3 to 1. These samples are all seeded with the digested nightsoil sludge by 30% of the final sample volume, then digested for 3 weeks at 30°C. The gas production rate, the constituents of the gas and the samples, taken before and during the digestion, are measured and analyzed. The gas production is represented in Fig. 5. It linearly increases during the 3 weeks of digestion in every case and the lower layer, the mixture, and the upper layer have a larger rate of gas production, in the order of their magnitudes. In other words, the more the organic contents, the faster the gas production. Discounting the gas produced from the seeding sludge, the

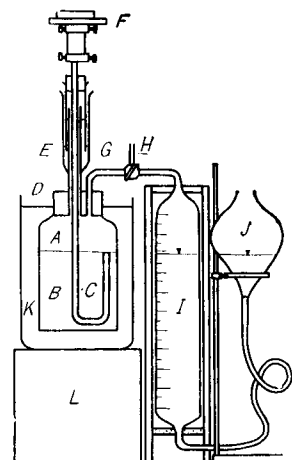


Figure 4. Bench scale digester.

A : 700 c.c. digester. G : Glass tube.
 B : 500 ml sample. H : Branched clamp.
 C : Mixer. I : 1,000 c.c. gas collector.
 D : Rubber stopper. J : Pressure controller.
 E : Mercury seal. K : Thermo-tank.
 F : Pulley. L : Bench.

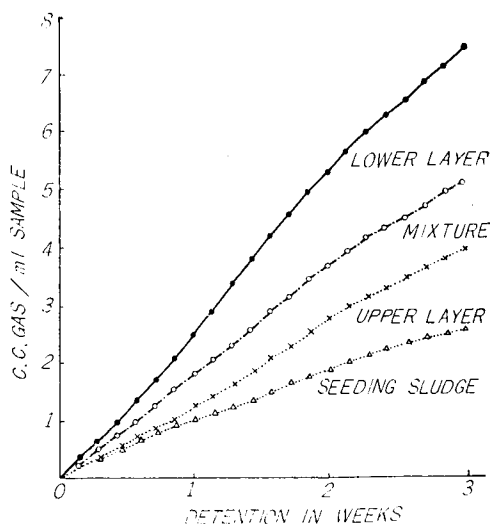


Figure 5. Volume ratio of the produced gas by mesophilic digestion to the nightsoil samples, prepared by the prethickening method.

gas from the lower layer is about twice that of the mixed nightsoil, and it contains slightly more carbon dioxide and hydrogen sulfide. Table 10 shows the gas constituents after 2-3 weeks of digestion.

The digestion of the lower layer is effective but may need a longer detention period, since it contains more organic matter than the upper layer. Therefore, the effect of the digestion period was investigated for 5 weeks under the same conditions as mentioned above. The results of gas production, sludge volume, volatile matter, BOD₅ and nitrogen-organic are shown in Fig. 6. The gas production linearly increases until the fourth week of digestion, but its rate gradually decreases after this period. The gas produced before the second week contains relatively large amounts of carbon dioxide and, in the later period, it consists

Table 10. Constituents of Gas from Three Different Samples, after 2-3 Weeks Digestion at 30°C.

Constituent		Mixed Nightsoil	Upper Layer	Lower Layer
Carbon Dioxide	%	18.8	16.8	25.8
Oxygen	%	0.4	0.4	0.2
Methane	%	80.8	82.8	74.0
Hydrogen	%	0.0	0.0	0.0
Hydrogen Sulfide	mg %	0.358	0.300	0.561
Nitrogen and Others	%	0.0	0.0	0.0

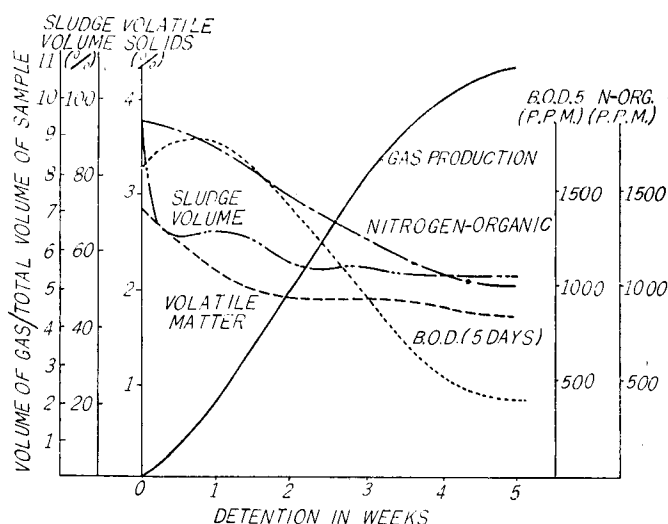


Figure 6. Gas production, sludge volume, volatile solids, five days BOD and nitrogen-organic, changing in mesophilic digestion of the lower layer of the pre-thickened nightsoil.

of 20% CO_2 and slightly less than 80% CH_4 . The volatile matter shows significant decrease during the first 2 weeks. Probably due to the progress of liquefaction, the BOD_5 reaches a maximum at the end of the first week and later decreases rapidly; 16,380 ppm of the original BOD_5 decreases to 5,122 ppm at the end of the fourth week of digestion. The volume of settling sludge in the digestion decreases very quickly within the first 2 days, being stabilized after about 2 weeks.

Some other conditions of the digestion for pre-thickened nightsoil sludge were also investigated, the results of which are as follows:

- The optimum digestion with the seeding sludge which has been preliminarily digested at 30°C for 3 weeks, is obtained at 30°C .
- The optimum amount of the seeding sludge is about 30%.
- The optimum pH is 8–9, somewhat higher than that for the digestion of sewage sludge.²⁷⁾
- The addition of 0.2% of ferrous sulfate or ferric chloride, which reduces the objectionable odour of the nightsoil, does not retard the digestion, though it hinders slightly the decomposition of nitrogen-organic.
- The addition of garbage, such as Chinese-cabbage, promotes gas production, while the addition of starchy wastes produces more carbon dioxide, but interferes with the digestion.
- The addition of commercial bacteria accelerates the digestion in some cases.

High-Rate Contact Digestion

Since the digestion of the nightsoil utilizes the action of anaerobic organisms to decompose organic matter, it is very important to keep the optimum conditions for the growth and the activity of the organisms as well as to provide their sufficient contact with the nightsoil. P. F. Morgan pointed out that the gasification might be completed within 12 hours of digestion under optimum conditions,²⁸⁾ and C. E. Keefer found that a good contact between the sewage sludge and the digested sludge promoted the digestion.²⁹⁾ Furthermore, the anaerobic contact process has been used for the treatment of industrial wastes and domestic sewage in recent years,³⁰⁻³³⁾ as an effective method to reduce the BOD of their liquid state. As shown in Table 3, the BOD of nightsoil mainly consists of volatile acid which can be easily decomposed by anaerobic bacteria. Therefore, it would be very effective for nightsoil to utilize such a method of high-rate contact digestion; the nightsoil is well mixed and contacted with a large amount of its digested sludge in the primary digester, from where it is sent to the secondary digester for settling, then the settled sludge is recycled to the primary digester for the contact mixing with the fed nightsoil and the supernatant is removed continuously from this tank. This method does not require a separate contact tank as used for the contact processes, proposed by American researchers, but performs the contact in the digester. The authors tried to apply it to the digestion of a four times larger amount of nightsoil by using the same volume of digestion tank which had been used for the conventional digestion.

The high-rate contact digestion experiment was carried out by means of the apparatus shown in Fig. 4 under a continuous feeding condition. The methods of conventional digestion and pre-thickening were also carried out at the same time as the control. The conditions for each case of the experiments are as follows:

- a) Conventional digestion: 7 parts of the collected nightsoil and 3 parts of the digested sludge which are mixed before the experiment are digested for 30 days at 30°C. Every two days for the later digestion period of more than 3 months, the nightsoil is agitated for 5 minutes, then the supernatant is immediately extracted by 1/14 of the total volume of nightsoil, being refilled at once by collected nightsoil of the same amount.
- b) Pre-thickening method: The same mixture is used for the preliminary aging and the same digestion conditions as the above case a) are adopted, but, for the later period, the extract is refilled by pre-thickened nightsoil in the lower layer instead of collected nightsoil. The calculated detention period is 28 days in cases a) and b).

- c) High-rate contact digestion: The conditions of the preliminary aging and the later digestion are the same as case a), but after 30 days aging, the supernatant, in 1/3.5 of the total volume of nightsoil is withdrawn after 2 hours static settling and refilled by collected nightsoil. The calculated detention period is 7 days in this case.

The volume of gas, produced in each of these three methods, was measured every day. After the rates of gas production reached a steady state, its constituents were analyzed, as shown in Table 11. As shown in Table 12, an analysis of nightsoil was also carried out on five different samples; 1) fed nightsoil, 2) the upper layer after 2 hours of static settling, 3) the lower layer after 2 hours of static settling, 4) a mixture, immediately after agitation, of seven samples of the digested nightsoil, which had been taken daily for one week and kept in an ice-box, and 5) the supernatant of number 4) after 2 hours of static settling.

As shown in Fig. 7, a steady rate of gas production is obtained after 3.5-4.0 months of digestion and its volume ratio to the nightsoil fed to the digester is 6.3 for the high-rate digestion, 11 for the prethickening method, and 8 for the conventional digestion. In other words, the gas production per day is 530 c.c. for the high-rate digestion, 430 c.c. for the pre-thickening method, and 660 c.c. for the conventional digestion. This shows that the high-rate contact digester has as high an efficiency as the conventional digester of the same capacity, despite

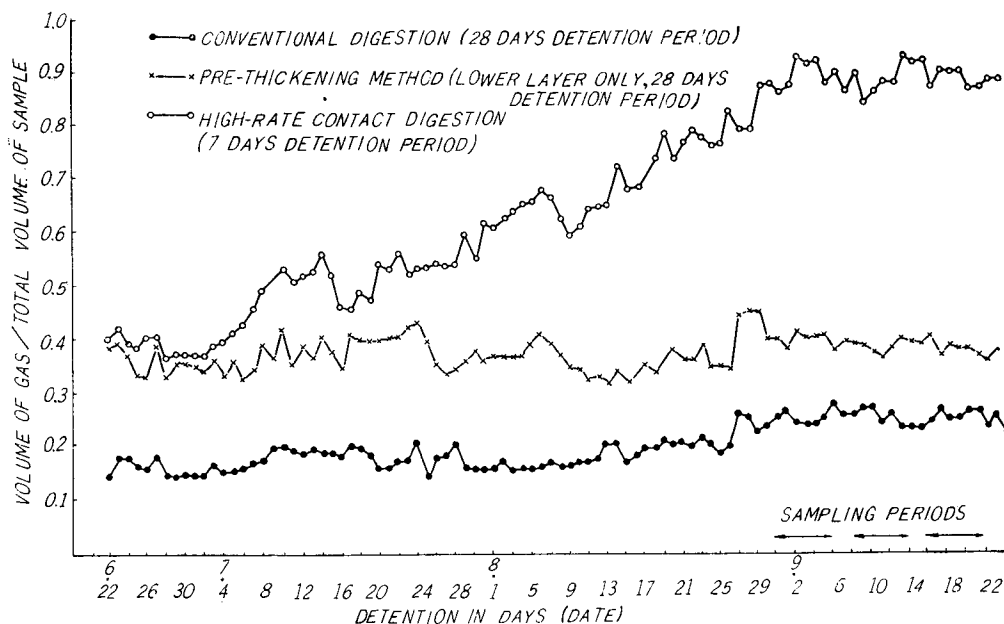


Figure 7. Gas production by these different mesophilic digestion methods of nightsoil, continuously fed every two days after the initial aging period,

Table 11. Gas Analysis after Three Different Digestion Methods at 30°C.

Conitituent		Conventional Mesophilic Digestion	Pre-thickening Method (Lower Layer only)	High-rate Contact Digestion
CO ₂	%	17.4	20.3	18.5
O ₂	%	1.3	1.3	2.2
CH ₄	%	81.3	73.2	78.3
H ₂	%	0.0	5.2	1.0
N and Others	%	0.0	0.0	0.0

Table 12. Constituents of Nightsoil by Three Different Digestion Methods at 30°C.

tem		Feed			Digested			
		Mixture	Lower Layer	Upper Layer	Conventional Digestion			
					Mixture		Supernatant	
					Measured	Removal Ratio %	Measured	Removal Ratio %
Volume Ratio	%	100.0	25.0	75.0	100.0	—	79.1	—
Colour		Yellowish Brown	"	"	Yellowish Brown	—	Yellowish Brown	—
pH		8.20	8.25	8.20	8.60	—	8.40	—
Total Solids	%	2.612	4.422	2.009	2.151	17.7	1.569	39.9
Suspended Solids	%	1.424	1.671	1.342	1.362	6.9	1.202	15.6
Volatile Matter	%	1.188	2.750	0.667	0.825	30.6	0.367	69.1
BOD ₅	ppm	12,130	18,060	10,150	2,583	78.7	2,190	81.9
Volatile Acid	ppm	6,675	6,432	6,755	946	85.8	772	88.4
COD	ppm	4,305	5,441	3,926	2,943	31.6	1,954	54.6
Nitrogen-Ammonia	ppm	3,626	3,519	3,662	3,930	—	4,016	—
Total Nitrogen	ppm	4,335	4,746	4,198	4,101	5.4	4,113	5.1
Nitrogen-Organic	ppm	709	1,228	535	171	75.9	97	86.3

Item		Digested							
		Pre-thickening Method (Lower Layer only)				High-rate Contact Digestion			
		Mixture		Supernatant		Mixture		Supernatant	
		Mea-sured	Removal Ratio %*	Mea-sured	Removal Ratio %*	Mea-sured	Removal Ratio %	Mea-sured	Removal Ratio %
Volume Ratio	%	100.0	—	56.8	—	100.0	—	88.0	—
Colour		Bluish Brown	—	Bluish Brown	—	Yellowish Brown	—	Yellowish Brown	—
pH		8.45	—	8.00	—	8.00	—	7.95	—
Total Solids	%	3.258	26.3	1.781	59.7	2.207	15.5	1.791	31.4
Suspended Solids	%	1.516	9.3	1.140	31.8	1.411	0.9	1.139	20.0
Volatile Matter	%	1.742	36.7	0.641	76.7	0.796	33.0	0.652	45.1
BOD ₅	ppm	4,452	75.4	3,160	82.5	3,630	70.0	3,370	72.2
Volatile Acid	ppm	1,308	79.7	1,363	78.8	1,008	84.9	1,015	84.8
COD	ppm	5,184	4.7	2,450	55.0	2,636	38.8	2,426	43.6
Nitrogen-Ammonia	ppm	4,303	—	4,177	—	4,024	—	4,048	—
Total Nitrogen	ppm	4,841	—	4,512	4.9	4,227	2.5	4,208	2.9
Nitrogen-Organic	ppm	538	56.2	335	72.7	204	71.3	161	77.3

Note: The ratios* are computed to the "Lower Layer", while the others to the "Mixture" in the "Feed" column.

its 4 times higher load. But, since such a comparison of the digestion efficiency by gas production does not take into account the detention period as one of its important factors, the promotive ratio of digestion, which W.N. Torpey,²⁵⁾ proposed as an index for sewage sludge, is used to compare the results of the high-rate contact digestion with the conventional digestion for 30 days at 30°C.

$$\text{Promotive ratio of digestion} = (G/QD)(Q_S D_S / G_S)$$

where G = gas production rate, per day,

Q = feed rate of nightsoil, per day,

D = digestion period in days,

G_S = gas production rate by the conventional method, per day,

Q_S = feed rate of nightsoil for the conventional method, per day,

D_S = digestion period by the conventional method in days.

Assuming 30 days digestion and $G_S/Q_S=8$ which is a very reasonable ratio for the conventional method of nightsoil digestion, the above equation becomes:

$$\text{Promotive ratio of nightsoil digestion} = (30G)/(8QD)$$

According to this equation, the promotive ratio is calculated as 1.4 for the pre-thickening method and 3.4 for the high-rate contact digestion.

The results of the gas analysis, listed in Table 11, reveals that there is no significant disparity between these three digestion methods, though the high-rate contact digestion has a tendency to produce slightly less combustible gas and more carbon dioxide. The production rate of the digested waste sludge, which is defined as the volume ratio of the difference between the total feed and the supernatant to the total feed, is 43-50% for the pre-thickening method, 21-25% for the conventional digestion and 12-16% for the high-rate contact digestion. Therefore, the high-rate contact digestion makes it easy to dispose of the waste sludge.

The records, listed in Table 12, show that the BOD₅ removal ratio of the digested supernatant to the feed is 75-80% by both the conventional and the pre-thickening digestion and 66-72% by the high-rate contact digestion. The BOD₅ of the supernatant is in the vicinity of 2,200 ppm for the conventional digestion, 3,300 ppm for both the pre-thickening method and the high-rate contact digestion. The behavior of organic acid follows closely that of BOD. As shown above, the high-rate contact digestion produces a somewhat lower quality than the supernatant but has a very high digestion efficiency.

Thus, the high-rate contact digestion successfully reduces the required capacity of the digester to 1/4 that of the conventional digestion. If the above-stated feed rate of nightsoil, which is 1/7 of the effective capacity of digester, per day, can

be increased, the effectiveness of this treatment process will be more and more elaborated. On our next experiment, therefore, the three feed rates of 1/7, 1/5 and 1/3.3 of the digester capacity per day were compared, without changing the other conditions.

As shown in Fig. 8, the ratios of gas production to the feed rate and the digester capacity are 0.28 and 8.0 respectively by the conventional digestion. The same ratios by the high-rate contact digestion, after the gas production rate has reached a steady state, are respectively: 1.0 and 7.0 for 1/7 feed rate, 1.2 and 5.8 for 1/5 feed rate, 1.4 and 4.5 for 1/3.3 feed rate. Hence, the promotive ratios of digestion on the basis of these gas production data are; 3.8 for 1/7 feed rate, 4.4 for 1/5 feed rate, 5.1 for 1/3.3 feed rate. The percentage of gas content does not show any difference between conventional digestion and the high-rate contact digestion with both 1/7 and 1/5 feed rates, and it is about 80% for combustible gas and 18-19% for carbon dioxide. However, the high-rate contact digestion with 1/3.3 feed rate produces about 77% combustible gas 20% carbon dioxide. The production rate of the digested sludge, which is measured as the volume of sludge after 2 hours settling of the sample, is 19% for conventional digestion;

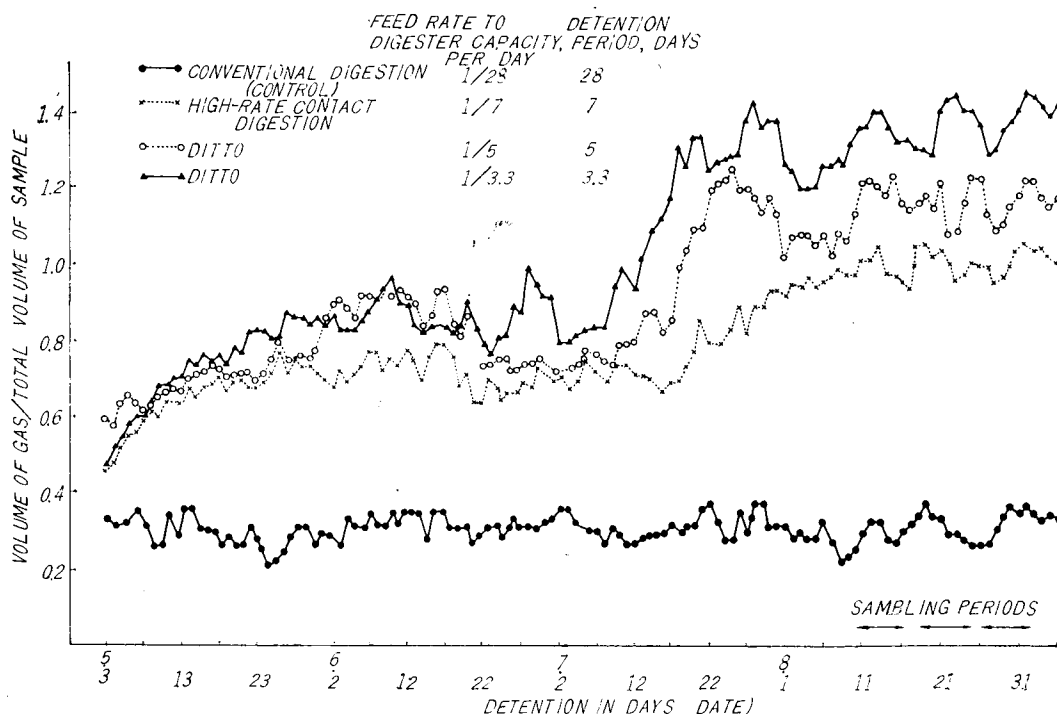


Figure 8. Gas production by the high-rate contact digestion of nightsoil, with three different feed rates,

while it is 7.3%, 6.7% and 9.0% for the high-rate contact digestion with 1/7, 1/5 and 1/3.3 feed rate, respectively.

Table 13 shows the analysis of the fed nightsoil and its digested supernatant. The removal efficiency of BOD is 85% for the conventional digestion; while 73%, 67% and 48% for the high-rate contact digestion with 1/7, 1/5 and 1/3.3 feed rate, respectively. The behavior of volatile acid follows that of BOD. The BOD₅ of the supernatant is 1,800 ppm, 4,000 ppm and 6,300 ppm, in the above order of the digestion methods and feed rates.

Table 13. Constituents of Digested Supernatant of The Nightsoil, by The High-Rate Contact Method, with Three Different Feed Rates.

Item	Feed		Digested Supernatant		Digested Supernatant					
	Mix-ture	Upper Layer	Conventional Digestion (Feed Rate is 1/28)		Feed Rate of Nightsoil to The Digester Capacity, per day					
					1/7		1/5		1/3.3	
			Mea-sured	Re-moval Ratio %	Mea-sured	Re-moval Ratio %	Mea-sured	Re-moval Ratio %	Mea-sured	Re-moval Ratio %
Produced Sludge Volume %	33.9	—	19.6	—	7.1	—	6.7	—	8.8	—
Colour	Yel-lowish Brown	"	Yel-lowish Brown	—	Yel-lowish Brown	—	Yel-lowish Brown	—	Yel-lowish Brown	—
pH	7.52	7.52	8.40	—	8.02	—	7.87	—	7.85	—
Total Solids %	2.545	2.038	1.587	37.6	1.701	33.2	1.712	32.7	1.757	31.0
Suspended Solids %	1.414	1.344	1.197	15.7	1.288	8.9	1.252	11.5	1.276	9.8
Volatile Matter %	1.131	0.694	0.395	65.1	0.413	63.5	0.460	59.3	0.481	57.5
BOD ₅ ppm	11,670	10,040	1,857	84.1	3,148	73.0	4,045	65.3	5,926	49.2
Volatile Acid ppm	6,656	6,453	843	87.3	1,756	73.6	2,442	63.3	2,820	57.6
COD ppm	3,037	1,934	1,287	57.6	1,784	41.3	1,821	40.0	1,869	38.5
Nitrogen-Ammonia ppm	2,897	2,833	3,103	—	3,198	—	3,198	—	3,150	—
Total Nitrogen ppm	4,337	4,089	3,166	27.0	3,356	22.6	3,340	23.0	3,377	22.1
Nitrogen-Organic ppm	441	256	63	85.6	158	64.1	142	67.7	227	48.4

Note: The removal ratios are computed to the "Mixture" in the "Feed" column.

As seen from these results, the maximum feed rate of the high-rate contact digestion is likely to be 1/5 of the digester capacity. With this feed rate, the concentration of organic acid can be surely kept less than 3,000 ppm which is considered the inhibitive limit.²⁷⁾

The following may be considered as the reasons for such a fast digestion speed of the high-rate contact method:

- Since the digested sludge is kept as amply as possible in the digester, where the density of the anaerobic organisms is raised, it has frequent contact with the organisms by proper mixing.

- b) Since the heavy particles of faecal matter remain in the digester longer, they will be more liquefied and gasified.
- c) Since the nightsoil is usually fed to the digester only in the daytime and the vast amount of organisms continue in the consumption of the organic matter as their nutrient during the night, these organisms must be in a state of hunger or antagonism, being ready to react on the large amount of nightsoil by feeding time of the next day.
- d) The C/N ratio of the collected nightsoil is about 2. Therefore, it will not be regarded as a good and balanced nutrient for the organisms. However, the C/N ratio in the digester, which is nearly filled with the digested sludge and heavy particles of nightsoil, must be rather high,³⁴⁾ resulting in the improvement of the condition for digestion.
- e) Although the concentration of the substances inhibiting the digestion does not differ much from the case of conventional digestion, the number of organisms which will be affected by these inhibitors is much larger in the case of high-rate contact digestion, resulting in the reduction of such a hindrance.

When the high-rate contact digestion method is applied to an actual plant, it seems necessary to provide a proper mixing unit either by a mechanical agitator or gas-recirculation, which is recommended by P. F. Morgan and other,³⁵⁻³⁸⁾ to improve the digestion efficiency. Besides this, a quiescent condition for effective gravity separation is naturally required. For this method, however, the two separate tanks of the conventional type are not necessarily needed, because the effective capacity of the digester is only one quarter of the conventional method. A circular digestion tank, in which a concentric partition wall is provided, is recommended in order to save the plant area, to facilitate the continuous recirculation of a large amount of sludge and to obtain a good heating efficiency. The layout of this type is sketched in Fig. 9. The digester is divided into parts: the inner part acts as the primary agitator and contact tank and the outer part act as the secondary settling tank.

The recommended ratio of the capacity of the inner part to the total is from 5/7 to 3/4. The collected nightsoil, entering the inner part, is mixed with the sludge by means of mechanical agitation, gas-diffusion or gas-lift, receives steam through the pipes from the boiler, illustrated as an example of various heating systems, then flows out to the outer part through the overflow pipe. In the outer part, the sludge settles while it flows along a circular path where a few perforated baffle boards are inserted, and, finally, the supernatant liquor is drawn out. The circular partition wall has as many openings as possible through which

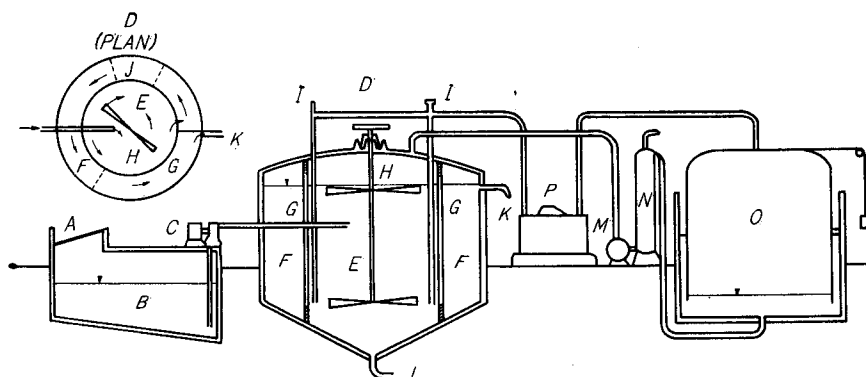


Figure 9. A model of the high-rate contact digestion tank for nightsoil

- | | |
|---|-------------------------------|
| A : Bar screen. | H : Mixer. |
| B : Holding tank for collected nightsoil. | I : Steam pipes. |
| C : Feed pump. | J : Perforated baffle boards. |
| D : Digester. | K : Effluent pipe. |
| E : Inner part for agitation and contact. | L : Waste sludge pipe. |
| F : Outer part for settling. | M : Blower. |
| G : Conventric partition Wall. | N : Desulfider. |
| | O : Gas-holder. |
| | P : Steam boiler. |

the sludge returns freely from the outer part into the inner part. The interior agitation would help this sludge movement with proper size openings and an adequate bottom-slope in the tank, but may need some control device. The BOD of the supernatant liquor by this process might be slightly higher than that by conventional digestion. However, this demerit would be overcome by adopting an effective secondary treatment for the liquor,^{39,40)} after diluting it with a sufficient amount of fresh water.

Summary

In Japan, since nightsoil is still collected from most houses and disposed of by primitive methods, public facilities are inevitably needed to treat it until we have a complete sanitary sewerage system. Although the anaerobic digestion has been the most popular procedure for this purpose, its efficiency is not satisfactory even with the detention period of more than 30 days at 30°C in the digester. In order to obtain a better and faster digestion method, the authors investigated the characteristics of nightsoil and the basic mechanism of digestion and also carried out several laboratory scale experiments on thermophilic digestion, the pre-thickening method and high-rate contact digestion. Summarizing the results:

- a) The collected nightsoil is a mixture of faeces and urine which has gone through some of the putrefaction process. It is abundant in BOD, suspended

- solids, nitrogen-ammonia, chlorine, sulfate, total and coliform bacteria as well as pathogens. The main constituents of BOD source consists of about 50% of volatile acid (mainly acetic acid), 20% of suspended solids and 30% of fat-soluble, fatty acids and non-saponificative matter.
- b) By gravity settling, sulfate, bacteria, carbon- and nitrogen-organic and suspended solids are transferred to the lower layer. Among the fatty acids, acetic acid is easily gasified and butyric and propionic acids also. The lower layer is gradually gasified through the state of fatty acids. The gas contains 60-80% methane and 10-30% carbon dioxide.
 - c) By increasing the digestion temperature to 37°C, the detention period can be reduced to about 2/3 of the standard period at 30°C. Moreover, increasing it to 50-55°C, can reduce the period to about 1/2 of the standard.¹⁵⁾ The destruction of pathogens is also promoted with a higher digestion temperature. The method which pasteurizes the nightsoil at 65°C for about 30 minutes and later holds it at 55°C completes the digestion in 12 days without any further heating during this period. The reaction velocity constants of BOD (k_D) are 0.061-0.077 per day by thermophilic digestion and 0.037-0.050 per day by the conventional mesophilic digestion, each based on 10. Seeding and agitation are effective. The dewaterability of sludge is not affected by the digestion temperature.
 - d) After 2 hours of settling, the nightsoil is separated into supernatant liquor and sludge, in the upper 3/4 and the lower 1/4 layers of its total volume, respectively. Since the upper layer can be treated the same as sewage, the digestion of the lower layer reduces the requirement for the tank capacity. The gas production is better for the lower layer and its optimum digesting condition is obtained at 30°C for 30 days, along with the seeding sludge which has been aged at 30°C for 3 weeks.
 - e) Deducing from the characteristics of nightsoil and the action of the digested sludge, the high-rate contact digestion method is proposed so as to hold more digested sludge and to make more contact between the nightsoil and the organisms in the digester. The nightsoil is continuously fed into the digester, being kept at 30°C by the feed rate of 1/7 to the effective capacity of the digester, per day. At a steady state of gas production, the volume ratio of the gas production of the high-rate contact digestion to conventional digestion is 5 and the same ratio to the pre-thickening method is 10. The maximum feed rate is proven to be 1/5 to the digester capacity. However, prior to practicing this method at an actual plant, such results, having been obtained by the small experimental apparatus shown in Fig. 4, must be carefully reexamined in a pilot plant,

The high-rate digestion methods which have been used for sewage sludge are experimentally verified as being applicable to actual plants for the digestion of nightsoil. It would be possible to save the digester capacity by 1/2 by the thermophilic method, by 3/4 due to the volume reduction of the collected nightsoil by the pre-thickening method and probably by 5/6-3/4 by the high-rate contact digestion method, in comparison with that by the conventional method of mesophilic digestion. These methods could be also adapted to the improvement of the efficiency of the existing conventional nightsoil digesters, with less construction cost. Furthermore, the newly proposed principle of the high-rate contact digestion would be applicable to sewage sludge in the future. The combination of the methods of gas recirculation and the high-rate contact digestion or the thermophilic digestion may contribute to the further reduction of the capacity requirement and the construction cost for digesters. Occupying the most expensive part of the plant operation cost, the annual average fuel consumption, which is necessary to replenish the deficiency of the produced gas, in order to keep 100 cub. m. of the daily collected nightsoil at its proper temperature in a digester, is estimated at 0.3 kl of fuel oil for the conventional and the high-rate contact digestion, 0.6 kl of fuel oil for the thermophilic digestion and none for the pre-thickening method. Therefore, when a cheap heat source is available, the thermophilic digestion would be the best, while, as far as the gas production rate is concerned, the pre-thickening method would be the best. In general, high-rate contact digestion would be the most recommendable method for nightsoil treatment. However, the selection of the treatment system should be carefully done as a whole, after investigating not only the method of digestion, but also the methods of treating the effluent biologically and of dewatering, drying and disposing the withdrawn sludge from the digester. These methods must be properly combined so that the most reasonable overall performance is obtained by the system, which also meets the requirements of the environmental situation.

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