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A RELIABILITY STUDY OF MECHANICAL EQUIPMENT AT MUNICIPAL WASTEWATER TREATMENT PLANTS

The University of Oklahoma

PH.D. 1985

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THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

A RELIABILITY STUDY OF MECHANICAL EQUIPMENT AT MUNICIPAL WASTEWATER TREATMENT PLANTS

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF PHILOSOPHY

By

ANDY LOK-YEE LAW

Norman, Oklahoma

1985

A RELIABILITY STUDY OF MECHANICAL EQUIPMENT
AT MUNICIPAL WASTEWATER TREATMENT PLANTS

A DISSERTATION

APPROVED FOR THE DEPARTMENT OF CIVIL ENGINEERING
AND ENVIRONMENTAL SCIENCES

By

James M. Robertson

ACKNOWLEDGMENTS

I am greatly indebted to Professor George Reid for his guidance and encouragement in the preparation of this dissertation, and perhaps more importantly for his teaching that goes beyond the engineering field to that of philosophy of education and life. The financial support that he provided through contracts and assistantships also enabled me to complete my graduate studies.

I am indebted to Dr. Larry Canter for teaching me the techniques of research in my Masters' program and continuing to guide and teach me in my doctoral program. I wish to thank Drs. Leale Streebin and James Robertson for their teaching and serving on my dissertation committee. To Dr. Marvin Baker, who graciously agreed to serve on my dissertation committee, goes my special thanks.

I am grateful to J.J. Chou at General Motors for providing computer programming assistance all through the data processing and analysis phase of this research. To Gene-Pai Chou at the Oklahoma Water Resources Board for his efforts in refining the equipment and manufacturer lists, in sending out the summary results to the wastewater treatment plants who expressed interest and above all for the times that we shared discussing our dissertations, is a simple thank you that only friends can understand. A thank you is also due Dr. Jerry Murphy for helping me on the survey cover letter.

I wish to thank Charles Imel at the Naval Civil Engineering Laboratory who recognized the value of my work in solving engineering problems and subsequently awarded the University of Oklahoma a contract to do work on equipment reliability.

Of critical importance was the contribution of those wonderful people at the surveyed municipal wastewater treatment plants who took the time and made super effort in completing the questionnaires. Without their valuable cooperation this research could never materialize.

I like to thank Sandy Kawano and Sandi Patrick for their efforts in typing my dissertation. Thanks are also due Wilma Clark and Dorothy Bush for typing sections of my dissertation.

This dissertation is dedicated to my wife Cynthia.

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ABSTRACT

The failure of equipment has been identified by various researchers to be among the major causes of municipal wastewater treatment plant failures. This research is initiated as a result of the concern with the questions involving the reliability of treatment equipment. Using a mail questionnaire survey, equipment performance data as well as operation and maintenance information were collected from over 300 municipal wastewater treatment plants in 20 states. The reliability data base established represents data from plants in the 1 million gallons per day or larger size group. The data base consists of data such as mean time between failures, mean downtime and others. Data application to assist in equipment related decision-making processes such as the selection of equipment and the improvement of maintenance programs were discussed. Attempts made at correlating equipment reliability with operation and maintenance factors, however, yielded no positive result.

A RELIABILITY STUDY OF MECHANICAL EQUIPMENT AT MUNICIPAL WASTEWATER TREATMENT PLANTS

CHAPTER I

INTRODUCTION

Background

The importance of preventing and controlling the pollution of the Nation's invaluable water resources cannot be overemphasized. The enactment of the Federal Water Pollution Control Act Amendments of 1972 (PL92-500) and the Clean Water Act of 1977 (PL95-217) are evidences of the public's awareness and concern with the pollution of the water resources. The U.S. Environmental Protection Agency (EPA) and its predecessor agencies have been providing financial aid to municipalities for wastewater treatment facility construction since 1957 (Dames and Moore, 1980). In over two decades of grant programs involving billions of dollars, thousands of new facilities have been constructed and old facilities enlarged or upgraded. According to the EPA's "1978 Needs Survey" (Chamblee, 1979), over 14,000 wastewater treatment plants (WWTPs) were in operation at the time of the survey.

In spite of the expenditure of enormous amounts of financial and human resources, the pollution control objectives specified for these WWTPs are not being met. Many WWTPs constructed in the past and recent times have encountered the fate of a partial or a total failure, with the end result that many were unable to attain treatment goals. Analysis of the data from the 1974 and 1975 EPA surveys revealed that less than half of the secondary treatment plants were in compliance with the secondary treatment definition of 30 mg/l for both 5-day BOD (Biochemical Oxygen Demand) and TSS (Total Suspended Solids) in the effluent (Gilbert, 1976). See Table 1. Recently, the General Accounting Office's (GAO) survey (1980) of 242 WWTPs in ten states indicated that more than 80% of the plants were not meeting treatment objectives. See Table 2.

To have a few failures among a large group of WWTPs is normal and can be expected. The high percentage of WWTPs that were reported to be incapable of meeting treatment goals, however, is alarming. Both the EPA and the GAO acknowledged that noncompliance with NPDES (National Pollution Discharge Elimination System) permits by publicly-owned treatment works (POTWs) is a significant problem. The failure of POTWs to meet performance goals not only has an adverse effect on the Nation's ability to protect its water resources, but it also represents the potential waste of millions of dollars of the taxpayers' money.

Numerous attempts have been made to identify and determine the causes of failure of these POTWs. The complexity of the problem is reflected by the number of different failure factors identified by concerned researchers. Ineptness of the operator to control process, improper technical guidance, inadequate performance monitoring, design deficiencies, insufficient funding, administrative shortcomings, improper installations and equipment malfunctions are among a plethora

Table 1. Compliance With Secondary Treatment Requirements-From 1974 and 1975 Surveys[a]

Degree of Compliance	Number of Trickling Filter Plants		Number of Activated Sludge Plants		Both Types	
	1974	1975	1974	1975	Total	%
Satisfactory	50	27	93	88	258	48
Unsatisfactory But Marginal	26	28	22	31	107	20
Poor	32	53	38	44	167	32
Total	108	108	153	163	532	100

[a] From Gilbert, 1976.

Table 2. Effluent Violations That Occurred in the GAO Sample During the Period 1978-1979[a]

Region	Sample Number	Facility Violations for the Following Number of Months--				
		At Least 1	1-3	4-6	7-9	10-12
Boston	100	94	13	20	28	33
Chicago	92	74	23	15	13	23
San Francisco	50	43	17	4	16	6
Total	242	211	53	39	57	62

[a] From GAO, 1980.

of reasons that have been identified as the causes of failures of POTWs (Gilbert, 1976; Gray et al., 1979; Hegg et al., 1978; Lang, 1980; and Michel et al., 1969).

Current research trends seem to focus on the operation and maintenance (O&M) aspect of the problem. The studying and mitigation of these O&M problems would most likely involve long-term training and education of plant personnel and modification of existing O&M practices. This, however, is not the objective of this research.

One commonly ignored and yet quite frequently reported contributing factor of WWTP failure concerns the reliability of treatment plant equipment. The reliable performance of treatment plant equipment is a prerequisite to the successful operation of a WWTP. A plant having frequent equipment failures cannot be expected to perform well or meet treatment goals. Lubetkin (1980) wrote that "a significant part of the problem of wastewater treatment plants not giving desired results is due to the breakdown of equipment because manufacturers, in an attempt to cut initial costs to be competitive, have reduced the quality of their products so they can be sold." One private consultant group (Search, Inc., 1979) in studying a problem-laden WWTP reported that due to unreliable equipment the probability of having all the equipment working at the same time was close to zero. In their 1980 report (GAO, 1980), the GAO identified equipment deficiencies as one of the five major causes of wastewater treatment plant failure. The other four major causes are design deficiencies, infiltration and inflow overloads, industrial waste overloads, and O&M deficiencies. It is apparent that unreliable equipment will affect the performance of WWTPs negatively.

This dissertation study is therefore formulated out of the concern with the question of WWTP equipment reliability. It is hoped that the result of this study can contribute to solving some aspects of the problems that have been identified as causes for the municipal WWTPs' failure to perform.

Objectives

Three objectives have been identified and delineated for this study,

1. To collect equipment performance data from the municipal wastewater treatment plants and to establish an equipment reliability data base to contain such data as total operating hours, mean time between failures, mean downtime, and best manufacturers.

2. To present and demonstrate method(s) by which the collected equipment performance data can be utilized to assist in solving equipment related problems faced by municipal WWTPs, such as the selection of reliable equipment and the improvement of equipment maintenance programs.

3. To collect data relating to the O&M practice of the municipal WWTPs and to correlate those data with the equipment performance data to determine if any quantifiable relationship could be established between O&M practice and equipment reliability.

CHAPTER II

LITERATURE STUDY

The Use of the Term Reliability in the Wastewater Treatment Field

The term reliability when used in the wastewater treatment field is often, if not always, for assessing the performance of the WWTP or the treatment processes. Typically, it is used to indicate the percentage of time a particular treatment plant can be expected to meet effluent discharge standards. For application to the treatment processes, the term reliability is commonly used in relation to the pollutant removal efficiency. There has been very little quantitative association between the term reliability and the equipment employed in the wastewater treatment field. The studies and discussions of equipment performance that have been carried out are almost exclusively qualitative in nature. This lack of a quantitative approach to measure the performance of equipment has kept any collected equipment information from being widely utilized because qualitative data are difficult to use and to manipulate.

To study the reliability of WWTP equipment, the concept of reliability has to be redefined. In this chapter the discussion will concentrate on the results of the literature search to gather equipment reliability information collected in the wastewater treatment field and the reliability concepts that have been used in association with mechanical equipment.

Wastewater Treatment Plant Equipment Reliability

Computer search of "DIALOG"* data base and library search were both performed to identify publications containing wastewater treatment plant equipment reliability information. It was found that in the literature studies on WWTP performance were quite common, but there were very few WWTP equipment performance studies and seldom were those studies pursuing equipment performance in a quantitative manner. Several of the studies reviewed that contained equipment reliability information will be discussed.

Shultz and Parr's (1982) report on wastewater treatment plant mechanical equipment reliability represents the only documentation in the literature that contained substantial quantitative equipment reliability information. The report contains data collected from nine treatment plants (design flows from 24 to 300 MGD) on eight critical equipment components, namely pumps, power transmission, motors, compressors, diffusers (air/water), valves, controls and conveyors. Reliability statistics such as mean time between failures and maintainability statistics such as mean time to repair, corrective maintenance time per unit per year were calculated. In addition, two estimators relating to the availability of equipment were also computed. The calculated values are presented in six groups. The grouping factors used are component type, size range and application. Shultz and Parr

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*"DIALOG" is from Dialog Information Services, Inc., 3460 Hillview Avenue, Palo Alto, California, 94304.

compared their data with those from two sources* and found that their calculated mean-time-between-failures values for the eleven equipment components considered were in each case lower than those from the other two sources. The discrepancy was explained by Shultz and Parr as due to the more stringent safety and reliability requirements in the other two systems.

Mallory and Waller (1973) evaluated the applicability of various industrial engineering techniques to the operation and maintenance of secondary waste treatment plants, and illustrated the collection of equipment performance data for reliability study. The data they presented contain such values as MTBF, number of failures, etc.; but their data represented equipment data from one Flint, Michigan waste treatment plant only.

Chesner and Iannone's (in publication) study concentrates on the Rotating Biological Contactors, or the RBC systems. They reported equipment performance to be the most severe limitation facing RBC systems. Ten out of the 16 facilities they reviewed in detail have experienced what was considered major equipment failures. Shaft failures, as a result of overloading or excessive growth, and media failures caused by sunlight (brittleness) represent the two most pressing problems. Chesner and Iannone's attention to equipment failure

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*The two sources:

(1) "Nonelectronic Parts Reliability Data," Reliability Analysis Center, Rome Air Development Center, Griffiss AFB, New York, 13441, Summer 1978.

(2) "Nuclear Plant Reliability Data System 1978 Annual Report of Cumulative System and Component Reliability," prepared by Southwest Research Institute, San Antonio, Texas.

are more detailed than other studies reviewed but their data are inadequate for calculating reliability statistics. Ettlich (1978) studied 40 oxidation ditch plants and reported that as a group, oxidation ditch plants are simple to operate and reliable (meeting effluent standards). He reported that the most serious process operation difficulties resulted from equipment related problems. Aerators and aerator-drives accounted for a major portion of the mechanical problem. Ettlich's equipment performance information were largely descriptive.

It is recognized that reliability data on mechanical equipment are quite commonly collected outside of the wastewater treatment field. Two examples involving efforts in large scale collection of mechanical component reliability data are:

(1) "Nonelectronic Parts Reliability Data," Reliability Analysis Center, Rome Air Development Center, Griffiss AFB, NY, 13441.

(2) "Summaries of Failure Rate Data," Failure Rate Data Interchange, USA Government-Industry Data Exchange Program (GIDEP), Officer-In-Charge, Program Operations Center, Corona, CA, 91720.

Example (1) is a data base that contains failure rate data on over 40 generic, nonelectronic parts. It represents equipment level experience under field conditions in military, industrial and commercial applications. Example (2) is a very large data base that contains equipment failure data. In this data base, failure information are reported as average failures over time by participating members in the Government-Industry Data Exchange Program (GIDEP). Although equipment failure data are available for many mechanical equipment, such data do not appear to be applicable to the wastewater treatment field because wastewater treatment equipment are manufactured by specialty manufacturers, making them different from other mechanical equipment and the environment under which these equipment will have to perform is also unique. Above all, the objective of this study is to pursue reliability information on WWTP equipment.

Reliability Concepts and Mechanical Equipment

The general lack of wastewater treatment equipment reliability data in the literature indicates the lack of pursuit of reliability concepts and their application to the mechanical equipment in the wastewater treatment field. Shultz and Parr's report (1982) discussed earlier is the only serious document identified. The importance of equipment reliability at wastewater treatment plants was acknowledged in EPA's *Supplement to Federal Guidelines, Design Criteria for Mechanical, Electrical and Fluid Component Reliability* (1974). That document, however, suggested only redundancy as a means to improve the reliability of critical components.

In attempting to adopt a workable reliability concept for application to the mechanical equipment of concern, a review of the literature in this subject area was performed.

In the literature, reliability is commonly defined as the probability of an equipment to perform satisfactorily for a specified period of time and condition. There are four elements in the definition of reliability, namely: probability, satisfactory performance, time, and operating conditions. The probability element, a quantitative term (a fraction or a percentage) indicates the number of times one can expect an event to occur out of a number of trials. The condition of satisfactory performance of an equipment is achieved when the equipment is operational and performing its intended function. When equipment cannot perform its intended function without corrective maintenance (or repair) then it is unsatisfactory. The time element is the most significant because it represents a measure of the period during which one can expect a certain degree of performance. The last element in the definition is operating conditions. Experience has shown that equipment operating under different operating conditions has different reliability. More detailed discussions of the definition of reliability can be found in the following references: Bazovski (1961), Blanchard and Fabrycky (1981), Calabro (1962) and O'Connor (1981).

In studying equipment reliability, one is interested in finding out the probability of the equipment encountering failure. In other words, one is involved in determining if the existing equipment failure pattern can be fitted to a certain mathematical model from which future failures can be predicted. A variety of mathematical models or distributions have been used for fitting failure data of mechanical equipment or components. Some of the typical distributions used are the exponential, the Weibull, the gamma, the normal and the log normal. Barlow, et al

(1965), Moan (1966) and O'Connor (1981) all have discussed these distributions in detail. Table 3 contains the mathematical expressions for these distributions.

Among the distributions mentioned above, the exponential and the Weibull distributions are widely used. These two will be discussed later. Hogg and Craig (1970) remarked that the gamma distribution is frequently the model for waiting times, for instance, in life-testing, the waiting time until "death" is the random variable which frequently has a gamma distribution. O'Connor (1981) stated that the normal distribution is a close fit to the lives of items subject to wearout failures. Moan (1966) indicated the normal distribution is usually used to approximate wearout failure. Kelly (1984) pointed out that age-related failure pattern approximates quite closely to the well known normal distribution. Barlow (1965), however, argued many life length distributions occurring in practical applications are obviously not normal because they are markedly skewed whereas the normal distribution is symmetrical. For the log normal distribution, Moan (1966) reported that it has been used to approximate wearout failure. O'Connor (1981) also argued that the log normal distribution is more versatile than the normal distribution as it has a range of shapes and therefore is often a better fit to reliability data, such as for population with wearout characteristics. The normal and the log normal distributions are therefore generally used in situations where the failure rate is increasing. The gamma distribution, although more versatile, is less frequently used due to difficulty in application.

Table 3. Mathematical Distributions Used for the Fitting of Failure Data

Name	Mathematical Distribution
Exponential	$f(x:\theta) = (1/\theta)e^{-x/\theta}$ $x \geq 0$ $= 0$ elsewhere Note: θ is mean time between failure.
Gamma	$f(x:\alpha,\beta) = (1/\alpha!\ \beta^{\alpha+1})x^{\alpha}\ e^{-x/\beta}$ $x > 0$ $= 0$ $x \leq 0$ Note: Scale parameter $\beta > 0$, shape parameter $\alpha > -1$.
Log Normal	$f(x:\gamma,\mu,\sigma) = [1/((x - \gamma)\ \sqrt{2\pi\sigma})]\ e^{-(\ln(x - \gamma) - \mu)^2/2\sigma^2}$ $x > \gamma > 0$ $\sigma > 0$ $= 0$ $x \leq \gamma$ Note: γ is location parameter, μ is mean, σ is standard deviation.
Normal	$f(x:\mu,\sigma) = (1/\ \sqrt{2\pi\sigma})e^{-[(x - \mu)/\sigma]^2/2}$ $-\infty < x > \infty$ $\sigma > 0$ Note: μ is mean, σ is standard deviation.
Weibull	$f(x:\alpha,\beta,\gamma) = (\beta/\alpha)(x - \gamma)^{\beta-1}\ e^{-(x - \gamma)^{\beta}/\alpha}$ $x \geq \gamma$ $\alpha > 0,\ \gamma \geq 0,\ \beta > 0$ $= 0$ elsewhere Note: α is scale parameter, β is shape parameter, γ is location parameter.

The Weibull distribution is a useful distribution and is a distribution favored by many practitioners at the present time. The Weibull distribution can be applied to represent an increasing, a constant or a decreasing failure rate. The exponential distribution is a special case of the Weibull distribution. O'Connor (1981) stated that the Weibull distribution can be used to model a wide range of life distributions characteristic of engineered products. Kelly (1984) and Moan (1966) both pointed out the versatility of the Weibull distribution in fitting various failure patterns. Barlow (1965) reported the use of the Weibull distribution for fatigue failure, vacuum tube failure and ball-bearing failure by various researchers. The Weibull distribution is defined by a three-parameter function. The determination of the three parameters is a requirement in the application of the Weibull distribution. Kececioglu (1980) reported that for most mechanical components and structural members, these parameters are not to be found conveniently. In the literature reviewed, there has been no example of application of this distribution to study the wastewater treatment plant equipment reliability.

The exponential distribution is characterized by a constant failure rate and is quite frequently used in reliability work. The exponential distribution has the simplest data needs in its application. The application of the exponential distribution has been controversial largely due to the constant failure rate assumption. Barlow (1965) argued that the constant failure rate assumption of this distribution makes it inadequate for describing the life distribution of any structure which, when in normal use, undergoes changes affecting its future life length. Moan (1966) also stated that this assumption neglects degradation failures. A question to be raised here is how significantly do the changes or degradations affect the change in the failure rate, especially for mechanical equipment such as the types used at wastewater treatment plants? On the other hand, Hausman and Kamins (1965), in studying the reliability of new automobile parts, concluded that among the mechanical parts the bearings for water pump and clutch release have constant failure rate. Sinha and Bhandari (1978) analyzed urban transit bus repair data for six subsystems of the bus and showed that for most cases, the failure intervals follow a negative exponential distribution. In a contract study to establish a reliability data base for nonelectronic parts for the Rome Air Development Center, Griffiss Air Force Base, Fulton (1978) assumed exponential distribution due to the absence of data containing individual times or cycles to failure. In both studies identified to involve reliability of wastewater treatment plant equipment, the exponential distribution was assumed. (Shultz and Parr, 1982; Mallory and Waller, 1973).

The findings of the literature study are summarized below:

(1) The reliability of wastewater treatment plant equipment has not been adequately studied. The term reliability is largely used in connection with pollutant removal efficiencies.

(2) There is no information in the literature to indicate which mathematical distribution is the more appropriate distribution to fit the failure data of WWTP equipment.

(3) The Weibull distribution appears to be a very versatile distribution and perhaps the best one for equipment failure mode studies when detailed data are available.

(4) The Exponential distribution appears to have been used quite frequently in reliability studies and it offers ease and flexibility in application.

CHAPTER III

APPROACH AND METHODOLOGY

To Adopt a Working Reliability Concept

To establish a reliability data base for the WWTP mechanical equipment, one of the first steps was to adopt a working reliability concept from which data algorithm can be derived. The literature reviewed does not indicate which distribution is a better fit for the WWTP equipment failure data. The Weibull distribution, due to its versatility in modeling different failure rates, is favored by many. In view of the general lack of WWTP equipment information in the literature, it would seem that the Weibull distribution might be a good choice. However, the use of the Weibull distribution requires the determination of three parameters, which, as noted by Kececioglu (1980), are not to be found easily for mechanical components. The detailed data, such as time to failure of each occurrence, needed for the determination of the Weibull parameter are not known to be available from the municipal WWTPs. This factor alone has made it impossible to adopt the Weibull distribution. An example of the status of record keeping on equipment performance at WWTPs is the study by Shultz and Parr (1982) in which they started with an initial candidate list of 200 plants and were only able to use records from nine plants. It is not practical for this study to initiate equipment data collection programs at WWTPs to collect the kind of data needed for the application of the Weibull distribution. Therefore, the application of the Weibull distribution will remain a task for future research.

The use of the exponential distribution in the reliability study of mechanical equipment is quite common. This has been discussed in Chapter II. In this study, the exponential distribution is adopted as a working concept, which allows for the systematic and uniform determination of equipment reliability. In addition, the status of record keeping on equipment performance at WWTPs is one of the many reasons for adopting the exponential distribution. The maintenance crew at the WWTP is interested only in keeping the equipment in good operating condition which they see as their duty and responsibility. They see equipment performance record keeping as something unrelated to their responsibility and, consequently, such "chores" are kept at a minimum or sometimes neglected, leaving failure events unrecorded. In most cases, failure events are recorded in the simplest manner with the briefest notes. In some situations, failure records are only in the memory of the maintenance crew. The status of practice of equipment record keeping at the WWTPs, therefore, was a significant factor in selecting and adopting a working reliability concept. The flexible data needs of the exponential distribution is a feature that makes it particularly suitable for the circumstances just discussed.

Many authors have pointed out, for complex structures whose components are replaced, the time between failures approximates the exponential distribution (Barlow, 1965; Bazovski, 1961 and Moan, 1966).

This concept further supports the adoption of the exponential distribution. In this study, equipment at WWTPs are identified by type, most of which are not single equipment components. They are in reality complex equipment component structures. For example, the equipment type identified as the mechanically cleaned bar screen, although it appeared to be "a rather simple piece of equipment," is composed of several equipment subsystems such as the motor, the power transmission, the raking mechanism, the bar screen itself and the control system. Each of these subsystems is, in turn, composed of many component modules or individual component pieces. The mechanically cleaned bar screens are, in fact, equipment structures with many components. Similar observations can be made on almost all the equipment type identified. Although the degrees of complexity varies, from the simplest pump to the very complicated incinerator, most of the equipment types identified can be considered to be largely complex component structures. Because the components of this equipment are replaced when failed, the time between failures for the WWTP equipment should approximate the exponential distribution.

In summary, the adoption of the exponential distribution as a working concept in this study is a matter of practicality in application in which one matches the requirement of a working concept with what is available in terms of data. Secondly, the WWTP equipment types identified in this study are largely complex equipment systems and their mean time between failures should approximate exponential distribution.

It must be pointed out here that among the large variety of WWTP equipment involved, there may be some equipment whose failure modes will be better described by a different distribution. It is, however, not the objective of this study to identify that equipment or to fit each identified equipment's failure pattern with a mathematical distribution.

It is further recognized that in adopting the exponential concept, it appeared that the wearout failures of the equipment were not considered. Wear and tear occurs every day in the use of WWTP equipment. It is not known at the present time how much such wear and tear contributes to the overall equipment failure rate, or if it is significant over the design life of a mechanical equipment at the WWTP. Such consideration can only be addressed properly when detailed study of specific equipment is conducted. Such a task is also not the objective of this study.

It is also recognized that in this study, due to the approach taken, many failure causing factors are not discussed. An equipment could fail due to a number of different reasons: design deficiency, manufacturing defects, mishandling in shipment, improper installation, wrong application, improper operation and maintenance, induced failures, and others. (Induced failures are caused as a result of failure of another equipment. For example, the failure of grit removal equipment at a WWTP could lead to the failure of downstream equipment whose failure is then said to be induced.) Some causes of failure can be identified without much difficulty, but the causes of many failures are not to be easily identified, requiring extended studies to separate or isolate possible contributing factors. The kind of data currently available at WWTPs do not permit the study of the causes of equipment failure and above all such a task is really outside the scope of this study.

The Exponential Concept and MTBF Algorithm

In general, the life of equipment can be divided into three stages. When equipment is first installed for operation there is usually a large number of breakdowns, and gradually as problems are debugged, the breakdown rate begins to level off. The equipment then enters a useful life period during which breakdowns are random events and the rate of failure is said to be constant. After this, the equipment enters a wear-out period during which breakdown rate increases following the normal or log normal curve. The failure rate curve of equipment is shown graphically in Figure 1. The exponential distribution deals with the failure rate during the useful life period.

Mathematically, the basic expression for the reliability of equipment during its useful life is:

$$\text{Reliability, } R = e^{-\lambda t} \qquad (1)$$

where t is the operating time and λ is the failure rate. R, or reliability, is commonly expressed as a percentage. Thus, it is also the probability of not encountering failure. Given a fixed failure rate, the probability of survival of equipment decreases with the increase in time.

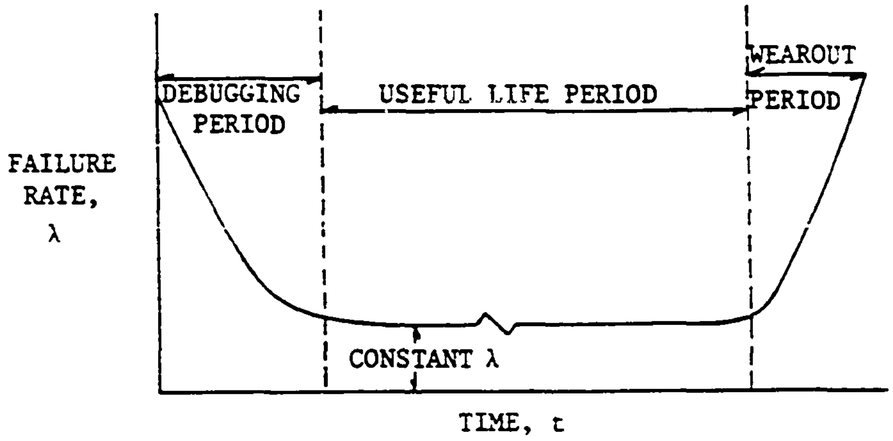


Figure 1. Typical Equipment Life Curve

The reciprocal of the failure rate, λ, is also known as the mean time between failure, or MTBF. MTBF is commonly used as a measure of reliability, and in this study it is also chosen as the primary reliability term. MTBF can be computed by dividing the total number of failures into the total operating time. In situations when failure is not encountered, the MTBF value cannot be computed. In situations when there is only one failure, the MTBF value would equal the total operating time. This method of computing the MTBF obviously has its limit.

The algorithm for the MTBF value adopted in this study is derived from the work of Epstein (1960). Epstein has shown that when the failure distribution is exponential and the test is terminated at a fixed time, not necessarily coinciding with the occurrence of a failure, the 2-sided confidence interval for the true MTBF is

$$\frac{2T}{\chi^2_{\alpha/2,\ 2r+2}}\ ,\ \frac{2T}{\chi^2_{1-\alpha/2,\ 2r}}$$

The algorithm for MTBF adopted for this study is simply the lower limit of Epstein's two-sided confidence interval for the true MTBF. Furthermore, this lower limit estimator is adjusted to the 50% confidence level. The end result of using this algorithm is that a slightly more conservative MTBF value would be obtained compared to that from using the simpler method of dividing the total number of failures into the total operating time. The algorithm also permits the calculation of MTBF values even when no failure is encountered, clearly an advantage over adopting the upper limit estimator or the simpler method of computing for MTBF values.

The MTBF algorithm is therefore expressed as

$$\text{MTBF} = \frac{2T}{\chi^2_{0.5,\ 2r+2}}$$

where: T = the total operating hours

$\chi^2_{0.5,\ 2r+2}$ = the table value of chi-square distribution with 2r+2 degrees of freedom at the fiftieth percentile

r = the number of failures

The MTBF algorithm generates only point estimates; therefore, it is necessary to define confidence intervals that would provide some indications of the reliability of the point estimates and their representativeness of the true MTBF values. One algorithm for the confidence interval has just been shown above. O'Connor (1981) also suggested a similar approach to confidence interval calculation. Although the use of chi-square distribution is more appropriate for estimating the confidence interval for conditions specified here, as attested by Epstein (1960) and O'Connor (1981), the algorithm for the upper confidence limit exhibited the same shortcoming as the traditional method for calculating MTBF in not being able to cover the no-failure situation. Fortunately, O'Connor (1981) also indicated that for situations where "x (the true MTBF) is not normally distributed provided that n (sample size) is large (>30), $\bar{x}$ (the MTBF estimate) will tend to a normal distribution." In this study the sample size is anticipated to be over 30 and, therefore, the MTBF values are also expected to approach normal distribution. For situations where equipment sample size is below 30, the use of calculated confidence intervals is therefore cautioned. Since normal distribution is assumed due to the expected large sample size, the confidence interval algorithm for the MTBF point estimate is computed as,

$$\text{MTBF} - z_{\alpha/2} \cdot \frac{s}{\sqrt{n}}, \qquad \text{MTBF} + z_{\alpha/2} \cdot \frac{s}{\sqrt{n}}$$

where: $z_{\alpha/2}$ = coefficient indicating the number of standard deviations from the mean for a confidence level of $100(1-\alpha)\%$

s = standard error of the estimate

n = sample size

In closing this discussion of reliability concepts used in this study, a noteworthy point about the use of the MTBF value must be brought out. It is best illustrated by an example as follows.

If an equipment has a MTBF value of 1,000 hours, or a λ of 0.001 per hour, this does not mean that this equipment can be expected to operate for 1,000 hours. The probability of survival to 1,000 hours is given by:

$$R = e^{-\lambda t} = e^{-(0.001)\,(1{,}000)} = 0.368$$

MTBF is, therefore, a useful value by which one equipment can be compared to another. It is really a measure of the chance failure rate during the useful life period of equipment, but it does not indicate the length of that period.

Mail Questionnaire Survey

The collection of data can usually be accomplished by three different methods, namely: search through literature for published data, site visits with interviews and mail questionnaire survey. Literature search cannot be used to collect WWTP equipment reliability data for such data are essentially nonexistent in the literature. The second alternative is site visits with interviews. However, the manpower and financial resources that would be required have excluded the possibility of utilizing this method of data collection. The remaining alternative is the collection of data by the mail questionnaire survey method.

There are different ways to conduct a mail questionnaire survey. A perfect survey is one in which a response is drawn from every surveyee. To conduct a mail questionnaire survey, some surveyors will provide some forms of incentive such as money or products to encourage a higher rate of response. Those techniques, however, are beyond the resources of this study. It is recognized that in conducting a mail questionnaire survey in which the response is voluntary, the rate of no-response can be expected to be high. To compensate for this characteristic of low response rate, as many questionnaires as possible will be sent out such that a significant number of responses can still be obtained. Hansen, et al (1953) suggested a method involving follow-up personal interviews to deal with the no-response. This will be impractical for this study.

The selected method of data collection is a mail survey. Therefore, the design of the survey questionnaire form becomes a very important task. Acquisition of treatment plant addresses and information, selection of survey candidates, processing of stationery and questionnaires are all necessary tasks before the mailing of survey questionnaires. When the questionnaires are returned, they will have to be carefully screened for usable information. This information will then have to be coded, edited and finally entered into the computer for analysis. A flow diagram of the entire data collection procedure is illustrated in Figure 2.

Questionnaire Design

The ultimate objective of a mail survey is the gathering of sufficient useful data or information. This depends on the rate of response which critically depends on the design of the questionnaire. The usefulness or representativeness of the data/information, however, is determined by the treatment plants selected for survey and responded.

A successfully designed questionnaire can enhance the response rate enabling the collection of sufficient good quality data/information to achieve survey objectives. Because the response to this survey is voluntary, the degree of ease in responding and the degree of interest that can be aroused in the surveyee will seriously affect the rate of return. It is clear that simplicity should be the key criterion in the design of the questionnaire. The collection of reliability data involves gathering fairly detailed performance data on an equipment, such as the operating time, the number of failures and the duration of

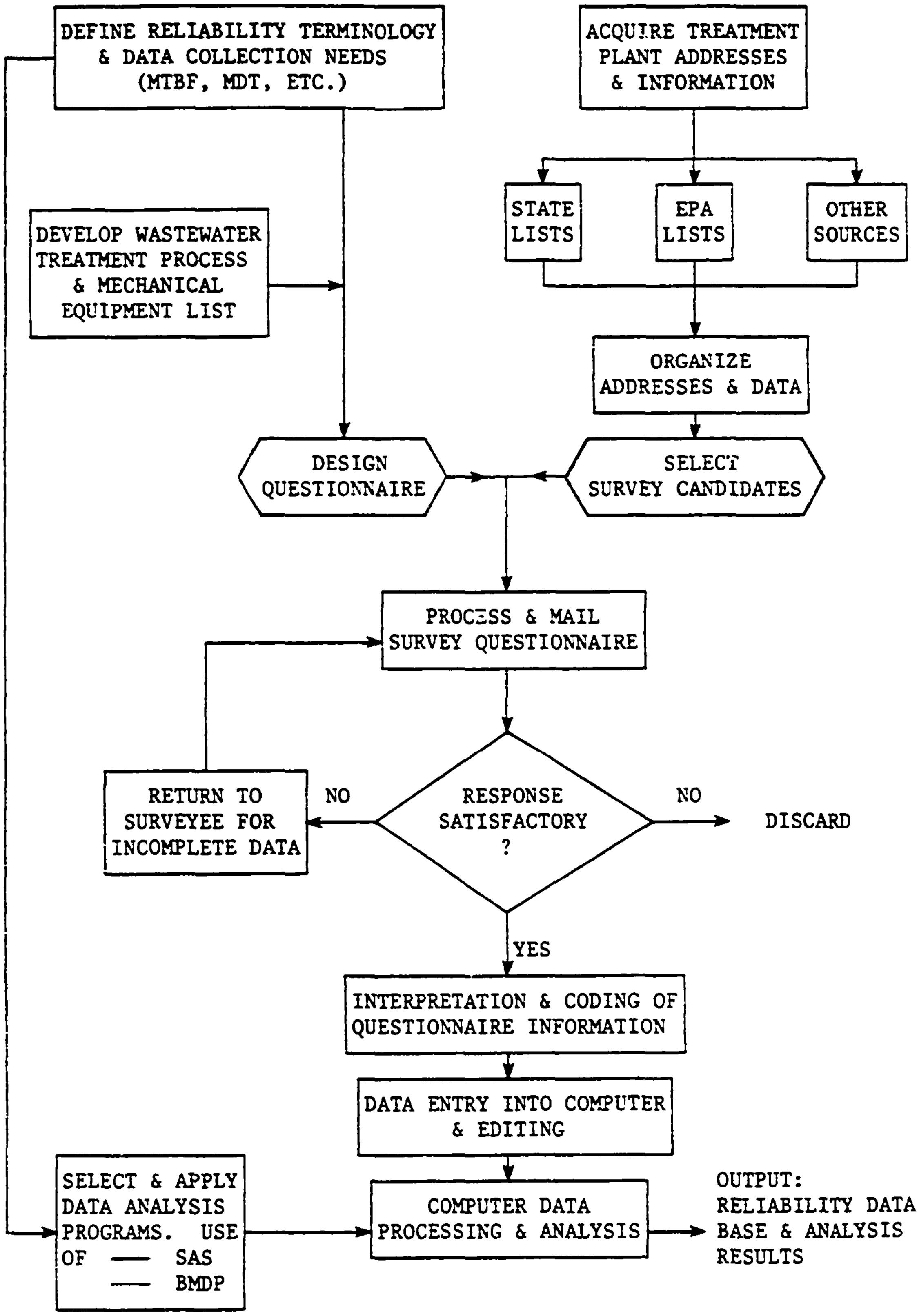


Figure 2. Flow Diagram of Reliability Data Collection Procedures.

downtime, etc. Due to the amount of data needed, a table form questionnaire is used. See Appendix A. Each of the column headings in the questionnaire is designed such that the information requested of the surveyee can be easily extracted from his records or recollection if detailed records were not kept. The column headings are also designed to minimize error. For example, instead of asking for total operating hours or the percentage of time in operation, each equipment's operating hours per day, days per week, and installation data are asked for. This should eliminate potential computational error on the part of the surveyee.

The final questionnaire is the result of many revisions and modifications. The initial questionnaires were tested by researchers at the University of Oklahoma's Bureau of Water and Environmental Resources Research and at local WWTPs. Suggestions received were incorporated. The questionnaire was next tested at other WWTPs and further improved.

One significant design feature of this questionnaire is the use of equipment lists to assist the surveyee in responding.

A complete copy of the survey questionnaire consists of the following items:

1. Cover letter

2. Survey questionnaire
   Page 1. General plant data
   Page 2. Treatment equipment list
   Page 3. Treatment equipment information for identified processes
   Pages 4 and 6. Blank
   Page 5. Treatment equipment information, continued

Equipment Lists for Wastewater Treatment Processes

Most WWTPs are highly complex systems composed of hundreds of different equipment systems, components and subcomponents. It would be quite unrealistic if one were to try to collect equipment performance data for all the equipment involved through a questionnaire. In a mail questionnaire survey in which response is voluntary, the rate of response will diminish rapidly with increasing time and effort required to respond to the questionnaire. Therefore, it was recognized that equipment that are of importance and interest would have to be identified. Then, it would be necessary to compile the selected equipment in a list to convey to the surveyee that the listed equipment are the ones of interest to this study.

The first step in development of an equipment list was the formulation of a treatment process alternative list. By using an EPA study (Chamblee, 1979) which identified the frequencies of process application at the municipal WWTPs, a list of common treatment processes was established. Next, important or vital equipment associated with these treatment processes were identified and combined to form a mechanical equipment list. Vital equipment is defined to be equipment or equipment systems whose operation or function is required for accomplishing treatment tasks, for meeting effluent limitations and for protecting other vital equipment from damage. Based on these criteria, a list of vital equipment was developed.

At this step of the equipment list development, it was decided that a generic approach would be taken in classifying the equipment. That is, the details of equipment classification will not go beyond the equipment type level to classifying equipment by size or by model. To request such information would increase the time and effort required for completing the questionnaire significantly and result in a lower number of responses. Equipment type information, extracted from manufacturers' catalogs, textbooks, reports and journals was then tagged to each vital piece of equipment in the list. Only common equipment types were selected. In this way, an equipment list was formulated.

The list was arranged according to the most common direction of flow or process sequence through a treatment system. First the liquid stream, then followed by the sludge stream. See Appendix A.

The equipment list, in addition to serving as a reference list, also served other purposes. The list would have the function of guiding the respondent in entering information into the survey form as well as assisting him in the organization of thought or recall.

Selection of WWTPs for Survey

The selection of WWTPs for survey is important in that it determines how representative the collected data will be. According to EPA's "1978 Needs Survey" (Chamblee, 1979), there were about 15,000 WWTPs at the time of survey. Analysis of EPA's data indicated that there were regional differences in the application of treatment processes. For example, 87% of all no-discharge lagoons are located in EPA regions IX, VII, VIII, and VI, while 84% of all tertiary treatment plants are in regions V, IV, and III. Regions V, IV, and VI contain 57% of all secondary treatment plants, and 60% of all primary treatment plants are in regions VII, VI, and V (see Table 4). Even though the EPA's classification of plant types is by level of treatment, it also reflects the different processes involved. This is because there are treatment capability limits for each treatment process. Based on these observations, it was decided that in order to draw a good sample,

a. at least one state would be selected to represent each EPA region (see Figure 3),

b. states selected would be geographically evenly distributed.

To maximize the economy of the survey, it was decided that only WWTPs equal to or larger than 1 MGD (million gallons per day) would be in the sample pool. This criterion is based on the fact that larger plants would have more equipment both by type and by number.

A list of wastewater plants, equal to or larger than 1 MGD and currently operating, was obtained from the EPA's Office of Water Program Operations, Washington, D.C. This list identified individual treatment processes that were reported by each WWTP to the EPA. This information enabled the design a of plant-specific questionnaire. That is, the treatment process information reported by each plant to EPA is transcribed onto the questionnaire to be received by the same municipal WWTP. The EPA list did not have mailing addresses in satisfactory format; therefore, addresses were obtained separately from the state agencies. Because not every state agency responded to the request for

Table 4. Number of Wastewater Treatment Plants by Types[a] in Each EPA Region[b]

EPA Region	No-Discharge Lagoons	Primary	Secondary	Tertiary	Total
I	6 (1.4)[c]	93 (22.1)	315 (74.8)	7 (1.7)	421
II	0	223 (32.3)	449 (65.1)	18 (2.6)	690
III	0	266 (21.6)	833 (67.7)	131 (10.7)	1,230
IV	1 (0.03)	439 (17.4)	1,940 (77.0)	138 (5.5)	2,518
V	72 (2.3)	656 (21.1)	2,056 (66.2)	322 (10.4)	3,106
VI	159 (7.7)	872 (42.2)	1,009 (48.8)	26 (1.3)	2,066
VII	222 (10.4)	1,030 (48.1)	888 (41.5)	2 (0.1)	2,142
VIII	164 (14.4)	310 (27.2)	647 (56.8)	18 (1.6)	1,139
IX	308 (41.0)	118 (15.7)	299 (39.8)	26 (3.5)	751
X	48 (8.5)	218 (38.4)	289 (51.0)	12 (2.1)	567
TOTAL	980	4,225	8,725	700	14,630

[a] Types by level of treatment (Chamblee, 1979)

Lagoons	- zero discharge
Primary	- BOD/SS Eff. > 30/30
Secondary	- BOD/SS Eff. < 30/30 - > 10/10
Tertiary	- BOD/SS Eff. < 10/10

[b] Number computed from "EPA 1978 Need Survey" (Chamblee, 1979), including only the 48 contiguous states.

[c] A percentage of the total number of plants within a region

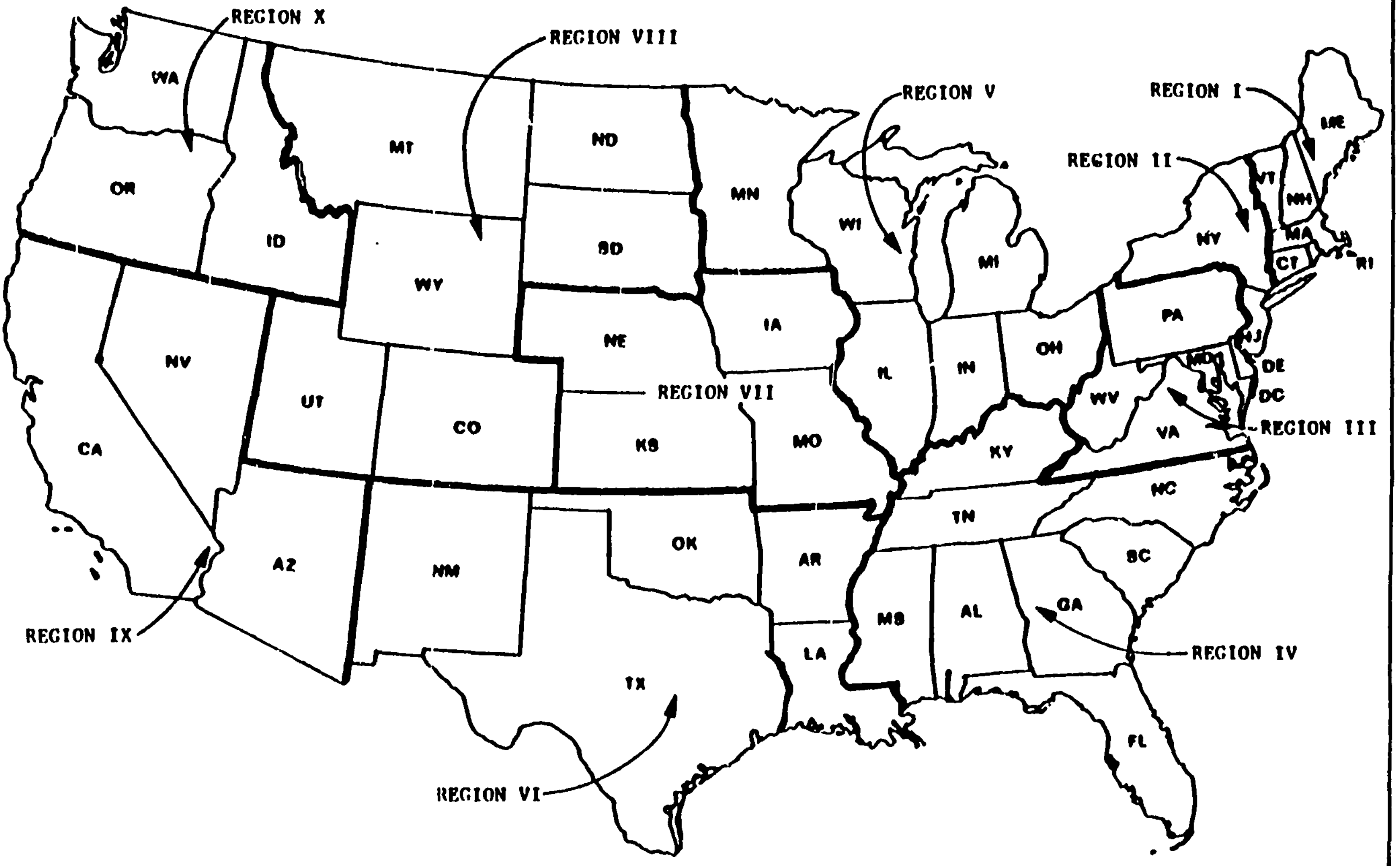


Figure 3. U.S. Environmental Protection Agency Regions

mailing address, nor did all those responding provide complete information, the selection of states for survey was limited to those that responded.

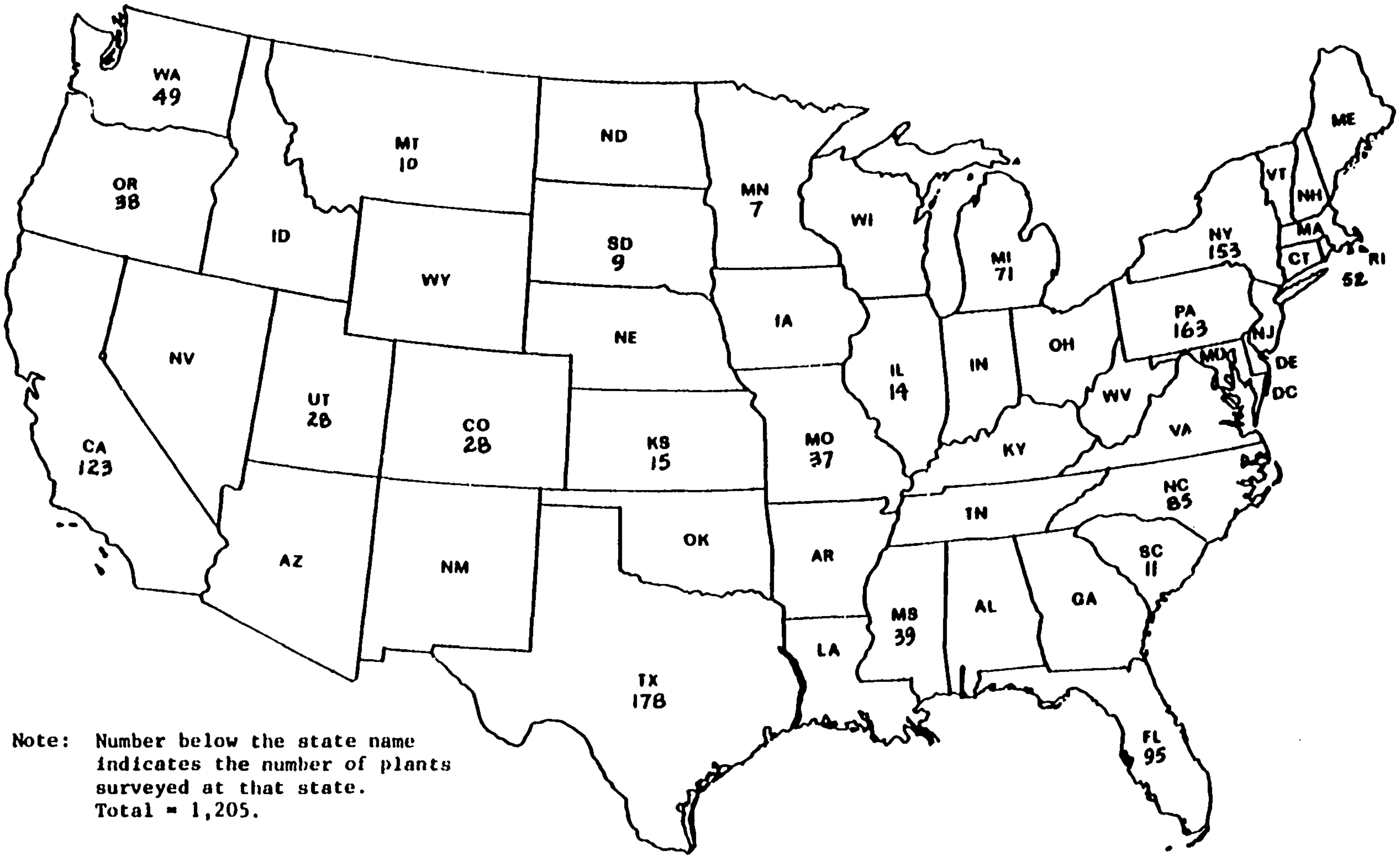
A total of 1,205 WWTPs (about 45% of all the plants 1 MGD or greater) were selected from the 48 contiguous states. The surveyed plants represented all 10 EPA regions and 20 states. They also represent about 10% of all POTWs in the U.S. Figure 4 identifies states included in this study.

Analysis Procedure

Because the amount of equipment data to be collected was anticipated to be very large, the use a of computer for data analysis would become inevitable. In this section, coding systems for identifying the equipment types and the manufacturers are discussed. This is followed by discussions on data analysis procedures and explanations of terms used in establishing the reliability data base. Finally, the regression analysis and the procedure/strategy utilized for executing the regression analysis are discussed.

Coding Systems for Equipment and Manufacturers

To facilitate the compilation and analysis of data, two coding systems are established; one code is for identifying mechanical equipment and one is for identifying manufacturers of equipment.



Note: Number below the state name indicates the number of plants surveyed at that state. Total = 1,205.

Figure 4. Number of WWTPs Surveyed at Each State Within Each EPA Region.

The equipment identification code, PET (an acronym for Process, Equipment and Type) is a five-digit number. The first two digits identify the treatment process in which the equipment is involved. The range of these two digits is from 01 to 84. Wastewater treatment processes are 01 to 58, and 60 to 84 identify sludge treatment processes. The third digit identifies the equipment or equipment system used. Up to six equipment or equipment systems are identified under each treatment process. The fourth and fifth digits specify the particular type of equipment involved. These two digits range from 00 to 10. The double zero (or unspecified) is used when information on equipment or equipment systems is available but not on the specific type of equipment. A respondent may report that he/she had a clarifier without saying whether it is a square or a circular one with a rim- or center-drive mechanism. In such cases, the double zero is used.

An example of a five-digit equipment code is: for PET 03203, the first two digits (03) identify the grit removal process, the third digit (2) points out a grit conveyor is used and the last two digits (03) specify that it is a bucket-type grit conveyor. Another example: PET 09107 identifies the primary clarification process (09, the first two digits) in which a clarifier (1, the third digit) of the rectangular trav. ing bridge type (07, the last two digits) is used. A complete list of the mechanical equipment codes can be found in Appendix B. This list is a modified and completed version of that in Appendix A.

For identifying manufacturers of equipment, a three-digit number is used. A list of manufacturers with codes can be located in Appendix C. Triple zeros (000) are used when the manufacturer's name is not available. It is recognized that some of the names listed are merely trade names and that some manufacturers listed are subsidiaries of others, however, no attempt was made to group or consolidate equipments or subsidiaries under the parent company's name.

Data Analysis and Explanation of Terms

The Statistical Analysis System (SAS) software package was used to handle the sorting and analysis of the large amount of collected data. The few programs generated for analysis were quite straightforward and will not be presented here. Detailed explanation on the use of SAS, however, can be found in the "SAS User's Guide" (1979).

The terms used and the algorithms involved in computing the various statistics are delineated in this section. Basically, reliability statistics were computed from the data base across all plants as follows:

N_j, Number of Units

The number of units for the jth equipment type group was computed by summing the number of units that contributed to the computation of statistics for the jth equipment type group.

NP_j, Number of Plants

The number of plants (users) for the jth equipment type group was computed by summing the number of plants that contributed to the computation of statistics for the jth equipment type group.

r_{ijk}, Number of Failures

The number of failures is the number of failures reported for the jth equipment type at the ith plant for the kth entry.

TOH_{ij}, Total Operating Hours (in hours)

The total operating hours for each equipment type group was computed as:

$$TOH_{ij} = \sum_{k=1}^{K} (HR_{ijk} \cdot DAY_{ijk} \cdot MONTH_{ijk} \cdot n_{ijk} \cdot \frac{52}{12})$$

where: n_{ijk} = number of units of equipment as reported in the questionnaire. k=kth entry.

HR_{ijk} = number of operating hours per day for the equipment in the jth equipment type group at the ith plant.

DAY_{ijk} = number of days per week the equipment is in operation.

$MONTH_{ijk}$ = total number of months the equipment is in operation from the first month it was installed to the month of termination or February 1982.

(52/12) = conversion factor for converting months to weeks.

K = number of entries of equipment in the jth equipment type group at the ith plant.

TBF_{ij}, Time Between Failures (in hours)

The TBF_{ij} is the time between failures for the jth equipment type group within the ith plant and is computed as:

$$TBF_{ij} = \frac{2\,(TOH_{ij})}{\chi^2_{0.5,\ 2r_{ij}+2}}$$

where: $\chi^2_{0.5,\ 2r_{ij}+2}$ = the value of the chi-square distribution (Epstein, 1960; and O'Connor, 1981) with $2r_{ij}+2$ degrees of freedom at the 50th percentile

For equipment that had been operating with no failure, the degree of freedom would be 2.

$MTBF_j$, <u>Mean Time Between Failures</u> (in hours)

The $MTBF_j$ is the Mean Time Between Failures for the jth equipment type group and is computed as:

$$MTBF_j = \frac{\sum_{i=1}^{NP_j} TBF_{ij}}{NP_j}$$

90% CL_j, <u>90% Confidence Limits</u> (in hours)

The 90% CL_j is the two-sided confidence limits within which one can be 90% confident that the true MTBF value of the j equipment type group will lie. The two-sided lower and upper confidence limits are computed as:

$$(MTBF_j - Z_{\alpha/2} \cdot s_j/(NP_j)^{1/2},\ MTBF_j + Z_{\alpha/2} \cdot s_j/(NP_j)^{1/2})$$

where: $Z_{\alpha/2}$ = coefficient indicating the number of standard deviations from the mean for a confidence level of 100(1-α)%. For 90% CL, $Z_{\alpha/2}$ is 1.645.

s_j = standard error for the jth equipment type group.

MDT_j, Mean Downtime (in hours)

The MDT_j for each jth equipment type group is computed in 2 steps:

(i) an average downtime (D_{ij}) for the equipment in the jth equipment type group at the ith plant was computed first:

$$DT_{ij} = \frac{\sum_{k=1}^{K} DT_{ijk} \cdot r_{ijk}}{\sum_{k=1}^{K} r_{ijk}}$$

where DT_{ijk} is the reported downtime for the equipment in the jth equipment type group at the ith plant for the kth entry.

(ii) the MDT_j is then computed as:

$$MDT_j = \frac{\sum_{i=1}^{DP_j} DT_{ij}}{NP_j}$$

Regression Analysis

One objective of this study is to find out if a significant relationship exists between equipment failure and the O&M of a plant. To achieve this, the technique of stepwise multiple regression analysis is utilized. The use of regression analysis permits one to gain an understanding of the interrelations between variables, however, it is also commonly used to establish a quantitative relationship between variables that is useful for making predictions. In regression analysis, the relationship between variables is expressed in a general form as follows:

$$Y = b_0 + \sum_{i=1}^{n} b_i X_i$$

where: Y = dependent variable, such as MTBF

X_i = independent variables or variables that quantified the level of O&M of a plant, such as,

1. O&M manpower level in number per MGD
2. O&M personnel experience in years per person
3. O&M personnel training in number of courses attended per person during the last three years
4. O&M practice including schedules and procedures, spare parts and technical assistance availability
5. Efficiency of pollutant removal including BOD and SS.

b_i = regression coefficient

b_0 = intercept

Given a set of data the regression analysis then is used to compute the regression coefficients, b_i. With the constants or coefficients established, the equation thus in effect provides a quantitative means by which one can describe the relationship between the dependent and independent variables. The operation of the regression analysis is based on the principle of least squares.

For the results to be valid, the regression analysis required that several assumptions be met. In regression analysis, the fundamental assumption is that the independent and the dependent variables are linearly related. It is further assumed that the residuals (or error terms) are normally distributed, independent of each other and have constant variance. Additional restriction requires that independent variables be not highly correlated among themselves. When these conditions are met, then the regression model(s) generated are considered to be acceptable.

Many times, several different but all statistically sound regression equations or models (subset of variables) can be generated from the same data set and it becomes necessary to select the model(s) with the best fit. In the selection process, model purpose, variables included and statistical significance are major factors that should be considered.

In determining the statistical soundness of a model, there are several statistical indexes or tools that are commonly used. They include but are not limited to the coefficient of determination (R^2), analysis of variance (F-test) and residual plots.

Coefficient of determination (R^2). The coefficient of determination, denoted by R^2, is the ratio of the explained variation to the total variation. The value of R^2 ranges from 0 to 1 with the latter representing a condition where all the variation is explained. A small R^2 can mean that one or more important variable(s) is not included in the regression model. The coefficient of determination is computed as:

$$R^2 = \sum(Y_c - \bar{Y})^2 / \sum(Y - \bar{Y})^2$$

where: Y = observed value of the dependent variable

Y_c = predicted value of Y

$\bar{Y}$ = arithmetic mean of Y

For example, an R^2 value of 0.6850 is interpreted as that 68.50% of the variation in the dependent variable Y can be explained by the combined variation in the independent variables in the equation.

The square root of the coefficient of determination is the correlation coefficient (R), a term that represents the relationship between the variables. The correlation coefficient is frequently computed on a pair-wise basis for all the variables in concern and assembled in a matrix form. The correlation matrix, as termed, is a useful tool in regression analysis for it tells how the variables are correlated. In addition, the matrix also reveals any independent variables which are highly correlated, a condition that creates a computation problem called multicollinearity. "Multicollinearity does not result in an answer of infinity but it can give a result that is extremely large and cannot be handled by the computer" (Wheelwright and Makridakis, 1973).

Analysis of variance (F-test). The analysis of variance, or F-test, is a valuable tool in using the regression analysis for it provides a mean by which one can judge the significance of the regression model created. The value of F-test is computed as the ratio of the explained variance over the unexplained variance, and in equation form it is:

$$F = \left[\sum(Y_c - \bar{Y})^2 / (k-1)\right] \Big/ \left[\sum(Y - Y_c)^2 / (n-k)\right]$$

where: k = number of variables

n = number of observations

Alternately, when R^2 is computed first, the F-test value may also be computed as:

$$F = \left[R^2 \Big/ (k - 1) \right] \left[(1 - R^2) \Big/ (n - k) \right]$$

When the computed F-test value for a regression model is compared to the F-value from the table of F-distribution for the corresponding degrees of freedom at selected confidence level and exceeded the F-value from the table, then the regression model is said to be significant.

Residual plots. Analysis of residuals is an effective means for detecting model deficiencies in regression analysis. The residual is defined as:

$$C_i = Y_i - Y_{ic}$$

where: Y_i = the ith observation

Y_{ic} = the predicted value corresponding to Y_i

Examination of residual plots is the tool used in this study for analysis of residuals. Residuals are plotted as the ordinate against Y_c, the predicted value. Model deficiencies or violation of basic assumptions of regression analysis are exposed when residuals are not normally distributed, not independent of each other and/or lack of constant variance. For a regression model to be correct statistically, residuals must exhibit behavior conforming to model assumptions. Regression assumption violations can usually be corrected by addition or transformation of variables.

Stepwise multiple regression analysis. The stepwise procedure, in which variables are selected to be entered into (forward stepping) or removed from (backward stepping) the equation, is probably the most frequently used by the multiple regression analysis practitioners. The selection of variable is based on an F-to-enter (or F-to-remove) criterion. It is important to note that this F-to-enter criterion is merely a measure of the importance of one variable relative to another, and should not be confused with the F-test value in the analysis of variance. The F-to-enter criterion can be defined in more than one way. For each independent variable X_k not in the equation at step (j + 1),

$$\text{F-to-enter} = \frac{\sum(\text{residuals at step } j)^2 - \sum(\text{residuals at step } (j+1))^2}{\sum(\text{residuals at step } (j+1))^2/(n-j-2)}$$

or

$$\text{F-to-enter} = (b_k/Se(b_k))^2$$

where: b_k = regression coefficient for X_k when added to equation

$Se(b_k)$ = standard error for the coefficient b_k.

The forward stepping procedure starts with a constant term in the equation. At step one, the variable with the largest F-to-enter value is selected and the equation becomes $Y = b_0 + b_1X_1$. At step two, the variable with the next highest F-to-enter value among the remaining variables is entered and the equation becomes $Y = b_0' + b_1'X_1 + b_2X_2$. It should be noted that b_0 changes to b_0' and b_1 to b_1'. This operation is terminated when the F-to-enter value falls below the preselected value which corresponds to the level of significance chosen by the analyst.

In the backward stepping procedure, the operation is similar with the variable having the smallest F-to-remove value being removed first from the equation. Furthermore, forward or backward stepping procedures do not always result in equations with the same variables. In this study computations in regression analysis are performed by using the BMDP statistical programs (Dixon et al., 1981).

Strategy for regression analysis. Three BMDP programs are involved in this study:

1. "BMDP2D - Detailed Data Description" is used for gaining a thorough understanding of each variable in the data set, identifying extreme values, detecting highly skewed distribution and identifying potential candidate variables for transformations to improve symmetry;

2. "BMDP6D - Bivariate Scatter Plots" is used for checking linearity between the dependent and each independent variable, identifying bivariate outliers and studying the effect of transformation; and

3. "BMDP2R - Stepwise Regression" is used for computing regression coefficients, R^2, F-test values and other statistics, and for establishing the regression equations. Forward and backward stepping options are utilized. Because R^2 increase as variables are entered, a special technique is used to exclude questionable variables. In this study, three variables of random numbers are generated and added to the data set. Variables that entered after any random number variable are to be

suspected because of the fact that artificially generated variables should have no meaningful relationship with the dependent variable. Residuals plot options activated include the plot of residuals vs predicted value Y_c and the normal probability plot of residuals.

"BMDP2D" and "BMDP6D" are used jointly for detailed study and preliminary screening of data set. Data with extreme values are checked for correctness and variables are transformed where necessary. "BMDP2R" is then used for executing stepwise regression analysis. Meaningful correlations expressed by equations are then selected based on statistical indicators. Finally, various statistical indicators are checked to determine if any regression assumptions had been violated which could invalidate the generated equations.

The basic data set for the correlation study using regression analysis consists of data from 319 municipal wastewater treatment plants. The purpose of the correlation study is to determine if any significant relationship exists between plant equipment failure and the O&M of a plant. It is assumed that well-operated and well-maintained plants would have fewer equipment failures.

To execute the analysis, a value representing the equipment failure rate of a plant or the Y variable is needed. This value is determined by taking the simple arithmetic mean of the MTBF of all the equipment at a plant. The algorithms for MTBF follow that explained in the Data Analysis and Explanation of Terms section for MTBF. Since there is no established way for determining the relative importance of the treatment processes or equipment or a representative plant equipment reliability value, it is computed as just explained and used as the Y variable in the regression analysis.

Fourteen variables are generated as the X variables. These variables are:

X_1	ONM	Number of O&M personnel per MGD
X_2	OME	Average number of years of education attained by O&M personnel
X_3	OMX	Average number of years of WWTP experience of O&M personnel
X_4	OMT	Average number of training courses attended by O&M personnel during the past 3 years
X_5	MFACTOR	Maintenance activity level factor generated by answers to questions (see sample questionnaire questions 5 and 6), pertains to the execution of maintenance schedules (MS) and the application of maintenance/repair procedures (MP). MFACTOR is computed as: $\text{MFACTOR} = \text{MS} \times \left(\frac{5}{2}\right)^{*} + \text{MP} \times \left(\frac{10}{3}\right)^{*}$
X_6	LFACTOR	Logistic support level factor generated by answers to questions (see sample questionnaire questions 7 and 9), pertains to the availability of spare parts (SP) and technical assistance (TA). LFACTOR is computed as: $\text{LFACTOR} = \text{SP} \times (2)^{*} + \text{TA} \times \left(\frac{5}{2}\right)^{*}$
X_7	BODEFF	5 days BOD removal efficiency (%)
X_8	SSEFF	Suspended solids removal efficiency (%)

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*Subjectively chosen values for representing the relative importance of the factors.

X_9	HOT	Highest mean monthly temperature (°F)
X_{10}	COLD	Lowest mean monthly temperature (°F)
X_{11}	PPCT	Highest mean monthly precipitation (in.)
X_{12}	RNV_1	Random Number Variable No. 1
X_{13}	RNV_2	Random Number Variable No. 2
X_{14}	RNV_3	Random Number Variable No. 3

Variable X_1 is used to determine if any relationship exists between manpower level and equipment failure. The values for Variable X_1 are the actual numbers of full-time employees reported by the surveyees.

Variables X_2 to X_8 are used to indicate the various aspects of O&M level of a WWTP. Variables X_2 to X_4 are intended to reflect the potentials of O&M level attainable. It is assumed that education, experience and training all would have positive effects on the O&M and hence the performance of plant equipment. For example, when the plant personnel have many years of related experience, the potential for having plant equipment well-operated and well-maintained is expected to be high. The values used for the Variables X_2 to X_4 are the actual numbers of years of education, years of experience and number of short-course/training programs attended, respectively as reported by the surveyees. Variables X_5 and X_6 are indicator variables formulated to represent the O&M practice in terms of maintenance activity level and logistic support level of a plant. Variable X_5 concerns the availability of maintenance schedules and maintenance procedures utilized at a plant. It is thought plants that have well-operated and well-maintained equipment are those that have implemented preventive maintenance schedules and followed correct maintenance/repair procedures such as specified by equipment manufacturers. These two factors are combined to form a maintenance activity level factor or variable X_5. The values for Variable X_5 are derived from responses to questions 5 and 6 in the questionnaire. See Appendix A. A range of values of 1 to 4 is assigned to the four listed answers for question 5. When a plant responded that their regular maintenance actions are performed when needed and no planned schedule exists, the scored value by that plant for this question is 1. When regular maintenance actions are performed as the planned schedule 75% of the time is indicated the scored value is 3. When it is 100%, the scored value is 4. Similarly, a range of values from 1 to 3 is assigned to the three listed answers for question 6. The scored value for choosing the first answer is 1, for the second answer, 2, and for the third, a value of 3. The fractions used in the equation for computing X_5 were subjectively assigned value in attempt to indicate the relative importance between the two factors. Example: When a plant indicated that their regular maintenance actions are performed as the planned schedule 100% of the time, and their maintenance and repair are carried out by following the manufacturer's manual exactly, the total scored value by that plant for this variable is:

$$\begin{aligned} X_5 \text{ MFACTOR} &= \text{MS} \times 5/2 + \text{MP} \times 10/3 \\ &= (4) \times 5/2 + (3) \times 10/3 \\ &= 20 \end{aligned}$$

In the worst case situation in which the first answers were picked for both questions 5 and 6, the scored value would be

$$(1) \times 5/2 + (1) \times 10/3$$
$$= 5.83$$

The range of values for Variable X_5 is therefore from 5.83 to 20.

Variable X_6 pertains to the spare parts and technical assistance availability. Inadequate logistic support such as difficulties in obtaining spare parts and technical assistance can certainly hinder the effective O&M of plant equipment. Variable X_6 is therefore a logistic support factor. The values for Variable X_6 are derived from response to questions 7 and 9 in the questionnaire. A range of values of 1 to 5 is assigned to the five listed answers for question 7. The scored values for choosing each answer regarding spare parts availability are:

Listed Answer	Value
(i) In-plant	5
(ii) Locally, in town	4
(iii) Within 50 miles	3
(iv) In-state	2
(v) Out-of-state	1

The range of values assigned to the listed answers to question 9 are 1 to 4. The scored values for each answer to the question on technical assistance availability are:

Listed Answer	Value
(i) In-plant	4
(ii) Local university or college	1
(iii) Local engineering firm	3
(iv) State agencies	2

The fractions used in the equation for computing X_6 were also subjectively assigned values. Example: For a plant with its spare parts usually available in-plant and with its technical assistance usually available from in-plant, the total value scored by that plant for this variable is:

$$\begin{aligned} X_6\text{, LFACTOR} &= SP \times 2 + TA \times 5/2 \\ &= (5) \times 2 + (4) \times 5/2 \\ &= 20 \end{aligned}$$

The scored value for the worst case is 4.5. The range of values for Variable X_6 is 4.5 to 20. Variables X_7 and X_8 represent BOD_5 and suspended solids removal efficiencies which are direct results of the O&M of a plant and its equipment. They are therefore indirect indicators included to reflect O&M practice at a plant and its relationship with equipment failure. The values used for Variables X_7 and X_8 are the actual values reported by the plants to the EPA on their BOD_5 and suspended solids removal efficiencies, respectively.

Variables X_9 to X_{11} are generated from climatological data. These variables are included as environmental considerations to see if they have any effect on plant equipment failure. The values used are the actual climatographical readings. Finally, variables X_{12} to X_{14} are random number variables which are generated for the purpose of excluding questionable variables that may enter the regression equation.

In summary, data for the regression analysis came from four sources. Data for the plant equipment reliability value variable Y and for the operation and maintenance level variables X_1 to X_6 were derived from information collected by the survey conducted. Pollutant removal efficiency data for variables X_7 and X_8 are from the EPA computer file.* Climate data for variables X_9 to X_{11} were extracted from the National Oceanic and Atmospheric Administration's (NOAA) "Climatography of the U.S. No. 60" for each state. Lastly, data for variables X_{12} to X_{14} are random numbers generated by the computer.

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*EPA computer file printout was obtained from the Priorities and Needs Assessment Branch, Office of Water Program Operations, EPA, Washington, DC 20460. The data in the file were collected by EPA in its survey to estimate municipal wastewater treatment facility requirements.

CHAPTER IV

RESULTS AND DISCUSSIONS

A reliability data base for selected mechanical equipment at municipal wastewater treatment plants is established in this study. A generic approach is used to identify the mechanical equipment in consideration, classifying equipment by their functional types rather than by their specific models. The method of data collection utilized is a mail questionnaire survey, a technique that has not been used for gathering data of this nature before. In addition to mechanical equipment performance data, treatment plant manpower and O&M practice information were also requested in the questionnaire.

In this chapter, the results of the survey are discussed; the emphasis, however, is placed on the discussion of the results of data analysis. The discussion on the results of data analysis is divided into three sections: (1) the general characteristics of the manpower and O&M practices of the municipal WWTPs that responded; (2) the data characteristics of the equipment reliability data base; and (3) the results of the use of regression analysis in an attempt to establish a relationship between the reliability of equipment and the O&M factors of WWTPs.

Results of Survey

A total of 1,205 questionnaires were sent to municipal WWTPs in 20 states in the continental United States. The surveyed plants are all 1 MGD or larger in size, representing about 45% of the municipal WWTPs in this size group. The total number of responses was over 30% or 389 plants. Seventy of the responses provided no or inadequate equipment performance data; ten indicated their plant was shut down; eight reported their plant was being upgraded and did not care to respond; and 52 provided incomplete or unusable data. In all, 323 plants responded to the O&M practice questions, 320 plants reported plant manpower data and only 319 provided adequate equipment performance data to contribute to the equipment reliability data base. The 319 plants represented about 12% of the plants in the 1 MGD or larger size group. Table 5 presents the total number of municipal WWTPs in the United States. The number of WWTPs surveyed and the number of plants responded. The most underrepresented municipal WWTPs in this size group is from that of EPA Region V or the industrial states in the mid-west, which include Ohio, Michigan, Illinois, Wisconsin, Indiana, and Minnesota. The number of WWTPs in the data base representing the 1 MGD or larger size group from EPA Region V is just above 5%, while the representations of the other EPA Regions are all about 10% or higher. The best represented are the WWTPs from EPA Region X (Idaho, Washington and Oregon) with 28%.

In view of the voluntary nature of the survey and the kind of data requested in the questionnaire, the number of WWTPs that responded to this survey is perceived as very satisfactory.

Table 5. Survey Response from Wastewater Treatment Plant Equal to or Greater than 1 MGD

EPA Region	State	Total WTP[a]	WTP≥1 MGD[b]	WTP≥1 MGD Region Total	No. of WTP Surveyed	No. of Responses	WTP Closed	WTP in Expansion	WTP Data Not Usable	No. of WTP in Data Base
I	Maine		26		--	--				
	New Hampshire		18		--	--				
	Vermont		10		--	--				
	Massachusetts		54		--	--				
	Rhode Island		11		--	--				
	Connecticut		52		52	19	--	--	2	17
		421		171						
II	New York		153		153	51	5	--	4	42
	New Jersey		121		--	--				
		690		274						
III	Pennsylvania		163		163	39	--	--	6	33
	Delaware		3		--	--				
	Maryland		30		--	--				
	West Virginia		20		--	--				
	Virginia		49		--	--				
		1,230		265						
IV	Kentucky		38		--	--				
	North Carolina		86		85	13	--	--	1	12
	Tennessee		58		--	--				
	South Carolina		49		--	--				
	Georgia		72		11	5	--	--	--	5
	Alabama		56		--	--				
	Mississippi		44		39	5	--	--	--	5
	Florida		95		95	36	3	--	9	24
		2,518		498						
V	Michigan		73		71	28	--	2	1	25
	Wisconsin		67		--	--				
	Minnesota		37		7	4	--	--	--	4
	Ohio		143		--	--				
	Indiana		77		--	--				
	Illinois		131		14	3	--	1	--	2
		3,106		528						
VI	Arkansas		42		--	--				
	Oklahoma		45		--	--				
	New Mexico		15		--	--				
	Louisiana		61		--	--				
	Texas		197		178	55	--	5	8	42
		2,066		360						
VII	Iowa		37		--	--				
	Missouri		52		37	13	--	--	--	13
	Kansas		35		15	8	--	--	1	7
	Nebraska		18		--	--				
		2,142		142						
VIII	North Dakota		8		--	--				
	Montana		11		10	3	--	--	--	3
	South Dakota		9		9	7	--	--	1	6
	Wyoming		12		--	--				
	Colorado		28		28	9			1	8
	Utah		29		28	4			1	3
		1,139		97						
IX	Nevada		9		--	--				
	California		180		123	51	2	--	11	38
	Arizona		12		--	--				
		751		201						
X	Idaho		20		--	--				
	Washington		49		49	17	--	--	3	14
	Oregon		38		38	19	--	--	3	16
		567		107						
	TOTAL	14,630		2,642	1,205	389				319

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[a] From EPA 1978 Needs Survey, EPA 430/9-79-002 (Chamblee, 1979).

[b] From EPA computer printout obtained from Priorities and Needs Assessment Branch, Office of Water Program Operations, EPA, Washington, D.C. 20460.

Results of Data Analysis

The discussions on the results of data analysis are divided into three parts: (1) the general characteristics of the manpower and O&M practice of the municipal WWTPs that responded, (2) the data characteristics of the equipment reliability data base, and (3) the result of the regression analysis.

(1) The General Characteristics of the Manpower and O&M Practice of the Municipal WWTPs that Responded

In addition to equipment performance data, information on the manpower and O&M practice of the WWTPs were also requested in the survey questionnaire. For the manpower aspect, information solicited was on the number of operators employed, years of school education, years of experience and number of training courses attended. The same information was solicited for maintenance personnel. A statistical analysis was performed on these reported manpower data. The statistics computed were the mean, the standard deviation, the minimum value, the maximum value and the standard error of mean. Because at some smaller WWTPs there is no differentiation of manpower (in other words, the operator also has plant equipment maintenance as part of his job responsibility), a new category of total O&M personnel was created in the analysis for all plants. Table 6 presents the results on the manpower statistics computed.

The results show that for the 320 WWTPs that responded, 243 plants differentiated their employees as operators or maintenance personnel while 77 plants made no such differentiation. In the operator category, an average of two operators are employed for every MGD of wastewater

Table 6. Operation and Maintenance Manpower Statistics

	N[a]	Mean	Standard Deviation	Minimum Value	Maximum Value	Standard Error of Mean
OPERATOR:						
Number per MGD	320	2.094	1.284	0.345	8.824	0.072
Years of School Eduation	320	11.865	2.780	0.000	18.000	0.155
Years of Experience	320	7.172	3.871	0.000	25.000	0.216
Number of Short-Course Training Programs Attended (Number/Person in 3 years)	320	2.619	2.164	0.000	9.000	0.121
MAINTENANCE PERSONNEL:						
Number per MGD	243	1.076	1.125	0.043	8.500	0.072
Years of School Education	243	10.511	3.782	0.000	16.000	0.243
Years of Experience	243	5.696	4.282	0.000	22.000	0.275
Number of Short-Course Training Courses Attended (Number/Person in 3 years)	243	1.630	1.914	0.000	9.000	0.123
TOTAL O&M PERSONNEL:						
Number per MGD	320	2.911	1.808	0.652	12.000	0.101
Years of School Education	320	11.551	2.759	0.000	16.800	0.154
Years of Experience	320	6.671	3.347	0.000	20.509	0.187
Number of Short-Course Training Programs Attended (Number/Person in 3 years)	320	2.330	1.937	0.000	9.000	0.108

[a] N represents the number of WWTPs contributed to the statistics computation.

flow. On the average, an operator has nearly 12 years of school education, just over seven years experience and attended a training program 2.6 times in three years. In the maintenance personnel category, the computed data show that for each MGD of wastewater flow one maintenance person is employed. The maintenance person has about 10.5 years of school education, about 5.7 years of experience and receives 1.6 units of continuing training in three years. In each of the areas of education, experience and training, the operator is better than the maintenance personnel. In view of these data, it becomes quite surprising that, on the average, "the operator is paid about $2,000 less than equivalent maintenance personnel," as reported from a 1978 Water Pollution Control Federation Salary Survey (Hadeed, 1978).

The total O&M personnel category was created by adding together the operator and the maintenance personnel categories. The total number of O&M personnel employed for each MGD of flow therefore becomes three, of which two are operators and one a maintenance worker. Over 60% of the 320 WWTPs in the data base have less than this number of O&M personnel. Burke (1976) compared three methods* for estimating manpower requirements for WWTPs and estimated by each method that more than three persons are required for a 1 MGD trickling filter plant. Two of the methods estimated manpower needs for the 1 MGD plant to be 4.62 and 4.7

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*The three methods reported by Burke (1976) are: (i) 1971 Black and Veatch report - studied 23 plants from 1 to 150 MGD; (ii) 1973 CH_2M Hill report - studied 35 plants from 0.5 to 26 MGD; and (iii) 1973 Iowa State report - studied 138 plants from 0.1 to 1 MGD.

persons. Does this mean that 60% of the 320 WWTPs surveyed is understaffed? What are the implications of this condition to the performance of plant equipment? These are questions that can be addressed by future WWTP manpower requirement studies.

In the survey questionnaire, there were five questions regarding the O&M practices at the surveyee's plant. The responses to these questions are compiled and frequency response expressed in percentage are computed. These results are presented in Table 7.

The first question concerns regular maintenance actions. Of the respondents, 95.6% indicated they have a planned schedule. Fourteen of the 323 plants reported that no planned maintenance schedule exists at their plants and that maintenance are performed on an as-needed basis. An additional 35 plants do maintenance on a similar basis even though they have a planned maintenance schedule. Only 26% of the plants have a planned maintenance schedule which they follow 100% of the time. A total of 69.6% of the plants cannot follow their maintenance schedules. Apparently, many of these WWTPs are understaffed in their equipment maintenance department.

The second question concerns maintenance and repair procedures practiced at a plant. Of the 322 plants, 57.3% responded that maintenance and repair are carried out according to procedures different from those suggested by the manufacturers. Sixteen plants actually do not have manufacturers' manuals at their plant. And 37.5% of the plants indicated they followed manufacturers' manuals for maintenance and repair.

Table 7. Responses to Questions on Mechanical Equipment O&M

Questions on Page 1 of Questionnaire	No. of Plants Responded	Percent[a]
REGULAR MAINTENANCE ACTIONS ARE PERFORMED:		
When needed, no planned schedule exists	14	4.3
When needed, planned schedule cannot be followed	35	10.8
As the planned schedule 75% of the time	190	58.8
As the planned schedule 100% of time	84	26.0
MAINTENANCE AND REPAIR ARE CARRIED OUT ACCORDING TO:		
Standard maintenance procedures; there are no manufacturers' manuals in the plant	16	4.9
Standard maintenance procedures, but different from the manufacturers' suggested procedures	185	57.3
Manufacturers' manuals	121	37.5
MECHANICAL SPARE PARTS ARE USUALLY AVAILABLE:		
In-plant	118	36.5
Locally, in town	37	11.5
Within 50 miles	56	17.3
In-state	64	19.8
Out-of-state	47	14.6
TOOLS FOR MAINTENANCE ARE USUALLY AVAILABLE:		
Yes	310	96.0
No	3	0.9
TECHNICAL ASSISTANCE IS USUALLY AVAILABLE FROM:		
In-house	172	53.3
Local university or college	15	4.6
Local engineering firm	103	31.9
State agencies	31	9.6

[a] When percentages do not add up to 100%, it is due to nonresponse to the question by some plants.

Availability of mechanical spare parts was the third question. It appeared that an adequate spare part inventory was carried by 36.5% of the plants as they indicated that mechanical spare parts are usually available in-plant. The rest of the plants probably do not have an adequate spare part inventory. A total of 28.8% reported that mechanical spare parts can usually be obtained with relative ease, either locally in town or within 50 miles. Almost 20% of the plants obtained their mechanical spare parts from sources within the state, while 14.6% usually had to resort to out-of-state suppliers.

The fourth question addressed the availability of tools for maintenance. An overwhelming majority of 96% of the plants responded that tools are usually available, and only three of the plants responded otherwise. It appeared that this may not be a necessary question for future research.

The last question in this section of the questionnaire concerns the availability of technical assistance. Of 321 plants, 53.3% responded that technical assistance is usually available from in-house sources. About 30% usually retained a local engineering firm for technical assistance. The remaining 14.2% usually obtained technical assistance from their local university or college, or their state agencies.

In reviewing the manpower and O&M practice data collected, it is observed that in the management of WWTPs the emphasis is usually placed with the operation rather than the maintenance aspects of the plant. This has resulted in a 2 to 1 ratio in staffing. That operators received more continuing training than maintenance workers is another positive indication of a management practice favoring operators. The better qualifications of the operators in terms of education background and experience also reflects the plant's higher demand from the operators. The data collected on the O&M practice area is consistent with this observation. As nearly 70% of the plants that responded cannot follow their planned maintenance schedule, it is very likely the maintenance departments are understaffed. If the inability to follow the maintenance schedule is due to incompetent maintenance workers, then the occurrence of this condition also shows the low importance level placed on equipment maintenance by the WWTP management. Lastly, that over 60% of the plants do not follow manufacturers' manuals in maintenance and repair work probably reflects the loose management of the maintenance department and its workers. In summary, all these indicate that in the management practice of WWTP, there is inadequate importance given to the operation and maintenance of treatment equipment.

(2) The Data Characteristics of the Equipment Reliability Data Base

The equipment reliability data base presented in this study contains equipment performance data from 319 municipal WWTPs from 20 states. A list of the names of the municipal WWTPs which contributed to the reliability data base is presented in Appendix E. Each of the ten EPA regions is represented. The sizes of the municipal WWTPs included in the data base range from 1 MGD to 78.8 MGD. The mean size is 5.88 MGD with the median at 2.65 MGD. The data base is based on reported performance data of nearly 10,000 pieces of of WWTP equipment and is probably the largest data base of its kind available.

The data base involves a total of 53 WWTP processes. Of the processes, 41 are associated with the liquid treatment stream while 12 processes are related to the sludge treatment stream. As expected, equipment performance information is not uniformly collected for all treatment plant processes. Since some treatment processes are more commonly used than others, equipment associated with those processes therefore are more frequently used and more data is available. In general, there is adequate equipment performance data collected on the common wastewater treatment processes while very little data is collected for some of the newer treatment process equipment. This data base is therefore looked upon as a first step toward the building of a broad and useful data base on WWTP equipment reliability. A planned survey program to obtain additional equipment performance data periodically can be used to update and expand the data base. Such a program can best be executed bi- or tri-annually with a different group of WWTPs and conceivably it can be most effectively implemented through regulatory agencies who issue NPDES discharge permits.

The reliability data base presented in this document contains only calculated reliability data. The raw data is too bulky to be included in this document and is stored on magnetic tape.* The calculated reliability data is presented in Appendix D.

The reliability data base contains performance data for 332 equipment types or PET code entries. Seventy-eight of the equipment types are unspecified equipment. For example, in the raw sewage pumping

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*Magnetic tape stored at the Bureau of Water and Environmental Resources Research, University of Oklahoma, Norman, Oklahoma, 73019.

process, some of the respondents did not specify a pump type for raw sewage pumping at their plants. Their raw sewage pumps data are therefore grouped under the 00 equipment code for unspecified equipment. For each of the 332 equipment types, the following data are calculated and presented: the number of WWTPs and equipment units involved, the total operating hours, the MTBF, the 90% confidence limits for the MTBF, the MDT and the best three manufacturers. These terms are briefly explained in the page preceding the reliability data presented in Appendix D. In the reliability data base, there are two items that are presented in numerical codes. These are the PET or Process Equipment Type code and the manufacturer's code. To decode the PET code so that the equipment type can be identified, the mechanical equipment code in Appendix B is used. The manufacturer's code is decoded by using Appendix C, the mechanical equipment manufacturers' codes.

In Chapter V several data application alternatives are discussed.

Results and Discussion of Regression Analysis

Stepwise multiple regression analysis was performed on data from the municipal wastewater treatment plants utilizing the strategy described in the Regression Analysis section of Chapter III. As a result of the initial analysis in which the entire data set was treated as one single group, two additional analytical approaches were explored.

In the initial analysis, the data set contained data from 319 plants and was analyzed as one single group. After excluding plants with extreme data values (outliers), 305 plants remained in the data set. Several WWTPs reported their O&M personnel totalled more than ten, but the EPA's record showed their plants are around 1 MGD in size.

These values are suspected and therefore are not entered into the regression analysis. Data of this nature that presented extreme values are excluded. Logarithmic transformations were performed on several variables (MTBF, ONM, OMT and PPCT) to improve data symmetry. In all analyses, correlation matrices revealed variable X_3 (O&M personnel experience) was the only variable that has some correlation with plant equipment reliability. The correlation, between X_3 and the dependent variable Y, however, was only 0.1733. The other correlations were 0.1 or less. Regression analysis generated the following equation:

$$\mathrm{LOG}\ (\mathrm{MTBF}/1000) = 2.9088 + 0.0515\ X_3$$

This equation had an R^2 value which indicated that less than 5% of the variations in MTBF is explained by the equation. Entering additional variables could improve the R^2 value slightly, but this would further reduce the marginally low F-test value, thereby undercutting the overall significance of the equation. Due to these results, no further analysis in this direction was pursued.

It is quite clear from the small R^2 value that important variable(s) that could explain the variations in the MTBF value is not among the variables in the data set. This aspect will be discussed later. Table 8 gives the characteristics of the variables.

After initial regression analysis of the entire data set did not uncover any significant relationship between the Y variable (plant equipment reliability) and the X variables, another approach was taken to look at the data set. It is possible that some significant relationships may be concealed in the data set due to the large variations in

Table 8. Statistics of Variables Used in Regression Analysis

Variable	Name	Mean	Standard Deviation	Smallest Value	Largest Value
Y	MTBF_{LOG}	4.0334	0.9280	1.3395	6.4618
X_1	ONM_{LOG}	0.8861	0.5854	-0.4274	2.7080
X_2	OME[a]	--	--	--	--
X_3	OMX	6.7993	3.3057	0.0	20.5091
X_4	OMT_{LOG}	0.5917	0.7206	-0.8473	2.1972
X_5	MFACTOR	15.3469	2.9833	5.8333	20.0000
X_6	LFACTOR	14.8491	4.1408	4.5000	20.0000
X_7	BODEFF	85.8049	15.7342	7.1429	100.0000
X_8	SSEFF	85.2912	13.6468	10.0000	100.0000
X_9	HOT	74.9592	6.6758	56.2000	92.0000
X_{10}	COLD	36.4074	13.3787	5.5000	65.5000
X_{11}	PPCT_{LOG}	2.4971	0.4207	0.5068	3.4898

[a] OME is excluded from analysis because it has a distribution with an exceedingly high percentage of observations falling on one single value.

sizes among the plants. Had the size group been separated, some hidden relationships may have been revealed. The data set was subsequently broken into 5 groups at the 2-, 5-, 10- and 20-MGD levels for further analysis.

The first group consisted of 114 plants which were less than 2-MGD size. MTBF, ONM, OME and OMT were variables transformed by logarithm. A correlation matrix showed MTBF to have the best correlations with OMX and SSEFF, with values of 0.1713 and 0.1619, respectively. Stepwise regression generated the following best equation after four regression runs:

$$\mathrm{LOG}_{10}(Y/1000) = 1.0634 + 0.0222\ X_3 + 0.0064\ X_8$$

The next variable to enter the equation was a random number variable. The R^2 of the equation was 0.0533 with F-test value of 3.13. These low F-test and R^2 values indicated the significance of the equation was marginal and that it explained only about 5% of the variations in MTBF.

The second group had 98 plants ranging from 2 to less than 5 MGD in size. MTBF and OMT were the only variables transformed logarithmically. The best correlation from the correlation matrix was between MTBF and PPCT, having a value of -0.2447. The best equation obtained after four runs was:

$$\mathrm{LOG}_{10}(Y/1000) = 1.8655 - 0.0232\ X_{11} - 0.0261\ X_6 + 0.0064\ X_8$$

The F-test value was 6.64 with R^2 of 0.1750. Although the R^2 value was higher than other R^2 values obtained in this study thus far, it was still low. Also, it could not be explained why the LFACTOR variable had a negative correlation with the MTBF variable as the opposite was expected.

The third group of plants was from 5 to less than 10 MGD in size. There were 54 plants. Three variables were transformed by taking the logarithms of MTBF, ONM and OMT. The best correlation was 0.3257, between variables Y and X_3. The best equation selected was:

$$\mathrm{LOG}_{10}(Y/1000) = 1.5908 + 0.0351\ X_3$$

The F-test value was 6.17, while the R^2 value was 0.1061, or that 10% of the variations in MTBF were explained by X_3.

Twenty-four plants ranging from 10 to less than 20 MGD were in group four. Logarithmic transformations were performed on variables MTBF, ONM and OMT. The regression equation obtained before any random number variables were entered was:

$$\mathrm{LOG}_{10}(Y/1{,}000) = 3.3148 - 0.0190\ X_8$$

The R^2 value was 0.2707 and the F-test value was 8.17 for the equation. It must be noted here that the next best correlation was -0.5010 between MTBF and random number variables number 2.

The last size group has 16 plants that were 20 MGD or larger. Variables that were logarithmically transformed included MTBF, ONM and OMT. The variable that had the best correlation with MTBF was variable X_{10} or the coldest mean monthly temperature. The correlation coefficient was 0.6348. This could be interpreted as plants located at colder climates had lower MTBF values. The best regression equation obtained was:

$$\mathrm{LOG}_{10}(Y/1000) = 1.1565 + 0.0157\ X_{10}$$

The R^2 value was 0.4030 and the F-test value was 9.45. These values are the best values obtained in all of the regression runs performed. Forty percent of the variations in MTBF could be explained by the equation.

In all the regression runs by size groups, none of the multiple regression coefficients exceeded 0.5 while the F-test values were all marginal. In all cases at least four runs were performed for each size group. As preliminary results generated (presented above) did not reveal any significant relationship, no additional examination of equations or analysis in this direction was pursued. Table 9 presented some statistics of the plants by size groups.

The third approach undertaken to execute the regression analysis was by grouping the data set according to the plant process types. Seven plant types were identified. There were 8 plants with primary treatment, 84 plants with trickling filter, 178 with activated sludge, 8 with pure oxygen activated sludge, 7 with bio-disc, 9 with oxidation ditch and 12 with aerated lagoon. Regression analysis was performed on two groups only: trickling filter and activated sludge.

In the analysis with the 84 trickling filter plants, logarithmic transformations were performed on four variables MTBF, ONM, OMT and PPCT. The X variable that had the highest correlation with MTBF was

Table 9. Statistics of Surveyed Municipal Wastewater Treatment Plants by Size Group

Variable	Plant Size											
	$Q<2$ MGD (114)[a]		$2 \le Q < 5$ MGD (98)		$5 \le Q < 10$ MGD (54)		$10 \le Q < 20$ MGD (24)		$20 \le Q$ MGD (16)		All Sizes (305)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
MTBF[b]	58.17	2.61	51.25	2.68	70.03	2.48	44.83	2.19	50.61	1.70	56.45	2.53
ONM	3.16	1.76	2.56	1.71	1.95	1.52	1.46	1.53	1.18	1.29	2.43	1.80
OME	10.39	1.76	11.68	2.27	12.19	1.70	12.00	0.86	12.29	0.66	--	--
OMX	6.53	3.09	6.74	3.41	7.26	3.67	6.74	3.49	7.20	3.10	6.80	3.31
OMT	2.01	1.94	1.92	1.93	1.61	1.92	1.91	2.01	1.70	2.24	1.81	2.06
MFACTOR	15.32	2.99	15.94	2.77	14.86	3.00	14.97	3.17	14.22	3.44	15.35	2.98
LFACTOR	14.21	4.25	14.70	2.42	15.07	3.83	16.08	3.59	17.72	3.18	14.85	4.14
BODEFF	86.83	13.24	84.08	19.64	86.13	15.49	87.66	11.24	83.45	13.36	85.81	15.73
SSEFF	87.24	10.11	84.25	16.19	84.59	12.90	87.38	9.31	75.51	21.91	85.29	13.65
HOT	75.31	6.46	74.31	7.19	75.05	6.94	75.83	5.11	74.83	6.24	74.96	6.68
COLD	36.46	12.83	36.49	14.53	38.54	13.62	31.80	12.23	34.88	9.34	36.41	13.38
PPCT	13.13	5.73	13.55	5.22	13.54	4.93	11.37	4.78	12.33	3.42	12.15	1.52

[a] Number in parentheses is the number of plants in the size category.

[b] ($\times 10^3$).

MFACTOR, with a correlation coefficient of 0.2378. Regression analysis yielded the equation as follows:

$$\mathrm{LOG}(Y/1000) = 2.3145 + 0.0678\ X_5 + 0.4416\ X_{11}$$

Having an R^2 value of 0.0940, this equation also explained less than 10% of the variations in the y variable. The F-test value was very small, at 4.20. Both these statistics demonstrated the very limited significance of the equation.

There were 178 plants in the activated sludge plant type group. MTBF, OMN, OMT and PPCT were the four variables logarithmically transformed. There were four variables in the regression equation generated:

$$\begin{aligned}\mathrm{LOG}(Y/1000) = {} & 3.5833 + 0.0775\ X_3 - 0.0270\ X_5 \\ & - 0.0245\ X_6 + 0.0072\ X_7\end{aligned}$$

This equation had an R^2 of 0.1036 and an F-test value of 5.00. As indicated by these statistics, the significance of the equation is marginal. Table 10 presented some of the statistics of the two plant process type groups.

In the regression analysis performed, no significant relationship is established between the plant equipment reliability variable and the selected operation and maintenance indicator variables. This means that the reliability of WWTP equipment is not affected by the operation and maintenance practice of a plant. If this is true, then there must be other factors that have more influence on the reliability of WWTP equipment than the O&M factors. Logically, one thinks of factors such as the quality control in the manufacturing processes, the design, the

Table 10. Statistics of Surveyed Trickling Filter and Activated Sludge Plants

Variable	Plant Type			
	Trickling Filter (84)[a]		Activated Sludge (178)	
	Mean	Std. Dev.	Mean	Std. Dev.
MTBF[b]	84.46	2.31	51.04	2.41
ONM	2.39	1.81	2.56	1.74
OME[c]	--	--	--	--
OMX	6.97	3.49	6.78	3.15
OMT	1.65	1.99	1.84	2.11
MFACTOR	15.21	2.94	15.35	3.01
LFACTOR	13.96	4.46	15.49	3.88
BODEFF	86.17	10.20	86.37	16.03
SSEFF	87.18	7.72	85.38	13.84
HOT	75.66	6.79	74.74	6.23
COLD	35.10	12.46	36.51	14.01
PPCT	11.83	1.44	12.35	1.52
Avg. Flow[d]	4.31	5.65	6.49	8.98

[a] Number in parentheses is the number of plants in the type category.

[b] ($\times 10^3$)

[c] Variable deleted due to highly skewed data.

[d] Average flow in million gallons per day.

the handling/shipment and the installation of equipment. All these factors can affect the performance of equipment at a WWTP. One factor that has not been commonly looked at is the selection of equipment for application. It would seem that equipment improperly selected for application would have higher breakdown frequencies. It is, however, not easy to determine what is proper or improper selection of equipment for many of the process application situations. The selection/application of equipment as a factor affecting equipment reliability is probably an important area to look at in future research on equipment reliability.

Although the results of regression analysis showed no significant relationship exists between the plant equipment reliability and the O&M factors, it is possible that significant relationships do exist but are not revealed by the regression analysis. The independent variables formulated to represent the operation and maintenance factors are indicator variables. They are not direct measurements of the O&M level of a WWTP and therefore may not reflect the real O&M level. The manpower related variables and the removal efficiency variables belong to this group. The available manpower to do work, the education level, the experience accumulated and the additional training received are all variables indicating potentials. Such variables point out what O&M level could be achieved; but what could be achieved may not necessarily always translate into what was achieved at a plant in terms of O&M. It was also thought that well-operated and well-maintained plants can achieve better treatment efficiencies. It is from this line of thinking that the removal efficiencies are used as variables to reflect the O&M

level of a plant. The two variables, MFACTOR and LFACTOR, that measure equipment maintenance are, to some extent, indicator variables, too, in that they pertained to the general practice at a plant, and therefore may not represent the actual O&M level adequately. Furthermore, these two variables do not differentiate the levels of O&M sufficiently as a result of the design of the questionnaire. On the other hand, the dependent variable of plant equipment reliability is formulated by computing the simple arithmetic average of the MTBF values for all the equipment at a plant. This may not be the most accurate way to formulate a value representing the plant equipment reliability. All these factors may have contributed to the regression analysis not revealing any significant relationship between the equipment reliability and the O&M level of a plant. The conclusion from this regression exercise is that the results obtained here do not invalidate the assumption that well-operated and well-maintained plants would have fewer equipment failures. It is apparent that further studies will be needed if one is to understand the relationship between operation and maintenance and the reliability of equipment.

CHAPTER V

DATA APPLICATION

The equipment reliability data collected in this study can be applied to the various equipment-related decision making processes in the operation of a wastewater treatment plant. There are many ways these data can be utilized, but the two general areas in which these data are currently conceived to be useful are related to the selection of equipment and the improvement of equipment maintenance programs at a WWTP. In this chapter, data application to these two areas is discussed and demonstrated.

Data Application to the Selection of Equipment

The construction of municipal WWTPs and the procurement of major equipment at these facilities are performed normally through an open bidding process in which the lowest price bidder wins the contract. The result of this practice is that the cheapest equipment that barely meets the contract specifications is often purchased and installed. Due to lack of equipment performance records, the design engineer is heavily relied upon to formulate specifications in the contracts that have the purpose of reducing the probability of purchasing inferior or undesirable type equipment. The writing of contract specifications is, however, very much an art. The specifications are only as good as the persons who wrote them, and frequently contractors are able to purchase equipment that are very low in price and low in quality, and still meet the contract specifications. The equipment reliability data collected in this study can be used to aid in the specification formulation process by identifying the more reliable equipment types. When this is done, then specifications can be written around those equipment types. From another perspective, these data can also be used to avoid selecting equipment that exhibit problematic performance records. With real information on equipment performance, the design engineer can more effectively formulate equipment specifications so that the purchase of inferior equipment is avoided. For older WWTPs which had been in operation for a few years, some equipment will eventually fail beyond repair. Replacement equipment will have to be purchased. Again, the equipment reliability data can be used by the plant engineer or the O&M personnel in selecting a new replacement equipment when the old equipment is no longer available or when the failed equipment does not have a satisfactory performance history. The reliability data is especially useful in this situation because the average person involved in WWTP acquisition is not as familiar with different treatment equipment as a design engineer is, and therefore purchase decisions can be more easily swayed by strong sales presentations. With the equipment reliability data, most WWTP personnel can make better decisions and be an informed buyer of equipment.

How does one go about using the data base to select equipment based on reliability? Obviously, the selection process would involve the comparison of equipment data representing reliability or MTBF. Any pair of MTBF values can be compared on their face values and determined whether they are equal or if one is larger than the other. However, such comparisons may not always be valid for there is no assurance that the difference, if any, is significant. This is because the MTBF values are estimates determined from different sets of samples. To make a valid comparison these factors must be considered. A method for making valid comparisons of the MTBF in a systematic way is therefore suggested here.

The purpose of comparing the MTBF values is to determine if any two values under comparison are statistically different and, more specifically, if one value is larger than the other. To accomplish this, a statistical test involving a test of a hypothesis concerning the difference between two means is used. The hypothesis set up to be tested is the null hypothesis which says there is no difference between the actual means of the two equipment types, or

$$H_o: \mu_1 - \mu_2 = 0$$

where μ_1 and μ_2 are the actual MTBF values. The alternative hypothesis is set up as

$$H_1: \mu_1 - \mu_2 > 0$$

because knowledge on whether the actual MTBF of one type of equipment is larger than the other is desired. To test the hypothesis, the z-test statistic for two populations is employed. The z-test statistic for two populations is

$$z = \frac{(\bar{y}_1 - \bar{y}_2) - D_o}{(s_1^2/n_1 + s_2^2/n_2)^{1/2}}$$

where: $\bar{y}_1$ and $\bar{y}_2$ = the estimates of MTBF for the two types of equipment in consideration.

D_o = the difference between the actual MTBFs, or $\mu_1 - \mu_2$. Here $D_o = \mu_1 - \mu_2 = 0$.

s_1^2 and s_2^2 = the variances of the MTBFs.

n_1 and n_2 = the sample sizes.

The z-test value, after computed, is compared with the z value from the normal curve area table corresponding to a certain level of significance. If the z-test value is larger than the table z value, then the null hypothesis is rejected and the alternative hypothesis is accepted. That means the difference between the actual MTBFs of the equipment is greater than zero. If, however, the computed z-test value is smaller than the z value from the table, the null hypothesis will be accepted. In testing the hypothesis there is a certain risk involved in the decision to reject or accept the hypothesis. This risk level is the level of significance mentioned earlier. For example, at a risk level or level of significance of 0.05, there is a 5% probability that the null hypothesis is rejected when in fact the null hypothesis is true; or there is a 95% probability in accepting the null hypothesis when it is true. In order to have a table z value to compare the computed z-test value, a level of significance must be decided beforehand. For this study's purpose, a level of significance of 0.10 is chosen for use here. In other words, a risk of having a 10% probability of rejecting the null hypothesis when in fact the null hypothesis is true is being taken here. At this level of significance, the table z value is 1.28, which is the value against which the computed z-test value is to compared. The following is an example to demonstrate this method of comparing a pair of MTBF values. Consider raw sewage pumps with PET codes 01101 and 01102. The values for these two pump types are:

PET Code	n	$\bar{y}$ (MTBF)	Variances*
01101	237	64,942	s_1^2
01102	248	109,026	s_2^2

$$z = \frac{109{,}026 - 64{,}942}{(s_2^2/248 + s_1^2/237)^{1/2}}$$

$$= 1.61$$

This computed z-test value of 1.61 is larger than the table z value of 1.28, therefore the null hypothesis is rejected. It is concluded that at a level of significance of 0.1, the MTBF of equipment type 01102 is larger than that of type 01101. In other words, the data showed that in the application to raw sewage pumping, the reliability of the centrifugal pump with variable speed control is higher than the centrifugal pump with constant speed control, and the probability of being wrong is 10%. Comparisons of MTBF values of selected equipment pairs were made using this method. Each equipment pair for comparison was selected from

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*Variance can be calculated by $s = [(\mathrm{MTBF} - \mathrm{L.L.})/1.645]n^{1/2}$.
L.L. = lower limit of the 90% confidence limits.

the same treatment process category. The results were tabulated in Table 11. It is interesting to note that the comminutor is more reliable than the barminutor. One comparison result showed that for the grit removal process, the centerdrive scraper collector is more reliable than the flight-type grit collector. The comparison of the primary clarifier pair showed that there is no difference in reliability between the centerdrive/scraper collector and the rectangular tank scraper collector. Using this method of comparing MTBF values, equipment from different treatment process categories can also be compared. For instance, one can compare the floating aerators with the brush aerators if one so desires.

The comparison of treatment processes is also possible by comparing the MTBFs of their main equipment systems. This is because the performance of a treatment process is determined by the performance of its main process equipment. Therefore, the results of comparing the MTBFs of the main equipment of treatment process can also aid in the decisions on process selection. Comparisons of selected pairs of main equipment, and therefore processes, were made with the results compiled in Table 12. For example, a comparison of the rock-media trickling filter process and the activated sludge process was made by comparing the MTBFs of the rotating distributor and the surface impeller type mechanical aerator. The result indicated that there is no significant difference between these processes in terms of the MTBFs of their main equipment. When the comparison was made between the rotating distributor of the trickling filter and the centrifugal blower air supply

Table 11. Comparison of MTBF Values of Selected Equipment Pairs

No.	Equipment Pair, PET Codes	Computed z-test	Compare to Table z Value	Results
1	01101, 01102	1.61	>1.28	01102 is better
2	03101, 03102	3.06	>1.28	03102 is better
3	03201, 03202	1.19	<1.28	No difference
4	03201, 03203	1.62	>1.28	03201 is better
5	03202, 03203	1.56	>1.28	03202 is better
6	04101, 04102	4.56	>1.28	04101 is better
7	09101, 09105	0.49	<1.28	No difference
8	09201, 09204	1.23	<1.28	No difference
9	09201, 09207	2.29	>1.28	09201 is better
10	14101, 14102	2.25	>1.28	14101 is better
11	14101, 14103	0.74	<1.28	No difference
12	14201, 14202	0.91	<1.28	No difference
13	22101, 22102	5.01	>1.28	22101 is better
14	22101, 22105	0.10	<1.28	No difference
15	51101, 51103	0.37	<1.28	No difference
16	68104, 68107	3.24	>1.28	68104 is better
17	75101, 75102	0.73	<1.28	No difference

Table 12. Comparison of Selected Process Pairs by Comparing their Main Equipment's MTBF Values

Process Pair PET Code	Computed z-test	Compare to Table z Value	Results
10101, 14101	0.17	<1.28	No difference
10101, 14201	3.72	>1.28	10101 is better
14101, 14201	2.58	>1.28	14101 is better
14201, 19101	1.44	>1.28	14201 is better
19101, 20101	0.44	<1.28	No difference
14201, 20101	1.82	>1.28	14201 is better
22201, 22301	0.62	<1.28	No difference
22201, 22401	1.58	>1.28	22201 is better
22301, 22401	1.48	>1.28	22301 is better
29101, 30101	3.32	>1.28	30101 is better
75101, 76101	0.50	<1.28	No difference
79101, 80101	3.40	>1.28	79101 is better

equipment of the activated sludge, the result showed that the trickling filter process is more reliable than the activated sludge process.

Once a piece of equipment or a process is identified to be more reliable through a rational comparison process utilizing actual performance data, the specification writer can be more specific on the formulation of the specifications and other decision makers can also be more confident about their selection. Of course, there are many factors involved in the decision-making process for the selection of wastewater treatment equipment or processes. The data presented in this study and the method just discussed add another important dimension to those equipment-related decision-making processes. The consideration of equipment reliability in the decision-making processes by the use of actual reliability data can improve the overall performance of the WWTP through the minimizing of equipment problems.

Data Application to Improve Equipment Maintenance Program

The equipment maintenance programs at many municipal WWTPs are typically set up on a simple time-interval basis. These maintenance programs commonly call for the routine inspection and service of equipment every two to four weeks. For some equipment groups, the time interval may be as long as six months. Generally, there are no sophisticated maintenance programs such as planned replacement programs at the municipal WWTPs. Because these programs are designed on a fixed-time basis, they do not take into consideration the length of time the equipment has been in operation. In other words, these programs do not acknowledge that equipment which has been placed in service for a longer period of time has lower reliability, and thus requires more maintenance and service effort.

To apply the collected reliability data to improve these maintenance programs, the MTBF values are used. As pointed out before in Chapter III, the MTBF value for equipment does not mean that the equipment will operate without failure during the time period designated by the MTBF value. The MTBF value really should be considered as a probability value. For example, consider the centrifugal pump used for primary sludge pumping (PET Code 09201) with an MTBF of 56,079 hours. The reliability or probability of not encountering failure, say during a 3-month period, for that pump is:

$$\begin{aligned}\text{Reliability} &= e^{-t/\text{MTBF}} \\ &= e^{-(3\text{ mo} \times 30\text{ day/mo} \times 24\text{ hr/day})/56{,}079\text{ hr}} \\ &= 0.9622\end{aligned}$$

This means that there is a 96% probability that the pump will not encounter failure during that time period. Similarly, the reliability of the centrifugal pump can be calculated for six and nine months, one year, and longer periods. For example, the 09201 type centrifugal pump for primary sludge pumping:

Time	3 mo	6 mo	9 mo	1 yr	2 yr	3 yr	4 yr	5 yr
Reliability	0.96	0.92	0.88	0.85	0.73	0.63	0.53	0.45

As the length of operating time increases, the probability of failure increases. Because of this, an equipment that has been operating for a long period will be better maintained by having closer-spaced inspection and service intervals. For example, a maintenance program calls for an inspection and service interval of four weeks for pump A. This program can be improved by using the reliability data. An improved program for pump A may be such that the service intervals be set at six weeks when it has a greater than 85% reliability, four weeks when its reliability is greater than 50%, and at three weeks when below 50%. Both the reliability level and the service interval can be selected by the plant personnel according to needs and resources available. The setting of service intervals to reflect the reliability of equipment is a more responsible way of formulating a maintenance program. It addresses the changing service needs of equipment while eliminating the manpower demand of unwarranted maintenance service. The reliability data and the method just discussed, therefore, provide a rational basis by which plant engineers or personnel can improve their equipment maintenance program.

In addition to the MTBF data, the reliability data base presented in Appendix D contains two other pieces of important information: Mean Downtime (MDT) and Best Three Manufacturers. These data can also be used in the various equipment-related decision processes.

The downtime of an equipment measured in this study is the total lapse time from breakdown to reactivation to service-ready mode. The downtime, therefore, includes the repair time, any administrative delays, the waiting time for parts or for repair and any other times incurred. For WWTP that have their equipment downtime longer than the MDT values in the data base, the MDT values can be used as a target reference by which to reduce their equipment downtimes. For example, if a mechanically cleaned bar screen downtime of 300 hours is experienced by WWTP X (which is high compared to the 201 hours in the data base for the same equipment), then WWTP X may want to seek ways to reduce its downtime using the MDT value as a target or reference. Improving spare parts inventory and reducing repair response time are two of the ways to minimize equipment downtime. The MDT data also expose equipment types that exhibit very large MDT values. This information can be applied to decisions regarding duplicate equipment needs and inventorying of spares. Equipment types that have comparatively large MDT also reflect the level of difficulty involved in repairing or getting the equipment back to working condition. Such information can certainly impact equipment selection decisions.

The way the best three manufacturers data can be used is self-evident. The data simply is the result of comparing MTBF values and then listing the three manufacturers with the highest MTBF values for an equipment type. It points out which of the manufacturers should be given first consideration in the selection of a particular equipment type.

In summary, the equipment reliability data collected can be used in the WWTP in many ways. In this chapter only two of the general areas in which these data can be used have been reported. These two areas are equipment selection and maintenance programs. It is recognized that there are many other factors involved in the decision process regarding those areas. The data and the methods presented in this chapter are, therefore, means to improve the existing decision processes involving equipment.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This study has demonstrated that the collection of equipment performance data from the municipal wastewater treatment plants through the use of a mail questionnaire survey is feasible. The equipment reliability data base established in this study is based on data collected from over 300 municipal wastewater treatment plants in 20 states. It represents about 12% of the plants in the 1 million gallons per day or larger size group. This data base, although containing adequate equipment reliability data for many common wastewater treatment processes, does not have equally sufficient equipment data for many of the less common treatment processes. This data base is therefore looked upon as a foundation for further studies.

In addition to data on equipment performance, data relating to WWTP manpower and O&M practices were also collected and presented in this study. Finally, regression analysis was utilized as a part of this study to determine if any significant relationship can be established between the reliability of equipment and the O&M factors of a WWTP. Based on the findings of this study, the following conclusions are drawn:

1. The study of wastewater treatment plant equipment reliability has been inadequately pursued as indicated in the literature. The term "reliability" is commonly used in the wastewater treatment field to mean pollutant removal efficiencies.

2. Although there are various mathematical distributions, such as the Normal, the Log-Normal, the Gamma, the Weibull, and the Exponential distributions, that can be applied to describe WWTP equipment failure patterns, the Exponential distribution is adopted as a working concept in this study. The Exponential distribution is a frequently used distribution in reliability studies. The limitations of data available from the WWTP and the ease and flexibility in applying the Exponential distribution are additional reasons that have led to its use in this study.

3. The equipment reliability data base contains data from 319 municipal WWTPs, which represented about 12% of the plants in the 1 MGD or larger size group. The sizes of the plants in the data base ranged from 1 to 78.8 MGD. The mean size is 5.88 MGD, with the median at 2.65 MGD. The most underrepresented WWTP group is that from EPA Region V, while the best represented group is from Region X.

4. The equipment reliability data base established is the most extensive data base of its kind at present. It contains equipment performance data for 53 treatment processes (41 liquid stream processes, 12 sludge stream processes) involving about 10,000 pieces of equipment.

Because the data base does not have sufficient equipment reliability data for the less common wastewater treatment processes, it is to be considered as a foundation for further study.

5. The data collected showed that for every million gallons per day of wastewater flow, three persons are employed on the average for the O&M of the municipal WWTPs. Of the three, two are operators and one is in maintenance. Nearly 70% of the plants responded cannot follow their maintenance schedule. These results and other results of analysis on O&M practice data have led to the conclusion that the equipment maintenance departments at many municipal WWTPs may be understaffed.

6. As the collected manpower data showed that WWTP operators are in general better educated, more experienced, and have received more training than the maintenance personnel, it appeared that in the current WWTP management practice inadequate importance has been given to the operation and maintenance of treatment equipment. A more balanced approach by the management of WWTP, such as providing more training to the maintenance personnel, could ultimately enhance the performance of the equipment and the WWTP as a whole.

7. The regression analysis performed did not reveal any significant relationship to exist between the reliability of equipment and the O&M factors. Because of the limits in formulating truly representative variables, the result obtained is not considered conclusive; therefore, it does not invalidate the assumption that well-operated and well-maintained plants could have fewer equipment failures.

8. Data applications to assist in the selection of equipment and to improve equipment maintenance programs have been presented. These are but two of the equipment-related decision-making areas to which the reliability data can be applied. It is recognized that the decision-making processes at WWTPs regarding the equipment are complicated and the reliability data base is intended for use in improving the current equipment-related decision process.

Recommendations

A significant amount of reliability data has been collected for the many types of equipment used in the more common wastewater treatment processes. For the less common treatment process equipment types, their reliability data are mostly lacking or insufficient. In order to improve and expand the equipment reliability data base, additional data will have to be collected. It is therefore recommended that planned survey programs be formulated to gather additional data on equipment performance. Such programs can best be executed bi- or tri-annually with a different group of WWTPs and conceivably they can be most effectively implemented through regulatory agencies who issue NPDES permits.

The data base established in this study represents equipment data from the municipal WWTPs in the 1 MGD or larger size group. The equipment from the less than 1 MGD size group, which accounts for over 80% of the nation's municipal WWTPs, is not represented. A survey program designed to collect equipment data from the smaller than 1 MGD size group WWTP is recommended. Such data, when available, can then be used to compare with the data collected in this study.

In future equipment data collection efforts, equipment size information such as gallons per minute, cubic feet per second and others should also be collected. As the data base expands, there will eventually be a sufficient amount of data for determining equipment reliability values by size group.

In addition to this approach of equipment performance data collection, which aims for an overall perspective of all the equipment at the WWTPs, an alternative approach is recommended here not as a substitute but as an additional means (to look at WWTP equipment). A program similar to the Government-Industry Data Exchange Program (GIDEP) can be set up to collect data on failure-prone equipment. The EPA would be an ideal agency to head such a program and to provide the data bank for data storage. Data collected in the GIDEP program are frequently used by participants to help make decisions on equipment purchase.

It is also recommended that research efforts be initiated to study the causes of failure and failure patterns of wastewater treatment equipment. Clearly, there is a need for studies in this subject area. The information gained here can be applied to preventing and correcting equipment problems by providing feedback data to the designers and the manufacturers.

Finally, one of the findings of this study is that many municipal wastewater treatment plants may be understaffed at their equipment maintenance department. This is conceived as an indication that the current practice of management does not acknowledge the importance of equipment performance in the operation and maintenance of the wastewater treatment plants. It is recommended for future studies concerning the manpower aspect of wastewater treatment plant operation that effort be spent in gathering data on manpower needs for equipment maintenance.

The question of equipment reliability is one of the most pressing problems facing the municipal wastewater treatment plants today. The lack of study on treatment plant equipment performance in the past should not continue into the future. It must be recognized that reliable equipment not only enhances the performance of the wastewater treatment plants, it ultimately affects the goal of the nation to protect its water resources.

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APPENDIX A

SAMPLE QUESTIONNAIRE

The
University of Oklahoma at Norman

Bureau of Water and
Environmental Resources Research

Mr.

Dear Mr.

The Bureau of Water and Environmental Resources Research at The University of Oklahoma is conducting a study on the performance of equipment at municipal wastewater treatment plants. Past experience and recent government reports both indicated to us that equipment breakdown problems are quite common among wastewater plants. Some of these problems may simply be caused by unreliable equipment. Our research is an attempt to scale the magnitude of the problem.

Your plant is one of the few in your state being chosen to assist us in this cooperative effort. The information you provide will be of exceptional value in selecting equipment for new plants, and possibly replacing individual components in your own plant. A courtesy copy of our findings will be provided to you upon completion of the study.

Data collected will not be referenced to the specific plant source so as to protect your privacy. This study is not connected in any way with government regulatory or enforcement agencies, or equipment vendors.

Your time and effort in participating in this research will be deeply appreciated.

Sincerely yours,

George W. Reid
Regents Professor/Director

GWR:sjl

202 West Boyd Street, Room 301, Norman, Oklahoma 73019 (405) 325-3600 3609

Questionnaire

WASTEWATER TREATMENT EQUIPMENT STUDIES

BUREAU OF WATER AND ENVIRONMENTAL RESOURCES RESEARCH

UNIVERSITY OF OKLAHOMA

June 1981

I. Please supply general plant data: Plant No.

Personnel Data: (Please fill in all blank spaces.)

	OPERATOR	MAINTENANCE
1. Number of full-time employees*:	____	____
2. Average number of years of school education:	____	____
3. Average years of wastewater plant experience:	____	____
4. Average number of short-course/training programs attended per person during past 3 years:	____	____

Equipment Operation and Maintenance Data:

5. Regular maintenance actions are performed: (Check ONE)
   - (i) when needed, no planned schedule exists . . . . ______
   - (ii) when needed, planned schedule cannot be followed. . . . ______
   - (iii) as the planned schedule 75% of the time . . . . ______
   - (iv) as the planned schedule 100% of the time. . . . . ______

6. Maintenance and repair are carried out by following: (Check ONE)
   - (i) standard maintenance procedures, there are no manufacturer's manual in the plant. . . . . ______
   - (ii) standard maintenance procedures, but different from the manufacturer's suggested procedures. . . . . ______
   - (iii) manufacturer's manual exactly . . . . ______

7. Spare parts are usually available: (Check FIRST correct answer)
   - (i) in-plant. . . . . ______
   - (ii) locally, in town. ______
   - (iii) within 50 miles (1-hour drive). . . . . ______
   - (iv) in-state. . . . . ______
   - (v) out-of-state. . . . . ______

8. Tools for maintenance and repair are usually available? YES ______
   NO ______

9. Technical assistance is usually available from: (Check ONE)
   - (i) in-plant. . . . . ______
   - (ii) local university or college . . . . ______
   - (iii) local engineering firm. . . . . ______
   - (iv) state agencies. . . . . ______
   - (v) others, please specify: ______________________________

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* Please convert all part-time employees into number of full-time equivalent employees. Count employees directly involved with wastewater plant only.

TREATMENT EQUIPMENT LIST*

TREATMENT PROCESS NO. PROCESS NAME	VITAL EQUIPMENT	EQUIPMENT TYPE
01 Raw Sewage Pumping	Raw Sewage Pump (& Motor)	Centrifugal/Constant Speed Centrifugal/Variable Speed
02 Bar Screening	Bar Screen	Mechanically Cleaned
04 Comminution	Comminutor	Comminutor Barminutor
05 Grit Removal	Grit Collector	Flight-type Collector Centerdrive Scraper Collector
	Grit Conveyor	Airlift Pump Screw Conveyor Bucket Conveyor
	Grit Separator	Cyclone Separator Cyclone Separator/Washer
06 Scum Removal	Scum Removal Equip.	Please specify type.
07 Flow Equalization	Mechanical Aerator (& Motor)	Fixed-mount Impeller/Surface Fixed-mount Turbine/Submerg. Floating Aerator
	Air Supply Equip.	Centrifugal Blower Positive Displacement Blower Centrifugal Blower Porous Cloth Diffuser Porous Ceramic Diffuser Sparger/Nozzle Flexible Diaphragm
08 Preaeration	Aeration Equip.	SEE PROCESS NO. 07
09 Primary Sedimentation	Clarifier Equip.	Centerdrive/Scraper Collector Centerdrive/Suction Collector Rim-Drive/Scraper Collector Rim-Drive/Suction Collector Rect. Tank Scraper Collector Rect. Tank Suction Collector
	Pump, Primary Sludge (& Motor)	Centrifugal Pump Screw Pump Airlift Pump Progressing Cavity Pump Piston Pump Plunger Pump
10 to 13 Trickling Filter	Pump, Lifting	SEE PROCESS NO. 09, PUMP.
	Revolv. Distributor	Revolving Distributor
14 to 18 Activated Sludge	Aeration Equip.	SEE PROCESS NO. 07
	Oxygen Generator	Cryogenic Pressure-Swing Adsorpt.(PSA)
19 Bio-Disc	Rotating Bio-Disc Unit	-
20 Oxidation Ditch	Brush Aerator	Please specify type.
22 Secondary Clarification	Clarifier Equip.	SEE PROCESS NO. 09, CLARIF.
	Pump, Recirculation	" , PUMP.
	Pump, Return Sludge	" , " .
	Pump, Waste Sludge	" , " .
23 to 24 Biol. Nitrification	Aeration Equip.	SEE PROCESS NO. 07
	Chemical Feeder	SEE PROCESS NO. 34, CHEM.
25 Denitrification	Mechanical Mixer	SEE PROCESS NO. 34, MIX.
	Chemical Feeder	" , CHEM.
R Tertiary Clarification	Clarifier Equip.	SEE PROCESS NO. 09, CLARIF.
	Pump, Return Sludge	" , PUMP.
	Pump, Waste Sludge	" , " .
26 Post Aeration	Aeration Equip.	SEE PROCESS NO. 07
27 to 28 Microstraining	Microstrainer	Please specify type.
29 to 30 Filtration	Filtration Equip.	Sand Filter Mixed-media Filter
34 to 37, 40 to 46 Chemical Treatment	Chemical Feeder	Dry-Volum./Conveyor Screw Dry-Volum./Rotating Disk Dry-Volum./Oscillat. Hopper Dry-Volum./Vibrat. Trough Dry-Gravimetric/Weighing Belt Dry-Gravimetric/Wt. Container Wet/Constant Head Orifice Wet/Metering Pump Lime Slaker
	Mechanical Mixer	Flash Mixer/Turbine Flash Mixer/Impeller Flash Mixer/Paddle Flocculator/Vert. Paddle Flocculator/Horiz. Paddle
48 Bk-pt Chlorination	Bk-pt Chlorin. Equip.	Break-point Chlorin. Unit
49 Ammonia Stripping	Stripping Tower	Cross-current Strip. Tower Counter-current Strip. Tower
51 to 53 Disinfection	Chlorination Equip.	Chlorin /Porous Diffuser Chlorin /Aspirator Chlorin /V-Notch Hypochlorin./Constant Head Hypochlorin./Metering Pump Hypochlorin./Dry Feed
	Ozonation Equip.	Ozonation Unit
58 Aerated Lagoon	Aeration Equip.	SEE PROCESS NO. 07
65 to 66 Aerobic Digestion	Aeration Equip.	SEE PROCESS NO. 07
	Oxygen Generator	SEE PROCESS NO. 14
	Pump, Digested Sludge	SEE PROCESS NO. 09, PUMP.
68 Anaerobic Digestion	Gas Circulation Equip.	Gas Circulation Unit
	Heating Equip.	Heating Unit
	Gas Safety Equip.	Gas Safety Equip. unit
	Pump, Digested Sludge	SEE PROCESS NO. 09, PUMP.
	Pump, Sludge Feed	" , " .
70 Heat Treatment	Heat Treatment Equip.	Heat Treatment Unit
72 Lime Stabilization	Lime Feeder	SEE PROCESS NO. 34, CHEM.
73 Wet Air Oxidation	Wet Air Oxidat. Equip.	Wet Air Oxidation Unit
79 to 80 Sludge Thickening	Sludge Thicken. Equip.	Gravity Thickener/Scraper Dissolv. Air Flotation Unit
	Pump, Thickener Sludge	SEE PROCESS NO. 09, PUMP.
	Pump, Return Flow	" , " .
75 to 77 Sludge Dewatering	Sludge Dewater. Equip.	Vacuum Filter/Drum-type Vacuum Filter/Coil-type Vacuum Filter/Belt-type Centrifuge/Solid Bowl Centrifuge/Basket Filter Press
	Chemical Feeder	SEE PROCESS NO. 34, CHEM.
	Pump, Return Flow	SEE PROCESS NO. 09, PUMP.
81 to 84 Incineration	Incinerator	Multiple Hearth Fluidized Bed Rotary Kiln

*This list was compiled to assist you in identifying the proper equipment type. The types of equipment listed are limited, please feel free to fill in types not listed here.

II. Please supply wastewater equipment information of the listed treatment processes: Plant No.

	Treatment** NO./Process	Equipment Type Description (Please see Treatment Equipment List)	Manufacturer	NO. of Units	Breakdowns*		Operation PER Unit		
					Total NO. of	Ave. Duration Day - Hrs.	Ave. Hrs. Per Day	Ave. Days Per Week	Date Installed Mo. - Yr.
Ex.	02 Bar Screen	Mech. Cleaned	"Enviro"	2	10	3 days	24	7	6-75

*Breakdowns occur when equipment cannot fulfill its required functions without repair or corrective maintenance.

**If treatment process information on your plant is inaccurate, please feel free to correct mistake(s).

II. Wastewater equipment information continued.   Plant No.

				Breakdowns*		Operation PER Unit		
Treatment** NO./Process	Equipment Type Description (Please see Treatment Equipment List)	Manufacturer	NO. of Units	Total NO. of	Ave. Duration Day - Hrs.	Ave. Hrs. Per Day	Ave. Days Per Week	Date Installed Mo. - Yr.

*Breakdowns occur when equipment cannot fulfill its required functions without repair or corrective maintenance.

**If treatment process information on your plant is inaccurate, please feel free to correct mistake(s).

APPENDIX B

MECHANICAL EQUIPMENT CODES FOR WASTEWATER TREATMENT PLANTS

MECHANICAL EQUIPMENT CODES FOR WASTEWATER TREATMENT PLANTS

TREATMENT PROCESS Code/Process	VITAL EQUIPMENT Code/Equipment	EQUIPMENT TYPE Code/Type of Equipment
01 Raw Sewage Pumping	1 Raw Sewage Pump (& Motor)	01 Centrifugal/Constant Speed (gpm)
		02 Centrifugal/Variable Speed (gpm)
		03 Screw (gpm)
		04 Plunger (gpm)
		05 Progressing Cavity (gpm)
		06 Submersible (gpm)
02 Bar Screening	1 Bar Screen	01 Mechanically Cleaned (ft, wide)
		02 Hydrosieve (MGD)
		03 Climber Screen (MGD)
03 Grit Removal	1 Grit Collector	01 Flight-type Collector (ft X ft)
		02 Centerdrive Scraper Collector (ft, dia.)
		03 Detritor (ft X ft)
	2 Grit Conveyor	01 Airlift Pump (gpm)
		02 Screw Conveyor (HP)
		03 Bucket Conveyor (HP)
	3 Grit Separator	01 Cyclone Separator (gpm)
		02 Cyclone Separator/Washer (gpm)
		03 Screw Washer (gpm)
	5 Grit Pump	01 Centrifugal (gpm)
	6 Grit Aeration	01 Centrifugal Blower (gpm)
		02 Positive Displacement Blower (gpm)
04 Comminution	1 Comminutor	01 Comminutor (MGD)
		02 Barminutor (MGD)
07 Flow Equalization	1 Mechanical Aerator (& Motor)	01 Fixed-mounted Impeller/Surface (HP)
		02 Fixed-mounted Turbine/Submerged (HP)
		03 Floating Aerator (HP)
		04 Rotor (HP)
	2 Air Supply Equipment	01 Centrifugal Blower (cfm)
		02 Positive Displacement Blower (cfm)
	3 Air Diffuser	01 Porous Cloth Diffuser
		02 Porous Ceramic Diffuser
		03 Sparger/Nozzle
		04 Flexible Diaphragm
		05 Duosparger
		06 Inka System
		07 Swing Arm Diffuser
	4 Pumping	01 Centrifugal (gpm)
08 Preaeration	Aeration Equipment	SEE PROCESS 07
09 Primary Clarification	1 Clarifier Equipment	01 Centerdrive/Scraper Collector (ft, dia.)
		02 Centerdrive/Suction Collector (ft, dia.)
		03 Rimdrive/Scraper Collector (ft, dia.)
		04 Rimdrive/Suction Collector(ft, dia.)
		05 Rectangular Tank Scraper Collector (ft X ft)
		06 Rectangular Tank Suction Collector (ft X ft)
		07 Rectangular/Travelling Bridge (ft X ft)
		08 Square Tank/Scraper Collector (ft, side)
		09 Square Tank/Rimdrive-Scraper (ft, side)
		10 Square Tank/Suction Collector (ft, side)
	2 Pump, Primary Sludge (& Motor)	01 Centrifugal (gpm)
		02 Screw (gpm)
		03 Airlift (gpm)
		04 Piston (gpm)
		05 Plunger (gpm)
		06 Positive Displacement (gpm)
		07 Progressing Cavity (gpm)
		08 Diaphragm (gpm)
		09 Submersible (gpm)
10 Trickling Filter /Rock Media	1 Distributor	01 Revolving (ft, each arm)
		02 Stationary
	2 Pump, Lifting	SEE PROCESS 09, PUMP

TREATMENT PROCESS	VITAL EQUIPMENT	EQUIPMENT TYPE
Code/Process	Code/Equipment	Code/Type of Equipment
11 Trickling Filter /Plastic Media	SEE PROCESS 10	
12 Trickling Filter /Redwood Media	SEE PROCESS 10	
14 Activated Sludge /Conventional	SEE PROCESS 07	
15 Activated Sludge /High-Rate	SEE PROCESS 07	
16 Activated Sludge /Contact-Stabilization	SEE PROCESS 07	
17 Activated Sludge /Extended Aeration	SEE PROCESS 07	
18 Activated Sludge /Pure Oxygen	SEE PROCESS 07	
	4 Oxygen Generator	01 Cryogenic (ton/day)
		02 Pressure-Swing Adsorption (PSA)(ton/day)
19 Bio-Disc	1 Bio-Disc	01 Bio-Disc Unit (HP)
20 Oxidation Ditch	1 Aerator	01 Brush Aerator (HP)
		02 Disk Aerator (HP)
22 Secondary Clarification	1 Clarifier Equipment	SEE PROCESS 09, CLARIFIER EQUIP.
	2 Pump, Recirculation	SEE PROCESS 09, PUMP
	3 Pump, Return Sludge	SEE PROCESS 09, PUMP
	4 Pump, Waste Sludge	SEE PROCESS 09, PUMP
23 Biological Nitrification /Separate Stage	SEE PROCESS 07	
	4 Chemical Feeder	01 Dry Volum./Conveyor Screw (lb/hr)
		02 Dry Volum./Rotating Disk (lb/hr)
		03 Dry volum./Oscillat. Hopper (lb/hr)
		04 Dry Volum./Vibrat. Trough (lb/hr)
		05 Dry Gravim./Weighing Belt (lb/hr)
		06 Dry Gravim./Wt. Container (lb/hr)
		07 Wet/Constant Head Orifice (gpm)
		08 Wet/Metering Pump (gpm)
		09 Lime Slaker (lb/hr)
		PUMP, SEE PROCESS 09, 11, 12, 13, etc.
	5 Mechanical Mixer	01 Flash Mixer/Turbine (HP)
		02 Flash Mixer/Impeller (HP)
		03 Flash Mixer/Paddle (HP)
		04 Flocculator/Vert. Paddle (HP)
		05 Flocculator/Horiz. Paddle (HP)
24 Biological Nitrification/Combined	SEE PROCESS 23	
25 Biological Denitrification	SEE PROCESS 23	
26 Post Aeration	SEE PROCESS 07	
27 Microstraining /Primary	1 Microstrainer	01 Microstrainer (gpm)
28 Microstraining /Secondary	1 Microstrainer	01 Microstrainer (gpm)
29 Filtration/Sand	1 Filter Unit	01 Sand Filter Unit (ft^2, surface area)
30 Filtration/Mixed-Media	1 Filter Unit	01 Mixed-media Filter Unit (ft^2, surface area)

TREATMENT PROCESS Code/Process	VITAL EQUIPMENT Code/Equipment	EQUIPMENT TYPE Code/Type of Equipment
34 2-Stage Lime/Raw	SEE PROCESS 23	
35 2-Stage Lime/Tertiary	SEE PROCESS 23	
36 1-Stage Lime/Raw	SEE PROCESS 23	
37 1-Stage Lime/Tertiary	SEE PROCESS 23	
40 Alum Addition/Primary	SEE PROCESS 23	
41 Alum Addition/Secondary	SEE PROCESS 23	
42 Alum Addition /Tertiary-Separate	SEE PROCESS 23	
43 Ferric Chloride/Primary	SEE PROCESS 23	
44 Ferric Chloride /Secondary	SEE PROCESS 23	
45 Ferric Chloride /Tertiary-Separate	SEE PROCESS 23	
46 Other Chemical Addition	SEE PROCESS 23	
48 Break-pt Chlorination	1 Chlorination Equip.	01 Break-point Chlorin. Unit (lb/day)
49 Ammonia Stripping	1 Stripping Tower	01 Cross-Current Strip. Tower (HP, fan)
		02 Counter-Current Strip. Tower (HP, fan)
51 Disinfection /Chlorine	1 Chlorination Equipment	01 Chlorinator/Porous Diffuser (lb/day)
		02 Chlorinator/Aspirator (lb/day)
		03 Chlorinator/V-Notch (lb/day)
		04 Hypochlorinator/Constant Head (gpm)
		05 Hypochlorinator/Metering Pump (gpm)
		06 Hypochlorinator/Dry Feed (lb/day)
		07 Evaporator (lb/day)
52 Disinfection/Ozone	1 Ozonation Equipment	01 Ozonation Unit (lb/day)
55 Tertiary Clarification	SEE PROCESS 22	
58 Aerated Lagoon	SEE PROCESS 07	
65 Aerobic Digestion/Air	SEE PROCESS 07	
	4 Pump, Digested Sludge	SEE PROCESS 09, PUMP
	5 Pump, Recirculation	SEE PROCESS 09, PUMP
66 Aerobic Digestion/Oxygen	SEE PROCESS 07	
	4 Pump, Digested Sludge	SEE PROCESS 09, PUMP
	5 Pump, Recirculation	SEE PROCESS 09. PUMP
	6 Oxygen Generator	01 Cryogenic (ton/day)
		02 Pressure-Swing Adsorption (PSA)(ton/day)
68 Anaerobic Digestion	1 Digester Equipment	01 Gas Circulation Equipment (cfm)
		02 Gas Compressor (cfm)
		03 Gas Meter (cfm)
		04 Gas Safety Equipment
		05 Heating Equipment (BTU X 1,000)
		06 Sludge Recirculation (gpm)
		07 Mixers (HP)
		08 Floating Cover (ft,dia.)
	2 Pump, Digest. Sludge	SEE PROCESS 09, PUMP
	3 Pump, Sludge Feed	SEE PROCESS 09, PUMP
70 Heat Treatment	1 Heat Treat. Equip.	01 Heat Treatment Equipment (ton/day)
72 Lime Stabilization	SEE PROCESS 23	
73 Wet Air Oxidation	1 Wet Air Oxidation System	01 Wet Air Oxidation System (ton/day)

TREATMENT PROCESS	VITAL EQUIPMENT	EQUIPMENT TYPE
Code/Process	Code/Equipment	Code/Type of Equipment
75 Sludge Dewatering /Vacuum Filter	1 Vacuum Filter Unit	01 Drum-Type (ft^2, filter area)
		02 Coil-Type (ft^2, filter area)
		03 Belt-Type (ft^2, filter area)
		04 Belt-Press (ft^2, filter area)
	2 Pump, Return Flow	SEE PROCESS 09, PUMP
	3 Pump, Sludge Feed	SEE PROCESS 09, PUMP
	4 Chemical Feeder	SEE PROCESS 23, CHEMICAL FEEDER
76 Sludge Dewatering /Centrifuge	1 Centrifuge Unit	01 Solid Bowl (gpm)
		02 Basket (gpm)
		03 Disc-Nozzle (gpm)
	SEE PROCESS 75	
77 Sludge Dewatering /Filter Press	1 Filter Press Unit	01 Filter Press Unit (HP)
	SEE PROCESS 75	
79 Sludge Thickening /Gravity	1 Gravity Thickener	01 Thickener Scraper (ft. dia.)
	2 Pump, Thick. Sludge	SEE PROCESS 09, PUMP
	3 Pump, Return Flow	SEE PROCESS 09, PUMP
80 Sludge Thickening /Air Flotation	1 Dissolved Air Flotation Unit	01 Dissolved Air Flotation Thickener (ft, dia.)
	SEE PROCESS 79	
	4 Chemical Feeder	SEE PROCESS 23, CHEMICAL FEEDER
81 Incineration /Multi-Hearth	1 Multiple Hearth Incinerator	01 Multiple Hearth Incinerator (ton/day)
82 Incineration /Fluidized-Bed	1 Fluidized-Bed Incinerator	01 Fluidized-Bed Incinerator (ton/day)
83 Incineration /Rotary Kiln	1 Rotary Kiln Incinerator	01 Rotary Kiln Incinerator (ton/day)

APPENDIX C

MECHANICAL EQUIPMENT MANUFACTURERS' CODES

MECHANICAL EQUIPMENT MANUFACTURERS' CODES

000	Not Named
043	Advance
001	Airopump
002	Allis-Chalmers
003	American
004	American Schack
005	American Well Works
006	Aqua-Aerobics
007	Aqua-Jet
008	Ashbrook-Simon-Hantley
009	Aurora Pump (Gen. Signal)
010	Automatic Pump
011	Autotrol
012	Louis Allis
013	American Standard
014	ATARA
015	Aqua
016	Adams, R.P
017	Air Mae
021	Bacharca
022	Badger
023	Baker, R. H.
024	Bauer, C. E.
025	Bethlehem
026	BIF (Gen. Signal)
027	Big Wheel
028	Bird Machine
029	BSP
030	Buffalo
031	Byron-Jackson (Borg-Warner)
032	Beloit
033	Bryant
034	Builders
035	Berkley
039	Chemtron
040	Carter, Stuart
041	Calgon (Merck)
042	Can-Tex (Hersco)
043	Capitol Control (Advance)
044	Carborundum
045	Carter, R. B.
046	Carver
047	Cascade
048	Case-Cotton/Hanson
049	Chemfix
050	Chemix
051	Chicago
052	Chicago Bridge & Iron
053	Chicago Pump
054	Clever-Brooks
055	Clow
056	Combustion Engineering
057	Copeland System
058	Cord
059	Cornell
060	Crane
061	Cyclone
062	Cyclotherm
063	Chemcon
064	Continental
065	Crowley Company
066	Crown
067	Coffman
069	Coscoe
070	Chemineer
071	Davco
072	Disposable Waste System
073	DeLaval
074	Deming
075	Dorr-Oliver
076	Dover
077	Draco
078	Dresser
079	Durco
080	Durham Bush
081	Duosparger
082	DCE Vokes
083	Dixie
084	Dorrco
085	Dayton-Dowd
090	E.P.I.
091	E. & I.
092	Eimco
093	Emerson
094	Engelhard
095	Envirex
096	Enviro-quip
097	Environmental Products
098	Environmental Elements (Koppers)
099	Envirotech
100	Escher-Wyss
101	Edward & Jones
102	Enterprise
109	Ferro Filter
110	Fairchild
111	Fairbanks-Morse(Colt)
112	Falk
113	Fischer-Porter
114	Fluid Bed
115	Flygt
116	FMC
117	Ford
118	Federal
119	Flowmatcher
120	Fairfield

121	Gardner-Denver
122	General Dynamics
123	General Electric
124	General Filter
125	Gorman-Rupp
126	Goulds Pumps
127	Grotty
128	Goodrich, B. F.
129	Hoesch
130	Haight
131	Hardinge (Koppers)
132	Harleroi
133	Healy Ruff
134	Herding
135	Hinde Engineering
136	Hoffman
137	Honeywell
138	Hydro-O-Matic
139	Hytor
140	Hills McCanna
141	Infilco-Degremont
142	Ingersoll-Rand
143	ITT Marlow
144	Ideal
145	Itdisco
146	Interface
147	IDI
151	Jeffrey
152	Johnson Pump
153	Johnston Pump
154	Joy
155	John Deer
156	Joos Equipment Co.
157	Jaccuzi
158	Jones Atwood
161	Kason
162	Keene
163	Komline-Sanderson
164	Krogh
165	Kohler
166	Krebs
167	KSB
168	Kewaunee
171	L.E.F./Midland Pump
172	Lakeside
173	Lamment-Mann (Lambert-Mann)
174	Lamson (Diebold)
175	Lapp
176	Leopold
177	Lightning
178	Lincoln-Multiguard
179	Link-Belt
180	Liquiflo
181	Layne (Central)
182	Limitorque
183	Lanford Engineering
184	Layne Bowler
191	Midland Pump
192	Milton-Roy
193	Mixing Equipment
194	Moyno (Robbins & Myers)
195	Morris Pump
196	M.D. Pneumatic
197	Mixco
198	Montgomery Engrs
201	Nalco
202	Nash
203	National Hydro
204	Neptune
205	Nicols
206	Norton
207	NMI
211	Omega
212	Ozark-Mahoning
221	P & H
222	P.S.I.
223	Pacific Flush Tank
224	Pacific Pump
225	Paco
226	Parkson
227	Passovant
228	Peabody-Barnes
229	Peabody-Wells
230	Pearl-lite
231	Peerless Pump
232	Pennwalt
233	Pentech-Houdalle
234	Perb
235	Permutit (Sybron)
236	Perth (Rex)
237	Philadelphia Gear
238	Prab
239	Process Engineering
240	Pulsafeeder
241	P & D Manufacturer
242	Purification Plants, Inc.
243	Patterson Pump Company
244	Penn
245	Phil. Mixer, Inc.
246	Pottstown
247	Pittsburg Filter Co.
248	Precision
249	Palmer
250	PCI
251	Quincy
256	Roberts
257	Reeves
259	Riverside Engineering

260	Roper Alz Industry
261	Reliance
262	Rex (Perth)
263	Rex-Chainbelt
264	Rockwell
265	Rooter
266	Roots
267	Roots-Connerville
268	Roots-Dresser
269	Rexnord
270	Richards of Rockford
271	Sanitare
272	Schramm
273	Schutte-Corting
274	Sharples (Pennwalt)
275	Sherpard-Niles
276	Smith & Loveless (Ecodyne)
277	Sparling
278	Spencer
279	Stephens-Anderson
280	Sterling
281	Suburbia
282	Sutorbuilt
283	SFM
284	Sludgemaster
285	Sihi
286	Sumo
291	Teel
292	Tutthill
293	Turbitrol
294	Torin
295	Tomco
296	Tonka
301	U.S. Motor
302	U.S. Ozonator
303	U.S. Syncrogear
304	Union Carbide
305	U.S. Electric
306	U.S. Filter
311	Varec
312	Vortair
313	Vortex
314	Von Ruden
315	Vaughn
316	Vari Drive
321	Walker Process (Chicago Bridge & Iron)
322	Wallace & Tiernan (Pennwalt)
323	Waukesha
324	Wemco (Envirotech)
325	Westinghouse
326	Westmont
327	Wheeler
328	Whil-Power
329	Whisper-Air (Roots-Dresser)
330	Williams
331	Win-Smith
332	Worthington
333	Weil-McLain
334	Wright
335	Wellsbach
336	Winkle
337	Weinman
338	White Superior
339	Warren
341	Yeomans Bros.
351	Zimpro
352	Zurick
353	Zurn
370	Galliger
371	Glenflield Kennedy
380	Hungerford & Terry
410	Stuart

APPENDIX D

RELIABILITY DATA BASE FOR MUNICIPAL WWTPS

AN EXPLANATORY NOTE ON RELIABILITY DATA

PET	Equipment Code: Process Equipment Type. See Appendix B for complete listing of equipment and codes.
NO. OF PLANTS	Number of plants with data for the computation of the MTBF value.
NO. OF UNITS	Number of units of equipment with data for the computation of the MTBF value.
TOTAL OPERATING HOURS	Total operating hours accumulated by all the equipment units with the same PET code.
MTBF (HR)	Mean Time Between Failures. See Data Analysis and Explanation of Terms section for algorithm for this value.
90% CONFIDENCE LIMITS (HR) LOWER UPPER	This is the two-side confidence limits within which one can be 90% confident that the true MTBF value will lie.
MDT (HR)	Mean Downtime. See Data Analysis and Explanation of Terms section for algorithm for this value.
BEST THREE MANUFACTURERS	The three manufacturers having the highest MTBF values. The MTBF value of equipment having the same PET code and by the same manufacturer was first computed. The MTBF values for different manufacturers are then compared and the best three chosen. The best is listed first. See Appendix C for listing of manufacturer's code.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : RAW SEWAGE PUMPING

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
01100	33	143	7551787	116058	39075	193042	120	045	143	009
01101	73	237	13485602	64942	45566	84318	276	152	111	012
01102	90	248	16830346	109026	68319	149732	293	327	195	116
01103	9	28	1148056	50107	5151	95063	272	116	032	179
01104	1	2	61152	16653	.	.	24	143	.	.

PROCESS : BAR SCREENING

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
02100	28	42	4514692	215830	147367	284292	114	162	321	052
02101	120	206	11858630	35217	26739	43696	201	227	000	075

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : GRIT REMOVAL

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	90% CONFIDENCE LIMITS(HRS.) UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
03100	30	48	2667760	48837	27240	70434	381	075	262	000
03101	28	51	1849389	23814	11967	35661	84	263	321	000
03102	37	51	5359224	66691	46892	86489	95	075	095	000
03103	5	7	662116	146704	55021	238387	40	321	075	.
03200	15	21	805497	9165	5157	13172	940	238	075	095
03201	18	29	2087592	64222	15147	113298	119	116	265	053
03202	55	73	3782068	27832	16767	38897	171	324	179	321
03203	29	52	1167344	15494	8691	22297	106	194	241	279
03300	12	22	1377801	62932	21755	104109	600	262	273	239
03301	30	44	2837844	26921	16972	36870	234	092	324	075
03302	23	30	821747	26108	15004	37213	35	324	228	179
03303	7	7	199602	12330	8273	16387	26	229	321	095
03500	16	31	1266408	25399	7658	43139	56	324	075	095
03501	10	15	657536	456 4	5697	85511	39	143	324	075
03600	10	19	826878	52249	4063	100434	336	151	266	282

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : COMMINUTION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
04100	3	5	625352	86625	44483	128768	344	053	276	332
04101	110	186	15587815	73775	59710	87840	497	179	053	051
04102	33	48	5116869	27947	19242	36651	634	332	000	053

PROCESS : FLOW EQUALIZATION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
07100	1	2	160160	59894	.	.	24	075	.	.
07101	2	2	119392	16590	-6670	39849	90	092	141	.
07103	2	10	646464	37429	17324	57535	1440	141	006	.
07200	1	2	2427	192	.	.	6	154	.	.
07201	6	27	1346800	122260	40807	203713	717	000	002	136
07202	2	3	112112	34190	31689	36690	24	095	282	.
07300	1	1	9464	13654	.	.	.	006	.	.
07301	1	1	52416	75621	.	.	.	000	.	.
07303	2	2	194376	140213	116889	163537	.	321	053	.
07304	1	1	46592	93	.	.	24	092	.	.
07401	1	4	14647	5477	.	.	720	332	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : PREAERATION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
08103	1	3	34944	13068	.	.	24	229	.	.
08200	2	4	302848	28050	21043	35056	96	282	278	.
08201	7	14	926016	89485	8172	170798	94	136	266	.
08202	6	12	637260	68267	13097	123436	210	282	121	267
08300	1	1	128856	185900	.	.	.	053	.	.
08301	1	1	84691	2855	.	.	1	053	.	.
08303	1	2	270816	161358	.	.	264	174	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : PRIMARY CLARIFICATION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
09100	23	64	6390852	90161	44127	136196	559	141	179	321
09101	111	223	26124947	132627	110374	154880	239	012	179	123
09102	2	7	1058512	116683	88852	144513	2196	075	321	.
09103	2	14	2960048	298874	87407	510340	108	262	075	.
09105	85	308	31309395	147609	102310	192908	230	163	092	263
09107	2	7	281736	11695	7232	16158	182	095	321	.
09108	1	2	198016	42393	.	.	96	092	.	.
09200	8	26	658961	21277	11675	30878	66	143	045	075
09201	27	99	3638947	56079	29143	83015	118	195	143	324
09202	4	10	142480	23324	-835	47484	48	194	.	.
09203	1	6	143520	85513	.	.	2160	001	.	.
09204	32	68	2399380	31140	11316	50963	61	075	163	228
09205	21	52	556933	3823	2199	5447	102	163	045	000
09207	16	47	830769	15819	5295	26343	37	194	000	228
09208	4	8	106349	1929	923	2936	52	075	143	125

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : TRICKLING FILTER/ROCK MEDIA

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
10100	10	23	2845752	159604	91044	228165	147	116	124	075
10101	78	165	25833548	199939	161290	238589	706	077	099	005
10102	2	2	457912	92623	-28643	213890	72	095	223	.
10200	17	59	7200180	180009	119684	240334	634	332	111	095
10201	20	60	7539575	235475	70565	400386	744	341	051	047
10202	1	2	75712	11352	.	.	2	227	.	.

PROCESS : TRICKLING FILTER/PLASTIC MEDIA

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
11100	3	4	156520	59710	12170	107250	720	005	052	204
11101	6	12	829192	140501	69552	211449	360	321	092	099
11102	2	3	244608	176448	31320	321576	.	128	204	.
11200	2	5	95368	29600	10912	48289	72	115	002	.
11201	5	18	1934296	29672	18071	41273	359	153	002	111

PROCESS : TRICKLING FILTER/REDWOOD MEDIA

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
12101	2	4	490672	78116	18115	138117	84	075	321	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

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PROCESS : ACTIVATED SLUDGE/CONVENTIONAL

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
14100	15	89	5965232	160527	84866	236188	51	000	092	262
14101	30	244	14095900	208344	138690	277998	708	092	321	055
14102	8	57	2117024	81317	19875	142759	151	177	002	303
14103	8	52	3085264	157626	69407	245844	2029	095	099	092
14200	16	52	3709212	121290	64238	178342	206	053	267	321
14201	41	138	7293494	89235	59169	119300	165	329	267	266
14202	21	74	4913116	64536	31990	97083	615	142	282	267
14300	15	46	2248168	184524	81902	287146	248	095	051	000
14301	5	12	679952	181698	155	363241	24	053	000	095
14302	2	5	152152	109755	41510	178000	.	206	000	.
14303	11	19	1292746	103474	22130	184818	108	000	053	271
14304	3	5	554008	73490	25325	121655	72	000	321	092
14305	1	1	83720	49882	.	.	4320	081	.	.
14306	2	8	1124032	18277	-6991	43546	120	075	.	.
14307	2	3	268632	193778	123805	263750	.	116	000	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : ACTIVATED SLUDGE/HIGH-RATE

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
15100	1	14	500864	136399	.	.	336	227	.	.
15101	1	1	8736	12603	.	.	.	229	.	.
15102	1	7	61152	88224	.	.	.	229	.	.

PROCESS : ACTIVATED SLUDGE/CONTACT-STABILIZATION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
16100	5	17	1392664	246668	22754	470582	1064	177	116	096
16101	3	14	692510	93370	-31514	218253	171	075	237	177
16102	1	4	381472	550349	.	.	.	177	.	.
16200	4	16	940576	87250	-12446	186947	129	136	278	.
16201	8	26	1738646	70179	33827	106531	741	266	136	278
16202	3	17	1330056	81339	50322	112356	504	282	266	.
16300	3	11	419328	201655	115338	287972	.	271	136	096

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : ACTIVATED SLUDGE/EXTENDED AERATION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
17100	2	10	206752	149141	-20176	318457	.	097	053	.
17101	3	13	801892	112544	16519	208568	2523	092	301	325
17102	1	8	1013376	275969	.	.	24	177	.	.
17103	2	34	1030363	17660	-2700	38020	48	006	229	.
17201	3	9	271570	21518	7252	35784	176	136	266	078
17202	1	4	126672	47371	.	.	336	282	.	.
17301	1	2	342160	8626	.	.	1	053	.	.

PROCESS : ACTIVATED SLUDGE/PURE OXYGEN

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
18100	1	12	314496	453723	.	.	.	000	.	.
18101	2	18	707616	43045	-2077	88168	64	197	191	.
18102	1	9	163800	236314	.	.	.	304	.	.
18200	1	1	26208	3929	.	.	1	244	.	.
18401	2	2	22568	13413	-7715	34541	6	304	.	.
18402	6	9	497224	76751	600	152901	61	321	304	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : BIO-DISC

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
19101	6	88	1274000	56193	33439	78946	1008	011	.	.

PROCESS : OXIDATION DITCH

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
20101	10	34	1977976	48363	26881	69846	212	172	227	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : SECONDARY CLARIFICATION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
22100	48	117	9190272	103589	81791	125386	322	112	262	095
22101	94	211	21813792	159112	126214	192011	298	341	077	075
22102	59	156	9901892	50722	37155	64289	227	099	162	075
22103	3	10	1414504	91934	-9266	193134	64	341	092	141
22105	47	178	13139198	155497	109818	201177	273	179	005	263
22106	2	4	33488	3024	2359	3690	27	053	176	.
22108	2	4	211120	18617	-8206	45440	60	092	098	.
22200	21	63	5162369	98879	60847	136910	151	051	163	301
22201	26	82	6112245	106497	35687	177307	93	066	053	002
22202	1	3	7280	10503	.	.	.	121	.	.
22203	2	7	559104	64501	41327	87675	24	321	095	.
22204	1	1	5200	1945	.	.	144	075	.	.
22207	1	2	936	1350	.	.	.	194	.	.
22300	58	168	9859157	59509	44617	74400	461	163	301	243
22301	34	107	4684216	76285	38829	113742	358	002	125	057
22302	5	14	380744	23447	2606	44288	22	227	262	116
22303	4	17	915824	192772	29743	355801	2	321	096	.
22400	32	66	3585647	54044	27237	80852	118	301	337	051
22401	21	44	1686408	32002	310	63693	320	225	332	195
22402	1	2	11648	4356	.		14	194	.	.
22403	1	1	8060	11628	.	.	.	276	.	.
22404	5	10	280228	19326	4640	34013	43	143	045	.
22405	3	6	83932	9679	1587	17772	85	163	143	.
22406	2	3	109473	26452	-12804	65706	48	194	143	.
22407	4	11	112953	28306	12451	44160	26	194	111	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : BIOLOGICAL NITRIFICATION/SEPARATE STAG

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
23200	1	1	52416	75621	.	.	.	321	.	.

PROCESS : BIOLOGICAL NITRIFICATION/COMBINED

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
24100	2	54	947856	41287	303	82272	3060	011	008	.
24102	1	8	17472	25207	.	.	.	237	.	.
24200	1	6	2044224	2949E3	.	.	.	053	.	.
24300	1	4	69888	100827	.	.	.	321	.	.
24408	1	4	2912	2101	-1355	5556	.	322	240	.

PROCESS : BIOLOGICAL DENITRIFICATION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
25100	1	2	14560	21006	.	.	.	099	.	.
25101	1	12	61152	16653	.	.	8	000	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : POST AERATION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
26101	1	4	107744	23067	.	.	5	312	325	.
26102	1	1	2340	875	.	.	240	191	.	.
26103	1	2	209664	124923	.	.	120	341	.	.
26201	1	1	20384	2351	.	.	8	136	.	.
26202	1	2	168896	100632	.	.	96	267	.	.

PROCESS : MICROSTRAINING/PRIMARY

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
27101	1	2	116480	31721	.	.	720	321	.	.

PROCESS : MICROSTRAINING/SECONDARY

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
28101	1	3	91728	24980	.	.	5760	095	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : FILTRATION/SAND

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
29101	11	36	1277640	24949	9496	40402	143	204	000	179

PROCESS : FILTRATION/MIXED-MEDIA

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
30101	24	95	4318964	120358	75721	164995	444	276	000	204

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : 2-STAGE LIME/RAW

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
34401	1	3	97500	36461	.	.	8	026	.	.
34404	1	1	52416	19602	.	.	2	041	.	.
34408	3	14	500760	24571	11134	38008	10	194	322	192

PROCESS : 2-STAGE LIME/TERTIARY

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
35408	2	4	64792	46738	11319	82156	.	146	194	.
35501	1	4	15773	2057	.	.	7	045	331	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : 1-STAGE LIME/RAW

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
36400	1	7	473512	100	.	.	12	026	.	.
36409	1	2	47623	35	.	.	24	026	.	.
36411	1	3	85722	427	.	.	168	324	.	.
36504	1	2	228592	136200	.	.	4320	177	.	.

PROCESS : 1-STAGE LIME/TERTIARY

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
37400	1	1	28392	10618	.	.	72	041	.	.
37401	1	1	2808	150	.	.	96	026	.	.
37409	1	1	2808	150	.	.	96	026	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : ALUM ADDITION/PRIMARY

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
40408	2	8	31425	1525	-567	3617	336	192	240	322
40416	1	3	131040	12283	.	.	3	201	.	.
40505	1	1	416	600	.	.	.	000	.	.

PROCESS : ALUM ADDITION/SECONDARY

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
41400	1	2	61152	13092	.	.	48	240	.	.
41408	6	14	585312	39784	15244	64325	390	322	009	240
41415	1	2	112112	161744	.	.	.	000	.	.
41500	1	2	180544	260471	.	.	.	000	.	.

PROCESS : ALUM ADDITION/TERTIARY-SEPARATE

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
42408	2	10	474656	162367	12758	311977	504	065	095	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : FERRIC CHLORIDE/PRIMARY

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
43200	1	2	114296	17137	.	.	384	051	.	.
43400	1	6	457184	11242	.	.	59	075	026	.
43408	1	3	79560	5424	.	.	2	322	.	.
43418	1	1	26208	7137	.	.	4	322	.	.
43502	1	1	37128	22122	.	.	8760	177	.	.

PROCESS : FERRIC CHLORIDE/SECONDARY

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
44400	3	6	253829	22250	-7852	52351	19	079	322	.
44408	9	23	1102608	21676	11981	31370	104	240	026	175
44410	2	5	211848	16549	2588	30511	36	322	026	.
44500	1	2	7644	11028	.	.	.	177	.	.
44502	1	1	52416	75621	.	.	.	177	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : FERRIC CHLORIDE/TERTIARY-SEPARATE

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
45408	1	5	253344	68992	.	.	96	175	322	.

PROCESS : OTHER CHEMICAL ADDITION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
46400	1	2	31304	6702	.	.	12	050	.	.
46404	1	1	78624	4212	.	.	504	026	.	.
46408	6	11	516152	57602	31727	83477	84	175	194	322
46418	1	4	164528	7960	.	.	4	322	.	.
46502	1	1	88088	127085	.	.	.	177	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : DISINFECTION/CHLORINE

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
51100	69	136	9163518	65294	43662	86925	57	322	043	321
51101	28	61	4490304	57986	33531	82441	291	075	026	322
51102	15	28	2099552	68353	35419	101286	302	322	113	043
51103	97	189	13643552	64213	50649	77778	121	332	322	113
51104	2	6	454272	118393	43626	193161	4	113	.	.
51105	1	1	35672	2816	.	.	120	045	.	.
51107	6	13	671580	59324	17084	101564	230	113	322	.

PROCESS : DISINFECTION/OZONE

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
52101	1	17	309400	3014	.	.	360	304	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : TERTIARY CLARIFICATION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
55100	2	4	264992	191152	125499	256805	.	204	321	.
55101	3	11	1452360	564617	-243E3	1372E3	24	321	075	095
55102	2	8	90272	9348	4747	13949	60	096	203	.
55105	2	6	349440	18423	12812	24034	5	092	116	.
55201	2	4	12497	6189	2549	9830	2	225	002	.
55302	1	3	52416	75621	.	.	.	227	.	.
55407	2	11	214760	7494	4148	10841	267	111	045	194

PROCESS : AERATED LAGOON

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
58100	3	16	180128	86624	10182	163065	.	008	227	325
58103	2	7	369096	251451	-128E3	630837	120	123	229	.
58200	5	13	581672	50752	22023	79481	176	136	266	135
58201	1	4	384384	18598	.	.	120	135	.	.
58202	1	3	185640	110609	.	.	336	078	.	.
58402	1	2	4992	7202	.	.	.	000	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : AEROBIC DIGESTION/AIR

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
65100	9	22	1134224	136750	1018	272481	293	177	301	116
65101	6	16	809536	134142	56330	211954	4	000	321	301
65102	2	8	298688	54517	-23423	132458	520	177	141	.
65103	8	26	734552	74371	34655	114086	55	008	092	099
65200	4	10	368368	49967	32113	67820	201	136	321	.
65201	11	41	1435581	68944	39859	98029	118	266	278	136
65202	2	3	13429	4138	-1898	10174	48	174	078	.
65300	4	12	532896	87494	35038	139951	3600	096	095	.
65303	2	2	107744	35546	9360	61731	24	271	321	.
65305	1	1	78624	113431	.	.	.	321	.	.
65400	5	7	335972	17837	4590	31084	76	223	125	051
65401	2	4	47320	29202	-7419	65823	5460	009	324	.
65402	1	2	306973	182902	.	.	5460	194	.	.
65404	2	5	103879	48011	31348	64674	24	045	143	.
65407	1	2	23400	1003	-647	2652	48	171	194	.
65500	1	2	113568	2241	.	.	36	194	.	.
65501	1	2	14075	5263	.	.	240	125	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : ANAEROBIC DIGESTION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
68100	36	89	12622931	220812	163551	278074	685	077	321	053
68101	67	117	7755267	67134	38219	96049	387	223	053	137
68102	5	10	108801	14764	8146	21381	976	278	116	341
68103	6	8	760032	64784	19588	109879	151	223	266	026
68104	47	173	19435173	351241	230526	471955	54	321	075	223
68105	106	167	15678360	76921	54137	99705	208	033	324	075
68106	45	79	5425966	57078	36101	78055	148	075	195	111
68107	17	48	3287605	104302	70430	138174	878	000	223	123
68108	8	14	2444624	258859	90784	426933	2764	223	075	311
68200	26	56	4764517	41662	20196	63121	84	224	301	163
68201	18	42	3184658	75915	28307	123523	43	053	324	111
68204	9	14	111648	6431	2998	9863	64	163	045	000
68205	5	7	137644	16129	-1562	33821	91	143	163	045
68206	1	1	754	133	.	.	24	143	.	.
68207	6	11	37267	3582	1466	5698	2	194	.	.
68300	21	45	2823994	88085	10178	165992	78	321	000	301
68301	4	15	675827	96909	-105	193922	18	324	002	051
68302	1	3	23296	3493	.	.	24	194	.	.
68304	10	19	323297	11671	4634	18708	741	053	143	045
68305	7	26	368741	21219	5516	36921	26	143	045	.
68306	2	2	35217	4565	-156	9286	84	194	143	.
68307	4	10	430309	10405	462	20347	72	194	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : HEAT TREATMENT

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
70101	3	4	515424	160324	-64126	384774	98	009	053	045

PROCESS : LIME STABILIZATION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
72101	2	3	47320	3343	-1034	7719	228	026	•	•
72400	2	4	43923	4030	-878	8938	56	192	163	•
72409	2	2	26841	441	105	776	14	069	322	•
72419	1	1	633	73	•	•	2	125	•	•
72500	2	5	422240	55204	-7917	118325	24	177	•	•
72503	1	1	53430	77083	•	•	•	000	•	•
72504	1	1	16380	6126	•	•	108	177	•	•

PROCESS : WET AIR OXIDATION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
73101	7	9	247693	19913	2072	37754	66	351	•	•

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : SLUDGE DEWATERING/VACUUM FILTER

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
75100	6	11	319592	45742	3870	87614	128	227	000	092
75101	26	56	1794299	16594	6829	26359	87	092	163	142
75102	24	46	1332166	11793	7218	16368	58	163	142	.
75103	8	15	225186	3102	1249	4955	77	163	092	263
75104	3	3	21701	3250	-1519	8018	192	336	008	163
75200	2	6	85419	5018	3630	6406	38	164	194	.
75201	2	4	173888	10713	3162	18265	24	163	324	.
75202	1	2	6552	2450	.	.	18	228	.	.
75205	1	4	104832	9826	.	.	60	026	.	.
75208	1	4	425152	25506	.	.	2	075	.	.
75300	2	5	98800	10243	3036	17450	6	143	177	.
75302	7	12	103463	15807	7142	24473	66	177	000	193
75303	2	3	54340	39198	-5332	83728	.	000	177	.
75305	6	9	80856	7926	1791	14060	4	163	045	143
75307	1	2	7098	10240	.	.	.	194	.	.
75308	1	1	45760	5967	.	.	48	143	.	.
75400	8	30	644722	6375	2999	9751	133	211	227	192
75401	2	3	100464	7843	-2776	18463	180	192	026	.
75402	1	2	11856	17105	.	.	.	026	.	.
75403	1	2	10608	837	.	.	2	322	.	.
75405	2	2	49656	5219	5056	5383	24	151	163	.
75407	1	4	190736	22002	.	.	24	192	.	.
75408	9	20	206379	11086	-737	22909	156	194	000	322
75409	2	3	49101	4680	-836	10196	36	026	163	.
75410	2	3	15054	1083	-207	2372	48	192	163	.
75411	1	1	7107	10253	.	.	.	194	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : SLUDGE DEWATERING/CENTRIFUGE

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
76100	5	11	100403	1365	750	1981	112	028	274	075
76101	23	70	1770825	11890	3450	20331	501	028	100	075
76102	2	3	33904	3237	2527	3947	72	274	.	.
76103	3	8	277316	7046	-3328	17421	690	075	274	.
76300	2	4	130000	69555	11201	127909	24	191	194	.
76307	2	3	50128	6274	2619	9930	368	194	.	.
76400	1	3	31200	8497	.	.	144	194	.	.
76401	1	2	198016	285678	.	.	.	002	.	.
76402	1	2	24024	1896	.	.	48	204	.	.
76407	1	1	10400	3889	.	.	168	194	.	.
76408	2	2	30576	11941	3942	19941	8	194	.	.
76417	2	7	202384	6295	-852	13442	6	194	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : SLUDGE DEWATERING/FILTER PRESS

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
77101	13	20	250454	6870	-686	14426	224	163	222	226
77102	1	1	9360	13504	.	.	.	227	.	.
77200	1	2	18720	27007	.	.	.	292	.	.
77204	1	2	61568	7102	.	.	4	143	.	.
77207	1	2	61568	4197	.	.	48	194	.	.
77300	2	5	7852	2437	-341	5215	3	194	.	.
77302	1	3	7488	1603	.	.	1	177	.	.
77400	3	6	21259	4922	1477	8367	24	322	026	194
77401	1	1	2496	680	.	.	1	232	.	.
77403	1	1	2496	3601	.	.	.	232	.	.
77408	5	11	164407	21580	-543	43703	977	322	180	291
77409	1	2	1430	2063	.	.	.	000	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : SLUDGE THICKENING/GRAVITY

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.)		MDT (HRS.)	BEST THREE MANUFACTURERS		
					LOWER	UPPER				
79100	2	4	56368	30547	-8059	69152	120	096	115	.
79101	66	96	5846109	62341	48955	75728	526	000	075	353
79200	9	23	357223	26580	102	53059	111	163	059	000
79201	1	1	3900	5627	.	.	.	125	.	.
79202	1	2	1456	2101	.	.	.	194	.	.
79204	3	7	60788	7730	-908	16368	18	143	045	.
79205	1	4	23487	3521	.	.	168	143	045	.
79206	2	4	66300	18757	4567	32946	528	051	194	.
79207	9	27	609271	15928	2879	28978	47	194	112	059
79300	1	2	10192	3811	.	.	2	111	.	.
79301	1	1	20020	28883	.	.	.	002	.	.
79303	2	3	37856	8245	-135	16626	168	009	096	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : SLUDGE THICKENING/AIR FLOTATION

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
80100	1	2	34944	9516	.	.	336	332	.	.
80101	33	65	3455240	27342	17088	37596	94	095	262	099
80200	4	6	175721	7535	-1358	16428	1101	051	143	075
80201	2	4	39139	25449	-15618	66516	24	332	324	.
80204	2	5	17680	528	245	810	150	143	.	.
80205	1	1	52416	4138	.	.	3	045	.	.
80207	3	5	37856	3635	188	7081	732	194	228	.
80300	2	2	149240	23657	3457	43857	85	332	126	.
80301	3	7	168272	8394	7209	9578	160	243	126	053
80404	1	1	4732	6827	.	.	.	204	.	.

WASTEWATER TREATMENT MECHANICAL EQUIPMENT RELIABILITY DATA

PROCESS : INCINERATION/MULTI-HEARTH

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	90% CONFIDENCE LIMITS(HRS.) UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
81100	1	2	46488	8199	.	.	48	056	.	.
81101	17	24	1180604	6337	3617	9057	132	025	099	092

PROCESS : INCINERATION/FLUIDIZED-BED

PET	NO. OF PLANTS	NO. OF UNITS	TOTAL OPERATING HOURS	MTBF (HRS.)	90% CONFIDENCE LIMITS(HRS.) LOWER	90% CONFIDENCE LIMITS(HRS.) UPPER	MDT (HRS.)	BEST THREE MANUFACTURERS		
82101	7	8	313040	18671	108	37234	1437	075	057	.

APPENDIX E

LIST OF MUNICIPAL WASTEWATER TREATMENT PLANTS THAT CONTRIBUTED TO THE RELIABILITY DATA BASE

California

1. Morro Bay Cayucos Wastewater Treatment Facility
2. El Paso De Robles Wastewater Treatment Facility
3. El Estero Wastewater Treatment facility, Santa Barbara
4. Watsonville Wastewater Treatment Facility
5. Lompoc Wastewater Treatment Facility
6. Gilroy Wastewater Treatment Facility
7. Holister Wastewater Treatment Facility
8. South San Luis Obispo County Wastewater Treatment Facility
9. Simi Valley Wastewater Treatment Plant
10. Eastside Wastewater Reclamation Plant, San Buenaventura
11. Hill Canyon Wastewater Treatment Facility, Thousand Oaks
12. Pomona Wastewater Reclamation Plant
13. Valencia Wastewater Reclamation Plant
14. Camarillo Wastewater Treatment Facility
15. Hanford Wastewater Treatment Facility
16. Bakersfield Wastewater Treatment Facility No. 2
17. Bakersfield Wastewater Treatment Facility No. 3
18. Porterville Wastewater Treatment Facility
19. Tulare Wastewater Treatment Facility
20. Los Banos Wastewater Treatment Facility
21. Lake County Northwest Region Wastewater Treatment Plant, Lakeport
22. White Slough Wastewater Treatment Facility, Lodi
23. Merced Sewage Treatment Plant
24. Yuba City Wastewater Treatment Facility
25. Scor Wastewater Treatment Facility, Oroville
26. Redding Regional Wastewater Treatment Facility
27. Sonora Wastewater Treatment Plant
28. Marysville Wastewater Treatment Facility
29. Davis Campus Wastewater Treatment Facility
30. Lake County Southeast Region Wastewater Treatment Facility, Clear Lake High
31. Barstow Regional Wastewater Treatment Facility
32. El Centro Wastewater Treatment Facility
33. Palm Springs Wastewater Reclamation Facility
34. Brawley Wastewater Treatment Facility
35. Banning Wastewater Treatment Facility
36. Big Bear Area Regional Wastewater Treatment Facility
37. Chino Basin Regional Treatment Facility No. 2
38. Chino Basin Wastewater Treatment Facility No. 3, Fontana

Colorado

39. Colorado Activated Sludge Plant
40. Pueblo Wastewater Treatment Plant
41. 75th Street Wastewater Treatment Plant, Boulder
42. Broomfield Wastewater Treatment Plant
43. Greeley Wastewater Treatment Plant
44. South Adams County Sewage Treatment Plant, Commerce City
45. Montrose Sewage Treatment Plant
46. Durango Wastewater Treatment Plant

Connecticut

47. Forestville Sewage Treatment Plant, Bristol
48. MDC Water Pollution Control Facility, Cromwell
49. Enfield Wastewater Treatment Facility
50. Glastonbury Water Pollution Control Facility
51. Greenwich Water Pollution Control Facility
52. Groton Water Pollution Control Facility
53. East Hartford Water Pollution Control Facility
54. Killingly Water Pollution Control Facility
55. Meriden Water Pollution Control Facility
56. Connecticut River Water Pollution Control Facility, Middletown
57. Norwalk Water Pollution Control Facility
58. Norwich Water Pollution Control Facility
59. Seymour Water Pollution Control Facility
60. Shelton Water Pollution Control Facility
61. Stafford Water Pollution Control Facility
62. West Haven Water Pollution Control Facility
63. Windsor Locks Water Pollution Control Facility

Florida

64. Sunrise Sewage Treatment Plant No. 1, A and B
65. Jacksonville Beach Sewage Treatment Plant
66. Buckman Street Sewage Treatment Plant, Jacksonville
67. Goulds-Perrine Wastewater Treatment Plant
68. Maitland Water Pollution Control Facility
69. Winter Park Sewage Treatment Plant
70. Bennett Road Water Pollution Control Plant, Orlando
71. L.B. McLeod Road Sewage Treatment Plant, Orlando
72. Sandlake Road Sewage Treatment Plant, Orlando
73. Sanford Water Pollution Control Facility
74. Avondale Wastewater Treatment Plant, Pensacola
75. Thomas P. Smith Waste Treatment Plant, Tallahassee
76. Marshall Street Wastewater Treatment Plant, Clearwater
77. Dunedin Waste Treatment Plant
78. South Cross Bayou Pollution Control Facility, Clearwater
79. McKay Creek Wastewater Treatment Facility, Largo
80. Boca Raton Sewage Treatment Plant
81. Delray Beach Wastewater Treatment Plant
82. Boynton Beach Treatment Plant
83. Rockledge Sewage Treatment Plant

Florida (continued)

84. Titusville North Sewage Treatment Plant
85. Ocala Sewage Treatment Plant No. 1
86. Lakeland Wastewater Treatment Plant
87. Sarasota Wastewater Treatment Plant
88. Martin Street Sewage Treatment Plant, Kissimmee

Georgia

89. Pole Bridge Sewage Treatment Plant, Decatur
90. Snapfinger Creek Sewage Treatment Plant, Decatur
91. President Street Water Pollution Control Plant, Savannah
92. Cartersville Water Pollution Control Plant
93. Fort Oglethorpe Sewage Treatment Plant

Illinois

94. Wheaton Sanitation District Sewage Treatment Plant
95. Galesburg Sewage Treatment Plant

Kansas

96. Wichita Wastewater Treatment Plant
97. Kansas City, Kansas Wastewater Treatment Plant No. 1, Kaw Point
98. Kansas City, Kansas Wastewater Treatment Plant No. 20
99. Lawrence Sewage Treatment Plant
100. Salina Wastewater Treatment Plant No. 1
101. Garden City Wastewater Treatment Plant
102. Minfield Wastewater Treatment Plant

Michigan

103. St. John Wastewater Treatment Plant
104. Greenville Sewage Treatment Plant
105. Ionia Sewage Treatment Plant
106. Grand Haven Sewage Treatment Plant
107. Port Huron Sewage Treatment Plant
108. Rochester Sewage Treatment Plant
109. Wyandotte Wastewater Treatment Plant, Detroit
110. Saline Sewage Treatment Plant
111. Monroe Metro Wastewater Treatment Plant
112. Buena Vista Township Sewage Treatment Plant
113. Bay City Sewage Treatment Plant
114. Benton Harbor - St. Joseph Sewage Treatment Plant
115. Niles Wastewater Treatment Plant
116. Battle Creek Sewage Treatment Plant
117. Sault Ste Marie Sewage Treatment Plant
118. Escanaba Wastewater Treatment Plant
119. Traverse City Area Sewage Treatment Plant
120. Adrian Wastewater Treatment Plant
121. Menominee Wastewater Treatment Plant
122. Midland Wastewater Treatment Plant
123. Paw Paw Lake Wastewater Treatment Plant, Coloma
124. Cheboygan Wastewater Treatment Plant

Michigan (continued)

125. Coldwater Wastewater Treatment Plant
126. Ludington Sewage Treatment Plant
127. Three Rivers Wastewater Treatment Plant

Minnesota

128. St. Cloud Wastewater Treatment Facility
129. Virginia Wastewater Treatment Plant
130. Alexandria Wastewater Treatment Plant
131. Two Harbors Waste Treatment Plant

Mississippi

132. Brookhaven Municipal Sewage Treatment Plant
133. South Lagoon, Hattiesburg
134. Jackson Municipal Water Treatment Plant
135. Oxford Sewage Treatment Plant
136. Yazoo City Sewage Treatment Plant

Missouri

137. Columbia Trickling Filter Plant No. 2
138. Fulton Wastewater Treatment Plant
139. Jefferson City Wastewater Treatment Plant
140. Middle Big Creek Wastewater Treatment Plant, Lee's Summit
141. Marshall Wastewater Treatment Plant
142. Rolla Southeast Wastewater Treatment Plant
143. St. Charles Missouri River Sewage Treatment Plant
144. St. Charles Mississippi River Sewage Treatment Plant
145. Sedalia Wastewater Treatment Plant North
146. Sedalia Wastewater Treatment Plant West
147. Sikeston Wastewater Treatment Plant
148. Monett Wastewater Treatment Plant
149. Boonville Wastewater Treatment Plant

Montana

150. Helena Wastewater Treatment Plant
151. Great Falls Sewage Treatment Plant

New York

152. Bay Park Water Pollution Control Plant, East Rockaway
153. Cedar Creek Water Pollution Control Plant, East Rockaway
154. Huntington Sewage Treatment Plant
155. Tallmans Island Water Pollution Control Plant, Whitestone
156. Oakwood Beach Water Pollution Control Plant, Staten Island
157. Goshen Sewage Treatment Plant
158. Middletown Waste Treatment Plant
159. Orangetown Sewage Treatment Plant, Orangeburg
160. Rock County Water Pollution Control Plant, Orangeburg
161. Suffern Village Wastewater Treatment Plant
162. Liberty Sewage Treatment Plant
163. Blind Brook Sewage Treatment Plant, Rye

New York (continued)

164. St. Johnsville Sewage Treatment Plant
165. North Albany Sewage Treatment Plant, Menands
166. South Albany Sewage Treatment Plant, Albany
167. Bethlehem Sewage Treatment Plant, Delmar
168. Rensselear County Sanitation District No. 1 Sewage Treatment Plant, Troy
169. Fonda-Fultonville Sewage Treatment Plant
170. Plattsburg Sewage Treatment Plant
171. Rouses Point Sewage Treatment Plant
172. Gloversville-Johnstown Wastewater Treatment Plant
173. Glens Falls Sewage Treatment Plant
174. Little Falls Water Pollution Control Facility
175. Massena Sewage Treatment Plant
176. Potsdam Sewage Treatment Plant
177. Auburn Sewage Treatment Plant
178. Wetzel Road Sewage Treatment Plant, Syracuse
179. Meadowbrook-Limeston Waste Treatment Plant, Manlius
180. Chemung County Elmira Sanitation District Sewage Treatment Plant
181. Chemung County Sanitation District No. 1, Elmira
182. Dansville Sewage Treatment Plant
183. Webster Treatment Plant
184. Marsh Creek Treatment Plant, Geneva
185. Seneca Falls Sewage Treatment Plant
186. Hornell Water Pollution Control Plant
187. Nemark Wastewater Treatment Plant
188. Amherst Water Pollution Control Facility
189. Big Sister Creek Sewage Treatment Plant, Angola
190. Springville Sewage Treatment Plant
191. Lewiston Master Sewage Treatment Plant
192. Niagara Falls Wastewater Treatment Plant
193. North Tonawanda Sewage Treatment Plant

North Carolina

194. Rocky River Waste Treatment Plant, Concord
195. Morehead Treatment Plant
196. Lake Hickory Wastewater Treatment Plant
197. Clark Creek Wastewater Treatment Plant, Newton
198. Longview Wastewater Treatment Plant
199. Pilot Creek Wastewater Treatment Plant, Kings Mountain
200. Tarboro Wastewater Treatment Plant
201. Archie Elledge Wastewater Treatment Plant, Winston-Salem
202. West Side Sewage Treatment Plant, High Point
203. Spindale Wastewater Treatment Plant
204. Clinton Waste Treatment Plant
205. Albemarle Sewage Treatment Plant

Oregon

206. Kellog Creek Sewage Treatment Plant, Oregon City
207. Oak Lodge Sewage Treatment Plant, Milwaukee
208. Durham Regional Sewage Treatment Plant, Tigaro

Oregon (continued)

209. Willow Lake Sewage Treatment Plant, Salem
210. Dallas Sewage Treatment Plant
211. Cottage Grove Sewage Treatment Plant
212. Springfield Sewage Treatment Plant
213. Astoria Sewage Treatment Plant
214. Coos Bay Plant No. 1
215. Medford Sewage Treatment Plant
216. Klamath Falls-Spring Street Sewage Treatment Plant
217. La Grande Sewage Treatment Plant
218. The Dalles Sewage Treatment Plant
219. McMinnville Sewage Treatment Plant
220. Lebanon Sewage Treatment Plant
221. Newport Sewage Treatment Plant

Pennsylvania

222. Upper Gwynedd Township Sewage Treatment Plant, North Wales
223. Pottstown Borough Sewage Treatment Plant
224. Hatfield Township Sewage Treatment Plant, Colmar
225. Warminster Sewage Treatment Plant
226. Oaks Wastewater Treatment Plant, Norristown
227. Perkasie Sewage Treatment Plant
228. Phoenixville Sewage Treatment Plant
229. Baldwin Run Sewage Treatment Plant, Aston
230. Allentown Sewage Treatment Plant
231. Lebanon Wastewater Treatment Plant
232. Schuylkill Haven Sewage Treatment Plant
233. Lancaster North Water Pollution Control Center
234. Ephrata Sewage Treatment Plant
235. Easton Sewage Treatment Plant
236. Kutztown Wastewater Treatment Plant
237. Scranton Sewage Treatment Plant
238. Dallas Area Municipal Authority Sewage Treatment Plant, Shavertown
239. Trhoop Wastewater Treatment Plant
240. Chambersburg Wastewater Treatment Plant
241. Lock Haven Wastewater Treatment Facility
242. Tyrone Borough Sewage Treatment Plant
243. Rochester Area Sewage Treatment Plant
244. Clairton Municipal Authority Sewage Treatment Plant
245. Oakmont Boro Sewage Treatment Plant
246. Brush Creek Sewage Treatment Plant, Irwin
247. Youghiogheny Sewage Treatment Plant
248. Greater Greensburg Sewage Treatment Plant
249. Mon Valley Sewage Treatment Plant, Donora
250. Ambridge Sewage Treatment Plant
251. Butler Area Sewage Treatment Plant
252. Bradford Sewage Treatment Plant
253. Corry Sewage Treatment Plant
254. Erie City Sewage Treatment Plant

South Dakota

255. Yankton Wastewater Treatment Plant
256. Mitchell Wastewater Treatment Facility
257. Aberdeen Wastewater Treatment Plant
258. Watertown Wastewater Treatment Plant
259. Pierre Wastewater Treatment Facility
260. Sioux Falls Wastewater Treatment Facility

Texas

261. Waco Regional Sewage Treatment Plant
262. Sugar Land Sewage Treatment Plant
263. Hollywood Road Sewage Treatment Plant, Amarillo
264. Borger Sewage Treatment Plant
265. Socorro Sewage Treatment Plant, El Paso
266. Harlingen Sewage Treatment Plant No. 1
267. Harlingen Sewage Treatment Plant No. 2
268. North Sewage Treatment Plant, Alice
269. Southeast Sewage Treatment Plant, Alice
270. Moore Street Sewage Treatment Plant, Beeville
271. Southeast Plants Nos. 1 and 2, Lubbock
272. Snyder Sewage Treatment Plant
273. Abilene Sewage Treatment Plant
274. Govalle Sewage Treatment Plant, Austin
275. Bryan Sewage Treatment Plant No. 1
276. Killeen-Fort Hood Sewage Treatment Plant
277. Roundrock Sewage Treatment Plant
278. McKinney South Sewage Treatment Plant
279. Denton Sewage Treatment Plant
280. Lewisville Sewage Treatment Plant
281. Cleburne Sewage Treatment Plant
282. Graham Sewage Treatment Plant
283. Texarkana Main Sewage Treatment Plant
284. Longview Main Sewage Treatment Plant
285. Kilgore Sewage Treatment Plant
286. Carthage Sewage Treatment Plant
287. Main Sewage Treatment Plant, Port Arthur
288. Nacogdoches Sewage Treatment Plant No. 2A
289. Rosenberg Sewage Treatment Plant No. 1
290. West Main Sewage Treatment Plant, Baytown
291. East District Sewage Treatment Plant, Baytown
292. Bellaire Sewage Treatment Plant
293. Fort Bend County WCID No. 2, Stafford
294. Harris County FWSD No. 51 Sewage Treatment Plant, Houston
295. Nassau Bay Sewage Treatment Plant
296. Seguin Sewage Treatment Plant
297. Scheibe Sewage Treatment Plant, New Braunfels
298. Salatrillo Sewage Treatment Plant, San Antonio
299. Upper Martinez Sewage Treatment Plant, San Antonio
300. Odo J. Riedal Sewage Treatment Plant, Schertz
301. Brownwood Sewage Treatment Plant
302. Sewer Farm Sewage Treatment Plant, San Angelo

Utah

303. South Davis County South Sewage Treatment Plant, West Bountiful
304. Murray City Sewage Treatment Plant
305. Granger-Hunter Sewage Treatment Plant

Washington

306. Aberdeen Sewage Treatment Plant
307. Bellingham Pollution Control Plant
308. Camas Sewage Treatment Plant
309. Edmonds Sewage Treatment Plant
310. Ellensburg Sewage Treatment Plant
311. Hoquiam Treatment System
312. Central Kitsap Regional Sewage Treatment Plant, Brownsville
313. Lynnwood Treatment System
314. Montesano Sewage System
315. Moses Lake Sewage Treatment Plant
316. Pullman Sewage Treatment Plant
317. Miller Creek Sewage Treatment Plant, Seattle
318. Wenatchee Sewage Treatment Plant
319. Sunnyside Sewage Treatment Plant