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December 1978

Prepared for the U.S. Department of Energy
under Contract EY-76-C-06-1830

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OPERATIONAL CHARACTERISTICS OF ANAEROBIC DIGESTERS AT SELECTED MUNICIPAL WASTEWATER TREATMENT FACILITIES IN THE UNITED STATES

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Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

Bench-scale and pilot plant studies at Pacific Northwest Laboratory have shown that powdered activated carbon is effective in improving volatile solids destruction and gas production in anaerobic digesters that are operating at less than normally expected levels of efficiency. To evaluate the applicability of this technology to digesters in the United States, digester operating characteristics at 60 facilities were surveyed and the number of stressed digesters estimated. The results show that although median values of the operating parameters conformed with those of a well-operated digester, 30% of the digesters surveyed were stressed with regard to at least one important parameter. Of the 30 largest treatment plants in the U.S., seven fell into this category.

Digester gas production and usage were then examined to determine the importance of methane off-gas as an energy source. A conservative estimate is that the gas produced nationally represents a heating value of about 2.36×10^{13} Btu/year with a present value of $40 million. Of this amount, an estimated 75% is used either onsite or sold. Onsite uses include heating digesters and buildings, incinerating sludge, operating equipment, and generating electricity. The other 25% is flared and the energy value lost. The present value of the flared gas is about $10 million/year. Natural gas prices are projected to increase 150% over the next seven years. If the present utilization ratio continues, the flared gas will be worth approximately $27 million in 1985.

Presently, digester gas is mainly used for process heating and operating equipment. The technical and economic feasibility of recovering digester gas for electrical power generation, onsite equipment operation, and sales to other consumers (utilities, private companies) should be thoroughly investigated. If fuel gas recovery and utilization are found to be desirable, consideration should be given to expanding and upgrading anaerobic digester facilities in the U.S.

TABLE OF CONTENTS

LIST OF TABLES

INTRODUCTION

During the past two years, Pacific Northwest Laboratory (PNL) has been engaged in a research program for the U.S. Department of Energy (DOE) evaluating the effect of powdered activated carbon on the anaerobic digestion of municipal sewage sludge. Both bench-scale and pilot plant studies have been performed. The PNL research indicates that carbon addition is effective in improving the operation of "stressed" anaerobic digesters. Stressed systems are defined here as those that are operating at less than normally expected levels of efficiency. Greater than 100% enhancement in methane production has been observed in carbon dosed units that are stressed. Other demonstrated benefits include increased volatile solids destruction, better sludge dewatering characteristics, and improved process stability. Alternatively, when carbon is added to well-operated digesters the effect is much less significant. Maximum increases in methane production of only 10 to 20% have been noted under these conditions.

The results of the PNL experimental studies suggest that carbon addition would be of greatest benefit if applied to poorly operating digesters. Therefore, in order to predict the impact of carbon addition on a national level, it is necessary to have some knowledge of the present operational conditions of anaerobic digesters in the United States. The primary objective of this report is to provide this baseline information. Accordingly, operating data from 60 U.S. digester facilities are analyzed. These data represent a wide variety of plant flow rates (1.2 to 800 mgd) and geographical locations, and are intended to generally characterize typical operations. Included in the survey are 30 of the largest municipal wastewater treatment plants in the country. Factors such as gas production, solids residence time (SRT), sludge flow, and volatile solids destruction are analyzed. Parameters are compared with values cited in the literature for normally operating systems. The results of the assessment will be used in the project interim report[1] as a basis for estimating the applicability of the carbon addition process at existing municipal facilities.

A secondary objective of this report is to evaluate the energy value and usage of digester gas in the U.S. Total current gas production at treatment plants is estimated, as well as the projected rate in 1985. The current and future value of the gas is estimated based on commercial natural gas price information furnished by the American Gas Association. In addition, the volume and replacement cost of digester gas not utilized (flared) at municipal wastewater plants is calculated. Based on current utilization practices, these parameters are also projected for 1985. A separate analysis is made with respect to digester gas production at 30 of the nation's largest treatment plants. The report also includes a discussion of the desirability of fully utilizing waste gas at the treatment plant.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were derived from the survey of 60 municipal wastewater treatment plants throughout the U.S.

1. Median values of operating parameters for the surveyed digesters generally conform to established standards for well-operated systems.

2. Eight facilities (13% of total sample) reported extremely low gas production rates.

3. Eighteen facilities (30% of total sample) exhibited at least one operational condition that indicated the digesters were significantly stressed.

4. In a number of cases, inconsistencies in the reported data made it impossible to firmly ascertain the actual state of the digesters.

5. Apparent causes of poor digester performance included low temperature, poor mixing, and hydraulic overloading. Several plants reported that grit buildup in the digester vessels contributed to their overloading problem.

6. It is estimated that 25% of the total quantity of methane gas generated at U.S. treatment plants is flared, and not utilized. This loss represents approximately 6.2 billion cubic feet of methane per year, having a current value of about $10 million annually.

7. Thirty of the largest municipal plants in the country collectively flare about 1.6 billion cubic feet of methane each year. This quantity of gas is presently valued at over $3.0 million annually.

8. Natural gas prices in the U.S. are projected to increase by 150% during the next seven years. If present utilization trends continue, the total annual value of flared digester gas in 1985 is estimated to be about $27 million.

Because of the magnitude of this untapped resource, further research should be conducted aimed at establishing the technical and economic feasibility of complete gas recovery and utilization at facilities having anaerobic digesters. Important factors that should be evaluated include: 1) required modifications in treatment plant boilers and internal combustion engines that would permit use of digester gas as a fuel; 2) installation of electrical power generators; 3) suitability and value of the product gas for sale to industrial consumers; and 4) the desirability of gas compression and storage facilities. In addition, it would be necessary to address site-specific conditions in examining the overall feasibility. Such factors as local natural gas prices and the availability of buyers for digester gas may be extremely important. Several plants contacted in the PNL survey practiced full recovery of off-gas for inplant use and/or sale to industrial clients. The experiences of these facilities would provide valuable information for support of the recommended study.

If the above analysis indicates that full gas recovery and utilization is attractive, then the study should be expanded to determine the advisability of retrofitting certain sewge treatment plants with anaerobic digesters. Facilities would be evaluated according to such criteria as: 1) flow rate; 2) type of treatment; 3) amount and characteristics of generated solids; 4) current sludge handling and treatment techniques; and 5) inplant energy requirements and costs. An updated inventory of U.S. municipal wastewater treatment plants is scheduled for publication in January 1979. This survey would provide a sound basis for such an assessment.

DATA COMPILATION METHODS

Beginning in the summer of 1977, 120 municipal wastewater treatment plants were contacted in a telephone survey. The purpose was to establish which plants had anaerobic digesters and to identify a person at each digestion facility with technical knowledge of the operation. A more detailed written survey form was then sent to each of these individuals. Persons responding to the survey were most often plant superintendents and managers. A sample survey form is presented in the Appendix. Requested information included typical data for plant flow, treatment type, sources of influent wastewater (municipal, industrial), digester parameters (temperature, detention time, gas production, etc.), digester system description, operational problems, and ultimate sludge disposal methods. Although every attempt was made to obtain accurate information, it is suspected that some of the returned data are only estimates. As a result, certain values may not be truly representative of actual plant conditions. Some of the respondents might have listed typical digester conditions for the particular time of year that the survey form was filled out, rather than submitting average yearly information.

Of the 120 plants initially contacted, 90 had anaerobic digesters, and of these, 60 facilities responded to the written survey. The sample of 60 plants represents about 1% of the total number of facilities with anaerobic digesters in the U.S. In general, the surveyed plants covered a wide variety of treatment types (primary, various secondary), flow rates (1.2 to 800 mgd), and geographical areas. Figure 1 illustrates the locations and plant sizes of the survey respondents. The inclusion of a considerable number of large plants was intentional, since these facilities represent a significant fraction of the total anaerobic digester capacity in the U.S.

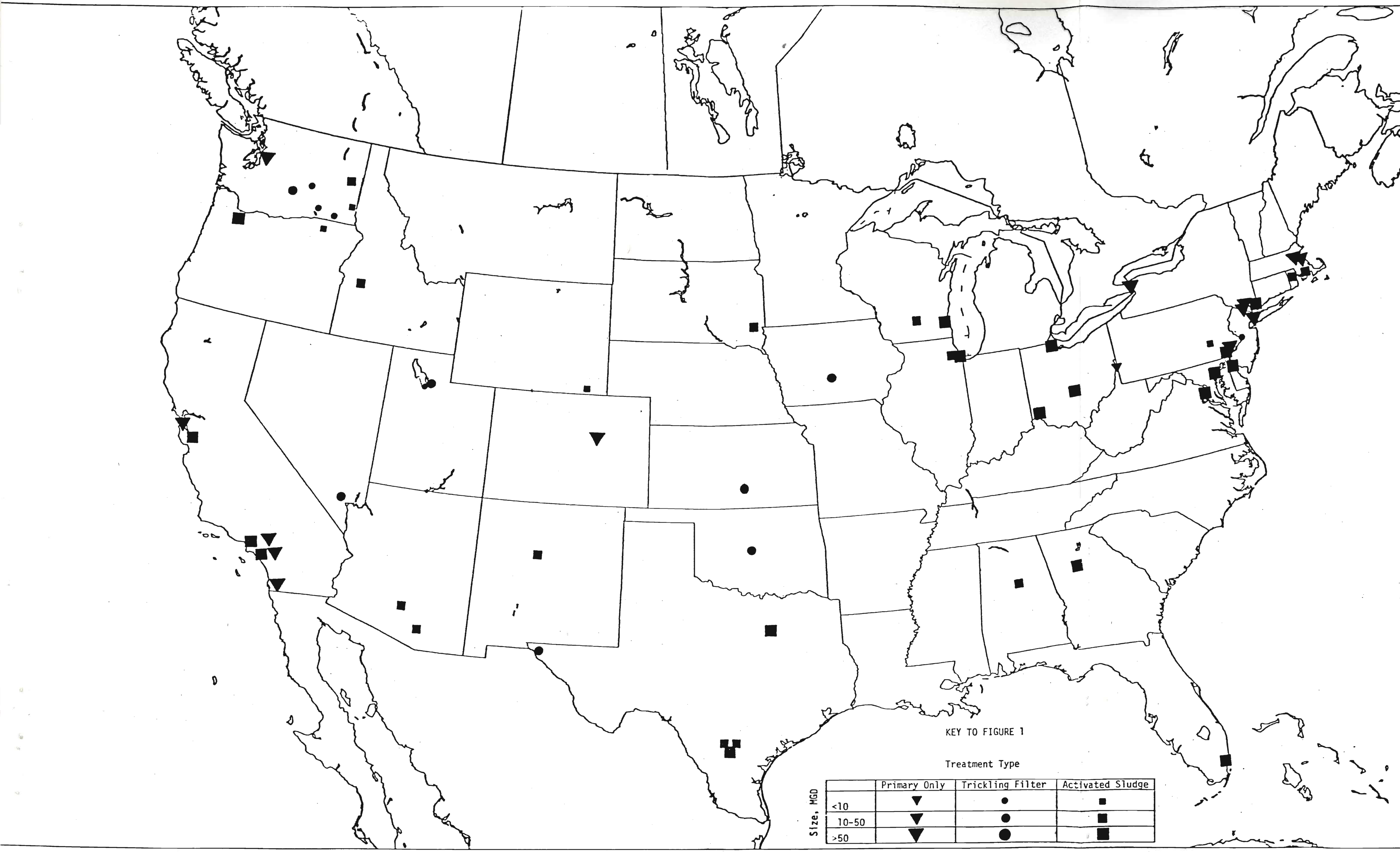

FIGURE 1. Anaerobic Digester Facilities Responding to the PNL Survey.

THE WELL-OPERATING DIGESTER MODEL

To assess relative operational success of conventional anaerobic digesters in the U.S., criteria for a well-operating digester must be established. Key control parameters in design and operation are solids retention time (SRT, which in completely mixed digesters is equal to hydraulic detention time), temperature, pH, and influent loading. Indicators of digester condition used in this study were volatile acids concentration, percent volatile solids destruction, gas production/lb volatile solids applied, gas production/lb volatile solids destroyed, and percent methane in the gas.

Solids retention time is the fundamental control variable in anaerobic digestion and determines system efficiency by controlling mixed liquor volatile suspended solids (MLVSS) concentration. Under good operating conditions with no nutrient limitations or toxicity, bacterial growth and respiration are enhanced by an elevated system temperature, leading to a higher MLVSS concentration and lower required SRT. The optimal range for reliable anaerobic treatment is generally considered to be approximately 30 to 38°C (85 to 100°F). According to McCarty,[(2)] for municipal sludge to attain the accepted level of treatment at 35°C, the minimum SRT necessary to avoid complete washout is about four days. For practical control and reliable treatment, detention times of 10 to 20 days are normally used. Design SRTs for various temperatures are given in Table 1.[(3)] For a conventional anaerobic digester operating at 35°C, the suggested SRT is 20 days. The table indicates that process efficiency drops off significantly at lower operating temperatures. This factor can be very important in operating treatment plants in northern climates.

Solids loading factors are mainly used in designing reactor size, but they can also indicate if overloading is a potential problem. Loading rates differ between standard and high rate digestion processes. Standard rate digesters are usually heated but not mixed, and sludge is generally transferred to and from the units on an intermittent basis. Because the vessels

TABLE 1. Solids Retention Times Required for Design of Complete-Mix Digesters

Operational Temperature, °F	SRT, Days (Minimum)	(Suggested for Design)
Mesophilic Range		
50	-	55
65	28	40
75	20	30
85	14	25
95	10	10
Thermophilic Range		
100	10	20
110	-	15
120	-	15
130	-	15
140	-	-

are unmixed, stratification takes place, and active digestion occurs in only about 50% of the tank volume. Conversely, high-rate digesters are much more efficient. These systems are both heated and mixed, and provide more desirable environmental conditions for the methane-forming bacteria. Both the standard-rate and high-rate processes may employ a secondary digester. The function of this unit is to provide additional gas storage and to serve as a sludge settling and thickening basin. Typical solids loading rates are 0.03 to 0.10 lb volatile solids/ft^3/day for standard-rate digesters and 0.10 to 0.4 lb volatile solids/ft^3/day for high-rate digesters.(4)

Waste stabilization occurs as the result of an interaction between two major groups of bacteria, the acid formers and the methane formers. The acid formers hydrolize and biologically convert complex organic materials to volatile organic acids. These acids are subsequently converted by the methane bacteria to gaseous end products, primarily methane and carbon dioxide. The methane formers are very sensitive to environmental conditions and are significantly inhibited at pH levels below 6.2. In addition, these bacteria are strict anaerobes and cannot tolerate even small quantities of free oxygen. A valuable indication of digester efficiency is provided by the volatile acids test. An increase in the volatile acids concentration of the mixed liquor signifies that the methane bacteria are inhibited, and corrective action must be taken before the pH drops. The normal volatile acids concentration in a digester is about 250 mg/l as acetic acid,[4] but preferably should be between 70 to 140 mg/l.[5]

Volatile solids destruction is closely related to gas production and methane content, which together indicate both the degree of waste stabilization achieved and the digester efficiency. Laboratory studies involving a well-operated digester functioning at an 11-day SRT and 35 C (95 F) reported a typical 55% volatile solids reduction for municipal sewage sludge.[7] Gas is a by-product of cellular breakdown and anaerobic respiration. In a well-operated digester, where methane is the main constituent (65 to 70% by volume), gas volume is a good indicator of waste stabilization. However, gas volumes alone do not signify good operation because excess CO_2 can be produced by the destruction of bicarbonate alkalinity. Typical gas production values cited by Metcalf and Eddy[4] are 8 to 12 ft^3/lb volatile solids added and 12 to 18 ft^3/lb volatile solids destroyed. Vesilind[10] reports that a well-operated digester should produce about 6 to 8 ft^3/lb volatile solids added. Normal operating parameters for anaerobic digesters are summarized below:

Temperature (Mesophilic)	90-95 F[2]
pH	6.6-7.6[2]
Alkalinity	1000-5000 mg/l as $CaCO_3$[4]
Volatile Acids	50-250 mg/l as Acetic Acid[9]
SRT	20 days[3]
Volatile Solids Destruction	55%[7]
Gas Produced/lb VS Applied	6-12 ft^3/lb
Gas Produced/lb VS Destroyed	12-18 ft^3/lb[4]
Percent Methane	65-70% Vol.[4]
Percent CO_2	25-30% Vol.[4]

OPERATIONAL CHARACTERISTICS OF THE SURVEYED ANAEROBIC DIGESTERS

From the plant responses, Table 2 was compiled listing city/plant, type of plant, flow rate, and various digester operational characteristics. The plants are listed in the order of increasing flow rates. Because of the large range of treatment plant sizes, 1.2 to 800 mgd, median values of the operational parameters, not averages, were used to reflect typical conditions. As shown in Table 2, the "median treatment plant" had a flow of 54 mgd, an SRT of 24 days, and operated at 95°F. Median values of gas production, volatile acids, methane content and volatile solids destruction generally typified those expected in a well-operated digester. Thus, it can be concluded that half of the digesters responding to the survey met or exceeded accepted standards for normal operation. Such analysis, however, fails to address specific digester problems identified in the survey. These will be considered next.

As previously mentioned, temperature is an important factor in determining the rate of anaerobic digestion, and affects the required solids retention time. Operation below 85°F is not recommended because of the slow rate of reaction and resultant low gas production. Temperatures of the 60 plants surveyed ranged from 70 to 100°F with a standard deviation of 5.6°F. Two of the three facilities that operated at temperatures below 85°F, Cheyenne, Wyoming, and Oklahoma City, Oklahoma, showed evidence of stress. The third, Birmingham, Alabama, gave inadequate information to firmly assess the condition of its digesters. The Cheyenne plant reported a high volatile acids concentration of 1200 mg/1, but gas production, methane content and percent volatile acids destruction were within the normal range. Since the volatile acids test is generally a reliable indicator of system imbalance, this system may have been approaching failure. Cheyenne operated at an SRT of 30 days, which should be an ample detention time. The Oklahoma City digesters functioned at

TABLE 2. Operational Characteristics of the 60 Digester Facilities

City/Plant	Type of Plant	Flow Rate (mgd)	SRT, Days	Temp. °F	Volatile Acids mg/l as HAc	Gas Prod/VS App. ft^3/lb	%VS Destruction	Gas Prod/VS Destroyed ft^3/lb	% CH_4
Moses Lake, WA	Secondary	1.2	30	90	92	5.5	60	9.1	80
Pasco, WA	Secondary	1.7	40	95	50	-	37	-	68
Pendleton, OR	Secondary	2.0	50	98	1200	10.3	70	14.7	64
Pullman, WA	Secondary	3.0	30	95	520	7.6	60	12.7	63
Reading, PA	Secondary	3.0	14	90	240	-	61	-	54
Cheyenne, WY	Secondary	3.1	30	73	1200	7.3	47	15.5	62
Granger, UT	Secondary	6.7	60	85	420	2.6	-	-	-
Walla Walla, WA	Secondary	6.8	17	96	52	6.0	47	12.7	75
Wheeling, WV	Primary	8.0	26	95	82	16.7	62	27.0	-
Ewing-Lawrence, NJ	Tertiary	9.5	30	92	100	2.9	67	4.3	70
Boise, ID	Secondary	11.0	22	99	600	14.9	60	24.8	68
Cranston, RI	Secondary	11.0	26	95	275	8.7	-	-	-
Sioux Falls, SD	Secondary	11.0	20	98	-	1.1	22	5.2	-
Yakima, WA	Secondary	12.0	25	91	250	8.8	46	19.1	69
Brockton, MA	Secondary	13.4	13	97	90	7.2	40	17.9	-
Chicago, IL (J. Egan)	Secondary	15.0	48	95	105	11.9	33	36.0	-
San Antonio, TX (S)	Secondary	16.6	20	92	67	-	58	-	-
San Antonio, TX (L)	Secondary	17.5	20	85	59	3.8	64	6.5	68
El Paso, TX	Secondary	21	20	95	240	11.1	32	34.7	72
Oklahoma City, OK	Secondary	25	30	70	450	5.0	41	12.2	72
Las Vegas, NV	Secondary	27	34	90	-	-	33	-	-
Tucson, AZ	Secondary	28	32	95	400	-	-	-	-
Spokane, WA	Secondary	29	70	96	596	10.2	43	23.8	68
Phoenix, AZ (23rd)	Secondary	30	19	90	100	-	68	-	-
Des Moines, IA	Secondary	34	28	92	80	3.8	53	7.2	-
Albuquerque, NM	Secondary	35	15	94	<1000	2.2	70	3.1	65
Birmingham, AL	Secondary	35	-	79	250	-	50	-	60
Madison, WI	Secondary	35	13	91	165	8.2	55	15.0	68
Wichita, KS	Secondary	36	55	96	375	11.7	63	18.7	65
Salt Lake City, UT	Secondary	42	22	-	-	10.1	41	24.6	71
New York/Tallman, NY	Primary	66	-	-	-	15.0	82	18.2	60
Miami, FL	Secondary	67	30	96	100	10.1	52	19.4	64
Milwaukee, WI	50% Primary 50% Secondary	70	19	90	250	5.0	45	11.0	71

TABLE 2. (Cont'd.)

City/Plant	Type of Plant	Flow Rate (mgd)	SRT, Days	Temp. °F	Volatile Acids mg/l as HAc	Gas Prod/VS App. ft^3/lb	%VS Destruction	Gas Prod/VS Destroyed ft^3/lb	% CH_4
Columbus, OH	Secondary	72	14	91	450	7.6	38	20.0	68
San Francisco, CA	Primary	74	20	93	120	10.6	52	20.3	64
Wilmington, DE	Secondary	75	18	91	-	7.0	25	27.0	65
Yonkers, NY	Primary	75	24	90	400	7.8	52	15.0	60
Portland, OR	Secondary	76	24	99	110	8.0	65	12.3	63
Denver, CO	Primary	80	18	95	500	10.8	69	15.7	60
San Antonio, TX (R)	Secondary	83	20	87	66	-	56	-	-
San Jose, CA	Secondary	90	18	95	250	15.0	53	28.3	63
Toledo, OH	Secondary	94	12	91	2500	-	10	-	-
Seattle, WA	Primary	97	20	96	40	11.7	56	16.5	65
New York (Jamaica)	Secondary	101	-	-	-	6.1	70	8.7	65
San Diego, CA		110	28	98	200	8.5	60	14.2	65
Atlanta, GA	Secondary	120	18	95	30	3.3	50	6.6	70
Cincinnati, OH	17% Primary 83% Secondary	120	27	90	400	4.9	30	16.2	70
Boston, MA (Nut Is.)	Primary	128	16	95	350	11.3	61	18.6	60
Dallas, TX	Secondary	135	16	98	175	7.5	38	19.6	65
Orange County, CA	Primary	138	35	95	100	6.8	68	9.9	60
New York, Hunts Pt.	Secondary	160	-	-	-	9.2	67	13.8	67
Baltimore, MD (BR)	Secondary	185	17	93	120	9.2	40	23.1	65
Philadelphia, PA (NE)	Secondary	190	28	91	1200	5.5	47	11.6	66
Buffalo, NY	Primary	192	18	98	170	5.2	40	13.0	65
Philadelphia, PA (SW)	Primary	280	28	95	1200	8.3	44	18.8	57
Washington, DC	Secondary	290	23	95	150	4.6	43	10.6	65
Boston, MA (Deer Is.)	Primary	312	17	95	350	5.6	61	9.7	63
Los Angeles, CA	17% Primary 83% Secondary	320	30	100	250	13.1	60	21.8	65
Los Angeles County, CA	Primary	350	50	94	57	6.9	50	13.8	60
Chicago, IL (W-SW)	Secondary	800	47	95	60	6.2	30	20.7	69
All Plants									
Median		54.	24	95	240	7.6	52	15.5	65
Average		91.3	26.7	93	352	8.0	51	16.3	66
Standard Deviation			12.5	5.6	437	3.5	14.3	7.3	4.7
30 Largest									
Median		115	20	95	133	7.7	52	15.9	65
Average		165	24	94	369	8.2	50	16.2	64
Standard Deviation			9.1	3.2	529	3.1	15.3	5.4	3.5

70°F, the lowest temperature encountered in the survey. These units were somewhat stressed, as evidenced by low gas production (5.0 ft^3/lb VS applied, 12.2 ft^3/lb VS destroyed), low volatile solids destruction (41%), and relatively high volatile acids (450 mg/l). A follow-up phone call revealed that the digesters are old and overloaded, and have not been operating well for some time.

Solids retention times ranged from 12 to 70 days, with a median of 24 days and standard deviation of 12.5 days. The plants that operated at 13 days, Brockton, Massachusetts, and Madison, Wisconsin, exhibited good volatile acids control and gas production. Brockton showed a lower volatile solids destruction, but, in general, these plants were operating well. Indications of stress in other digesters with low SRTs were evident for Toledo (12 days), Columbus (14 days) and Albuquerque (15 days). Toledo displayed the worst performance, with a volatile acids concentration of 2500 mg/l, a 10% volatile solids destruction and essentially zero gas production. Columbus showed a somewhat high volatile acids concentration (450 mg/l) and low volatile solids destruction (38%). Albuquerque reported a volatile acids concentration of less than 1000 mg/l with extremely low gas production (2.2 ft^3/lb VS applied, 3.1 ft^3/lb VS destroyed). An unexplainable anomaly was the reported 70% volatile solids destruction. Other plants with low SRTs generally exhibited decreased volatile solids destructions.

Digesters operating at extremely long detention times (>40 days) did not perform significantly better than average. In fact, they all seemed to be having problems of some sort; either high volatile acids (Pendleton, Granger, Wichita, Spokane), low volatile solids destruction (Pasco, Chicago W-SW), or poor gas production (Granger). These facilities may have resorted to high SRTs in an attempt to improve digester efficiencies.

Volatile acids concentrations were above the recommended limit of 250 mg/l in 19 cases. Facilities reporting the highest acid levels were Pendleton, Cheyenne, the two Philadelphia plants and Toledo. Other operating characteristics of these plants, with the exception of Toledo, were generally normal. One of the Philadelphia plants had a low percent methane with normal gas production. On the other hand, some plants with volatile acids below 150 mg/l exhibited extremely depressed gas production. Ewing-Lawrence, San Antonio, Des Moines and Atlanta fell into this category. Albuquerque noted that its depressed gas production could be due to poor mixing, in addition to a low SRT and high volatile acids.

Volatile solids destruction in a well-operated digester is generally about 50 to 55%. The range reported for the survey digesters was 10 to 70%. Since gas production is directly related to volatile solids destruction, close correlation of these parameters was expected. On the contrary, plants that reported a low volatile solids destruction (<40%) often produced an amount of gas equal to or greater than the median. The percent methane of this gas was also often above the median. In several cases where low volatile solids destruction was consistent with low gas production (Sioux Falls, Cincinnati), the respondents noted that problems were occurring, and suggested reasons: need for cleaning the digesters in Sioux Falls and start-up problems with a new activated sludge system in Cincinnati. Volatile acids data were not supplied for Sioux Falls. Cincinnati's volatile acids were somewhat high, 400 mg/l, further indicating system imbalance.

Nine facilities, Wheeling, Boise, Chicago (J. Egan), Wichita, San Jose, New York (Tallman), Seattle, Boston (Nut Island) and Los Angeles (City), reported gas production/VS applied data greater than one standard deviation above the medan value. Of these, four facilities San Jose, Seattle, Wheeling, Los Angeles (City) , demonstrated characteristics consistent with well-operated digesters. High volatile acids were present at Boise, Boston (Nut Island) and Wichita, although volatile solids destructions were higher than normal. The Chicago (J. Egan) plant showed a depressed volatile solids destruction of 33% with otherwise normal operating characteristics. The fraction of methane in the off-gas was slightly low at New York (Tallman), only 60%. Of the 16 plants exhibiting enhanced gas production (>10 ft^3/lb VS applied), six reported higher than normal volatile acids concentrations. The median value of gas production/lb VS applied for all plants, 7.6 ft^3/lb, was slightly low according to Metcalf and Eddy,[4] but was within the typical range suggested by Vesilind.[10]

Eight plants exhibited very low gas production for both volatile solids applied and destroyed. Of these, Granger, Utah and Toledo, Ohio, expressed an interest in the addition of powdered activated carbon to their digesters. Toledo was willing to test it, but wanted to correct other operational problems first. Toledo's digesters depended on gas circulation for mixing, but the clogged pipes prevented effective mixing. The digesters have recently been cleaned and Toledo has again showed serious interest in serving as a test site for carbon addition. Commercial natural gas is presently being used as a supplemental fuel for the digester heating system. If the digesters can be successfully operated, off-gas can be substituted for the natural gas at significant energy and cost savings.

Granger indicated an interest in carbon addition to stabilize its process and increase gas production, but no firm plans have been made. The other six plants which appeared to be the most stressed based on gas production data were Ewing-Lawrence, Sioux Falls, San Antonio (L), Des Moines, Albuquerque and Atlanta. None of these plants commented on the applicability of powdered activated carbon to their systems. San Antonio noted that its low gas production could be due to leakage from faulty seals on the retrofitted digester covers. Des Moines mentioned problems with fluoride and heavy metal toxicity.

Several other plant respondents mentioned that they have considered adding powdered activated carbon to their anaerobic digesters. Tampa, Florida, and Charlotte, North Carolina, decided that the process would not provide significant benefits at their installations. Tampa's decision was based on the results of a five-month study in which carbon was added to a full-scale digester. Columbus expressed interest, but did not feel that testing was presently justified due to possible phase-out of the plant's anaerobic digesters. Atlanta, Georgia, and Madison, Wisconsin, have also considered implementing carbon addition. Presently, Brockton, Massachusetts, is very interested in powdered carbon as a means to enhance volatile solids destruction and increase gas production. This facility, like Toledo and Granger, has not yet finalized plans for carbon addition.

Three treatment plants reported that they were presently adding carbon to their anaerobic digesters. Reading, Pennsylvania, indicated that it had used carbon for over two years. Advantages which were cited included fewer overloading problems, clearer supernatant and improved sludge dewatering characteristics. Norristown, Pennsylvania, did not respond to the survey in time to be included in the data summary. The response did indicate, however, that carbon addition was responsible for increased gas production and a shorter required detention time at that plant. In addition, carbon reduced sludge toxicity and digester odor. The facility had used carbon for about a year at the time they responded to the PNL survey. Operating data from Salt Lake City were recently reviewed by PNL, and it was concluded that carbon did not produce any substantial enhancement at that site.

A separate analysis was performed on the 30 largest plants surveyed to determine if economies of scale applied and if the larger plants were more efficient and stable. As shown in Table 2, the median values are similar to those observed for the total sample, but the standard deviations are smaller for all parameters except volatile solids destruction and volatile acids. Smaller standard deviations indicate that the 30 largest plants operate more consistently close to the mean and suggested that as a group they are more reliable. Median values show that this group is operating close to established values for the well-operated digester model and performance is generally good.

Operating statistics for the surveyed digesters show that most are well operated. However, 18 of the 60 plants displayed one or more of the following conditions that indicate severe stress: low volatile solids destruction ($<35\%$), low gas production (<4.0 ft^3/lb VS applied), or high volatile acid concentrations (>600 mg/l). The 18 plants included seven of the 30 largest municipal wastewater treatment facilities in the U.S. Values of selected operational parameters for the stressed system are listed in Table 3. Low volatile solids destruction is shown to be the most common operational failure in these digesters. It should be noted that in many cases the reported data for a particular plant were inconsistent. For example, a high volatile solids destruction may have been listed, as well as low gas production. This type of disparity suggests that some of the submitted survey information might not have been completely accurate. The most that can be said is that as many as 18 (30%) of the surveyed plants may have been significantly stressed.

TABLE 3. Operational Parameters for Anaerobic Digesters Exhibiting Some Evidence of Significant Stress

	Flow Rate (mgd)	Volatile Acids (mg/l)	% VS Destruction	ft^3 gas/lb VS Applied
Pendleton	2.0	1200	70	10.3
Cheyenne	3.1	1200	47	7.3
Granger	6.7	420	-	2.6
Ewing-Lawrence	9.5	100	67	2.9
Sioux Falls	11.0	-	22	1.1
Chicago (J. Egan)	15.0	105	33	11.9
San Antonio (L)	17.5	59	64	3.8
El Paso	21	240	32	11.1
Las Vegas	27	-	33	-
Des Moines	34	80	53	3.8
Albuquerque	35	<1000	70	2.2
Wilmington	75	-	25	7.0
Toledo	94	2500	10	0
Atlanta	120	30	50	3.3
Cincinnati	120	400	30	4.9
Philadelphia (NE)	190	1200	47	5.5
Philadelphia (SW)	280	1200	44	8.3
Chicago (W-SW)	800	60	30	6.2

DIGESTER GAS PRODUCTION AND USAGE

To assess the energy potential of municipal anaerobic digesters, gas production, percent methane, methane production, methane production efficiencies, and percent of the off-gas flared were examined for the 60 U.S. treatment plants surveyed. These data are shown in Table 4. Methane production for each plant was determined from the percentage of methane in off-gas and the total gas generation rate. The total reported methane production rate for the 60-plant sample is 23 million ft^3/day, of which 21 million ft^3/day is attributable to the 30 largest plants surveyed. This group of 30 of the largest treatment plants in the U.S. produces a substantial portion, about 31%, of the nation's digester gas.

Of the 23 million ft^3/day of methane produced at the surveyed facilities, a median 75% is used either onsite or offsite and the remainder is discharged to waste gas burners (flared). Heating digesters is the most common application of the off-gas, followed by heating buildings, operating equipment and generating power. Three plants sell gas to utilities; two compress and store it. Complete gas usage data for the 60 plants surveyed are shown in Table 5. From Table 5 it is evident that most plants have multiple gas usages. The 30 largest plants have a better gas utilization record than the total sample, a median 78% of the total gas produced by these 30 plants is used, and nine of them use all the gas they produce. On the other hand, the 30 smaller plants surveyed use only a median 60% of their gas, with six plants reporting complete utilization.

The data from the survey were used as a basis for estimating the future energy potential of anaerobic digesters on a national scale. For this extrapolation, it was necessary to approximate present and future population size and sewage flow. Two simplifying assumptions were made: 1) that total sewage flow and the flow through plants with anaerobic digesters increased at the same rate as population, and 2) that digester gas production would increase in proportion to sewage flow. Therefore, population and gas production would increase at the same rate. These assumptions are not totally valid because

TABLE 4. Digester Gas Production for the 60 Treatment Plants Surveyed

City/Plant	Flow Rate (mgd)	Gas Production (ft^3/day)	CH_4	CH_4 Production (ft^3/day)	% Gas Flared	CH_4 Production Efficiency (ft^3/mg)
Moses Lake, WA	1.2	1.0×10^4	80	8.0×10^3	0	6,700
Pasco, WA	1.7	1.8×10^4	68	1.2×10^4	50	7,100
Pendleton, OR	2.0	2.0×10^4	64	1.3×10^4	75	6,500
Pullman, WA	3.0	3.0×10^4	63	1.9×10^4	70	6,300
Reading, PA	3.0	2.5×10^4	54	1.4×10^4	0	4,700
Cheyenne, WY	3.1	2.5×10^4	62	1.6×10^4	30	5,200
Granger, UT	6.7	1.8×10^4	--	--	70	--
Walla Walla, WA	6.8	2.5×10^4	75	1.9×10^4	40	2,800
Wheeling, WV	8.0	2.5×10^4	--	--	100	--
Ewing-Lawrence, NJ	9.5	5.5×10^4	70	3.9×10^4	60	4,100
Boise, ID	11.0	1.2×10^5	68	8.2×10^4	0	7,500
Cranston, RI	11.0	7.9×10^4	--	--	40	--
Sioux Falls, SD	11.0	4.1×10^4	--	--	5	--
Yakima, WA	12.0	7.4×10^4	69	5.1×10^4	98	4,300
Brockton, MA	13.4	7.9×10^4	--	--	50	--
Chicago, IL (J. Egan)	15.0	1.5×10^5	--	--	100	--
San Antonio, TX (S)	16.6	--	--	--	-	--
San Antonio, TX (L)	17.5	6.8×10^4	68	4.6×10^4	-	2,600
El Paso, TX	21	2.7×10^5	72	1.9×10^5	2	9,000
Oklahoma City, OK	25	3.5×10^5	72	2.5×10^5	0	10,000
Las Vegas, NV	27	--	--	--	50	--
Tucson, AZ	28	3.0×10^5	--	--	35	--
Spokane, WA	29	4.1×10^5	68	2.8×10^5	25	9,700
Phoenix, AZ (23rd)	30	--	--	--	-	--
Des Moines, IA	34	2.0×10^5	--	--	0	--
Albuquerque, NM	35	1.3×10^5	65	8.4×10^4	0	2,400
Birmingham, AL	35	--	60	--	-	--
Madison, WI	35	3.6×10^5	68	2.4×10^5	15	6,900
Wichita, KS	36	6.0×10^5	65	3.9×10^5	75	11,000
Salt Lake City, UT	42	3.6×10^5	71	2.6×10^5	65	6,200
New York/Tallman, NY	66	9.37×10^4	60	5.6×10^4	0	850
Miami, FL	67	4.9×10^5	64	3.1×10^5	5	4,600
Milwaukee, WI	70	7.1×10^5	71	5.0×10^5	0	7,100
Columbus, OH	72	5.4×10^5	68	3.7×10^5	0	5,100
San Francisco, CA	74	7.4×10^5	64	4.7×10^5	99	6,400
Wilmington, DE	75	3.5×10^5	65	2.3×10^5	0	3,100
Yonkers, NY	75	3.5×10^5	60	2.1×10^5	85	2,800
Portland, OR	76	4.4×10^5	63	2.8×10^5	65	3,700
Denver, CO	80	8.5×10^5	60	5.1×10^5	55	6,400
San Antonio, TX	83	--	--	--	-	--
San Jose, CA	90	2.7×10^6	63	1.7×10^6	10	19,000
Toledo, OH	94	--	--	--	100	--
Seattle, WA	97	9.3×10^5	65	6.1×10^5	50	6,300
New York/Jamaica, NY	101	2.06×10^5	65	1.4×10^5	24	1,400
San Diego, CA	110	1.4×10^6	65	9.1×10^5	70	8,300
Atlanta, GA	120	3.0×10^5	70	2.1×10^5	10	1,800
Cincinnati, OH	120	8.5×10^5	70	6.0×10^5	0	5,000
Boston, Nut Island, MA	128	9.0×10^5	60	5.4×10^5	30	4,200
Dallas, TX	135	9.0×10^5	65	5.9×10^5	75	4,400
Orange County, CA	138	2.5×10^6	60	1.5×10^6	10	11,000
New York/Hunts Point, NY	160	3.6×10^5	67	2.4×10^5	22	1,500
Baltimore, MD (BR)	185	1.5×10^6	65	9.8×10^5	50	5,300
Philadelphia, PA (NE)	190	7.7×10^5	66	5.1×10^5	25	2,700
Buffalo, NY	192	5.7×10^5	65	3.7×10^5	0	1,900
Philadelphia, PA (SW)	280	9.0×10^5	57	5.1×10^5	20	1,800
Washington, DC	290	9.0×10^5	65	5.9×10^5	30	2,000
Boston/Deer Island, MA	312	6.3×10^5	63	4.0×10^5	0	1,300
Los Angeles, CA	320	4.4×10^6	65	2.9×10^6	0	9,100
Los Angeles County, CA	350	5.5×10^6	60	3.3×10^6	0	9,400
Chicago, IL (W-SW)	800	2.6×10^6	69	1.8×10^6	25	2,300

TABLE 5. Gas Usage in the Surveyed Treatment Plants

City/Plant	Flow Rate (mgd)	% of Gas Utilized	Usages
Moses Lake, WA	1.2	100	1,2
Pasco, WA	1.7	50	1,2
Pendleton, OR	2.0	25	1,2
Pullman, WA	3.0	30	1,2
Reading, PA	3.0	100	1,2
Cheyenne, WY	3.1	70	1,2
Granger, UT	6.7	30	1,2
Walla Walla, WA	6.8	60	1,2
Wheeling, WV	8.0	0	-
Ewing-Lawrence, NJ	9.5	40	1,2
Boise, ID	11.0	100	1,2,3
Cranston, RI	11.0	60	1,2,3
Sioux Falls, SD	11.0	95	1,3,5
Yakima, WA	12.0	2	1,2
Brockton, MA	13.4	50	1,2
Chicago, IL (J. Egan)	15.0	0	-
San Antonio, TX (S)	16.6	NA	1
San Antonio, TX (L)	17.5	NA	1
El Paso, TX	21	98	4
Oklahoma City, OK	25	100	2,3
Las Vegas, NV (NE)	27	50	1
Tucson, AZ	28	65	1,3
Spokane, WA	29	75	1,2
Phoenix, AZ (23rd)	30	NA	1
Des Moines, IA	34	100	6
Albuquerque, NM	35	100	1,4
Birmingham, AL	35	NA	1,3
Madison, WI	35	85	1,2,3
Wichita, KS	36	25	1,2
Salt Lake City, UT	42	35	1,2
New York/Tallman, NY	66	100	3
Miami, FL	67	95	3
Milwaukee, WI	70	100	1,3,4

TABLE 5. (Cont'd.)

City/Plant	Flow Rate (mgd)	% of Gas Utilized	Usages
Columbus, OH	72	100	1,4,5
San Francisco, CA	74	1	1,2
Wilmington, DE	75	100	1,2
Yonkers, NY	75	15	1,2
Portland, OR	76	35	1,2
Denver, CO	80	45	1,2
San Antonio, TX (R)	83	NA	1
San Jose, CA	90	90	3,4
Toledo, OH	94	0	-
Seattle, WA	97	50	1,2,3,7
New York/Jamaica, NY	101	76	1,2
San Diego	110	30	1
Atlanta, GA	120	90	1,2,3,5,7
Cincinnati, OH	120	100	4
Boston/Nut Island, MA	128	70	1,3,4,5
Dallas, TX	135	25	1
Orange County, CA	138	90	1,2,3,6
New York/Hunts Point, NY	160	78	1,2
Baltimore, MD (BR)	185	50	1,2
Philadelphia, PA (NE)	190	75	1,2
Buffalo, NY	192	100	1,2,5
Philadelphia, PA (SW)	280	80	1,2
Washington, DC	290	70	1,2,3
Boston, MA (Deer Is.)	312	100	1,3,4
Los Angeles City, CA	320	100	4,6
Los Angeles County, CA	350	100	4,6
Chicago, IL (W-SW)	800	75	1

USAGE KEY

1 - Heat Digesters
2 - Heat Buildings
3 - Operate Blowers, Pumps, Aerators
4 - Power Generation
5 - Incineration
6 - Sell
7 - Compress/Store

NA - Not Available

national sewage flow per capita will probably increase due to industrial expansion, and a greater proportion of the sludge flow may be anaerobically digested in the future. Furthermore, increasing numbers of wastewater treatment facilities are being constructed to meet environmental requirements. Thus, the projections made in this report should represent a conservative estimate of future digester gas production and energy value.

The most recent sewage flow data were found in the 1968 Inventory of Municipal Waste Facilities.[12] Statistics taken from this inventory were: the population served by sewerages, total sewer service (mgd), population served by anaerobic digesters and total flow through facilities with anaerobic digesters. These factors were linearly extrapolated for 1978 and 1985 based on population data supplied by the U.S. Bureau of Census. Data for 1968, 1978 and 1985 (projected) are displayed in Table 6. The data indicate that an estimated 70% of the national sewerage flow is processed through anaerobic digesters.

The total amount of digester methane produced in the U.S. was calculated using the median methane production efficiency (ft^3 CH_4/day/mgd) for the 60 plants surveyed. The median value, 5100 ft^3 CH_4/mg, was used to project the national methane production for 1978 and 1985 by the relationship:

National CH_4 Production (ft^3/day) = total flow with anaerobic digesters (mgd) x median methane production efficiency (ft^3 CH_4/mg)

The computed quantities of methane are presented in Table 6. Annual energy production by U.S. digesters is estimated at 2.46×10^{10} ft^3 CH_4 (2.36×10^{13} Btu) for 1978 and 2.63×10^{10} CH_4 (2.52×10^{13} Btu) for 1985.

The value of the digester gas was determined in order to assign a dollar amount to the quantity of gas lost by flaring. Although the volume of off-gas estimated for 1985 is proportional to population increase, the gas value in 1985 is significantly higher due to a projected 150% increase in natural gas prices. The worth of the digester gas is based on the price of a volume of

TABLE 6. Total Value of Digester Gas Generated at U.S. Wastewater Treatment Facilities

Year	Population	Population w/Service	Total Service (mgd)	Population w/Anaerobic Dig.	Total mgd w/Anaerobic Dig.
1968	201×10^6	130×10^6	17,599	89.6×10^6	12,021
1978	219×10^6	142×10^6	19,028	97.9×10^6	13,217
1985	233×10^6	151×10^6	20,234	105.0×10^6	14,108

Year	Total CH_4 Production (ft^3/Day)	Price of Natural Gas	Total CH_4 Value $/Day	CH_4 Flared (ft^3/Day)	CH_4 Flared Value $/Day
1968	61.3×10^6	-	-	-	-
1978	67.4×10^6	$1.70/$10^6$Btu	110,000	16.9×10^6	27,500
1985	72.0×10^6	$4.24/$10^6$Btu	293,000	18.0×10^6	73,000

natural gas having the same total Btu content. An average heating value of 959 Btu/ft^3 was assumed for methane. Natural gas prices for industrial users were obtained from the American Gas Association. These prices, along with the value of the total digester gas production, are included in Table 6. The median percentage of gas flared at the 60 plants was 25%. Applying this factor, the present daily worth of flared gas in the U.S. is $27,500, or an annual loss of $10 million. In 1985 this value is projected to increase to $37,000/day, or nearly $27 million per year. With dwindling energy resources and increasing energy costs, it may soon become an economic necessity to capture this energy for in-plant usage or sale to a local industrial consumer.

The value of each plant's digester gas is given in Table 7. The natural gas prices which were used to assess the value of the generated methane are presented in Table 8. These prices are fixed by state agencies and are generally uniform throughout each state. As previously noted, the 30 largest plants surveyed are of major interest because they produce 31% of the total U.S. digester gas. In addition, an estimated 37% of the national sewage flow through anaerobic digesters is treated in these facilities. A cost analysis indicates that although these plants flare only 26% by volume of the methane flared nationally, they account for 31% of the value lost because of higher natural gas costs in those areas ($\$2.03/10^6$ Btu = 30 plant average; $\$1.70/10^6$ Btu = national average).

The two largest gas producing plants, Los Angeles (City) and Los Angeles (County) do not flare any gas. In a recent report,[11] Los Angeles (County) indicated that the total heating value of its generated gas is 3.4×10^9 Btu/day. The significant gas production at this facility is due in part to additional sludge solids received from upstream San Gabriel River treatment plants. The largest in-plant use is electrical generation. Assuming an overall gas-to-wire efficiency of 34%, about 5.3×10^8 Btu of digester gas is converted daily to 1.8×10^8 Btu (52,000 KWH) of electricity. To fulfill its total electrical requirements of 124,000 KWH/day, Los Angeles County buys 72,000 KWH/day from Southern California Edison. Digester gas is also used

TABLE 7. Total Value of Digester Gas Generated at the 60 Surveyed Treatment Plants

City/Plant	Flow Rate (mgd)	Cost of Natural Gas ($/$10^6$ Btu)	CH_4 Production (ft^3/day)	CH_4 Production (10^6 Btu/day)	Value of CH_4 Production ($/day)	Volume CH_4 Flared (ft^3/day)	Value of Flared Gas ($/day)
Moses Lake, WA	1.2	2.15	8.0×10^3	7.7	16	0	0
Pasco, WA	1.7	2.15	1.2×10^4	12.0	26	6.0×10^3	13
Pendleton, OR	2.0	2.33	1.3×10^4	12.0	28	9.8×10^3	21
Pullman, WA	3.0	2.15	1.9×10^4	18.0	39	1.3×10^4	27
Reading, PA	3.0	2.03	1.4×10^4	13.0	26	0	0
Cheyenne, WY	3.1	1.04	1.6×10^4	15.0	16	4.8×10^3	5
Granger, UT	6.7	1.18	-	-	-	-	-
Walla Walla, WA	6.8	2.15	1.9×10^4	18.0	39	7.6×10^3	16
Wheeling, WV	8.0	1.70	-	-	-	-	-
Ewing-Lawrence, NJ	9.5	2.74	3.9×10^4	37.0	100	2.3×10^4	61
Boise, ID	11.0	1.98	8.2×10^4	78.0	150	0	0
Cranston, RI	11.0	3.10	-	-	-	-	-
Sioux Falls, SD	11.0	1.13	-	-	-	-	-
Yakima, WA	12.0	2.15	5.1×10^4	49.0	110	5.0×10^4	100
Brockton, MA	13.4	3.21	-	-	-	-	-
Chicago, IL (J. Egan)	15.0	1.79	-	-	-	-	-
San Antonio, TX (S)	16.6	1.96	-	-	-	-	-
San Antonio, TX (L)	17.5	1.96	4.6×10^4	44.0	90	-	-
El Paso, TX	21.0	1.96	1.9×10^5	190.0	370	3.8×10^3	7
Oklahoma City, OK	25.0	1.31	2.5×10^5	240.0	310	0	0
Las Vegas, NV	27.0	1.82	-	-	-	-	-
Tucson, AZ	28.0	1.23	-	-	-	-	-
Spokane, WA	29.0	2.15	2.8×10^5	270.0	580	7.0×10^4	150
Phoenix, AZ (23rd)	30.0	1.23	-	-	-	-	-
Des Moines, IA	34.0	1.31	-	-	-	0	0
Albuquerque, NM	35.0	1.19	8.4×10^4	81.0	100	0	0
Birmingham, AL	35.0	1.27	-	-	-	-	-
Madison, WI	35.0	1.81	2.4×10^5	230.0	420	3.6×10^4	62
Wichita, KS	36.0	1.09	3.9×10^5	370.0	400	2.9×10^5	300
Salt Lake City, UT	42.0	1.18	2.6×10^5	240.0	280	1.7×10^5	180
New York/Tallman, NY	66.0	2.27	5.6×10^4	54.0	120	0	0

TABLE 7. (Cont'd.)

City/Plant	Flow Rate (mgd)	Cost of Natural Gas ($/10^6 Btu)	CH_4 Production (ft^3/day)	CH_4 Production (10^6 Btu/day)	Value of CH_4 Production ($/day)	Volume CH_4 Flared (ft^3/day)	Value of Flared Gas ($/day)
Miami, FL	67	1.35	3.1×10^5	300	400	1.6×10^4	21
Milwaukee, WI	70	1.81	5.0×10^5	480	870	0	0
Columbus, OH	72	1.84	3.7×10^5	350	650	0	0
San Francisco, CA	74	1.95	4.7×10^5	450	880	4.6×10^5	860
Wilmington, DE	75	1.97	2.3×10^5	220	440	0	0
Yonkers, NY	75	2.27	2.1×10^5	200	460	1.8×10^5	390
Portland, OR	76	2.33	2.8×10^5	270	630	1.8×10^5	400
Denver, CO	80	1.02	5.1×10^5	490	540	2.8×10^5	280
San Antonio, TX	83	1.96	-	-	-	-	-
San Jose, CA	90	1.95	1.7×10^6	1,600	3,200	1.7×10^5	320
Toledo, OH	94	1.84	-	-	-	-	-
Seattle, WA	97	2.15	6.1×10^5	580	1,300	3.05×10^5	620
New York/Jamaica, NY	101	2.27	1.4×10^5	130	300	3.4×10^4	74
San Diego, CA	110	1.95	9.1×10^5	870	1,700	6.4×10^5	1,200
Atlanta, GA	120	1.37	2.1×10^5	200	280	2.1×10^4	28
Cincinnati, OH	120	1.84	6.0×10^5	570	1,100	0	0
Boston/Nut Island, MA	128	3.21	5.4×10^5	520	1,700	1.6×10^5	480
Dallas, TX	135	1.96	5.9×10^5	570	1,100	4.4×10^5	820
Orange County, CA	138	1.95	1.5×10^6	1,400	2,800	1.5×10^5	270
New York/Hunts Point, NY	160	2.27	2.4×10^5	230	230	5.3×10^4	120
Baltimore, MD (BR)	185	2.09	9.8×10^5	940	2,000	4.9×10^5	980
Philadelphia, PA (NE)	190	2.03	5.1×10^5	490	1,000	1.3×10^5	240
Buffalo, NY	192	2.27	3.7×10^5	350	800	0	0
Philadelphia, PA (SW)	280	2.03	5.1×10^5	490	1,000	1.0×10^5	200
Washington, DC	290	2.17	5.9×10^5	570	1,200	1.8×10^5	370
Boston/Deer Island, MA	312	3.21	4.0×10^5	380	1,200	0	0
Los Angeles, CA	320	1.95	2.9×10^6	2,800	5,400	0	0
Los Angeles County, CA	350	1.95	3.3×10^6	3,200	6,200	0	0
Chicago, IL (W-SW)	800	1.79	1.8×10^6	1,700	3,100	4.5×10^5	770
Total	5,479.5		2.3×10^7	23,300	43,700	5.1×10^6	9,380
30 Largest	4,950.0		2.1×10^7	20,400	40,600	4.4×10^6	8,440

TABLE 8. Industrial Natural Gas Prices ($\$/10^6$ Btu)

State	1976[a]	1978 (Projected)	1985 (Projected)
Alabama	0.98	1.26	3.15
Alaska	0.66	0.85	2.11
Arizona	0.95	1.23	3.05
California	1.51	1.95	4.85
Colorado	0.79	1.02	2.54
Delaware	1.53	1.97	4.91
Florida	1.05	1.35	3.37
Georgia	1.06	1.37	3.40
Idaho	1.54	1.98	4.94
Illinois	1.39	1.79	4.46
Iowa	1.01	1.31	3.24
Kansas	0.84	1.08	2.70
Maryland	1.62	2.08	5.20
Massachusetts	2.49	3.20	8.00
Nevada	1.40	1.80	4.50
New Jersey	2.11	2.72	6.77
New Mexico	0.92	1.18	2.95
New York	1.76	2.27	5.65
Ohio	1.43	1.84	4.59
Oklahoma	1.01	1.30	3.24
Oregon	1.81	2.33	5.81
Pennsylvania	1.57	2.03	5.04
Rhode Island	2.39	3.08	7.67
South Dakota	0.87	1.12	2.79
Texas	1.52	1.96	4.88
Utah	0.91	1.17	2.92
Washington	1.67	2.15	5.36
Washington, D.C.	1.68	2.17	5.40
West Virginia	1.31	1.67	4.20
Wisconsin	1.40	1.81	4.50
Wyoming	0.80	1.03	2.57

[a] From the American Gas Association.

for steam heating the digesters and for pumping primary effluent. The remainder of the gas, over half the total volume produced, is sold to an adjacent oil refinery. The amount sold to the refinery (about 1.7×10^9 Btu/day) exceeds the energy purchased from the utility, implying that Los Angeles County is presently a net energy producer. By 1981 Los Angeles County plans to upgrade its plant to provide secondary treatment and to use all of the gas for onsite electrical power generation, operation of sewage pumps and process heating. As a result of the increased energy requirements, purchase of offsite electrical power probably will still be required. However, by supplying 88% of its in-plant energy needs, Los Angeles County will approach an energy independent operation.

Los Angeles (City) currently produces 2.8×10^9 Btu/day of digester gas. Like Los Angeles (County), the City presently uses a portion of its gas for onsite power generation. About half is sold to a local utility. Other surveyed facilities that reported electrical power generation capabilities did not flare or sell any of their digester gas. It was not clear what fraction of the total plant energy demands were being supplied by the off-gas in these instances.

Another large gas producer, Chicago (W-SW), flares only 25% of its digester gas. However, due to the magnitude of its total gas production, the unused portion has a value of $770/day. Together, the five plants flaring the largest volumes of gas [San Diego, Baltimore (Back River), San Francisco, Dallas, and Chicago (W-SW)] flare 8.7×10^{11} Btu/year, or 15% of the total flared nationally. This gas has a present value of about $1.7 million annually. Based on projected gas price increases, the utilized gas would be worth approximately $4.2 million in 1985. If more efficient gas utilization practices could be implemented at these large plants, as they have in Los Angeles County, the full economic advantage of anaerobic digestion, both for sludge stabilization and energy production, could be realized.

On a national scale, an estimated 16.9 million cubic feet of methane is flared per day, amounting to a daily energy loss of 1.62×10^{10} Btu (5.91×10^{12} Btu/yr). As a comparison, the current estimated quantity of digester gas being flared is equivalent to the energy required to supply 50,000 homes (at the 1977 average residential consumption rate of 118.7 million Btu/yr/home) with their natural gas needs. Even if this gas were not used directly in the homes, it could help defray fuel costs in municipal facilities and thus indirectly benefit the community.

Impurities in the digester gas have raised some questions about its desirability as an energy source. Untreated off-gas typically contains 25 to 30% CO_2 and small quantities of N_2 and H_2S. Scrubbing is not usually necessary to ensure adequate burning of the gas, but odor can be a problem. Restricting the burning of digester gas to municipal plants may be one solution. Another alternative is to convert the gas to electrical energy for either in-plant or community use. As an essentially free by-product of anaerobic digestion, various applications of methane as a fuel should be thoroughly investigated.

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APPENDIX

ANAEROBIC DIGESTION SURVEY FORM

ANAEROBIC DIGESTION SURVEY FORM

Location of Facility: ______________________________

Name of Facility: ______________________________

Information Supplied By:

Name ____________________ Title ____________________

Address ______________________________ Phone ______________

General Information

Schematic of Treatment Process: (On separate sheet)

Average Plant Flow: __________ mgd

Type of Treatment:

Process	% of Total Flow, or Actual Flow
Primary	
Conventional Activated Sludge	
Pure Oxygen Activated Sludge	
Trickling Filter	
Aerated Lagoon	
Other ______________	

Sources of Influent Sewage:

Source	% of Total Flow, or Actual Flow
Municipal	
Industrial (Specify Below)	

Anaerobic Digesters: Yes ______ No ______

If no, are anaerobic digesters planned in the future: Yes ______ No ______

Digester Feed

Loading Rate: ________________ lb $VS/ft^3/day$

Sludge Flow Rate: ________________

% Total Solids: ________________

% Volatile Solids: ________________

Composition of Feed Sludge:

Source	% Solids	% of Total Flow, or Actual Flow
Primary Sludge		
Activated Sludge		
Trickling Filter Sludge		
Other ______________		

Specify any prethickening of the feed sludge: ______________________

____

____

System Description

Describe the digestion system (e.g., conventional, high rate, two stage, etc.): ______________________

____

____

____

No. and volume of digesters: ______________________

____

____

Type of digester heating system: ______________________

____

____

Type of digester mixing system: ______________________

____

____

Digester Operating Data

Parameter	First Stage	Second Stage
Temperature		
pH		
Alkalinity (mg/l as $CaCO_3$)		

Parameter	First Stage	Second Stage
Volatile Acids (mg/l as HAc)	____	____
% Volatile Solids	____	____
% Total Solids	____	____
% Volatile Solids Destruction	____	____
Gas Production	____	____
Gas Composition	____	____
Average Solids Residence Time	____	____

Are any chemicals added to the digester(s)?

Type ____________ Amount ____________

Frequency of addition ____________

Purpose ____

____

____

List any digester operating problems:

Heavy Metal Toxicity ____________________

Ammonia Toxicity ____________________

Salt Toxicity ____________________

Excessive Scum Formation ____________________

High Suspended Solids in Digester Supernatant ____________________

Excessive Loading Rate ______________________

Others ____________ ______________________

____________ ______________________

Discussion of Problems: ______________________

____

____

____

____

____

Gas Production

How is the digester gas used? ______________________

____

____

____

____

Percent of total gas production, or volume, used for the following purposes:

Heating the Digester(s) ______________________

Heating Buildings ______________________

Operating Sewage Pumps ______________________

Operating Aerators ______________________

Flared ______________________

Sold (Specify Type of Buyer) ______________________________

Other ______________________________

Sludge Disposal

Volume of digested sludge generated: ______________________________

What is the disposal method for digested sludge? ____________________

____

____

____

____

Is the digested sludge dewatered prior to disposal? Yes _____ No _____

If so, what type of dewatering process is used? (e.g., centrifugation, vacuum filtration)

____

____

____

Dewatering Process:

Influent Percent Solids ____________

Effluent Percent Solids ____________

Are any chemicals added to aid in dewatering? Yes _____ No _____

Type ______________ Amount ______________

Frequency of Addition ______________

Are there any characteristics of the digested sludge that make it unsuitable for a desired end usage? ____

____

____

____

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