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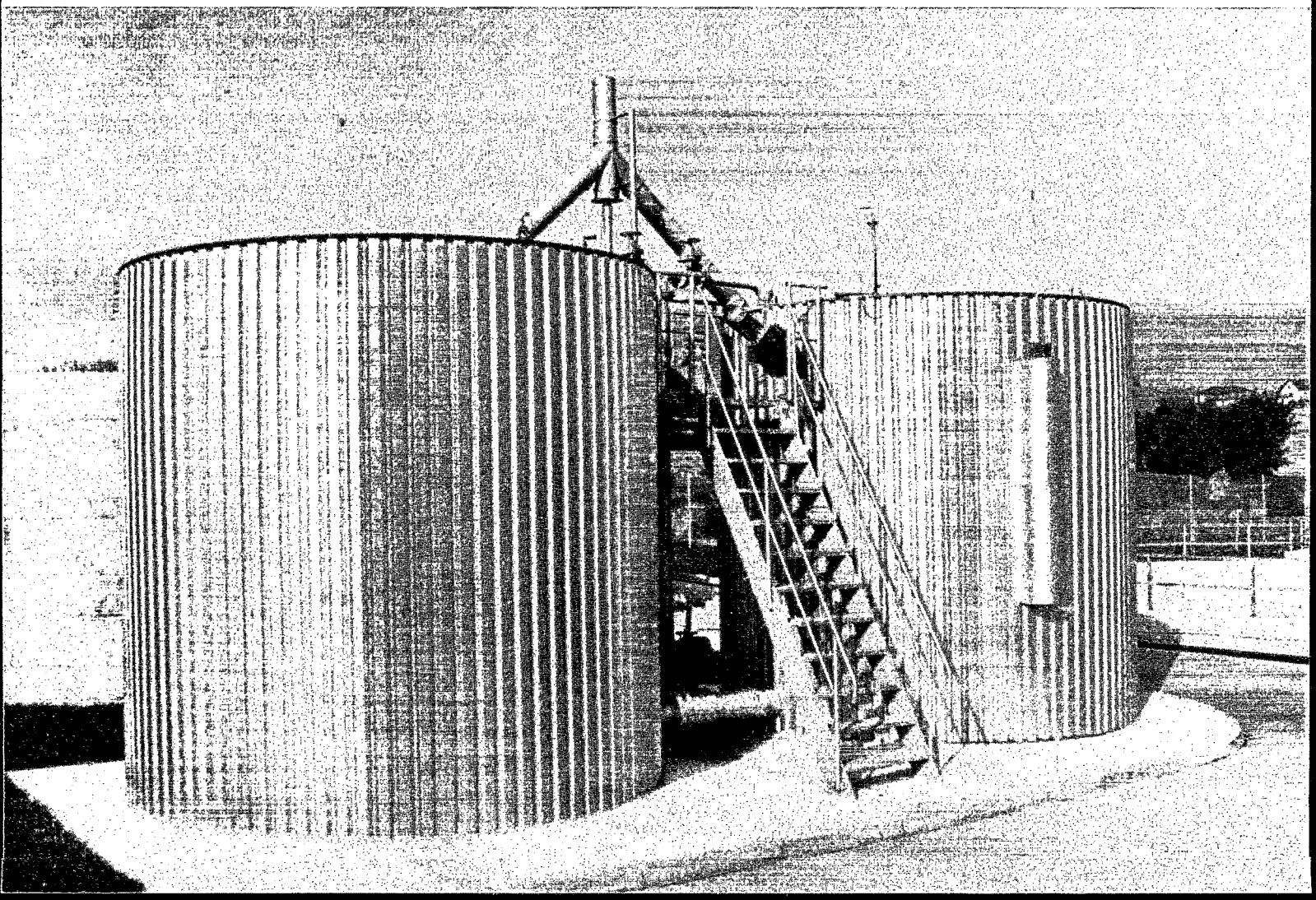
Environmental Regulations and Technology

Autothermal Thermophilic Aerobic Digestion of Municipal Wastewater Sludge



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September 1990

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and the Center for Environmental Research Information,
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Notice

This document has been reviewed by the U.S. Environmental Protection Agency and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Cover Photograph: Autothermal Thermophilic Aerobic Digestion System at Gemmingen, Federal Republic of Germany.

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Abbreviations and Acronyms

AOR	process oxygen requirement
ATAD	autothermal thermophilic aerobic digestion
BOD_5	5-day biochemical oxygen demand
Btu	British thermal unit(s)
°C	degrees Centigrade
CFR	Code of Federal Regulations
CFU	colony-forming unit(s)
COD	chemical oxygen demand
d	day(s)
DM	Deutsche mark
ENR-CCI	Engineering News Record - Construction Cost Index
EPA	U.S. Environmental Protection Agency
F/M	food-to-mass ratio
FRG	Federal Republic of Germany
ft	foot/feet
ft^3	cubic foot/feet
g	gram
gal	gallon
h	height
H/D	ratio filling-depth-to-diameter ratio
hp	horsepower
hr	hour(s)
HRT	hydraulic residence time
k	decay coefficient
kg	kilogram(s)
kJ	kilojoule
kW	kilowatt
kWh	kilowatt-hour(s)
IAWPRC	International Association on Water Pollution Research and Control
L	liter(s)
lb	pound(s)
m	meter(s)
m^3	cubic meter(s)
MCD	Municipal Construction Division
mg	milligram(s)
MG	million gallons
MGD	millions of gallons per day
mL	milliliter(s)
MPN	most probable number
NVSS	nonvolatile suspended solids
O_2	oxygen
OSS	Ordinance of Sewage Sludge
OTE	oxygen transfer efficiency
P.E.	population equivalent
PEC	EPA's Pathogen Equivalency Committee
PFRP	process to further reduce pathogens
PFU	plaque-forming units
PSRP	process to significantly reduce pathogens
SOUR	specific oxygen uptake rate
s	seconds
TS	total solids
TSS	total suspended solids
TVS	total volatile solids
TVSS	total volatile suspended solids
t	ton (metric)
UTB	Umwelttechnik Buchs
VS	volatile solids
VSS	volatile suspended solids
W	watt(s)
yr	year(s)
$	U.S. dollars

Conversion Factors

Unit	Multiply by	To get
°C	(°C x 1.8) + 32	°F
g/L	8.345	lb/1,000 gal
kg	2.205	lb
kg/m^3	6.243×10^{-2}	lb/ft^3
kJ	0.9486	Btu
kJ/kg	0.430	Btu/lb
kg/m^3	1.686	lb/yd^3
kW	1.341	hp
kWh/m^3	96	Btu/ft^3
L	0.2642	gal
m	3.281	ft
m^3	35.32	ft^3
m^3	1.308	yd^3
m^2	10.76	ft^2
m^3/s	2,119	ft^3/min
m^3/s	22.83	MGD
mg/L	8.345	lb/1,000,000 gal
W	3.4129	Btu/hr
W/m^3	9.66×10^{-2}	$Btu/hr/ft^3$

Chapter 1. Introduction

This document describes a promising technology — autothermal thermophilic aerobic digestion — for meeting the current and proposed U.S. federal requirements for pathogen control and land application of municipal wastewater sludge. Autothermal thermophilic aerobic digestion, or ATAD, has been studied since the 1960s and significantly developed since the mid-1970s. It is currently widely and successfully implemented in Europe, particularly the Federal Republic of Germany (FRG), where there are over 35 full-scale operating facilities. Facilities can also be found in Great Britain, France, and Italy. Four full-scale facilities are operational in Canada, and one is planned for Connecticut. The growing interest in the technology has evolved following increased scientific and regulatory concern for sludge-borne pathogens. Full-scale development of the technology in the FRG closely parallels advances made by a German aerator manufacturer.

ATAD systems are normally two-stage aerobic processes that operate under thermophilic temperature conditions (40°C to 80°C) without supplemental heat. Typical ATAD systems operate at 55°C and reach 60°C to 65°C in the second stage. They rely on the heat released during digestion to attain and sustain the desired operating temperatures.

The ATAD process has many benefits: a high disinfection capability, low space and tankage requirements, and a high sludge treatment rate. It is a relatively simple technology that is easy to operate (automatic monitoring or control equipment and full-time staff are not required) and economical, particularly for small facilities. It provides a proven, cost-effective way to achieve aerobic digestion and to produce sludge that can be applied to land in the U.S. without any management restrictions for pathogen control.

This document provides detailed information concerning the history, design, operation and maintenance requirements and performance of ATAD systems. Limited information is also provided on another thermophilic aerobic digestion system currently operating in Europe — the pre-stage system. Pre-stage systems are typically retrofitted into existing facilities already equipped with anaerobic digesters. They are used to enhance treatment and pathogen destruction. Unlike ATAD systems, they are not completely autoheated. Supplemental heat, provided through an auxiliary heat exchanger, is required to achieve the desired operating temperature of 65°C. Pre-stage systems are operating primarily in Switzerland and Germany.

The document is intended primarily for owners and operators of treatment plants and their consulting engineers who are interested in using ATAD treatment to achieve the regulatory requirements for land application of municipal sludge. Regional, state, and local government officials responsible for implementing and enforcing the land application regulations will also find the document useful.

The information in this document is primarily from a 1989-1990 EPA study that collected and analyzed design and operating data from ATAD systems in the FRG. Information was obtained from several sources: a review of German and U.S. literature, telephone contact with FRG facilities, site visits to selected facilities to observe operating and design conditions and to interview plant operating personnel and design engineers, telephone contact and meetings with system manufacturers, and contact with researchers at Darmstadt University to discuss completed and ongoing research. In addition, this document includes information obtained from three of the Canadian facilities operating in 1990. Note that key design data are highlighted in *italics*.

Chapter 2.
Process Concepts and Development

2.1 Autothermal Digestion

With an adequate supply of oxygen, microorganisms, nutrients, and biodegradable organic material, autothermal aerobic digestion can degrade complex organic substances into end products including carbon dioxide and water. Some of the energy released by microbial degradation is used to form new cellular material; much of it is released as heat. Typical biological heat production values reported or assumed range from 14,190 to 14,650 kJ/kg O_2 (1, 2, 3). The carbonaceous oxygen requirements vary, but are often considered to be 1.42 kg O_2/kg volatile suspended solids (VSS) oxidized. In autothermal thermophilic aerobic digestion, the heat released by the digestion process is the major heat source used to achieve the desired operating temperature.

References 1, 2, and 4 provide detailed discussions of the heat and mass balance equations necessary for describing aerobic thermophilic systems operation. The same basic analytical approach has also been utilized in the FRG (5). Figure 2-1 shows the various inputs, outputs, and heat production items to be included in a heat balance. Autothermal conditions result from an adequately thickened sludge feed, a suitably insulated reactor, good mixing, and an efficient aeration device that keeps the latent heat loss to an acceptable level. ATAD systems currently operating in Europe and Canada do not use heat exchange between reactor feed and effluent to warm the incoming sludge because sufficient heat is generated and sustained in the process. Heat ex-

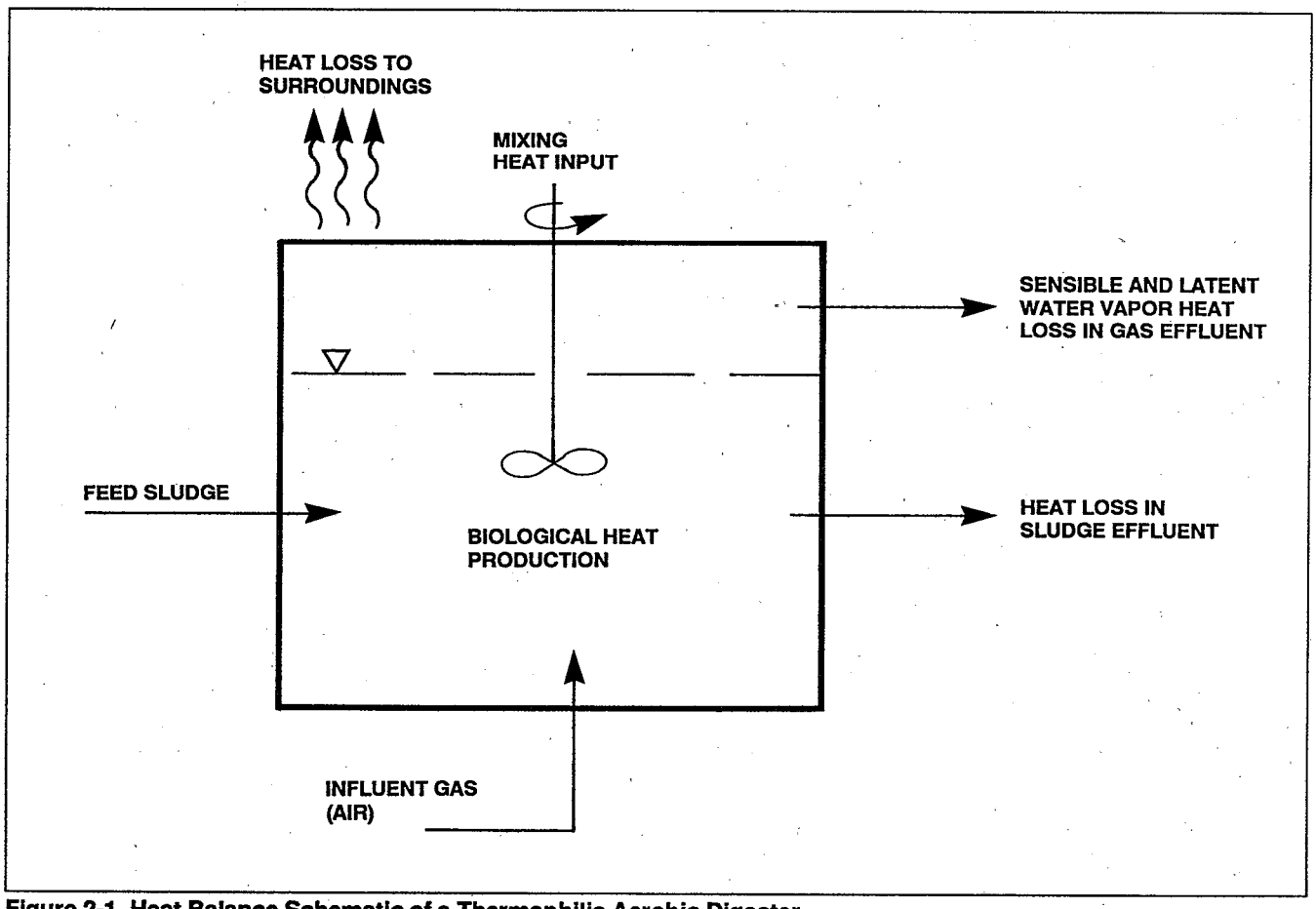

Figure 2-1. Heat Balance Schematic of a Thermophilic Aerobic Digester.

change is occasionally practiced for waste heat recovery such as to provide building heat.

2.2 ATAD Process Development

2.2.1 European Experience

Much of the developmental work leading to the ATAD process has been described by Pöpel (6, 7, 8, 9, 10). These references include detailed discussions of the heat and mass balances, biochemical cell composition, kinetics of the metabolic reactions, kind of aerating device needed, and the research results.

The early studies used a self-aspirating aeration device (known as the Umwälzbelufter) developed by Herr Fuchs and manufactured by Alfa Laval. Using this aerator, the process was demonstrated both with animal manure and with sludge having high concentrations (10 to 60 kg/m^3) of volatile suspended solids. Temperatures of 50°C to 60°C were achieved in 20-m^3 reactors. These studies showed the importance of periodic feeding in relation to both reactor temperatures and the degree of stabilization, and relationships were developed to determine the required reactor size for the degree of decomposition and temperature desired. Pöpel reported (8) that a properly designed system could reach temperatures of 60°C to 70°C, kill pathogens, produce an odor-free humus, and produce a readily dewaterable product.

Fuchs continued to improve its aeration devices and to revise its overall ATAD system design. It sold the license for its previous aeration system to Alfa Laval (DeLaval in the USA) in the mid-1970s.

The first full-scale municipal ATAD system in the FRG was a Fuchs system installed in Vilsbiburg in 1977, which continues to operate to this day. As of 1989, 35 ATAD systems were installed or under construction in the FRG, 30 of which were supplied by Fuchs.

Significant advances have been made in optimizing and adapting ATAD technology since the original development work 20 years ago. Much of the experimental work on which the present ATAD systems are based was performed by Breitenbücher (5) at the full-scale ATAD plant at Gemmingen, FRG. Current European design practices, process performance, and implementations of ATAD technology are discussed in the subsequent chapters of this document.

2.2.2 North American Experience

As indicated above, the thermodynamic requirements for ATAD systems along with process simulation predictions have been described in the U.S. literature for many years. Self-aspirating aerators manufactured by DeLaval, Inc. were marketed in the 1970s for high-strength industrial and liquid manure waste treatment in the U.S. in a patented process called the LICOM (liquid composting) system. Several short-term batch tests with various industrial and animal wastes were reported to produce autoheating to 50°C to 60°C (11). Studies on dairy, beef, and swine wastes demonstrated that autoheating to thermophilic temperatures was possible (12, 13).

In the early 1970s, Union Carbide was active in developing an ATAD system that utilized high-purity oxygen. Pilot plant studies were conducted under autothermal thermophilic conditions at Tonawanda, New York (14). The researchers concluded that an ATAD system operating at a 5-d hydraulic residence time (HRT) could achieve volatile solids destruction equivalent to conventional aerobic digestion operated at a 15- to 20-d HRT. The thermophilic conditions inhibited nitrification, thus eliminating this factor as a source of oxygen demand. By maintaining the temperature at 50°C for 5 or more hours, pathogenic organisms could be reduced to less than detectable levels.

The most extensive U.S. study of ATAD using air aeration was conducted at Binghamton, NY in 1977 and 1978 (2). The design was based on the system marketed by DeLaval, Inc. Two aerators were studied: an LFE Corporation Midland-Frings self-aspirating aerator and a DeLaval centri-rator self-aspirating aerator. Regardless of air and sludge temperatures, reactor temperatures after startup were always in the thermophilic zone and often above 50°C. No nitrification occurred, but some ammonia was lost due to stripping. The study reported a high degree of pathogen control with respect to bacteria, viruses, and parasites. Practical operation and maintenance problems were minimal, although problems with poor mixing were noted. Currently the only ATAD systems for municipal sludge stabilization on the North American continent are in Canada, where three systems have been installed in British Columbia and one in Alberta. Two installations use Fuchs-supplied equipment: One is a pump and venturi-air-supplied plant, and one is a retrofit facility that uses aspirator-type aerators developed in Canada (15, 16). Details of the last plant (Salmon Arm) appear in this report. As of 1990, no ATAD systems were operating in the U.S.

Chapter 3.
Engineering and Design Criteria

3.1 Introduction

Several single- and multiple-stage versions of ATAD are under development or operating in the FRG, Canada, and Great Britain. Systems in the FRG include those manufactured and/or distributed by Babcock, Fuchs, Limus, and Thieme. In Great Britain, the Water Research Centre has been developing a version of the process. Canadian facilities include two equipped by Fuchs and two retrofitted plants with locally supplied equipment.

The Fuchs system of the FRG is by far the most widely used system (17), and it is therefore the system for which the greatest amount of full-scale operating experience exists — exceeding 10 yr at some facilities. For these reasons, this system is used as the design standard described here. Key design parameters for this system are summarized in Table 3-1 and discussed in this section. Alternative systems must be evaluated on an individual basis.

Table 3-1 Design Parameters for ATAD Systems[1]

Reactors:	Two or more stages, depending on plant size; tanks of equal volume operating in series; daily batch operation
Reactor type:	Cylindrical; height/diameter ratio 0.5-1.0
Sludge type:	- Primary - Secondary activated sludge, trickling filter - Gravity or air flotation thickened - Mixture of primary and secondary - Domestic, industrial origin - Manure
Feed TS range:	40-60 g/L (4-6%)
Required VSS:	≥25 g/L (2.5%)
Detention time:	5-6 d
Minimum reaction time:	20 hr/stage
Temperature and pH:	Reactor I: 35 -50°C , pH ≥7.2 Reactor II: 50 -65°C , pH ~8.0
Air input:	4 $m^3/hr/m^3$ active reactor volume
Specific power:	85-105 W/m^3 active reactor volume
Energy requirement:	9-15 kWh/m^3 of sludge
Heat potential for recovery:	20-30 kWh/m^3 of sludge

[1]These parameters are based on Fuchs-equipped facilities.

3.2 Process Configurations

Figure 3-1 illustrates configurations for three ATAD systems in the FRG. Typical features include pre-thickening, two enclosed and insulated reactors configured in series, mixing/aeration and foam control equipment, and a final storage/post-thickening tank.

Like most digestion processes, ATAD systems exist as both single- and multiple-stage processes that can be configured with a multitude of pre- and post-thickening arrangements. Single-stage systems can achieve similar volatile solids reduction to multiple-stage systems, but cannot reduce pathogens to the same extent. Therefore, single-stage configurations are more suitable for disposal options (such as landfilling or restricted-use land application) that do not require enhanced pathogen reduction. The multiple-stage process has been recommended as a design standard for European systems where the sludge may be applied to land. Two-reactor systems are typical.

3.3 Sludge Feed Source and Thickening Requirements

Most digestion processes thicken the sludge prior to digestion to minimize the size of the digestion tanks and to limit the energy requirements for mixing and heating. This is also true for ATAD systems.

Like composting, ATAD systems rely on conserving the heat released during digestion to attain and sustain an operating temperature of 55°C to 65°C. Thus, sludge is both the material being treated and the "fuel" that drives the process.

A sludge in a Fuchs system is adequate to support process temperature requirements if it is thickened to 4-6% TSS, of which at least 2.5% is mostly biodegradable volatile solids. Gravity thickening can usually achieve this concentration. Some plants also successfully co-thicken the waste-activated sludge with the primary solids and thereby avoid the need for a separate sludge thickener.

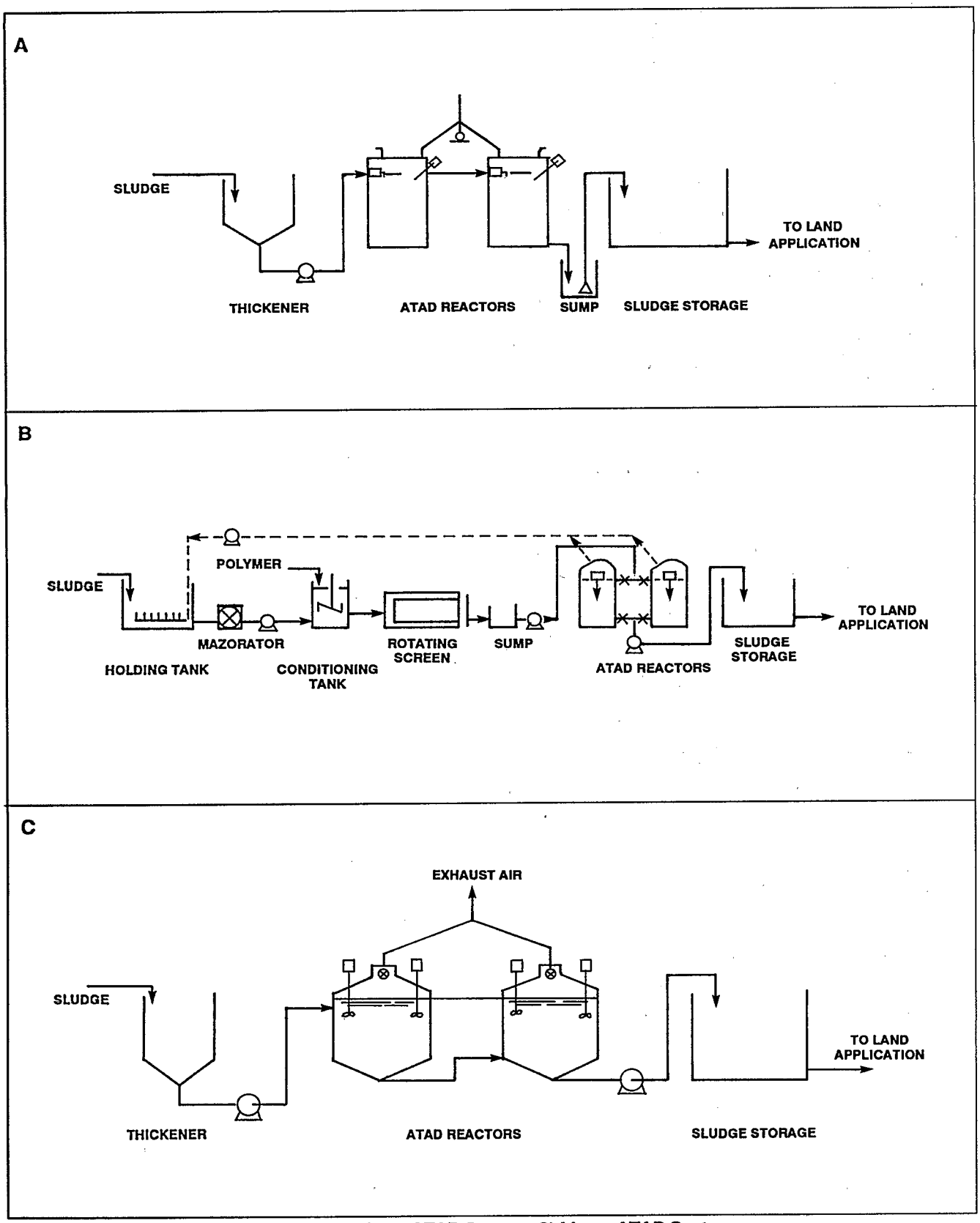

Figure 3-1. A) Fuchs ATAD System, B) Thieme ATAD System, C) Limus ATAD System.

Although some ATAD systems receive only waste-activated sludge (e.g., Gemmingen), most ATAD facilities in the FRG have both primary and secondary sludge sources.

Sludge from plants without primary clarifiers and with activated sludge food-to-mass ratio (F/M) loadings as low as 0.1 to 0.15 (kg BOD_5/d) /kg TVSS still seems to be suitable for ATAD. No data are available from extended air plants, although one plant, Mundelsheim, is known to have taken the digestion system off line as a result of low loading conditions (F/M < 0.1).

Two nonmunicipal applications by Thieme have used rotary screens to pre-thicken the sludge to 7.5-10% volatile solids (VS) prior to digestion. Aeration and mixing energy requirements are reportedly high for these systems; limited performance data exist.

3.4 Detention Time

To satisfy the FRG process requirements for destruction of pathogens and total organic solids, *the design hydraulic detention time for Fuchs systems is established at 5 to 6 d (2.5 to 3 d per reactor).* Sixty percent of the volatile solids destruction reportedly occurs in the first reactor.

3.5 Feed Cycle and Isolated Reaction Time

Batch feeding is established by design intent and is reflected in the sizing of the sludge feed pump(s). *The feed sludge pumping system is sized to deliver the daily thickened sludge volume to the reactor in less than 1 hr. Since all sludge is pumped within a 1-hr period, the reactors are isolated for the remaining 23 hr during each day.* This undisturbed reaction time is considered an important factor in attaining a high degree of pathogen destruction.

The series reactor configuration and a reverse-order filling procedure further isolate treated sludge from partially treated or raw sludge to prevent reinoculation of the final treated product. The operating strategy is best understood by referring to the process flows in Figure 3-1. Each day, aeration and mixing are stopped, and stabilized sludge is discharged from reactor II into the storage tank, thus lowering the level in that reactor. Sludge is then allowed to flow by gravity from reactor I to reactor II until both tanks reach equilibrium. Raw sludge is added to reactor I to raise the level and displace sludge into reactor II. When both reactors reach full operating level, aeration and mixing are resumed.

The entire daily feeding process is typically accomplished in 30 minutes, resulting in an undisturbed reaction time of 23.5 hr in both tanks. In addition, the displaced volume should be adjusted in such a way that the average residence time will vary by less than approximately 20% (5).

3.6 Aeration and Mixing

Aeration efficiency and mixing efficiency are probably the two most important factors to consider when designing an ATAD system. A highly efficient aeration system is needed for two process purposes (aside from minimizing energy requirements): to keep pace with the extremely high oxygen demand that results in the process, and to minimize the latent heat loss from the reactors that occurs when air is exhausted. Both the air flow rate and oxygen transfer efficiency depend on system geometry (height/depth, location of aerators), substrate characteristics (e.g., TSS, viscosity); and turbulence conditions that are specific to the procedure as well as to the substrate.

The aeration systems of several early pilot operations failed to attain the necessary efficiency and/or reliability to support the process requirements. Much research and development continues today concerning ATAD aeration and mixing systems. However, the aeration system used for the Fuchs ATAD systems throughout the FRG is not developmental, since considerable successful operating experience has been amassed. The Fuchs ATAD systems utilize aspirator aerators of the type illustrated in Figure 3-2. Two aerators are side-mounted into each reactor; depending on reactor size, a third aerator can also be mounted in the center of the reactor.

Typical design ranges for empirical aeration/mixing parameters include:

Specific power:	85-105 W/m^3 of active reactor volume
Air input:	4 m^3/hr/m^3 of active reactor volume
Energy requirement:	9-15 kWh/m^3 of sludge throughput

The specific power range of 85-105 W/m^3 is comparable to a mixing energy range of 430-530 hp/MG, which represents a high mixing intensity.

The air input value of 4 m^3/hr/m^3 of active reactor volume is premised upon a feed TVSS range of 2.5-5.0%. This value relates to a design process air

requirement of 1.42 kg of O_2/kg VSS destroyed. (See Chapter 4 for a design example.)

The energy requirement of 9-15 kWh/m^3 of sludge throughput also includes the energy required for foam cutters (minimum of two per tank, requiring from 0.3 to 0.75 kW each).

3.7 Temperature and pH

An average temperature of 55°C in the second reactor is used for design purposes. This is consistent with FRG design recommendations. The temperature in the second reactor can exceed 55°C (and, according to observations made during site visits, often does). *However, to prevent resolubilization of organics, the temperature should not exceed 65°C (5).*

During batch feeding, which results in a 33% reactor volume displacement, the temperature drop ranges from 5°C to 10°C in reactor I with a recovery rate of about 1°C/hr. To avoid biological adaptation problems, temperatures in reactor I should not be allowed to fall below 25°C (13). The temperature drop in reactor II is about 4°C to 6°C, with a higher recovery rate.

The design areas that most affect operating temperature include the efficiency of the aeration system, reactor insulation, foam management in the reactor, and sludge pre-thickening.

Generally, process pH does not have to be controlled by special design considerations. The thermophilic operating temperatures of the reactors suppress nitrification in the process. Consequently, the pH depressions that could occur in a nitrifying environment are not experienced. With a feed sludge pH of 6.5, pH values in the first reactor are typically near 7.2 and may approach 8.0 in the second reactor.

3.8 Foam Control

The foam layer in the treatment reactor plays an important role in the ATAD process, though this role has not been fully evaluated. The foam layer appears to improve oxygen utilization, enhance the biological activity, and provide insulation, but it retards the amount of air entering the reactor. The amount of foam should be optimized and not eliminated.

Treatment reactors are sized to accommodate about 0.5 to 1.0 m of freeboard, which is partially used as volume for foam development and control. Control consists of densifying the foam (i.e., breaking up the large foam bubbles into small bubbles) to form a

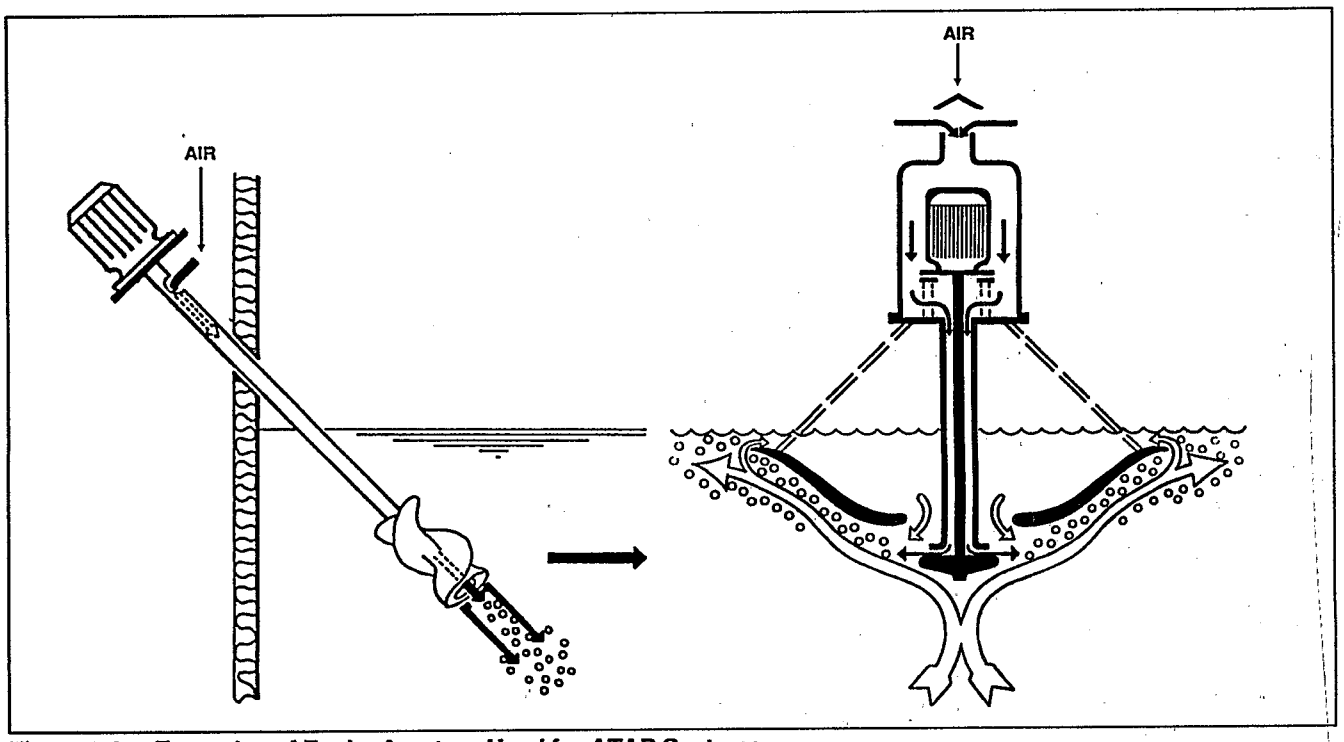

Figure 3-2. Examples of Fuchs Aerators Used for ATAD Systems.

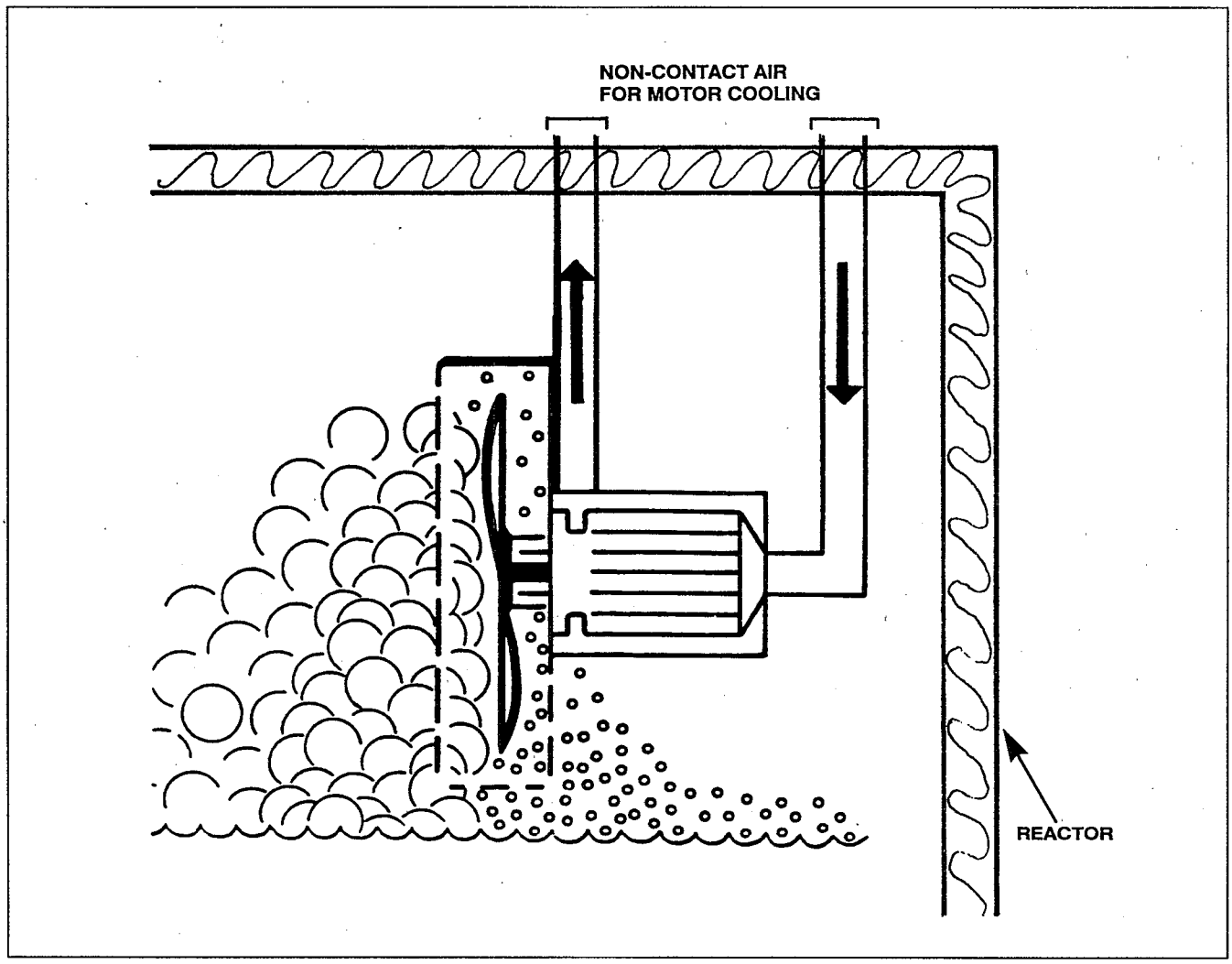

Figure 3-3. Example of Fuchs Foam Cutter.

compact layer floating above the liquid surface of the reactor. In Fuchs systems, foam control is achieved by mechanical foam cutters installed in the reactor at fixed elevations. These units cut through foam that rises above the predetermined level (see Figure 3-3).

The design basis for foam cutters is determined empirically and is a function of the surface area of the reactor. All tanks have at least two foam cutter units.

3.9 Post-Thickening/Dewatering

In general, the gravity-thickening performance of the hot effluent sludge is poor immediately after treatment, due to the thermal convection currents that occur in a thickening tank. If the sludge is allowed to cool in the post-thickening/storage tank or additional heat exchangers exist that cool the sludge down, thickening performance is usually satisfactory (18, 19). Old Imhoff tanks have been very suitable for post-thickening. Values of 6-9% TS are typically achieved. Values up to 10-14% TS and even 18% TS have often been reported (e.g., from Ellwangen, Gemmingen, and Kirchberg). High thickened concentrations can, in unfavorable cases, lead to problems with sludge pumping if not considered during design.

Limited data exist on dewaterability since most plants land apply sludge as a liquid. However, the limited data that do exist from the FRG indicate that dewaterability is generally comparable to that of anaerobically stabilized sludge (20, 21). Preliminary Canadian experience confirms similar dewaterability, but with significantly higher polymer dosages (16).

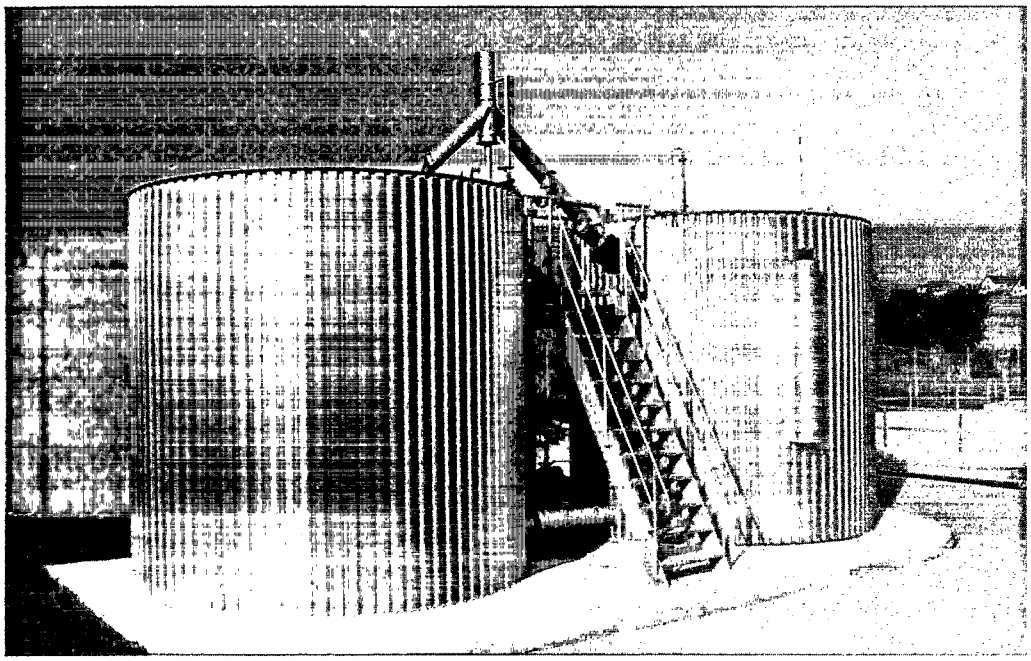

Figure 3-4. ATAD System Installed at Gemmingen, FRG.

3.10 Sludge Storage and Disposal

Agricultural use of sludge requires sufficient capacity to store sludge during those periods when sludge cannot be land applied. *A 3-month capacity is standard in Switzerland and recommended in Germany.* Storage tanks are typically uncovered and equipped with a mixer. Few problems with odor nuisance, reactivation of damaged pathogens, or reinfection during storage have been reported in systems equipped with storage tank mixing. Aeration during storage does not appear to be necessary if the sludge is fully stabilized. *Usually, sludge storage tanks are mechanically mixed once a day for about an hour.*

Odor problems have been experienced either as a result of ATAD overloading or when storage tanks remained un-mixed for significant periods. See Section 5.6 for a discussion of odor control.

3.11 Construction Features

A complete sludge-handling system may include pre-thickening, post-storage/thickening, and dewatering. When utilized with the Fuchs ATAD process, these process units are typical of and comparable to U.S. engineering and construction practice. This section emphasizes other construction features that are unique to ATAD systems.

3.11.1 Tank Construction

The system shown in Figure 3-4 is typical of ATAD systems installed throughout the FRG. Due to the reduced residence time requirement (6 d), ATAD reactors are much smaller than their conventional counterparts. *ATAD reactors are usually cylindrical and constructed of carbon steel with an interior coal-tar-based coating.* These systems tend to be aboveground installations requiring base concrete slab construction and piping and utility connections. Concrete tanks are not used for new construction for cost reasons. One concrete tank retrofit using Fuchs equipment is known to exist in the FRG. Two retrofit facilities are operating in Canada using local equipment.

One manufacturer (Limus) has proposed conical bottom areas to avoid grit deposits. However, since only two plants reported operating trouble as a result of grit deposits, such measures do not seem necessary unless the waste sludge contains a significant amount of grit.

The reactor must be insulated. *ATAD tanks are insulated with mineral wool (~10-cm thick) around the tank walls and styrene foam material on the cover, resulting in a typical overall heat transfer coefficient of 0.3-0.4 W/(m^2 °C) (19, 22). The entire tank is covered with a metallic skin (corrugated steel or aluminum) to protect the insulation and enhance the appearance of the tanks.*

With near-surface aerators, such as the Fuchs spiral ejector or circulation aerators, the filling-depth-to-diameter (H/D) ratio of the reactor must be relatively small to ensure complete mixing. *The H/D ratio typically varies between 0.5 and 1. This type of tank is relatively common in the U.S., since it can be used for many different applications. Total tank height includes foam layer thickness, typically 20-30 cm, and freeboard. The total free space above the filling level varies between 0.5 and 1 m.*

When using jet aerators, diffused air, or submerged turbine aerators (Roediger, Oswald-Schulze), the H/D ratio has to be higher than 1. The typical design range for the H/D ratio is 2-5.

3.11.2 Heat Exchange

In principle, no heat exchangers are needed to operate an ATAD process. However, economic- or process-specific reasons could recommend their installation. Economically, heat exchangers may reduce the operating costs by utilizing the excess heat for building heating or other uses. From a process standpoint, heat exchangers could be required if the feed sludge has insufficient biodegradable solids to sustain process temperatures. Due to the lack of data on extended aeration waste sludge applications, each such application must be evaluated, including an assessment of the need for heat recovery or supplementation. Here, the term "heat exchange" will be limited to heat recovery. However, the explanations are also valid for auxiliary heating.

Heat exchange is occasionally used in two basic ways to recover surplus heat from the exothermic aerobic digestion process: (1) cooling the effluent, usually coupled with heating up the influent in sludge/sludge heat exchangers, and (2) cooling the reactor, i.e., direct recovery from the process itself by sludge/water heat exchangers. The latter allows continuous recovery as well as direct heating of the process whenever necessary. For this reason exchanger designs may involve double-mantle reactors and intermediate heat-exchanging coils.

There are many kinds of sludge/sludge and sludge/water heat exchangers. The sludge/sludge exchangers (e.g., two concentric chambers) have better direct heat transfer but are more difficult to operate. They are used for heat exchange between effluent and influent. Conversely, sludge/water type exchangers are easier to operate but less efficient due to the double heat transfer via water (warm sludge/water/cold sludge). They are used for immediate recovery from the tank or, as in pre-stage plants, for heating the recirculating sludge volume.

According to literature reports, energy equivalent to 15-30 kWh/m^3 sludge can be recovered (23, 18). The feasibility for energy recovery strongly depends on local conditions, such as the heat potential of sludge, the heat demand of the process itself, climatic conditions, and the potential proximate uses for low-temperature heat.

Chapter 4.
Design Example

4.1 Introduction

This example illustrates the design approach for an ATAD facility. It is specifically suited for the FRG version equipped with Fuchs aerator/mixers and foam cutters. Many of the design concepts would also apply to other systems. Caution should be used in extrapolating the aeration power requirements and air flow rates to other systems since these are specific to Fuchs equipment.

4.2 Plant Information

Figure 4-1 illustrates the process flow diagram for the example wastewater treatment plant. Major treatment units include primary clarification, conventional activated sludge-secondary treatment, gravity thickening, sludge digestion (ATAD), sludge storage, and land application of treated sludge. Design conditions for the plant include:

Parameter	Design Average Value	Design Loading	
Flow	7,570 m^3/d		(2.0 MGD)
BOD_5	200 mg/L	1,514 kg/d	(3,330 lb/d)
TSS	200 mg/L	1,514 kg/d	(3,330 lb/d)
TVSS	150 mg/L	1,136 kg/d	(2,500 lb/d)

The wastewater treatment facility is expected to meet typical secondary limits for BOD_5 and TSS of 30/30 mg/L.

4.3 Solids Balance

The table in Figure 4-1 summarizes the solids balance for the overall treatment system. Sidestream solids quantities have been neglected. The treatment system configuration will result in two major sludge streams requiring treatment: primary sludge and waste-activated sludge.

4.3.1 Primary Solids Removal

Primary clarification is anticipated to remove approximately 65% of the typical influent suspended solids. These solids will become the primary sludge, with an expected solids content of about 50 g/L (5%). The estimated primary sludge mass and volume are therefore:

Mass

Influent TSS x 0.65 = primary sludge TSS

1,514 kg/d x 0.65 = 984 kg/d

Volume

$$\frac{(984\ \text{kg/d})/(0.05\ \text{kg/L})}{1{,}000\ \text{L/m}^3} = 19.7\ \text{m}^3/\text{d}$$

Of the 530 kg of TSS that remains in the effluent from the primary clarifiers, 25% is expected to be nonvolatile (inert) solids and the remaining portion volatile solids.

Approximately 30% of the influent BOD_5 will also be removed through primary clarification. The resultant overflow from the primary clarifiers can be characterized as:

Flow = 7,550.3 m^3/d

BOD_5 = 1,060 kg/d

TSS = 530 kg/d

VSS = 397.5 kg/d

NVSS = 132.5 kg/d

4.3.2 Secondary Sludge Production

The effluent from the primary clarifiers represents the loading to the secondary activated sludge process. Excess sludge production is estimated using methods generally adopted by the IAWPRC (24), which are represented by equation 1.

$$X_T = (NVSS + NBVSS) + X_a + X_e \qquad (1)$$

where:

X_T = total secondary sludge production

NVSS = nonvolatile suspended solids in feed

Parameter	Stream (1) Influent	(2) Side-streams[1]	(3) Primary Feed	(4) Primary Sludge	(5) Primary Effluent	(6) Waste Acti-vated Sludge	(7) Thick-ened Super-natant	(8) ATAD Feed	(9) Reactor I Effluent	(10) Reactor II Effluent	(11) Tank Super-natant	(12) Final Sludge
Flow (m^3/d)	7,570		7,570	19.7	7,550.3	92.1	46.8	45.3	45.3	45.3	24.65	20.65
BOD_5 (mg/L)	200		200	—	140	—	—	—	—			
BOD_5 (kg/d)	1,514		1,514	454	1,060	—	—	—	—	—		
TSS (mg/L)	200		200	50,000	70	9,000	—	40,000			27,360	60,000
TSS (kg/d)	1,514		1,514	984	530	829.1	—	1,813.1	1,469	1,239		1,239
VSS (mg/L)	150		150	37,500	52.5	—	—	—				
VSS (kg/d)	1,136		1,136	738	397.5	696.6	—	1,434.6	1,090.3	860		860
NVSS (mg/L)	50		50	12,500	17.5	—	—	—				
NVSS (kg/d)	378		378	246	132.5	132.5	—	378.5	378.5	378.5		378.5

[1] Sidestream loadings have been neglected for sludge digestion estimating purposes.

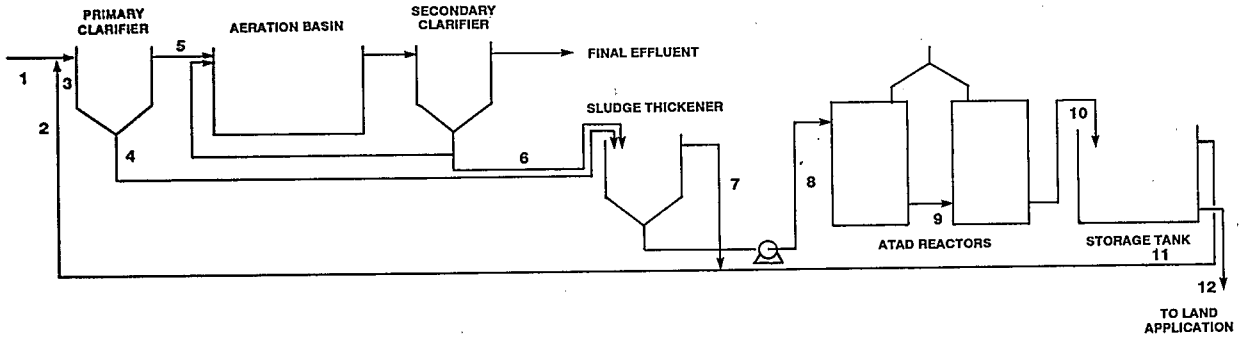

Figure 4-1. Process Flow Diagram for the Example Wastewater Treatment Plant.

NBVSS= nonbiodegradable volatile suspended solids in feed

X_a = active biomass

X_e = particulate biomass decay products

The active biomass fraction, X_a, is determined by:

$$X_a = \frac{Y(S_o - S_e)}{(1.0 + b\ SRT)} \qquad (2)$$

where:

Y = yield coefficient

S_o = influent substrate

S_e = effluent substrate

b = specific decay rate for active biomass

SRT = solids residence time

The particulate products arising from biomass decay, X_e, are determined by:

$$X_e = X_a\ (1.0 - f_d)\ b\ SRT \qquad (3)$$

where:

f_d = degradable fraction of active biomass

For this estimate, the following conditions or assumptions have been adopted:

NBVSS	=	40% of VSS
f_d	=	0.8
b	=	0.24 d^{-1}
SRT	=	5 d
Y	=	0.45 VSS/g chemical oxygen demand (COD)
COD/BOD	=	2.0

For sizing purposes, 100% substrate removal has been assumed, which reduces equation 2 to:

$$X_a = \frac{Y(S_o)}{(1.0 + b\ SRT)} \qquad (4)$$

Therefore:

$$NBVSS = 397.5 \times 0.4 = 159 \text{ kg/d}$$

$$X_a = \frac{0.45 \times 1{,}060 \times 2.0}{[1.0 + (0.24 \times 5.0)]} = 433.6 \text{ kg/d}$$

$$X_e = 433.6 \times (1.0 - .8) \times 0.24 \times 5.0 = 104 \text{ kg/d}$$

For design purposes, no credit has been taken for the loss of suspended solids to the effluent. Although the facility permit limitation is 30 mg/L, the facility is expected to operate consistently at lower levels and occasionally at much lower levels. Ignoring the credit for effluent loss will provide sufficient capacity during periods of exceptional treatment efficiency.

Therefore, total secondary sludge production is:

$$X_T = 132.5 + 159 + 433.6 + 104 = 829.1 \text{ kg/d}$$

(~ 830)

The volatile portion is:

$$VSS = 159 + 433.6 + 104 = 696.6 \text{ kg/d}$$

(~ 697)

The nonvolatile (fixed) portion is:

$$NVSS = 132.5 \text{ kg/d}$$

(~ 133)

This excess sludge will be wasted from the process at a concentration approximately equivalent to the secondary clarifier underflow concentration. For estimating purposes, this concentration has been assumed to be 9 g/L (0.9%).

The volume of waste-activated sludge, Q_w, is:

$$Q_w = (830 \text{ kg/d})/(9 \text{ kg/m}^3) = 92.2 \text{ m}^3\text{/d}$$

4.3.3 Digester Feed

Primary sludge and waste secondary sludge are discharged to a gravity thickener. The underflow concentration from the thickener is estimated to be 40 g/L (4%). For sizing purposes, 100% solids capture is assumed in the thickener. Sludge will be pumped directly from the gravity thickener to the ATAD system on a daily basis.

The ATAD feed conditions are:

TSS	=	984 + 830	= 1,814 kg/d
VSS	=	738 + 697	= 1,435 kg/d
NVSS	=	246 + 133	= 379 kg/d
Q_d	=	(1,814 kg/d)/(40 g/L)	= 45.3 m^3/d

Note that the VSS concentration (1,435/45.3 = 31.7 g/L or 3.17%) satisfies the minimum feed requirement of 2.5%.

Sludge feed pumping is sized to accomplish sludge pumping during a 30-minute period. From the above estimates, the daily sludge volume required to be pumped is 45.3 m^3/d. To deliver the daily volume of sludge in 30 minutes, the pumping rate is:

$$\text{Feed pump rate} = (45.3 \text{ m}^3\text{/d})/(30 \text{ min/d}) \times 1{,}000 \text{ L/m}^3$$

$$= 1{,}500 \text{ L/min (400 gpm)}$$

Depending upon site elevations, additional pumping may be required after ATAD to deliver sludge to a holding tank. If post-ATAD pumping is required, the pump sump must be sized to contain the daily feed volume that will be displaced from the process. Pump sizing is not dictated by process conditions and can be sized according to typical methods.

4.3.4 Digestion

The digestion process is expected to attain 35-45% reduction in overall VSS when treating a mixture of primary and waste-activated sludge. A 40% reduction has been assumed for this estimate. Approximately 60% of the total VSS reduction repor-

tedly occurs in the first-stage reactor. The resultant digester performance is:

Reactor I Effluent:

VSS= 1,435 x [1.0 - (0.4 x 0.6)]	= 1,090 kg/d
NVSS	= 380 kg/d
TSS= 1,090 + 380	= 1,470 kg/d

Reactor II Effluent:

VSS= 1,435 x [1.0 - 0.4]	= 860 kg/d
NVSS	= 380 kg/d
TSS= 860 + 380	= 1,240 kg/d

4.3.5 Sludge Storage and Disposal

Digested sludge will be discharged to a storage tank that will be equipped with the capability to decant supernatant. Although higher sludge concentrations can be achieved, this estimate assumes that the final sludge product, after storage and decant, will thicken to 60 g/L (6%). Neglecting solids loss with the decant stream, the final daily sludge volume is:

$$Q_{fs} = (1{,}240 \text{ kg/d})/(60 \text{ g/L}) = 20.7 \text{ m}^3/\text{d}$$

4.4 Reactor Sizing

Reactor sizing involves a multi-step process that begins with determining the active reactor volume, selecting dimensions for circular tanks with a height/diameter (H/D) ratio of 0.5 to 1.0, and adding additional height for foam management and freeboard.

The minimum active volume is based on hydraulic detention time. A 6-d total system hydraulic detention time is used as the design basis. With two tanks operating in series, each will have half the system detention time (3 d each). Based on the solids balance determined above, the active volume reactor sizes are:

$$V_R = 45.3 \text{ m}^3/\text{d} \times 3 \text{ d} = 140 \text{ m}^3$$

The typical range of 0.5 to 1.0 for reactor H/D ratio is considered during reactor sizing. Through trial and error, the active volume reactor dimensions are determined to be:

Active volume dimensions:	6.0-m diameter, 5.0-m height
Actual active volume:	141.3 m^3
Actual H/D:	0.83

Added height is required for foam management and freeboard. An additional 1.0 m is added for this purpose. The resultant final theoretical dimensions of the reactors are:

Reactor dimensions:	6.0-m diameter, 6.0-m height

(The above tank dimensions equate to a 18.8-ft diameter, 18.8-ft height, which represents odd-size dimensions for U.S. manufacturers. Adjustments in dimensions can usually be made to accommodate standard size tank dimensions. As an example, the tank diameter can be set at a standard 20 ft and the operating height determined accordingly [16-ft operating depth]).

4.5 Process Oxygen Requirement

The process air requirement is determined using conventional methods for aerobic digestion. However, one significant difference in the design approach is that the oxygen requirement for nitrification is not included because nitrification is suppressed at the higher operating temperatures of thermophilic systems. The process oxygen requirement (AOR) is estimated by the following:

$$AOR = 1.42 \text{ kg } O_2/\text{kg } VSS_d$$

where:

VSS_d = volatile suspended solids destroyed

Volatile solids destruction is estimated to be 575 kg/d (40%). The process oxygen requirement is:

$$AOR = 1.42 \times 575 = 815 \text{ kg } O_2/\text{d}$$

4.6 Aeration and Mixing Requirements

The aeration and mixing requirements for ATAD systems are crucial design elements. However, this part of the design process is the least defined theoretically and therefore requires further discussion before proceeding with the design example.

4.6.1 Discussion

A typical procedure for sizing aeration equipment is to adjust aerator standard transfer rates to field conditions (equation 5) and then to calculate total aeration requirements using the field transfer rate (equation 6).

$$OTR_f = \frac{\alpha(SOTR) \times 1.024^{(T_f-20)} \times (t_f\, \beta\, w_f\, C^*_{20} - C)}{C^*20} \quad (5)$$

$$A_{tp} = AOR/OTR_f \quad (6)$$

where:

OTR_f	=	field oxygen transfer rate, kg O_2/kWh
SOTR	=	standard oxygen transfer rate, kg O_2/kWh
α	=	oxygen transfer coefficient
β	=	oxygen saturation coefficient
C^*_{20}	=	equilibrium dissolved oxygen concentration at 20°C, mg/L
C	=	operating dissolved oxygen concentration, mg/L
T_f	=	field temperature, °C
t_f	=	temperature correction factor (C_{sat}^*/C_{S20}^*)
w_f	=	barometric pressure correction
A_{tp}	=	total aeration power required, kWh/d

Using the above method requires some knowledge of specific conditions, such as alpha (α) and beta (β), that are relevant for ATAD applications. Although these coefficients have been measured in wastewater environments, no coefficients are known to exist that are specific to ATAD systems. As can be seen from equation 5, the alpha value is an important coefficient that materially affects the calculated OTR_f value. Accurate estimates of oxygen transfer require representative alpha coefficients.

As an example, for a 5-m liquid depth, C^*_{20} would be about 10.4 mg/L. On the other hand, C_{SAT}^* varies as a function of temperature (5.93 mg/L at 45°C; 5.05 mg/L at 55°C). Under these conditions the field oxygen transfer rate from equation 5 is

	OTR_f	
Temperature (°C)	0 mg/L DO	1 mg/L DO*
45	1.18 $\alpha\beta$ SOTR	0.98 α SOTR
55	1.27 $\alpha\beta$ SOTR	1.03 α SOTR

* assumes β = 0.98

According to this table, the decrease in oxygen transfer that would be expected at higher temperatures because of decreased oxygen solubility is offset by the increase in the term 1.024 (T_f-20). Hence α is the key coefficient when translating clean water test performance into field transfer efficiencies in the ATAD environment.

An additional complicating condition, although a positive one, relates to observations by various researchers that oxygen utilization efficiency appears to be significantly enhanced in the ATAD environment (5, 25, 26). This enhancement is believed, in part, to be related to the presence and extent of foam in the reactors. The foam itself can have a high oxygen demand, probably as a result of entrained biology (26). Air entering into the foam layer from the liquid phase may provide significant oxygen transfer into the overlaying foam. This additional transfer would not be included with traditional computational procedures (equation 5).

This observation indicates that the efficiency of aeration is inextricably linked with the process operating conditions and that typical methods for estimating field efficiency from standard conditions cannot be used with confidence until process factors have been fully defined and quantified. These and other factors are the subjects of ongoing research in the FRG that will aid in developing the theoretical design basis for ATAD aeration and mixing.

Although not all mechanisms that may be contributing to oxygen transfer are understood, ATAD systems are being routinely designed using empirical methods developed from extensive pilot- and full-scale operations. This approach is illustrated in the following example.

4.6.2 Empirical Aeration/Mixing Sizing

As a result of full-scale research at Gemmingen (20), direct estimates of field oxygen transfer rates were made in ATAD systems equipped with Fuchs aerators. Values ranged from 1.5 to 3.7 kg O_2/kWh. The manufacturer utilizes 2.1 kg O_2/kWh for design purposes.

Using the manufacturer's design value assuming a peaking factor of 1.5 (see Section 5.3), the aeration requirement is determined by:

$$\frac{815 \text{ kg } O_2/\text{d} \times 1.5}{24 \text{ hr/d}} = 51 \text{ kg } O_2/\text{hr}$$

$$\frac{51 \text{ kg } O_2/\text{h}}{2.1 \text{ kg } O_2/\text{kWh}} = 24.3 \text{ kWh}$$

(32.6 hp)

A minimum of two foam cutters is required for each ATAD reactor and, depending on reactor geometry, as many as three can be installed. Recently designed facilities with a reactor diameter less than or equal to 6 m have been equipped with two units, each rated at 0.75 kW. Reactor sizes greater than 6 m have been equipped with three units at 0.75 kW. For this example, a 6-m diameter reactor size has been selected. Therefore, each reactor will be equipped with two units rated at 0.75 kW each.

Mixing and energy requirements are checked to determine that they are within design ranges given below:

Specific power:	85-105 W/m^3 of active volume
Throughput energy:	9-15 kWh/m^3 of sludge throughput

Theoretical specific power requirement:

$$\frac{\text{Aeration: 24,300 W}}{(140\ \text{m}^3 \times 2\ \text{reactors})} = 87\ \text{W/m}^3$$

$$\frac{\text{Foam Cutter: 3,000 W}}{(140\ \text{m}^3 \times 2\ \text{reactors})} = 10.7\ \text{W/m}^3$$

Total $= 97.7\ \text{W/m}^3$

Theoretical throughput energy requirement:

$$\frac{27.3\ \text{kW} \times 23.5\ \text{hr/d}}{45.3\ \text{m}^3/\text{d}} = 14.2\ \text{kWh/m}^3$$

(Note that 23.5 hr/d is used in the above calculation because the aeration equipment is turned off for one-half hour per day during feeding.)

The above values do fall within the typical design ranges.

4.7 Sludge Storage

Sludge storage requirements will vary for each application. This estimate assumes that the final sludge will be land applied as a liquid and that, due to frozen or snow-covered conditions, 90 consecutive days of storage will be required. Note that more northern climates (e.g., New England, Canada) may consider additional storage capacity to suit local conditions. Other factors, such as warmer climates, rainfall, crop rotation, and seeding/harvesting schedules, may impact the total storage volume required for a specific site.

The required storage volume is:

$$V_s = 20.7\ \text{m}^3/\text{d} \times 90\ \text{d} = 1{,}863\ \text{m}^3$$

The storage tank must be equipped with a mixer and the ability to decant supernatant.

4.7.1 Mixing

The sludge storage tank must be mixed for about an hour each day to limit the potential for storage odors and reactivation of pathogens. Submerged mechanical mixers are typically used for this purpose. The procedure for mixer sizing is typical of mixer sizing procedures for other sludge storage applications. However, the potential exists to thicken beyond the 6% solids concentration used for the volume estimates. Mixer sizing should be capable of handling about 12% solids in the storage tank.

4.8 Cost Estimate[1]

For planning purposes, a cost estimate is presented here using the data summarized in Chapter 8. The cost data are presented on the basis of a sludge throughput of 1,814 kg/d (see Section 4.3.3). Figure 8-1 is a plot of cost data summarized in Table 8-3 and includes estimated costs for a prethickener, ATAD system, and post-storage tank (20-d storage basis). The projected cost for 1,800 kg/d sludge throughput is $480,000, of which $50,000 is for a sludge storage tank with a 20-d capacity. The scaled up storage tank cost (for 90-d storage capacity) is $225,000, resulting in a total system cost of $655,000. The actual ATAD component cost is $330,000, or about one-half of the total system cost.

[1]The cost estimate summarized here is included as an example for planning purposes. Each facility will have site-specific factors to take into account in assessing system cost, including site conditions, disposal limitations, climate, and availability of existing equipment.

Chapter 5.
Performance Data

5.1 Introduction

The proliferation of ATAD systems throughout the FRG has given researchers the opportunity to study and collect operating data on full-scale operating systems over the last decade. The system located in Gemmingen was studied extensively by Breitenbücher, resulting in a comprehensive summary of performance levels (5). Other studies have focused on particular issues related to ATAD, such as pathogen destruction and oxygen transfer efficiency (25, 27). In the United Kingdom, studies at the Water Research Centre have led to commercial applications of ATAD technology utilizing venturi aeration (26). Four full-scale facilities are located in Canada, three of which have been studied under the sponsorship of the Environment Canada's Wastewater Technology Centre. These comprehensive studies include data and experience concerning the retrofit of mesophilic aerobic digesters to achieve autothermal thermophilic conditions (16). In the U.S., several laboratory and pilot studies have been conducted.

This chapter discusses and summarizes performance data and experience related to several factors that characterize digestion systems in general and ATAD systems in particular.

5.2 Volatile Solids Reduction

ATAD, like other digestion systems, is intended to reduce the total mass of sludge requiring disposal and to produce a stabilized final product suitable for disposal or reuse. Digestion processes reduce sludge mass by destroying some of the volatile suspended solids. The percent VSS reduction achievable by digestion varies depending on the feed sludge make-up and operating conditions in the overall treatment plant. For example, VSS reduction can be influenced by process residence time, operating temperature, VSS concentration of raw sludge, and VSS mass loading. Long-term controlled studies by Breitenbücher indicate that VSS removal efficiency is strongly related to both reactor detention time and temperature (5).

Data on VSS reductions obtained from nine ATAD facilities in the FRG are summarized in Table 5-1.

The data reflect a range of HRTs (5-12 d) and raw sludge feed concentrations. These values are in agreement with minimum VSS removal efficiencies of 25-35% (27) and 35-45% (28, 29), and COD removal efficiencies of 40-45% (30) for ATAD systems with HRTs of 6 or more days. Generally, VSS reduction efficiencies for ATAD systems are comparable to those of other forms of digestion.

Changing operational modes as well as seasonal influences make it difficult to define precise design and/or operational relationships for some plants. For example, the loading of the Kirchberg plant fluctuates between 350 and 900 kg VSS/d, with reduction efficiencies between 66% and 43%. This is also the case in Gemmingen, where a variation in loading from 130 to 420 kg VSS/d leads to varying reduction efficiencies between 30% and 45%. Additionally, the Gemmingen facility treats only waste-activated sludge, whereas the Kirchberg facility treats a combination of primary, trickling filter, and waste-activated sludges.

Data from the Tönisberg plant show how strongly sludge degradability affects the average degradation efficiency. Because the plant had unused free capacity, it was fed with sludge from other plants.

Table 5-1. Summary of VSS Reduction Observed at Nine ATAD Facilities Where Data Were Available

Facility	VSS Reduction (%)
Backnang	48
Gemmingen[1]	25 - 40
Kirchberg	43 - 66
Neckarwestheim	35
Nette[2]	30
Rheinhausen[3]	44
Römersberg	41
Tönisberg[4]	33 - 56
Vilsbiburg	41 - 44

[1]Waste-activated sludge only.
[2]Industrial waste contribution - 50%.
[3]During a 14-week test period.
[4]During 1- and 2-stage operation.

After extraneous sludge was introduced, the average degradation efficiency dropped from 56% to 33%. This drop occurred even though the operational mode was changed from one to two stages during the same period, which should have compensated for the increased loading and allowed the plant to sustain a similar performance level. Even with the decreased VSS reduction, the second-stage temperatures were still > 50°C.

5.3 Pathogen Reduction

Several studies have been performed at pilot- and full-scale plants with different substrates and various indicator organisms. Table 5-2 summarizes results from selected published studies and the respective conditions that have been identified as necessary to achieve disinfection. These data indicate that a properly operated ATAD process can achieve the FRG requirements for the disinfection of sewage sludge or manure (see Appendix for a discussion of the FRG regulations). (Chapter 6 discusses the ability of ATAD to meet proposed U.S. standards for land application of sludge.)

The actual disinfection mechanisms are still largely unclear. Various organisms are probably destroyed by different, partly synergistic, combinations of mechanisms. For example, *Ascaris* egg cytoplasm is destroyed by temperatures ≥ 50°C (31). Reduction of enterovirus appears to require a combination of temperature and basic pH. Martin (32) has determined a strong relationship between temperature conditions and enterovirus reduction. Other data indicate that the chemical or biochemical reactions initiated by increasing pH values (e.g., release of virucide ammonia) are important factors in enteroviruses destruction (33). Jakob et al. (34) have proposed that disinfection may also occur through an inhibiting ("antibiotic") effect of microbial metabolism products; Strauch (35) reports that this has been proven experimentally while treating pig manure. Still other phenomena that have not been quantified are believed to participate in disinfection (36). During investigations in Gemmingen, organisms in closed ampules that had been fed to the reactor and that were not in direct contact with the substrate survived much longer than equivalent free-swimming organisms (see Table 5-3).

Tables 5-3 to 5-6 summarize the results of disinfection studies for various organisms at four full-scale plants: Gemmingen, Kirchberg, Ellwangen, and Nette. Since these are exclusively Fuchs plants, all conclusions derived from these studies are valid only for this type of plant. The investigations were carried out under operational conditions. At Ellwangen (Table 5-5) the temperature in reactor II was maintained by a heat exchanger within a narrow

Table 5-2. Investigations of the Influence of Time, Temperature, and pH on Disinfection at Pilot- and Full-Scale ATAD Plants in the FRG

		Investigated		Inactivation		
Authors	Scale	Pathogens	Substrate	pH	°C	t (hr)
(33, 37)	pilot	bovine enterovirus	pig manure	6.5	55	48
(38, 37)	pilot	rhinovirus, foot-and-mouth disease	pig manure	8.0	50	48
(39, 37)	pilot	pseudorabies virus	pig manure	8.0	40	50
(40, 37)	pilot	reovirus	pig manure	9.0	48	78
		enterovirus		9.0	48	48
		adenovirus		9.0	48	87
(37)	pilot	swine vesicular disease	pig manure	8.0	45	48
(41)	pilot	*Salmonella*	pig manure	8.5	40	10
		Salmonella	cattle manure	8.7	45	48
(31, 41)	pilot	*Salmonella*	sewage	8.7	40	48
			sludge	8.5	45	10
		Ascaris eggs		7.5	50	57
(36, 42)	full	*Salmonella*, enterobacteriaceae	sewage sludge	8.0	50	48

Table 5-3. Pathogen Reduction at the Gemmingen Plant (4, 18, 19, 49)

Parameter[2]	Test Series[1] A	B	C	D	E	F	G	H	I	J
Temperature (°C)										
Influent	10	13	15	16	17	16	18	16	12	9
RI min	36	34	45	44	49	48	48	57	39	35
RI max	45	39	53	52	62	61	63	67	46	43
RII min	46	45	53	55		63			52	48
RII max	47	47	53	58		65			59	54
pH[3]										
Influent	6.4	6.6	6.2	6.5	6.2	6.3	6.3	6.2	6.4	6.3
RI	7.9	7.8	7.6	8	8	8	8.2	8.2	7.6	7.7
RII	8.3	8.2	8.4	8.4		8.4			8.5	8.2
Coliform (mL^{-1})										
Influent	2.7E+06	1.6E+06	3.1E+07	9.7E+04	1.3E+06	1.6E+06	8.3E+04	1.1E+05	2.3E+06	3.4E+06
RI	6.1E+03	2.3E+04	-	-	-	-	-	-		
RII	9.4E+04	2.4E+04	-	-		-			-	-
Salmonella[4]										
S. senftenberg										
RI										
A	+	+	+	+	-	-	-	-		
K	+	+	+	+	-	-	+	-		
RII										
A	+	+	-	-		-			-	-
K	+	+	-	-		-			-	-
S.typhimurium										
RI										
A	+	+	+	+	-	-	-	-		
K	+	+	-	-	-	-	-	-		
RII										
A	+	+	-	-		-				
K	+	+	-	-		-				
Contact Time (hr)										
RI	96	96	96	96	96	96	48	24		
RII	96	96	96	96	96	96	10	48		
HRT (days)	8	8	8	8	8	8	4	6	6	6

Notes:
[1]A-H test series performed with coliform organisms in a closed container, I-J series with coliforms in direct contact with substrate.
[2]RI = Reactor I; RII = Reactor II; HRT = hydraulic residence time.
[3]pH values are average over test period.
[4]A = *Salmonella* in a closed container; no substrate contact.
K = *Salmonella* in contact with substrate.
+ = detected.
- = not detected.

range between 47.5°C and 50°C. These relatively low temperatures reduced all tested pathogens as effectively as the higher temperatures in the other plants.

Most indicator organisms are significantly reduced in the first reactor. An exception is *Salmonella*, which is only reliably eliminated during the second stage (34, 35). This observation supports the two-stage design concept.

Figures 5-1 and 5-2 show the pathogen reduction performance at two operating facilities: Kirchberg and Ellwangen. At Kirchberg, a 4.5-log reduction in

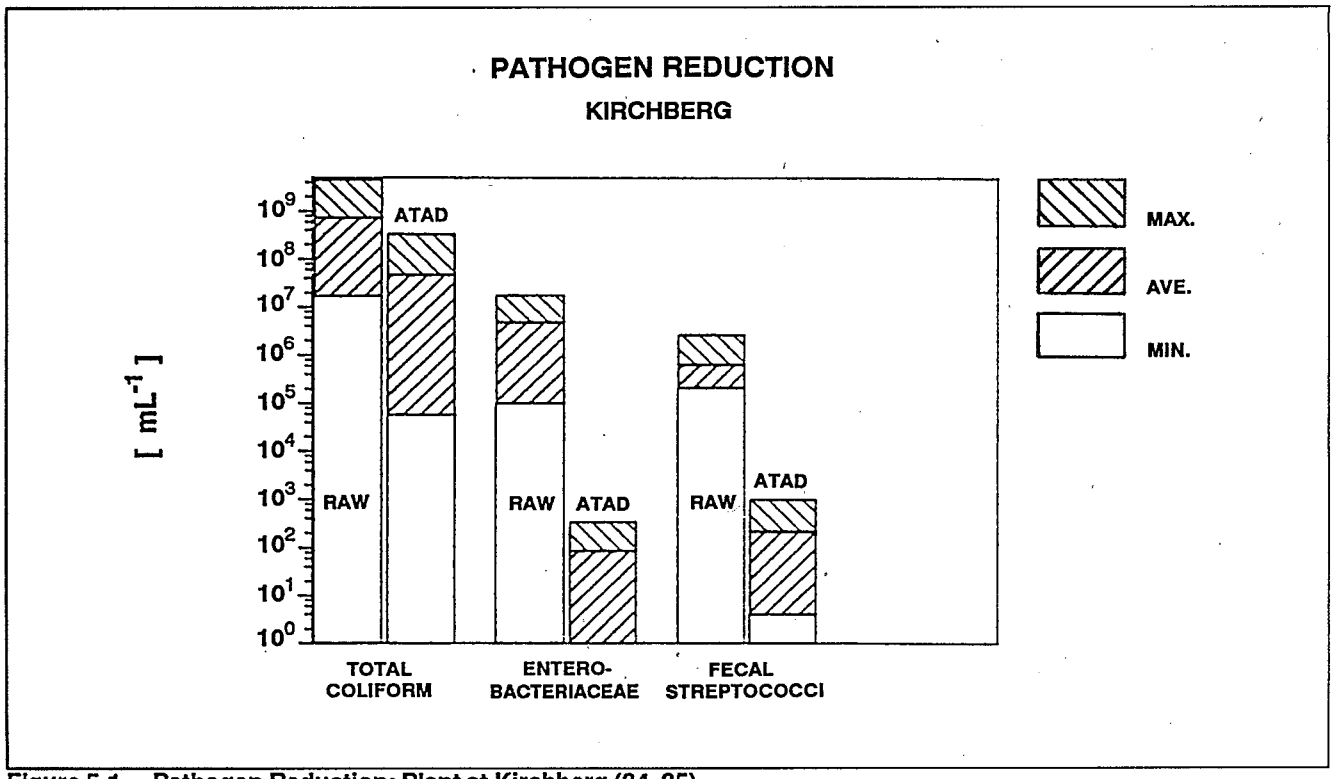

Figure 5-1. Pathogen Reduction: Plant at Kirchberg (34, 35).

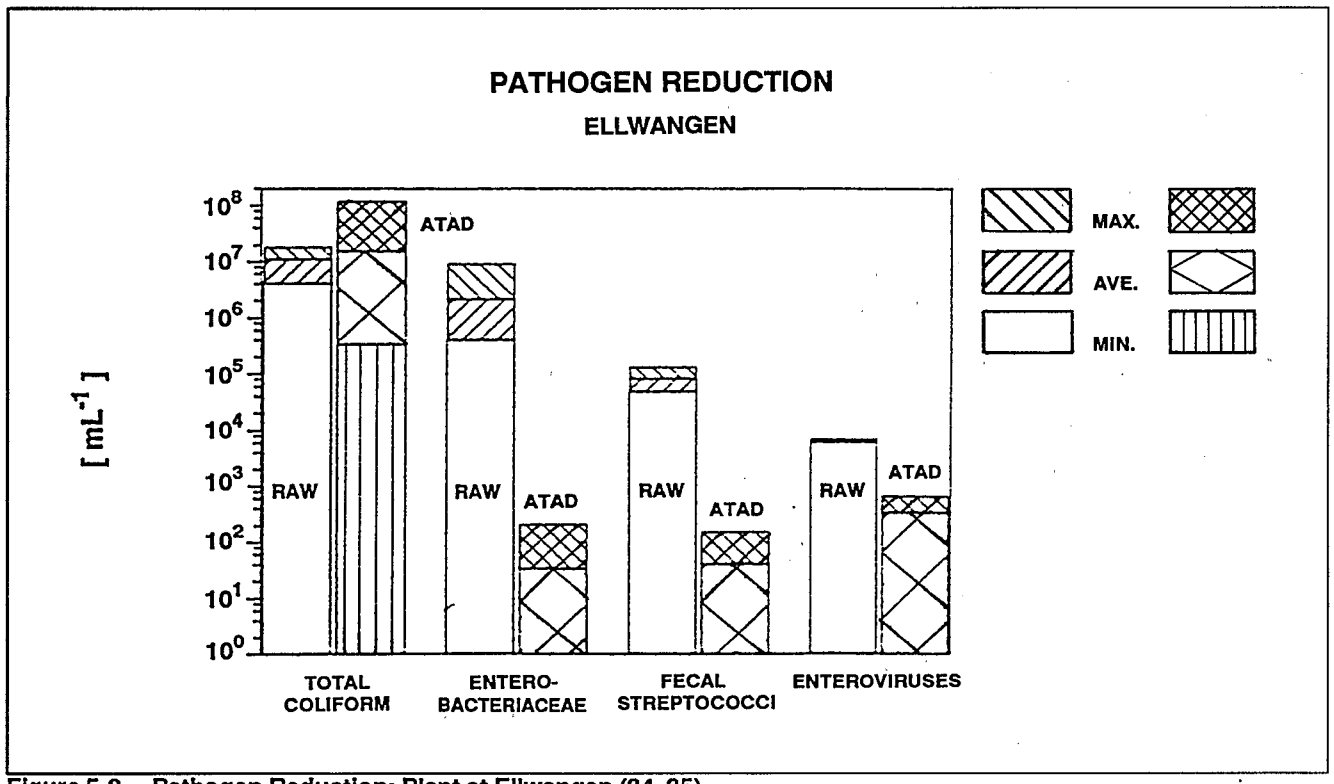

Figure 5-2. Pathogen Reduction: Plant at Ellwangen (34, 35).

enterobacteria and a 3.0-log reduction in fecal streptococci were observed at an average temperature of 53°C and an 8-d residence time. At Ellwangen, a 5.5-log reduction in enterobacteria, a 3.5-log reduction in fecal streptococci, and 1.0- to 3.5-log reduction in enterovirus were observed at an average temperature of 49°C and a residence time of 5 d. *Salmonella* and *Ascaris* (not shown) were not detected at either facility in the treated sludges.

5.4 Dissolved Oxygen Concentrations and Respiration Activity

Dissolved oxygen measurements in some ATAD studies have varied from 0.7 mg/L to more than 3 mg/L for about 80% of the reactor height (5). Other recent measurements in a single-stage ATAD system have shown negligible dissolved concentrations ranging between 0 to 0.2 mg/L (25). These recent measurements suggest that oxygen concentration can be a limiting factor for a portion of the batch cycle after new sludge feed has been introduced and is not uniform throughout.

Figure 5-3 illustrates the course of the respiration rate in an experimental ATAD system over several days. These measurements were taken from a single-stage ATAD plant with the following basic design features: reactor volume of 27 m^3, two spiral aerators (2.2 and 4.0 kWh), specific power input 230 W/m^3 (note: the specific power value of 230 W/m^3 for this experimental observation period is over twice the normal design power input for Fuchs full-scale systems), specific air input 6.9 (m^3/hr air)/m^3, feed solids concentration between 6 and 6.5% and reactor solids between 4 and 4.5% (33).

Figure 5-3 indicates the cyclic nature of the specific oxygen uptake rate (SOUR), which is consistent with the batch feeding strategy. The SOUR values observed during this study averaged 287 (g O_2/d)/kg VSS [11.96 (mg O_2/hr)/g VSS], which is equivalent to an oxygen uptake rate of 476 (mg/L)/hr. The maximum and minimum values were about 140% and 35%, respectively, of the average value.

5.5 Oxygen Transfer Efficiency (OTE)

Earlier evaluations of ATAD processes that used air aeration emphasized the need for an efficient aeration system to limit the heat loss through the exhaust of latent heat from the reactor. This factor was considered crucial for the process to achieve the autoheated state. Several attempts at developing ATAD systems have been affected by factors related to aeration and mixing.

The first known full-scale ATAD system using air aeration was developed by Fuchs. So many of these systems are now operating successfully that there is a general belief that aeration and mixing in an ATAD system must be efficient and effective to support the

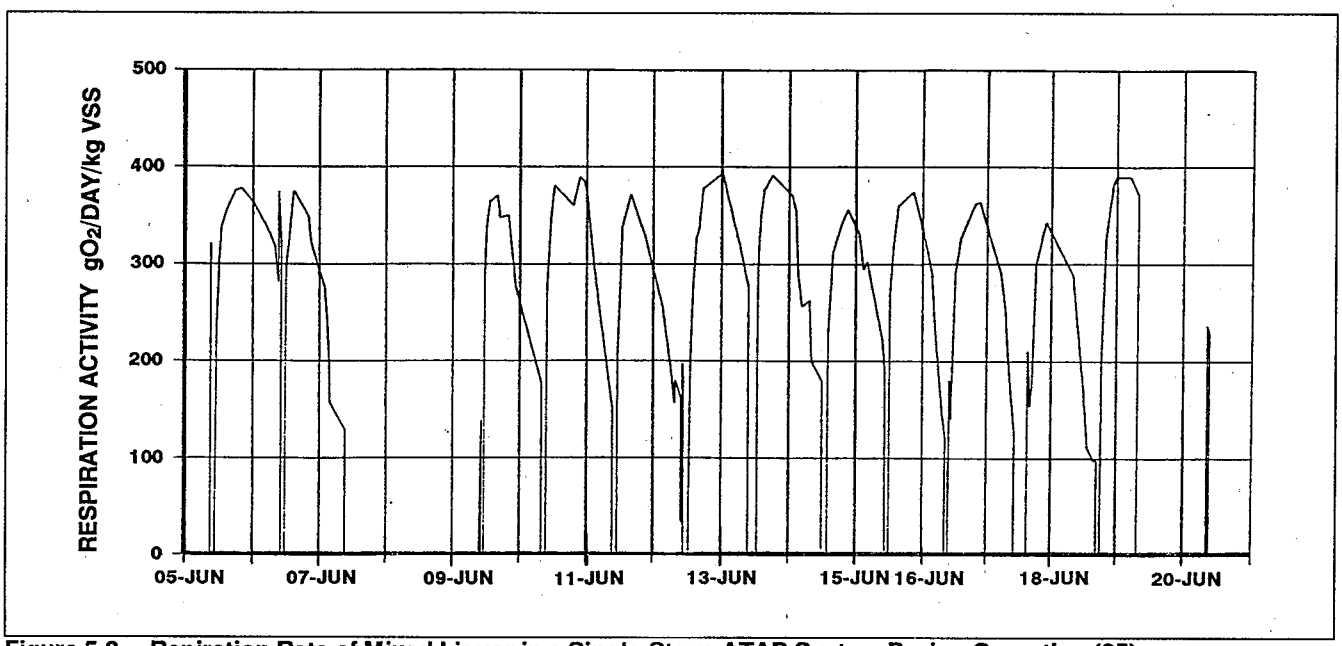

Figure 5-3. Repiration Rate of Mixed Liquor in a Single-Stage ATAD System During Operation (25).

Table 5-4. Pathogen Reduction at the Kirchberg Plant (34, 35)

Parameter		Raw	ATAD
Residence time (d)			5
Temperature (°C)	min	NA	44
	max	NA	60
	av.	NA	53
No. of samples		8	8
pH - value	min	5.9	8.6
	max	6.3	8.9
	av.	6.1	8.8
Total bacteria count (mL^{-1})	min	$1.7\ 10^7$	$5.8\ 10^4$
	max	$4.4\ 10^9$	$3.3\ 10^8$
	av.	$7.3\ 10^8$	$4.7\ 10^7$
Enterobacteriaceae (mL^{-1})	min	$1.0\ 10^5$	NA
	max	$1.8\ 10^7$	$3.4\ 10^2$
	av.	$4.8\ 10^6$	$8.6\ 10^1$
Fecal streptococci (mL^{-1})	min	$2.1\ 10^5$	$4.0\ 10^0$
	max	$2.6\ 10^6$	$1.0\ 10^3$
	av.	$6.3\ 10^5$	$2.2\ 10^2$
Salmonella (% positive)		100	ND

NA = not available.
ND = not detected.
av. = average.

process. This section describes the present level of understanding concerning these factors.

The Fuchs aeration devices are best described as aspirator-type aerators (see Figure 3-2). In a typical ATAD system, aerators are installed in ports through the reactor side walls. An additional aerator, centrally located in the reactor, may also be required depending on the diameter of the tank. An average of 2.1 kg O_2/kWh is used by the manufacturer to estimate the oxygen transfer capacity in the sludge environment. However, sizing is normally based on mixing energy requirements.

Breitenbücher observed an apparent relationship between the oxygen utilization efficiency (analogous to oxygen transfer efficiency), reactor solids concentrations, and the presence or absence of foam in the reactor. Specifically, he indicated that oxygen utilization efficiency increases with increased solids concentrations (to about 5% TS) and that it also increases with the presence of a foam layer in the reactor (43). Later studies by Wolenski and Bruce (with an ATAD system using an exterior venturi for oxygenation), confirmed that the foam layer that developed in their reactor enhances oxygen utilization efficiency (26). The foam layer was shown to

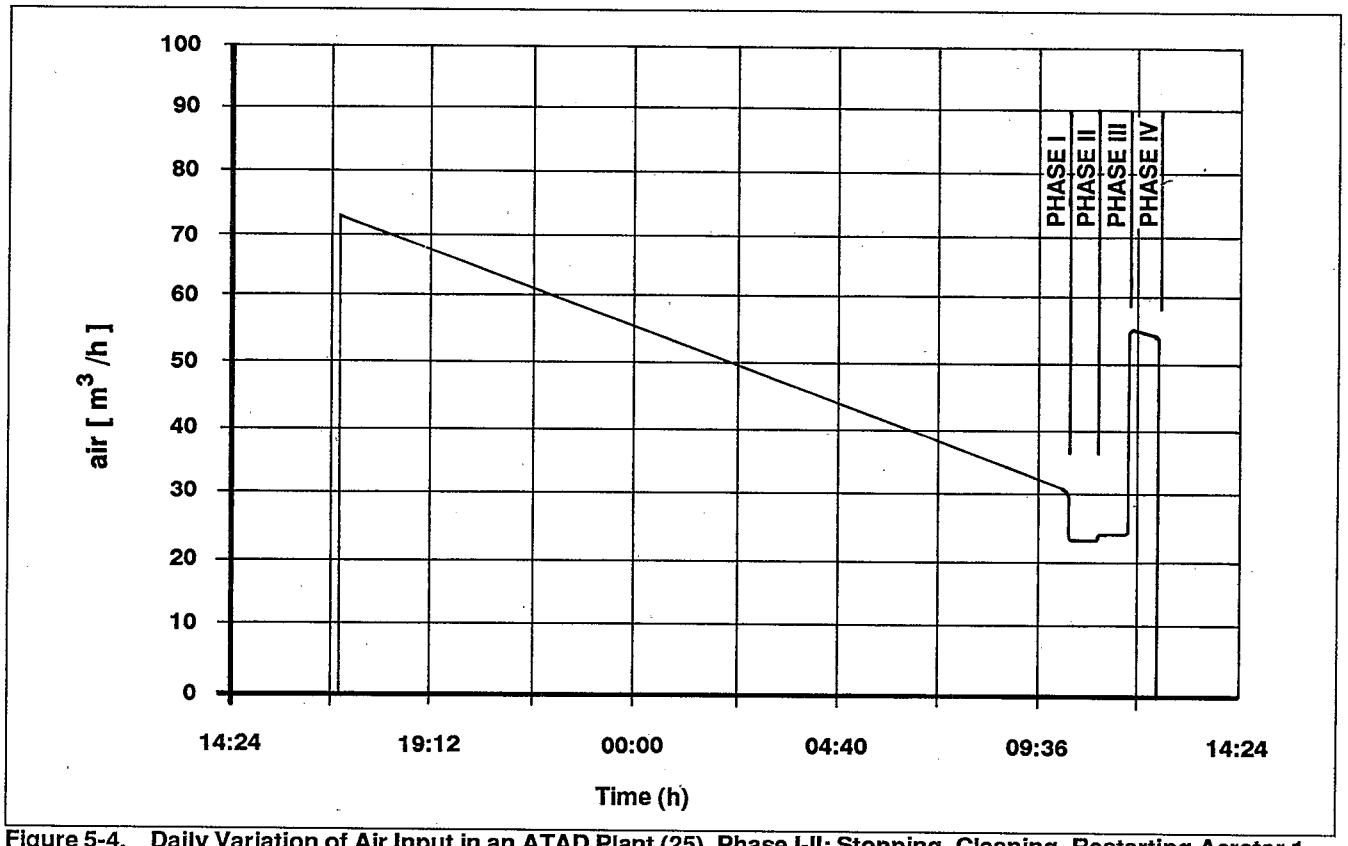

Figure 5-4. Daily Variation of Air Input in an ATAD Plant (25). Phase I-II: Stopping, Cleaning, Restarting Aerator 1. Phase III-IV: Stopping, Cleaning, Restarting Aerator 2.

contain high concentrations of sludge solids. Process air that is trapped in the foam layer for a time prior to being exhausted will increase contact time with the sludge solids, resulting in the opportunity for additional oxygen utilization.

Clean water oxygen transfer tests have been performed on Fuchs aeration equipment in Europe; however, the above observations indicate that the issue of oxygen transfer efficiency cannot be separated from the process conditions, especially mixing.

Investigations at Gemmingen reported OTE values between 12% and 37%, with an average of 18% (5). The transfer rate varied between 0.4 and about 3.0 kg O_2/kWh, with an average of 1.8 kg O_2/kWh.

OTE values between 11% and 70% have been reported from investigations at a pilot facility in Darmstadt (25). At 230 W/m^3, most values ranged above 50%. Further measurements on various full-scale plants range between 20% and 90% OTE (44, 27). Wolenski and Bruce (26), utilizing a venturi aeration system, reported oxygen utilization efficiencies as high as 100% although mixing requirements were high.

In one study, the air flow rate into an ATAD reactor was approximately 50% lower than in clean water conditions, presumably due to higher viscosity conditions (Figure 5-4). A further reduction also appeared within a day due to the accumulation of deposits inside the hollow shafts of the aerator. Periodic flushing limited buildup, which leads to a recommendation to carefully maintain the aerators through periodic flushing to sustain process performance.

Figure 5-5 shows a typical variation of the OTE during the same reactor cycle as in Figure 5-4. The increasing oxygen utilization is attributed to the foam layer formed during operation (25). (This should be understood as an empirical explanation, and not a direct definition of the role of the foam layer.) The effect in Figure 5-5 could also be explained by different phenomena, such as an increased oxygen residence time in the foam layer with decreases in air input. The interrelationships among sludge viscosity, mixing energy, temperature, foam, and oxygen transfer efficiency in the ATAD environment

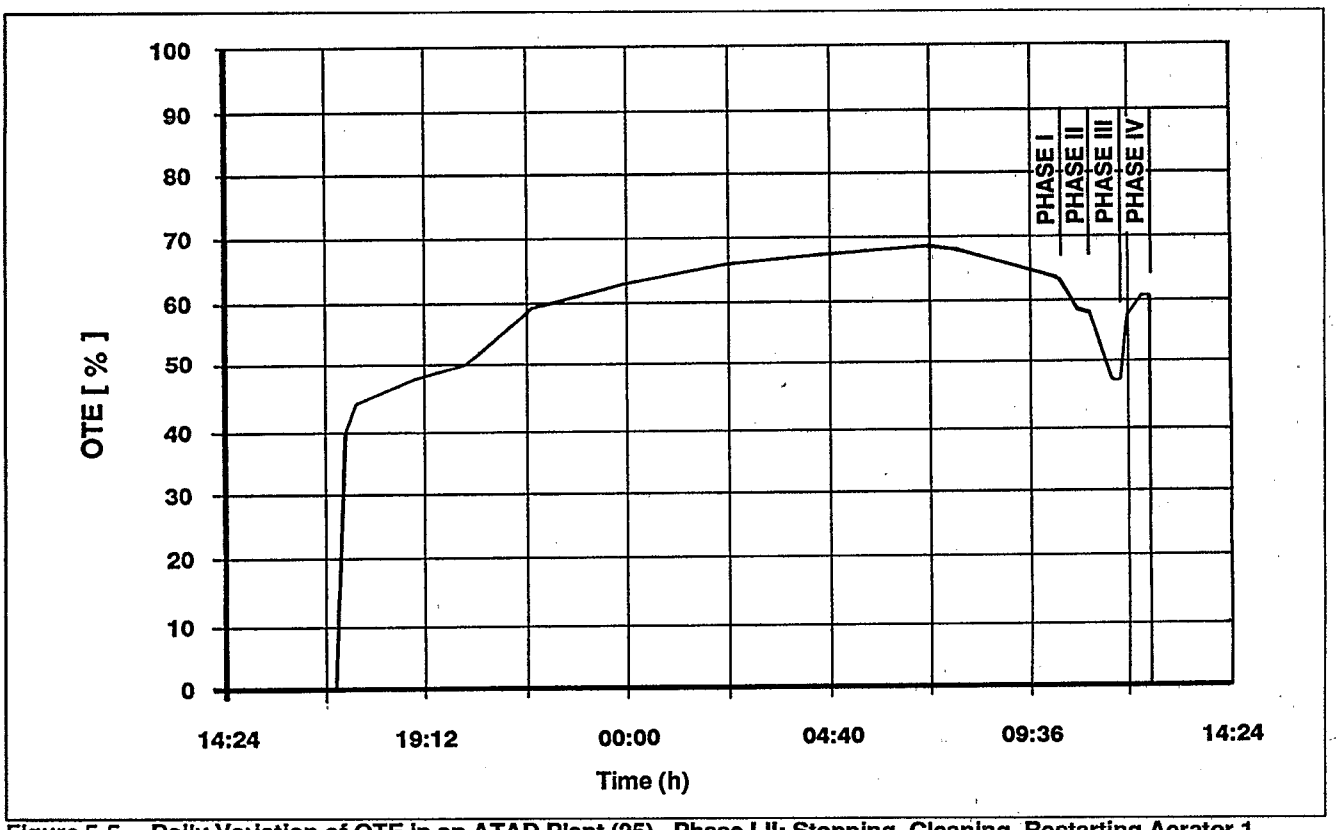

Figure 5-5. Daily Variation of OTE in an ATAD Plant (25). Phase I-II: Stopping, Cleaning, Restarting Aerator 1. Phase III-IV: Stopping, Cleaning, Restarting Aerator 2.

are not adequately defined, which explains the empirical approach to aeration and mixing design.

5.6 Odor Control

ATAD odors are characterized mainly as humus-like, with some gaseous ammonia. At the Nette plant in the FRG, triethylamine was also detected. Ammonia is released by thermophilic aerobic degradation during digestion and cannot be avoided. Ammonia is not subsequently nitrified due to the suppression of nitrification at thermophilic temperatures. Depending on the pH of the reactor, ammonia can be stripped into the exhaust. ATAD systems typically exhibit an elevated pH, particularly in the second-stage reactor (5), which enhances the stripping potential for ammonia.

Many of the early facilities did not include provisions for odor control. Exhaust air was generally characterized as having a humus-like odor that did not require treatment. With an increasing number of facilities located in nonrural areas, provisions for odor control have become routine.

Sufficient odor control can usually be accomplished by returning the exhaust air to the activated sludge aeration tank or into trickling filters. Odor control devices are used for situations requiring long pipe runs or more precise control.

Seven plants, representing about 16% of all ATAD plants, reported odor problems, and seven plants reported using control devices. These two groups of seven facilities are not identical, i.e., not all plants with problems have control devices and vice versa.

Site visits indicated that most odors were short-term events that occurred when raw sludge was pumped into the reactor and when raw sludge odors were stripped out into the exhaust. One plant reported odors when the temperature in the second-stage reactor approached 70°C. Another experienced odor problems (along with the entire treatment plant) during an organic overload condition (50% above design) that resulted during peak vineyard processing periods. This plant was not equipped with odor controls.

Common odor control devices are biowashers and biofilters. Not enough experience has been gained

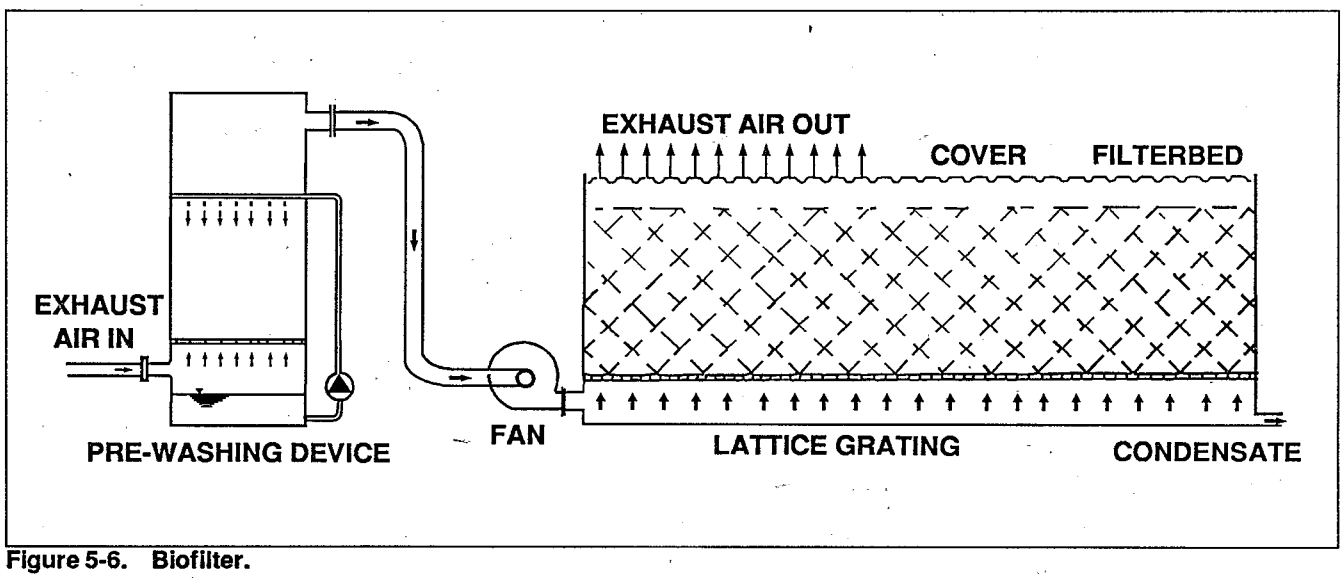

Figure 5-6. Biofilter.

with either device to compare their performance. The biowashers are designed as tower-like counter-current washers filled with filter elements and equipped with a water recirculation system. The condensate is removed from the air by a drop separator. At the Nette plant in the FRG, a system has been installed for a maximum of 2,000 m^3/hr exhaust air with a 2 x 30 m^2 filter area. No odor problems have been reported for this facility (23).

The biofilter (see Figure 5-6) consists of a simple tank containing a filterbed of biologically active material (compost, bark, or similar material). Odors are removed by adsorption and digestion. The filter bed should have a moisture content between 40% and 60%.

A water scrubber precedes the actual filter to pre-humidify the air to a moisture level of about 95%. Additional parameters for biofilter design are hydraulic filter load (m^3 air/(m^2 filter hr), void volume ($\leq$ 80%), reaction time ($\geq$ 50 s), specific biomass load, VSS in the odor control device, respiration activity, and pH (25). No odor-related problems have been reported at the Walheim facility in the FRG, which uses a biofilter-type system for odor control.

5.7 Operation and Maintenance

All ATAD facilities in the FRG are reportedly easy to operate and require very little process control and maintenance. In most cases, process control consists of performing periodic suspended solids and pH analyses, monitoring reactor temperatures, and controlling the pumping of specific volumes of sludge to the ATAD reactors on a batch basis. The normal control parameter for sludge volume management is the filling level.

Most operators of ATAD plants prefer to run their plants manually or semi-automatically, even if they are equipped with the necessary equipment for full-automatic control. "Semi-automatic" operation means that the program for withdrawal and filling is started manually.

Aeration control can be optimized through the use of Programmable Logic Controllers (PLCs) or timers. Automatic aeration control could provide important energy savings, even with simple timer-controlled strategies such as running on full speed for 4 to 5 hr after batch filling followed by a downshift to half speed.

At least three FRG facilities have been equipped with two-speed drive motors for the aerators because of the extremely variable seasonal loading. It is not known if the operators have attempted to optimize aeration on a daily basis. The use of respiration activity as the control variable has recently been proposed as a more direct control concept for the process (25).

Maintenance requirements are reported to be low — from 2 to 6 hr/week (excluding sampling or analysis). The most frequently reported maintenance requirement is flushing the aerator hollow shafts, which requires a few minutes for each aerator. One plant reports the practice of flushing the shafts twice per day, while others report twice per week requirements. *Flushing of the aerator hollow shafts is an important practice that must be conducted on a scheduled basis.* The importance of the

Table 5-5. Pathogen Reduction at the Ellwangen Plant (34, 35)[1]

Parameter		Period 1 Raw	Period 1 ATAD	Period 2 Raw	Period 2 ATAD
			5		5
Residence time (d)					
Temperature (°C)	min	NA	48.5	NA	43
	max	NA	50	NA	5
	av.	NA	49	NA	49
No. of samples		9	9	10	10
Total bacteria count (mL^{-1})	min	$4.0\ 10^6$	$3.3\ 10^5$	$3.6\ 10^6$	$7.0\ 10^5$
	max	$1.8\ 10^7$	$1.21\ 10^7$	$3.6\ 10^7$	$5.3\ 10^7$
	av.	$1.1\ 10^7$	$1.5\ 10^7$	$1.6\ 10^7$	$1.2\ 10^7$
Enterobacteriaceae (mL^{-1})	min	$4.0\ 10^5$	ND	$1.1\ 10^5$	ND
	max	$9.0\ 10^6$	200	$6.6\ 10^6$	300
	av.	$6.3\ 10^6$	33	$1.9\ 10^6$	77
Enteroviruses (mL^{-1})	min	$6.0\ 10^2$	ND	$4.6\ 10^3$	ND
	max	$6.6\ 10^3$	660	$1.4\ 10^4$	ND
	av.	$6.3\ 10^3$	330	$1.1\ 10^4$	ND
Fecal streptococci	min	$4.8\ 10^4$	ND	$3.3\ 10^4$	ND
	max	$1.3\ 10^5$	150	$2.1\ 10^5$	490
	av.	$8.1\ 10^4$	39	$8.7\ 10^4$	140
Salmonella (% positive)		78	ND	90	ND

NA = not available.
ND = not detected.
[1]Second-stage reactor cooled to 50°C during test period.

flushing is emphasized by the findings illustrated in Figure 5-4: Significant air volume reductions occur under fouling conditions.

One Canadian facility experienced erosion of aerator impellers after a 1-yr period due to accumulation of grit in the sludge (16).

Table 5-6. Pathogen Reduction at the Nette Plant (23)

Parameter		Raw	ATAD
Residence time (d)			5
No. of samples		9	
Temperature (°C)	min	NA	46
	max	NA	66
	av.	NA	59
pH - value	min	NA	7.3
	max	NA	8.7
	av.	NA	8.2
Enterobacteriaceae (mL^{-1})	min	$1.0\ 10^6$	100
	max	$1.0\ 10^7$	$1.0\ 10^4$
	av.	$8.0\ 10^6$	$1.2\ 10^3$
Salmonella (% positive)		100	ND

NA = not available.
ND = not detected.

Chapter 6.
Ability to Meet U.S. Regulatory Standards

6.1 Introduction

Regulations governing the land application of sludge have been in force since 1979 (16); new regulations were proposed in 1989 (46). This chapter describes the current and proposed regulations, and presents data indicating that the ATAD process can be operated to meet the most stringent U.S. regulatory requirements. ATAD sludges that meet the requirements can be applied to agricultural and forage land without access and use restriction.

As of publication, the new regulations were scheduled for promulgation in October 1991. The final regulations almost certainly will differ somewhat from the proposed regulations discussed here. The reader should obtain a copy of the most recent proposed or final regulations in order to fully assess the operational requirements for ATAD to meet the future U.S. regulations for land application of municipal sludge.

6.2 Current U.S. Federal Regulations (as of 1990)

U.S. federal regulations governing land application of municipal wastewater sludge are currently defined in 40 CFR Part 257 Criteria for Classification of Solid Waste Disposal Facilities and Practices. These are technology-based regulations that specify acceptable technologies for treating sludge. Other technologies can be used if they can be demonstrated to provide the same level of treatment.

The 40 CFR Part 257 regulations require that wastewater sludge be treated prior to land application to reduce pathogen levels and to reduce its attractiveness to disease vectors (flies, mosquitos, rodents, etc.). The regulations list acceptable treatment technologies and divide them into two categories based on the level of pathogen control they can achieve: processes to further reduce pathogens (PFRPs) and processes to significantly reduce pathogens (PSRPs) (see Tables 6-1 and 6-2).

6.2.1 Processes to Further Reduce Pathogens

PFRPs are processes capable of reducing pathogens to below detectable levels. No site management restrictions regarding biological and microbiological contaminants apply to land application of sludges treated by a PFRP. Thermophilic aerobic digestion is listed as a PFRP at a residence time of 10 d and a temperature of 55°C to 60°C (see Table 6-1), on the assumption that a single tank is being operated with some interior baffeling to prevent short circuiting. However, the ATAD process, as designed by Fuchs and operated in Germany, has two tanks and generally has a residence time of 5 to 6 d at a temperature of 55°C. Because of its lower residence time, ATAD is considered an unlisted process. The EPA's Pathogen Equivalency Committee (PEC) has developed performance criteria concerning reduction of pathogens and vector attraction to judge whether an unlisted technology is equivalent to PFRP (47). These criteria vary depending on the type of process and the type of sludge. For the ATAD process, the relevant criteria are:

1. Pathogen Reduction

100 mL treated sludge at 5% solids must contain:[1]

< 3 MPN *Salmonella* spp.

< 1 PFU total enteroviruses

< 1 viable *Ascaris* spp. ovum

Studies discussed in Section 6.3 indicate that enteroviruses are more resistant to the ATAD process than are *Salmonella* spp. or *Ascaris* ova. Therefore, according to the criteria set forth by the PEC, PFRP equivalency can be demonstrated simply by showing that total enteroviruses are not detectable in 100 mL treated sludge at 5% solids. It is not necessary to test for the other two organisms.

Anyone applying for PFRP equivalency must demonstrate that the organisms tested for are in fact present in the untreated sludge at certain levels:

1,000 MPN *Salmonella* spp./g TSS, 1,000 PFU total enteroviruses/g TSS, and 100 viable *Ascaris* spp./g

[1]Indicator organisms may be substituted in some cases. See (47) for further discussion.

TSS. If the untreated sludge does not contain the test organisms at these levels, then it must be spiked to those levels to demonstrate the reduction.

2. Reduction of Vector Attraction

To be equivalent to a PRFP, the ATAD process must achieve:

EITHER:

A 38% reduction in VSS in the treated sludge compared to the untreated sludge

OR:

A specific oxygen uptake rate (SOUR) of less than 1/mg O_2/hr/g TSS at 20°C in the treated sludge

OR:

A total suspended solids concentration in the treated sludge of 75% or greater (which must be maintained until land application)

Table 6-1. Regulatory Definition of Processes to Further Reduce Pathogens (PFRPs)

Composting: Using the within-vessel composting method, the solid waste is maintained at a temperature of 55°C or greater for 3 d. Using the static aerated pile composting method, the solid waste is maintained at a temperature of 55°C or greater for 3 d. Using the windrow composting method, the solid waste attains a temperature of 55°C or greater and maintains it for at least 15 d during the composting period. Also, during the high temperature period, there is a minimum of five turnings of the windrow.

Heat Drying: Dewatered sludge cake is dried by direct or indirect contact with hot gases, and moisture content is reduced to 10% or lower. Sludge particles reach temperatures well in excess of 80°C, or the wet bulb temperature of the gas stream in contact with the sludge at the point where it leaves the dryer is in excess of 80°C.

Heat Treatment: Liquid sludge is heated to a temperature of 180°C for 30 minutes.

Thermophilic Aerobic Digestion: Liquid sludge is agitated with air or oxygen to maintain aerobic conditions at a residence time of 10 d and a temperature of 55°C to 60°C, with a volatile solids reduction of at least 38%.

Other Methods: Other methods or operating conditions may be acceptable if pathogens and vector attraction of the waste (volatile solids) are reduced to an extent equivalent to the reduction achieved by any of the above methods. Any of the processes listed below, if added to a PSRP, further reduce pathogens.

Beta Ray Irradiation: Sludge is irradiated with beta rays from an accelerator at dosages of at least 1.0 megarad at room temperature (ca. 20°C).

Gamma Ray Irradiation: Sludge is irradiated with gamma rays from certain isotopes, such as ^{60}Cobalt and ^{137}Cesium, at dosages of at least 1.0 megarad at room temperature (ca. 20°C).

Pasteurization: Sludge is maintained for at least 30 minutes at a minimum temperature of 70°C.

Other Methods: Other methods or operating conditions may be acceptable if pathogens are reduced to an extent equivalent to the reduction achieved by any of the above add-on methods.

Source: 40 CFR 257, Appendix II.

6.2.2 Processes to Significantly Reduce Pathogens

PSRPs effectively reduce (but do not eliminate) pathogenic viruses and bacteria; they are less effective in reducing helminth eggs. This level of pathogen reduction — comparable to that which can be achieved with a well-run anaerobic digester — is currently the minimum requirement if sludge is to be applied to land (see Table 6-2). Since PSRPs reduce but do not eliminate pathogens, the regulations require site management practices to reduce the potential for human contact with the sludge. Specifically, the regulations control public access, the growing of human food crops, and grazing by livestock at sites where PSRP-treated sludges have been applied.

To be classified as a PSRP, ATAD must achieve the following two criteria (57):

1. Pathogen Reduction

EITHER:

A 2-$\log_{10}$ reduction (i.e., the difference between the treated and untreated sludge) in either:

—fecal coliforms and fecal streptococci *or*

—fecal coliforms and enterococci

OR:

An average log density (no/g TSS) of less than 6.0 for fecal coliforms and fecal streptococci in the treated sludge

2. Reduction of Vector Attraction

EITHER:

A 38% reduction in VSS

OR:

A SOUR of less than 1 mg O_2/hr/g TSS at 20°C

6.3 Proposed U.S. Regulations

In February 1989, the EPA proposed new standards (Subpart F, Part 503 Standards for Disposal of Sewage Sludge — see Reference [46]), which are intended to replace all aspects of the existing Part 257 regulations except for co-landfilling of municipal sludge and solid waste. These proposed regulations are performance-based and would require routine sampling and analysis.

The proposed standards for pathogen management are classified into three categories (A, B, and C). Class A standards correspond with PFRP performance levels. Class B standards correspond with PSRP performance levels. Class C standards correspond with PSRP levels established for treatment systems without primary clarification and with a long mean cell residence time. These standards are summarized as follows:

Class A - Pathogen Reduction Requirements

To achieve Class A, one of the following two groups of standards must be met:

Group 1

—Pathogen densities in the treated sludge must be:

$\leq$ 3 *Salmonella* spp./g VSS

$\leq$ 1 plaque-forming virus unit/g VSS

$\leq$ 1 protozoan organism/g VSS

$\leq$ 1 helminth egg/g VSS

Group 2

—One of these three time-temperature conditions must be met:

$t_{min} \geq$ 120 hr @ 53°C

$t_{min} \geq$ 72 hr @ 55°C

$t_{min} \geq$ 0.5 hr @ 70°C

—*And* densities of indicator organisms in the treated sludge must be:

$\leq$ 2 $\log_{10}$ fecal coliform/g VSS *and*

$\leq$ 2 $\log_{10}$ fecal streptococci (enterococci)/g VSS

Class B - Pathogen Reduction Requirements

To achieve Class B, one of the following two groups of standards must be met:

Table 6-2. Regulatory Definition of Processes to Significantly Reduce Pathogens (PSRPs)

Aerobic Digestion: The process is conducted by agitating sludge with air or oxygen to maintain aerobic conditions at residence times and temperatures, respectively, ranging from 60 d at 15°C to 40 d at 20°C, with a volatile solids reduction of at least 38%.

Air Drying: Liquid sludge is allowed to drain and/or dry on underdrained sand beds, or on paved or unpaved basins in which the sludge depth is a maximum of 9 inches. A minimum of 3 months is needed, for 2 months of which temperatures average on a daily basis above 0°C.

Anaerobic Digestion: The process is conducted in the absence of air at residence times and temperatures, respectively, ranging from 60 d at 20°C to 15 d at 35°C to 55°C, with a volatile solids reduction of at least 38%.

Composting: Using the within-vessel, static aerated pile, or windrow composting methods, the solid waste is maintained at minimum operating conditions of 40°C for 5 d. For 4 hr during this period the temperature exceeds 55°C.

Lime Stabilization: Sufficient lime is added to produce a pH of 12 after 2 hr of contact.

Other Methods: Other methods or operating conditions may be acceptable if pathogens and vector attraction of the waste are reduced to an extent equivalent to the reduction achieved by any of the above methods.

Source: 40 CFR 257, Appendix II.

Group 1

—2 $\log_{10}$ reduction of *Salmonella* spp./g wastewater plant influent VSS

—2 $\log_{10}$ reduction of viruses/g wastewater plant influent VSS

Group 2[1]

—Densities of indicator organisms in the treated sludge must be:

[1]This group applies only if the influent to the treatment plant is processed by a physical or biological method and when the sewage sludge from those methods is treated in a physical, biological (e.g., ATAD), or chemical additional method, or is stored for at least one day.

≤ 6 $\log_{10}$ fecal coliform/g VSS *and*

≤ 6 $\log_{10}$ fecal streptococci (enterococci)/g VSS

Class C - Pathogen Reduction Requirements

To achieve Class C, one of the following two groups of standards must be met:

Group 1

—1.5 $\log_{10}$ reduction of *Salmonella* spp./g wastewater plant influent VSS

—1.5 $\log_{10}$ reduction of viruses/g wastewater plant influent VSS

Group 2

—Densities of indicator organisms in the treated sludge must be:

≤ 6.3 $\log_{10}$ fecal coliform/g of VSS *and*

≤ 6.7 $\log_{10}$ fecal streptococci (enterococci)/g VSS

Class B and C Use and Access Restrictions

Use and access restrictions apply for Class B and Class C sludges. These requirements restrict crops, foraging, and public access. Class C restrictions are more stringent than Class B due to the lower level of pathogen reduction (see reference [48] for more detailed information on operational restrictions).

Class A, B, and C Vector Attraction Reduction Requirements

All three classes of treated sludge must also demonstrate reduced potential for vector attraction by meeting at least one of several additional criteria. For aerobic processes, these are:

- A 38% VS reduction
- A SOUR ≤ 1 mg O_2/hr/g TS
- TSS > 75% prior to mixing
- Sewage sludge is subsurface-injected with no evidence of the sewage sludge on the land surface 1 hr after injection

6.4 Ability of ATAD to Meet the Proposed U.S. Standards for Pathogen Reduction

Most of the data concerning ATAD performance come from the FRG. There the process has been shown to meet the FRG criteria for agricultural use of sludge, described in the Appendix. The performance criteria and goals for land-applied sludge in the U.S. differ from those in the FRG. Figure 6-1 illustrates the time/temperature functions proposed by each country. The U.S. proposed 503 criteria generally require a significantly longer detention time (almost seven times as long at 55°C) than the proposed FRG criteria. The differences between the two diminish with increasing temperature. The time-temperature functions eventually converge at temperatures above 65°C. An important difference between the two criteria is that the FRG time-temperature function specifies time during isolated conditions, whereas the proposed U.S. time-temperature function does not include this distinction.

FRG and U.S. studies generally differ in terms of time, temperature, isolation of reaction conditions, and indicator organisms studied. However, where possible, organism-specific performance data from FRG studies have been compared to the existing U.S. 257 regulations and the proposed 503 regulations. In addition, data from U.S. and Canadian studies are useful in evaluating ATAD performance.

Studies of ATAD-treated sludges in the FRG, U.S., and Canada indicate that ATAD can reduce fecal coliform, *Salmonella* and *Ascaris* ova to nondetectable densities (5, 23, 35, 16, 32). One FRG study reported that enterovirus was generally reduced to nondetectable densities at 50°C (35). Recent U.S. studies observed enterovirus densities to be < 100 PFU/g TSS in most cases within a relatively low temperature range (29.0°C to 39.8°C) and with a system residence time between 10 and 20 d (32). The study noted a much stronger relationship between enterovirus reduction and temperature than between enterovirus reduction and residence time, which suggests that the higher temperature and lower residence times characteristic of the FRG systems could yield a similar enterovirus reduction performance.

Fecal streptococci reduction was significant but variable in several studies where temperatures exceeded 50°C (34, 35). Reductions to nondetectable densities were observed during some tests; however, densities were also observed to exceed 100 CFU/g TSS under similar detention time and temperature conditions. The reason for this variability is not known.

In summary, under appropriate operating conditions, ATAD systems can reduce *Salmonella* and *Ascaris* ova to nondetectable levels; thus, the process meets the current criteria for PFRP equivalency and the proposed Class A Group 1 standards. Additional

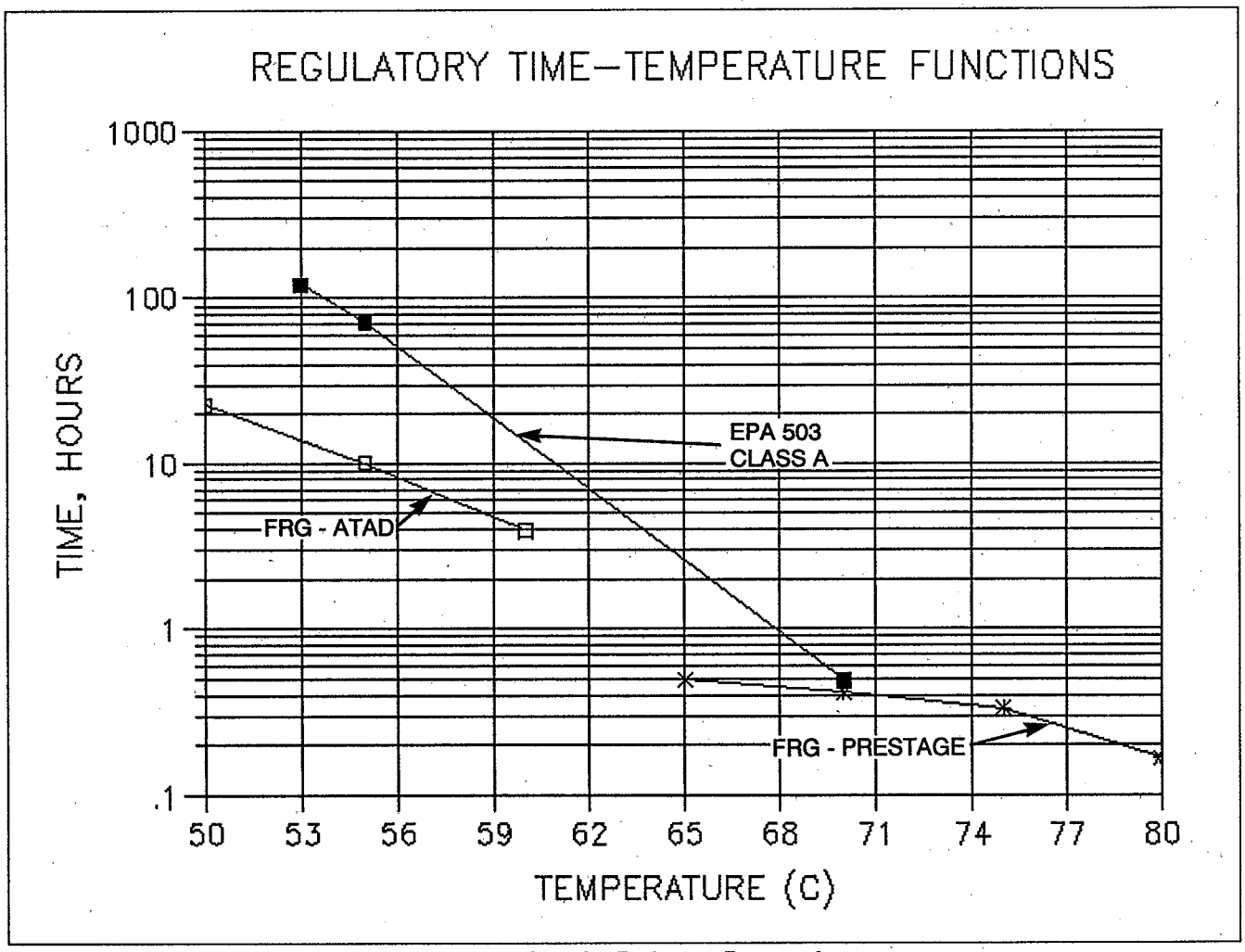

Figure 6-1. Regulatory Time-Temperature Functions for Pathogen Destruction.

the proposed Class A Group 1 standards. Additional data on enterovirus reduction at temperatures representative of operating ATAD systems (55°C) are required to confirm the ability of ATAD systems to meet the current PFRP equivalency requirement to reduce enterovirus to nondetectable levels and the U.S. Class A requirement to reduce enterovirus to ≤1 PFU/g VSS. No data are currently available on the ability of ATAD to reduce protozoan organisms to the levels required under the proposed 503 regulations. Data indicate that ATAD reduces fecal coliform to below the proposed limits required for PSRP equivalency and under Class A, B, and C Group 2 standards. The ability of ATAD to consistently meet either the current PSRP requirements or the proposed Group 2 requirements for fecal streptococci reduction is less certain. However, there is no need to demonstrate PSRP equivalency if the process already achieves the more stringent PFRP equivalency status, and there is no need to meet Group 2 requirements if Group 1 requirements can be met for Classes A, B, and C. Thus, based on the temperatures reached and the available pathogen data, ATAD systems can apparently meet the existing and proposed U.S. requirements for pathogen destruction.

6.5 Ability of ATAD to Meet the Proposed U.S. Standards for Reduction of Vector Attraction

The current PSRP and PFRP equivalency criteria and the proposed 503 standards for reduction of vector attraction are almost identical. The major difference is that, under the proposed 503 standards, reduction can be achieved by injecting sludge below the soil surface. Both the current and proposed regulations accept a suitably dried sludge (75%

TSS) as satisfactorily reducing vector attraction. Drying is an additional treatment process that would follow ATAD and therefore is not discussed here. A reduction in the SOUR is also accepted as satisfying the vector attraction reduction requirement. Insufficient data are available at this time to comment on ATAD's ability to meet this requirement. At present, therefore, the option for demonstrating reduction of vector attraction that is most generally relevant to the ATAD process is reduction of volatile solids.

Limited data are available on the ability of ATAD to reduce VSS. The literature shows minimum removal efficiencies of 25-35% (27), 35-45% (28, 29) (based on VSS), and 40-45% ([30] based on COD) with a minimum detention time of 6 d.

Table 5-1 in Chapter 5 summarizes VSS reduction data for nine plants in West Germany. These nine ATAD plants reduced VSS by 29-56%. This relatively wide range suggests that degradation is influenced by design differences such as the wastewater characteristics, the presence or absence of primary clarification, and F/M conditions on various mainstream biological processes, each of which would impact the nature of the sludge fed to the digestion process. These sludges had low heavy metals load, indicating that industrial influences are not responsible for the differences. The existing PFRP and PSRP and the proposed Class A, B, and C standards require at least a 38% reduction in volatile solids. Most of the nine plants in Table 5-1 can meet this requirement. Thus, the data indicate that ATAD systems, if properly operated, can achieve the necessary reduction.

Chapter 7.
Case Studies

This chapter summarizes available data on FRG two-stage facilities. Data were obtained through contact with system manufacturers, engineers, owners, operators, and researchers; site visits; and published sources.

7.1 General Description

Table 7-1 summarizes selected design data and identifies the system manufacturer for 35 existing ATAD plants in FRG. Reference lists from manufacturers only provide data either on the basis of sludge throughput or population equivalent (P.E.). Where necessary in Table 7-1, the facility P.E. and sludge throughput quantity have been calculated using design values typical for FRG (49): 1.87 L/P.E./d of sludge at 4.5% TS (primary + secondary sludge) for plants employing primary clarification, and 2.07 L/P.E./d of sludge at 1.5% TS (secondary sludge) for plants without primary clarification. The calculated values in Table 7-1 are marked with an asterisk (*). Table 7-2 similarly summarizes operating conditions for the same facilities.

Figure 7-1 shows the location of ATAD facilities in the FRG. The installation numbers are keyed to Table 7-1. Most ATAD plants are located in central and southern West Germany. The southern plants are situated almost exclusively in regions where sludge can be utilized for agriculture. However, not a single plant is located in Schleswig-Holstein, a state in northern Germany that also has a mostly agricultural economic structure and a comparatively low population density.

Over 85% of ATAD systems are supplied by Fuchs. Thieme and Babcock have supplied systems in the past but seem to be no longer active in the market. The Babcock plant is a single-stage system and thus does not correspond to current FRG criteria that recommend at least two-stage operation. The Thieme system, which uses a rotary screen to prethicken sludge to 10% VSS concentrations, has been sold by the Rapiddrain Company, Emmendingen. Except for the two nonmunicipal Thieme systems listed in Table 7-1, no other Thieme installations could be found.

7.2 Overview of Existing Facility Applications

Table 7-1 shows the growing importance of ATAD plants in the German market during the last 15 years. The ATAD technology is considered to be state of the art, as evidenced by the proliferation of facilities in the past decade. Thirteen years ago, no full-scale plants existed; today there are over 35 full-scale operating facilities.

ATAD plants were installed in facilities ranging in capacity between 4,000 P.E. (700 m^3/d; 0.18 MGD) and 80,000 P.E. (14,005 m^3/d; 3.7 MGD). More than 60% are in plants with capacities less than 15,000 P.E. (2,650 m^3/d; 0.7 MGD). Over 25% of all plants have a daily sludge throughput of about 20 m^3/d, corresponding to an installation size of about 10,000 P.E.

FRG cost evaluations indicate that ATAD is cost-effective over a range of 5,000 to 100,000 P.E. with an optimal range between 10,000 and 50,000 (19, 50). Actual installations generally fall within the recommended range. These cost comparisons were based on digestion performance and did not consider the value attributed to enhanced pathogen reduction.

In 1988, about 86% of operating ATAD facilities applied the stabilized sludge to agricultural land, 7% utilized landfilling exclusively, and 7% alternated landfilling with agricultural disposal. The large number of facilities that reported the practice of land applying sludge is consistent with the distribution shown in Figure 7-1.

7.3 Highlighted Facilities

Three facilities are highlighted here to provide examples of current ATAD technology: the Fassberg and Gemmingen facilities in the FRG and the Salmon Arm facility in Canada. There is no special significance to the selection of these facilities. Detailed information on a wider range of facilities is available in several sources (51, 52, 16).

Table 7-1. Summary of ATAD Operating Conditions

No.	Name	Vendor	Size (P.E.)	Design Loading (av.) (kg/d)[2]	Feed Volume (m^3/d)	No. of Reactors	Dimensions Dia., Height (m)	Active Volume, each (m^3)	SRT (d)	Volumetric Loading (kg/d/m^3)	No. of Aerators per Reactor	Installed Aeration Power (kW)	No. of Foam Cutters per Reactor	Installed Foam Cutter Power (kW)	Total Installed Power (kW)	Power Density (W/m^3)	Daily Power Use (kW/day)	Specific Power Applied (W/kg VSS)	Years in Service
										12.1	2	11	2	1.5	12.5	189	300	375	0.75
1	Backnang	Fuchs	10,000	800	20	2		3.3	3.3										
2	Bad Grund	Roediger	25,000[3]	2,000	50					6.7	3	27	3	4	31	120	744	433	3
3	Bergen	Fuchs	20,000	1,720	43	2	7.0, 4.0	129	6.0	5.7	2	13.6	2	3	16.6	119	398	498	6
4	Bruderbach	Fuchs	8,500	800	20	2		70	7.0	9.7	2	20.4	2	4.5	24.9	208	598	515	3
5	Ellwangen	Fuchs	22,000	1,160	29	3	5.0, 4.0	60	4.1	7.3	3	18	2	2	20	83	480	273	7
6	Fassberg	Fuchs	22,000	1,760	40	2	7.0, 3.2	120	5.5	6.7	1	5	2	0.6	5.6	117	134	420	9
7	Gemmingen	Fuchs	4,000	320	8	2	3.5, 2.5	24	6.0										7
8	Isenbüttel	Fuchs	10,000	800	20														3
9	Jork	Fuchs	36,000	2,680	67					8.9	2	13.6	3	3	16.6	132	398	356	2
10	Kirchberg	Fuchs	12,000	1,120	28	2	5.0, 4.0	63	4.5	6.3	2	22							5
11	Kronach	Limus	7,600	908	22.7	2		72	6.3										5
12	Lauterbach	Fuchs	60,000	4,800	120					6.7	3	23.6	2	3	26.6	127	638	456	2.5
13	Lengede[4]	Fuchs	17,000	1,400	35	2	6.5, 4.0	105	6.0										1.4
14	Losheim	Fuchs	12,000	520	13					6.8	1	5.75	2	1.5	7.25	145	174	512	0
15	Meinersen/ Leiferde	Fuchs	4,000	340	8.5	2	3.5, 3.5	25	5.9										0
19	Nesselwang	Fuchs	10,000	1,000	25	2		75	6.0	6.7	3	16.4	2	3	19.4	129	466	466	4
20	Nette	Fuchs	80,000	3,040	76	2		180	4.7	8.4	3	39	4	4.5	43.5	121	1,044	343	6
21	Neuhaus	Fuchs	12,500	1,000	25														4
22	Rangendingen	Limus	6,000	600	15	2		30	4.0	10.0	2	12							1
23	Rheinhausen	Thieme	5,300	320	8														6
24	Römersberg	Thieme	18,000	840	21	2		48+24	3.4	11.7	1	16							5
25	Schöntal	Fuchs	10,500	840	21	1													11
26	Schwarmstedt	Fuchs	20,100	1,440	36	2	7.0, 4.0	115	6.4	6.3	3	24.8	3	4.5	29.3	127	703	488	2
27	St. Goarshausen	Fuchs	11,000	880	22														0
28	Thallen	Fuchs	7,000	320	8														7
29	Toging	Fuchs	15,000	1,120	28														4
30	Tönisberg	Fuchs	13,000	680	17	2		60	7.1	5.7	2	13.2	2	3	16.2	135	389	572	3
31	Trebur	Fuchs	8,000	640	16														0.25
32	Vilsbiburg	Fuchs	28,000	800	20	2													12
33	Walheim[4]	Fuchs	5,000	400	10	2		40	8.0	5.0	2	7.8	2	1.5	9.3	116	223	558	0.25
34	Wesendorf[4]	Fuchs	13,000	620	15.5	2		50	6.5	6.2	2	13	2	1.5	14.5	145	348	561	1
35	Winsen[4]	Fuchs	15,000	1,400	35	2		110	6.3	6.4	3	25	3	4.5	29.5	134	708	506	1

Notes
1 As of Fall 1989.
2 Design loading calculated at average 4% VSS concentration.
3 Calculated value.
4 Lengede, Walheim, Wesendorf, and Winsen equipped with 2-speed aerators. Power calculated at max. speed.

Table 7-2. Summary of ATAD Installations and Design Conditions[1]

No.	Name	Percent of Capacity	Type of Waste	Type of Sludge	Feed Solids (%)	Feed Freq. (per day)	Isolated Reaction Time (hr)	Temperature (°C) RI	Temperature (°C) RII	Post Thickening % Solids	O&M Time Required (hrs/wk)	Odor Control System	Maintenance Tests	Comments
1	Backnang	60	Domestic w/industrial	P+WAS	7.5	1-3	7-23		to 68		4	Installed	Aerator cleaning	Poor thickening at high temperatures. Odors in holding tank. Landfilled.
2	Bad Grund													
3	Bergen										2-3			
4	Bruderbach	100	Domestic	P+WAS	4-5	1	23	50	62		3		Aerator cleaning	
5	Ellwangen	55	Domestic w/leachate	WAS	4-5	1	23	45	55	up to 14	4		Aerator cleaning 3x/wk	
6	Fassberg		Domestic	P+WAS	4	1	23	45	55	up to 8				
7	Gemmingen	80	Domestic	WAS	6.7	0.17	156	55	55	up to 13	2.5		Aerator cleaning	Sand deposits noted due to I/I. Crossover freezing.
8	Isenbüttel													
9	Jork													
10	Kirchberg	55	Domestic w/fruit waste	P+TF+WAS	5	1	23	40-50	55-69	up to 11	7	Will install	Aerator cleaning	
11	Kronach		Domestic	P+WAS	3-4.5	1	23		>50					
12	Lauterbach											Installed		Odor control system not used.
13	Lengede				4	1	23							
14	Losheim										2-3			2-speed aerators.
15	Meinersen/ Leiferde			P+WAS	4	1	23							2-speed aerators.
16	Messel													
17	Mundelsheim	50-200	Domestic w/fruit waste	P+WAS										
18	Neckarwestheim	40	Domestic w/industrial	WAS	4	1	23	45	52		6		Aerator cleaning 1/wk	
19	Nesselwang		Domestic	WAS		1	23							
20	Nette		Domestic 50% w/textile	P+WAS	5.7	1	23	42	56	up to 7	2	Installed	Aerator cleaning	Odor control required. Retrofit project.
21	Neuhaus													
22	Rangendingen		Domestic	P+WAS	3-4	1	23		>60		2-5			External heat required due to low load.
23	Rheinhausen													
24	Römersberg		Domestic w/industrial	P+WAS	7.9-10	0.42	56	45	55-70			Installed	Aerator problems	Odor problems, poor stability.
25	Schöntal													
26	Schwarmstedt				4	1	23				2-5			
27	St. Goarshausen													
28	Thallen													
29	Toging													
30	Tönisberg	54	Domestic 30%; Meat proc. 70%	P+TF+WAS +Misc.	2.7	0.28	72	38	50					External sludge treated.
31	Trebur													
32	Vilsbiburg													
33	Walheim	60	Domestic	P+WAS	3.5-4	1	23	>38	>50		2	Installed	Aerator cleaning 1/wk	Underloaded. 2-speed aerators.
34	Wesendorf			P+WAS	6	1	23				2-5			
35	Winsen				3.5		23				2-5			

Notes
P = Primary Sludge
TF = Trickling Filter Sludge
WAS = Waste Activated Sludge

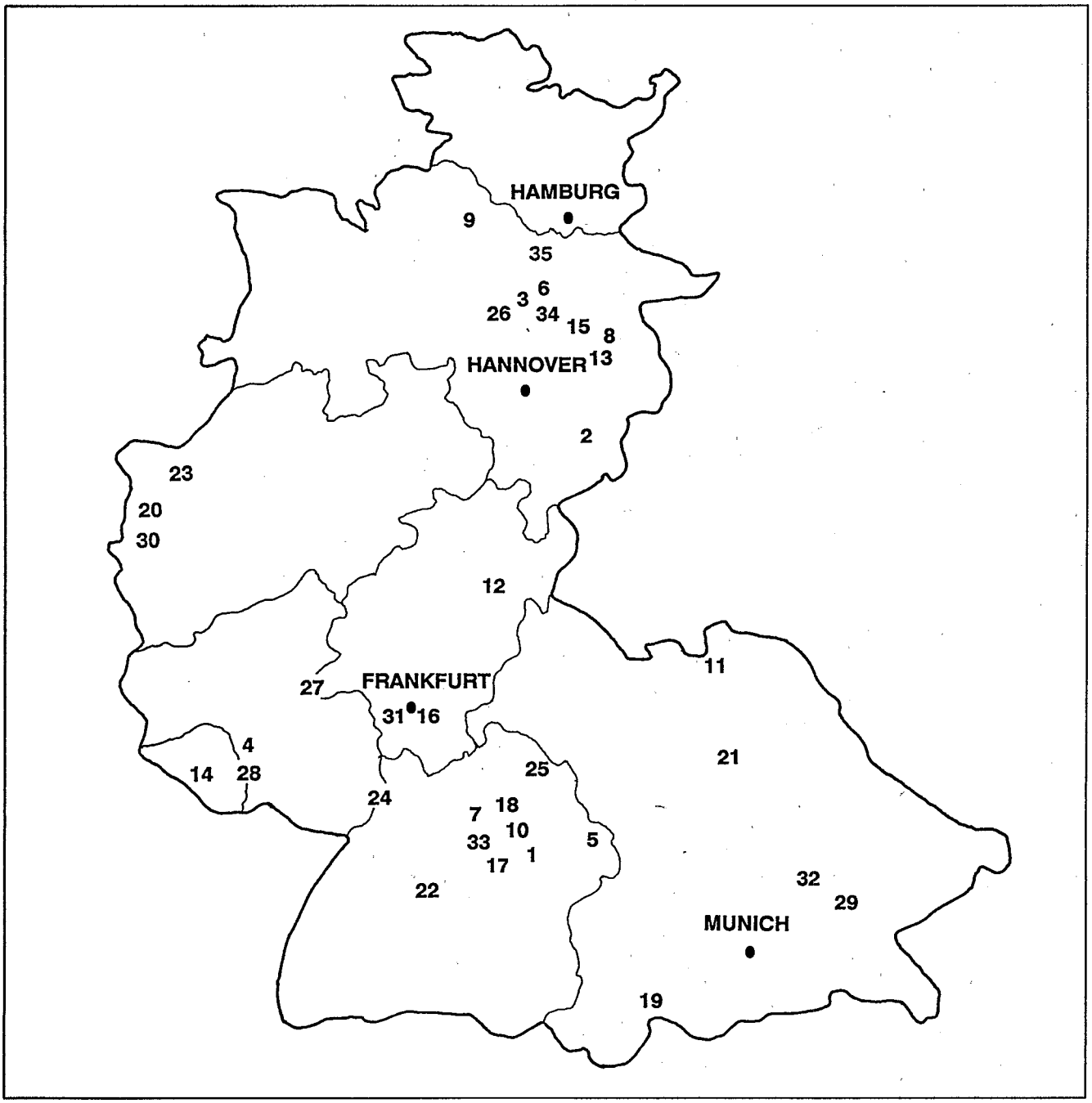

Figure 7-1. ATAD Plants in FRG. Installation Numbers Are Keyed to Table 7-1.

7.3.1 Fassberg

Fassberg exemplifies an ATAD installation that is equipped with a heat exchanger for heat recovery and that practices co-removal of primary and waste-activated sludge in the same unit process: a flotation/sedimentation unit.

Fassberg is located in north-central FRG in an agricultural area north of Hannover. The ATAD system was commissioned in 1983 and was the first system in the FRG to use a heat exchanger for heat recovery. The treatment plant serves two communities (Fassberg and Munden) and receives no in-

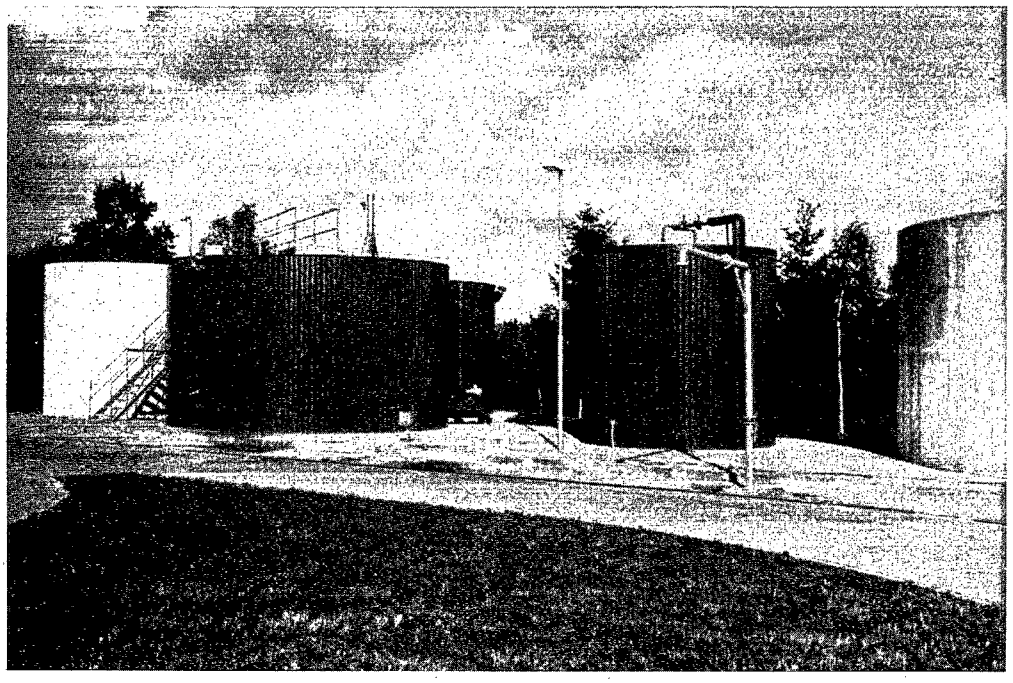

Figure 7-2. ATAD System Installed at Fassberg, FRG.

dustrial waste. Sludge from the facility is land applied for agricultural utilization.

7.3.1.1 General Facility Design Basis

The design conditions for the overall treatment system include:

- Population 22,000
- Flow 6,000 m^3/d
- BOD 1,320 kg/d
- TSS 1,760 kg/d*

*Estimated using FRG standard 80 g/day/P.E.

The major unit processes utilized at the plant include:

- Mechanical screening
- Primary sludge removal - flotation/sedimentation with co-removal of waste-activated solids
- Activated sludge - conventional complete mix
- Final polishing lagoons
- Autothermal thermophilic aerobic digestion
- Heat exchange - energy recovery for building heat
- Sludge storage (liquid)

7.3.1.2 ATAD

Figure 7-2 illustrates the ATAD facilities at Fassberg. Design conditions include:

Feed Conditions

- Sludge feed source: Primary + waste-activated
- Feed strategy: Batch, once/day
- Feed volume, m^3/d: 40
- Feed TSS, %: 4
- Feed mass loading, kg/d: 1,600

Reactors

- Number: 2 (w/bituminous base coating)
- Materials of construction: Steel

- Dimensions: 7.0-m diam., 3.2-m SWD
- Active volume, m^3 ea.: 120

Equipment

Aerators

- Number of side-mounted per reactor: 2
- Number of center-mounted per reactor: 1
- Connected power per reactor, kW: 2@3.4+1@2.2

Foam Cutters

- Number per reactor: 2
- Power rating, kW: 0.5

Performance Factors

- Total detention time, days: 6
- Batch isolation time, hours: 23
- Volumetric loading rate, (m^3 sludge/d)/m^3: 0.17
- Mass loading rate, (kg sludge/d)/m^3: 6.66
- Power density, W/m^3 active volume: 83.3
- Feed temperature, °C: 6 - 8
- Reactor I temperature, °C: 45
- Reactor II temperature, °C: 55

Sludge Holding Tank

- Volume, m^3: 620
- Holding time, days: 56

The Fassberg ATAD facility has been in operation since 1983. Site visits have confirmed reactor II temperatures at or above 55°C under autothermal conditions. The facility is not equipped with an odor control system, and no complaints have been noted. Operating personnel have reported that the system requires minimal operation and maintenance. The hollow aerator shafts occasionally became plugged due to rags passing through the plant screening facilities.

7.3.2 Gemmingen

Gemmingen is one of the earliest full-scale ATAD systems treating municipal sludge. Located in southern Germany in an agricultural area, the facility has been operational since 1980. It is one of the smallest facilities, serving an equivalent population of 4,000. A significant amount of research has been conducted there.

The facility design is basic and not as sophisticated as later designs. Nonetheless, the facility demonstrates the fundamental operating characteristics for ATAD.

7.3.2.1 General Facility Design Basis

The design conditions for the overall treatment system include:

- Population 4,000
- Flow 1,600 m^3/d
- BOD 290 kg/d
- TSS 320 kg/d*

*Estimated using FRG standard 80 g/d/P.E.

The major unit processes utilized at the plant include:

- Storm water retention
- Screening and grit removal
- Activated sludge - oxidation ditches
- Sludge thickening
- Autothermal thermophilic aerobic digestion
- Sludge storage (liquid)

7.3.2.2 ATAD

Figure 7-3 illustrates the ATAD facilities at Gemmingen. Design conditions include:

Feed Conditions

- Sludge feed source: Waste-activated

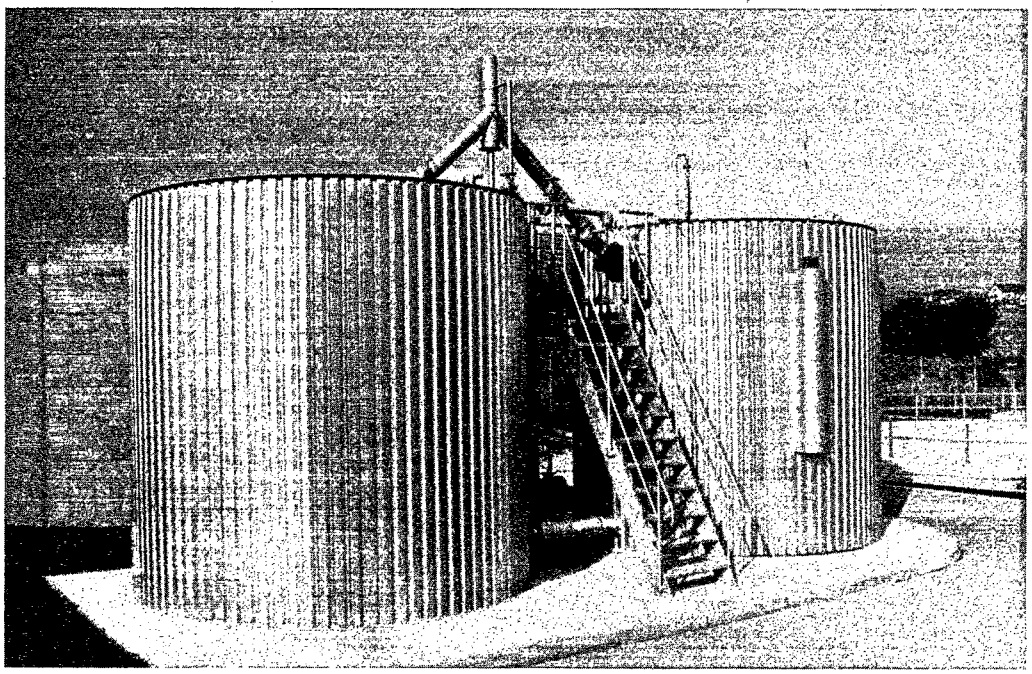

Figure 7-3. ATAD System Installed at Gemmingen, FRG.

• Feed strategy:	Batch, once/day
• Feed volume, m^3/d:	8
• Feed TSS, %:	5
• Feed mass loading, kg/d:	400

Reactors

• Number:	2
• Materials of construction:	Steel (coated)
• Dimensions:	3.5-m diam., 2.5-m SWD
• Active volume, m^3 ea.:	24

Equipment

Aerators

• Number per reactor:	1
• Connected power per reactor, kW:	1 @ 2.5

Foam Cutters

• Number per reactor:	2
• Power rating, kW:	0.3

Performance Factors

• Total detention time, days:	6
• Batch isolation time, hours:	23
• Volumetric loading rate, (m^3 sludge/d)/m^3:	0.17
• Mass loading rate, (kg sludge/d)/m^3:	8.33
• Power density, W/m^3:	129
• Feed temperature, °C:	6 - 14
• Reactor I temperature, °C:	45
• Reactor II temperature, °C:	55

Sludge Holding Tank

• Volume, m^3:	280
• Holding time, days:	35

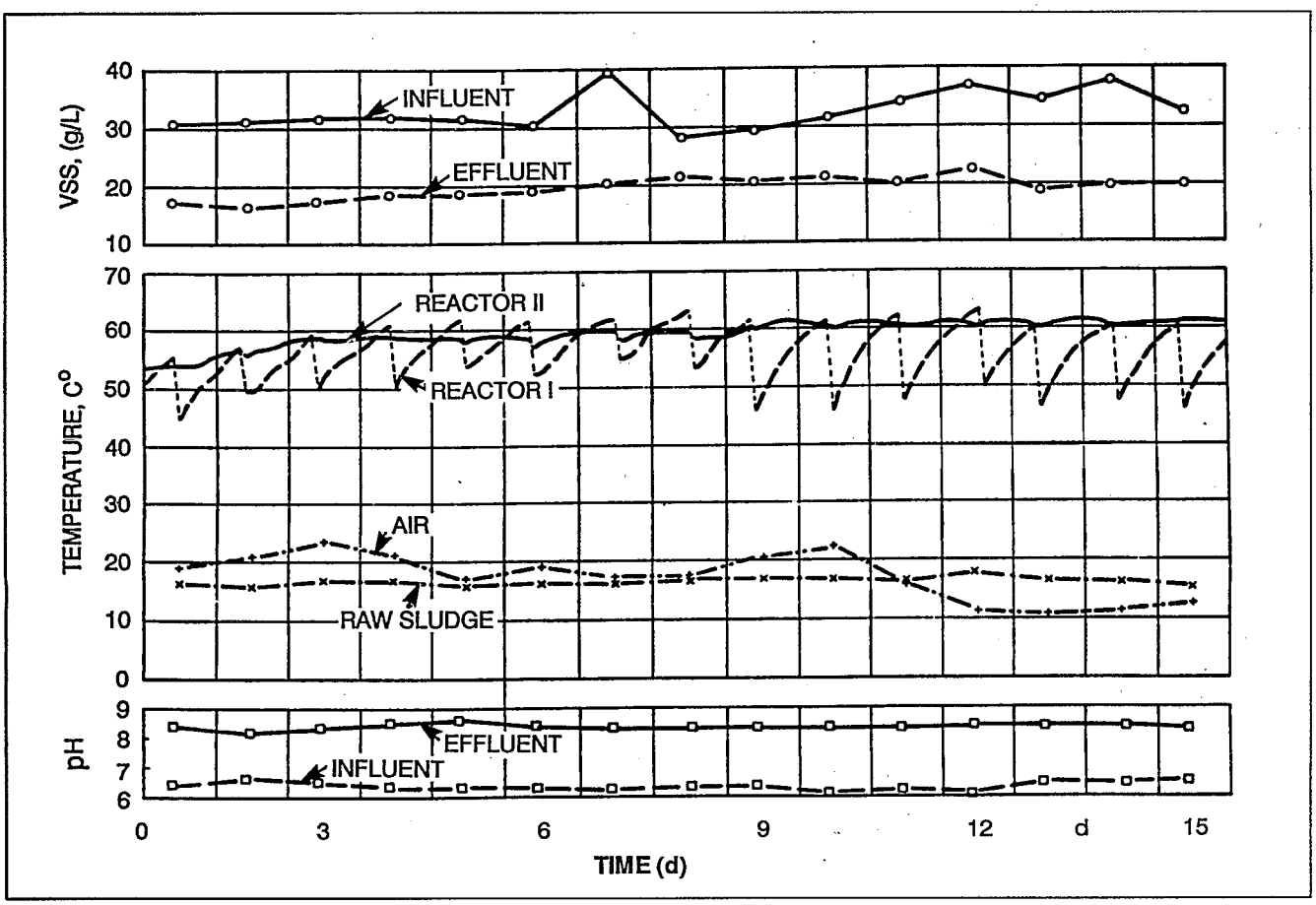

Figure 7-4. Data from the Gemmingen ATAD Facility (5).

This facility was studied extensively and documented in a doctoral thesis on aerobic thermophilic digestion (5). Figure 7-4 illustrates typical results of various operating parameters during these studies. The system achieved approximately 33% reduction in VSS for the waste-activated sludge feed source during the study period. A "sawtooth" temperature curve is evident in both reactors and is the result of batch reactor feeding. During treatment, the pH increased from approximately 6.5 to 8.0.

Since the study, the Gemmingen facility changed its operation to feed the ATAD system once a week. This results in a complete displacement of the ATAD reactors on a weekly basis, which effectively constitutes a weekly restart of the process. Limited operating data are available to characterize this mode of operation. Both ATAD reactors achieve temperatures over 55°C. Odors are experienced during start-up.

7.3.3 Salmon Arm

Salmon Arm is an example of a retrofitted ATAD system and is one of two such facilities studied in Canada. The facility utilizes rectangular, concrete reactors and a locally supplied aeration system for the ATAD system. The plant is equipped with trickling filters operated with both fixed and suspended growth for biological phosphorus removal. As is typical for many trickling filter systems, secondary waste solids are returned to the primary clarifier for co-settling and removal.

Salmon Arm is located in British Columbia, Canada, and serves an equivalent population of 6,000. The facility partitioned and insulated an existing mesophilic digester for ATAD operation.

7.3.3.1 General Facility Design Basis

The design conditions for the overall treatment system include:

- Population 6,000

- Flow 2,300 m^3/d
- BOD 425 kg/d
- TSS 400 kg/d

The major unit processes at the plant include:

- Primary clarification
- Trickling filters
- Autothermal thermophilic aerobic digestion
- Sludge storage (liquid)

7.3.3.2 ATAD

Figure 7-5 illustrates the ATAD facilities at Salmon Arm. Design conditions include:

Feed Conditions

- Sludge feed source: Primary + trickling filter
- Feed strategy: Batch, once/day
- Feed volume, m^3/d: 8.8 - 14.6
- Feed TSS, %: 1.2 - 9.3
- Feed mass loading, kg/d: 178 - 1,362

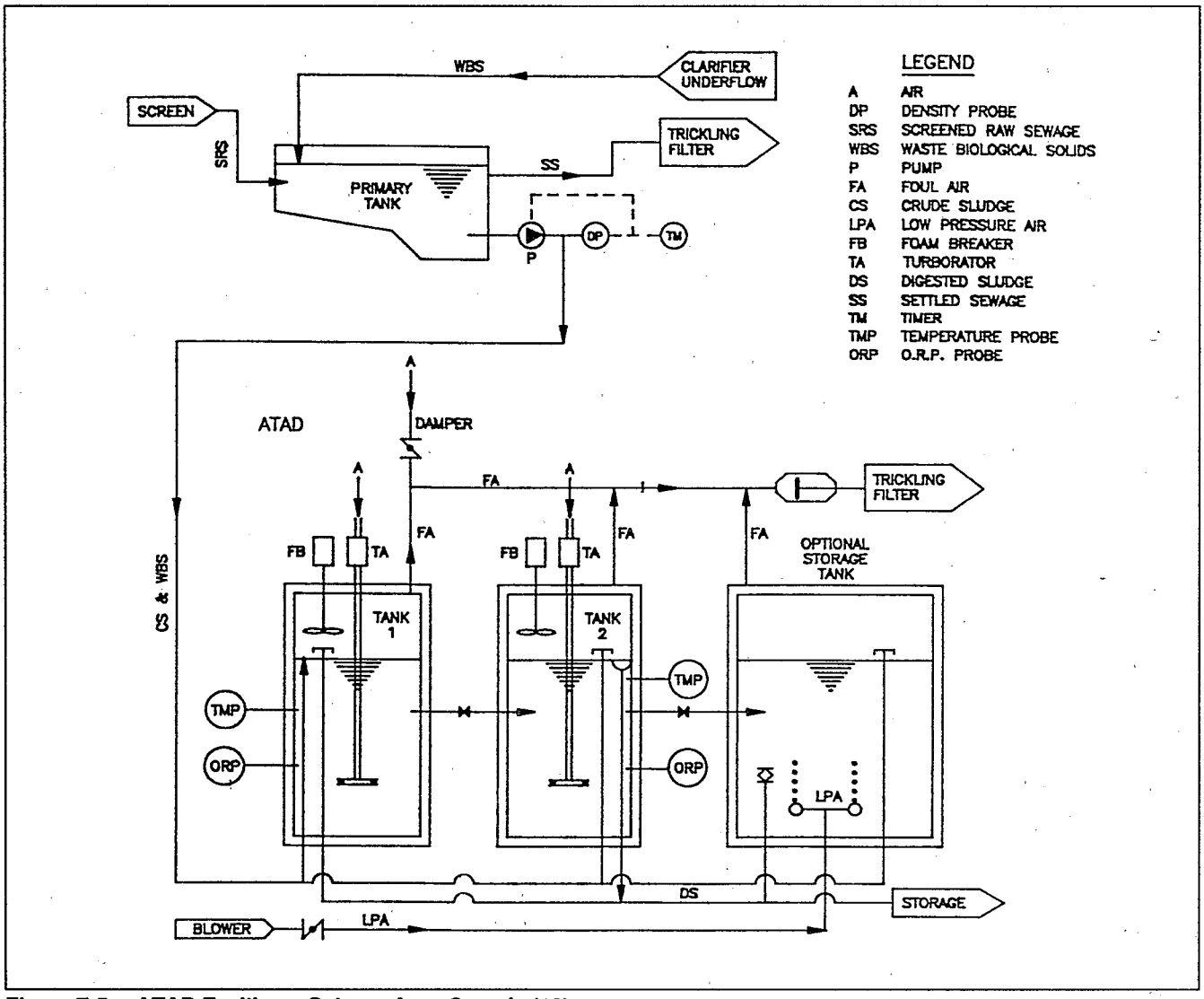

Figure 7-5. ATAD Facility at Salmon Arm, Canada (16).

Reactors

- Number: 2
- Materials of construction: Concrete (insulated)
- Dimensions, m: 2.59W, 3.96L, 3.2 SWD
- Active volume, m^3 ea: 32.82

Equipment

Aerators

- Number per reactor: 1
- Connected power per reactor, kW: 1 @ 5.7

Foam Cutters

- Number per reactor: 1
- Power rating, kW: 0.75

Performance Factors

- Total detention time, days: 4.5 - 7.5
- Batch isolation time, hours: unspecified
- Volumetric loading rate, (m3 sludge/d)/m^3: 0.27 - 0.44
- Mass loading rate, (kg sludge/d)/m^3: 5.42 - 41.5
- Power density, W/m^3 (aeration only): 174
- Feed temperature, °C: 8 - 21
- Reactor I temperature, °C: 46 - 66
- Reactor II temperature, °C: 52 - 66

Sludge Holding Tank

- Volume, m^3: unspecified
- Holding time, days: unspecified

This plant was studied extensively under the sponsorship of Environment Canada, British Columbia Ministry of the Environment, District of Salmon Arm and Dayton & Knight Ltd. Detailed information is available in reference (16).

Thermophilic operating temperatures were achieved and sustained in the process as illustrated in Figure 7-6. Volatile solids reduction ranged from a high of 55% to a low of 12% experienced during low detention time (washout) conditions. Although variable, significant reductions in pathogens were experienced at detention times at or greater than 5.3 d.

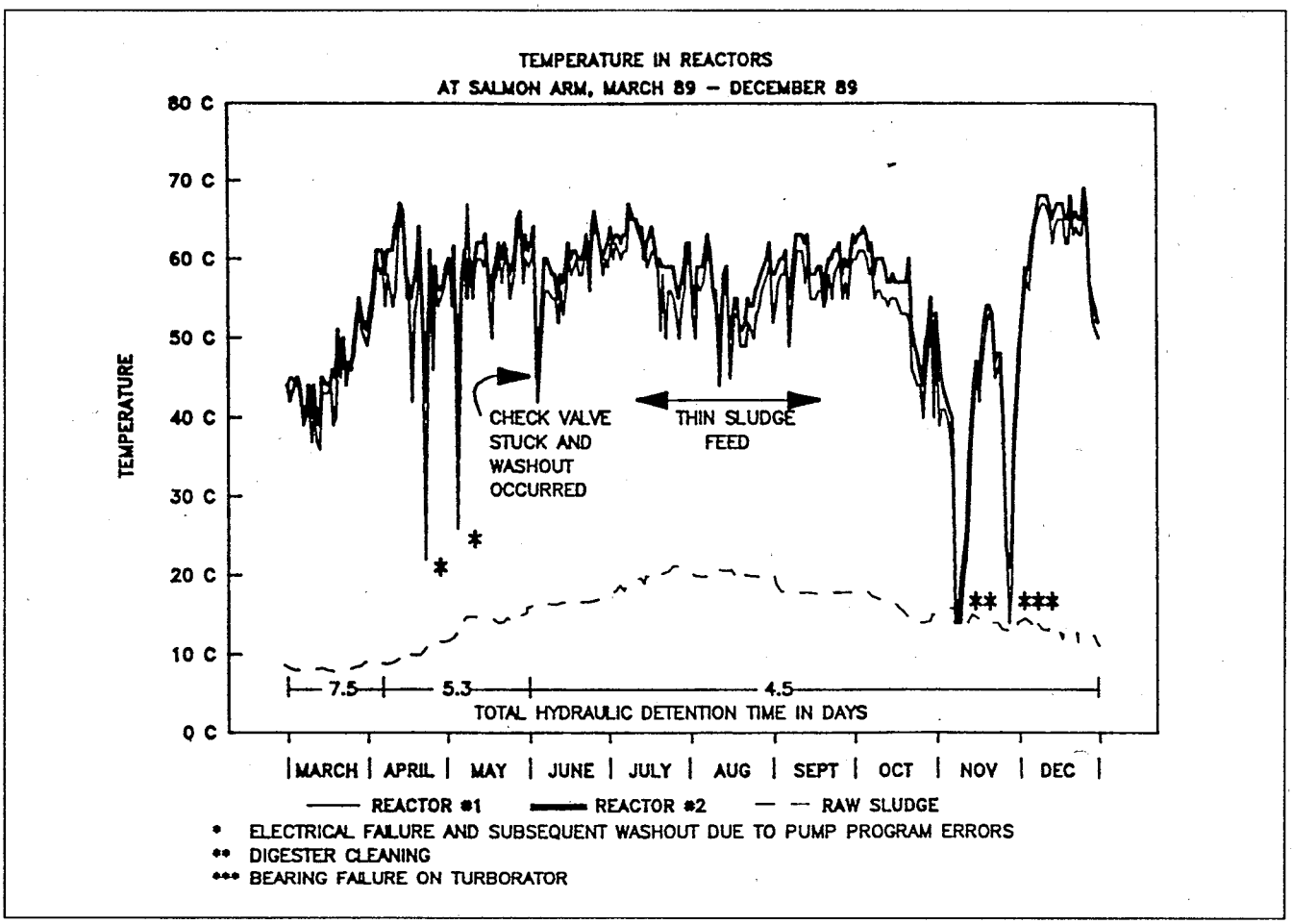

Figure 7-6. Temperatures in Reactors at Salmon Arm (16).

Chapter 8. Costs

8.1 Introduction

The ATAD cost information presented in this chapter comes from two sources: system suppliers and literature sources. Since literature sources do not always identify the facilities to which the cost data apply, these sources have been evaluated and presented separately to avoid double counting of facilities that may be represented in both data bases. The cost information summarized here applies only to ATAD systems.

The majority of components required for an ATAD system (similar to the Fuchs example) are available locally in the U.S. These would include reactors, valves, interconnect piping, controls and instrumentation. Unique requirements include the aerator/mixer apparatus and foam cutters that have been estimated to be about 25% of the ATAD systems cost.

8.2 Source Cost Data

The ATAD systems marketed in the FRG are supplied as package systems and, therefore, the cost information provided is limited to the extent of the supplied equipment. Typically, the manufacturers provided information on total package costs. Occasionally, more detailed cost information was made available. Fuchs and Thieme were the only manufacturers that provided cost information.

To provide a basis for comparing system costs, Table 8-1 lists items that are or are not included in the manufacturer's package cost. Table 8-2 summarizes cost data from the facility engineers or manufacturers of the ATAD system. For comparison purposes, these costs have been converted and adjusted to 1990 U.S. dollars (January 90 ENR-CCI = 4701). Unit costs, i.e., $/kg of sludge throughput, are also presented.

Cost estimates have been prepared for unit processes (pre- and post-thickener) that were not typically included in the manufacturer's cost information. These estimated costs are presented with the ATAD system costs in Table 8-3 as a total cost for the sludge handling system. Total system unit costs are also presented. Figure 8-1 illustrates the ATAD sludge-handling system cost data as a function of designed sludge throughput.

Table 8-1. ATAD System Component Comparison

Component	Number	Included in Fuchs Cost	Included in Thieme Cost
Pre-ATAD thickener	1	No	Yes[1]
ATAD digestion reactors	2	Yes; covered steel tanks with insulation	Yes; enclosed FRP tanks with insulation[2]
Aerators		Yes	Yes
Foam cutters		Yes	N/A[3]
Interconnect piping		Yes	Yes
Locally mounted electrical controls		Yes	Yes
Exhaust blower[4]		Yes	N/A
Aeration blower		N/A	Yes
Sludge transfer pump		N/A	Yes
Sludge feed pump		No	No
Post-ATAD thickener/holding tank		No	No
Concrete slab for reactors		Yes	No

[1] Pre-thickener is actually a flocculation/straining system referred to as the "Rapid Drain" system.

[2] Thieme reactors are reported to be one-third of Fuchs reactor volume due to increased feed concentration.

[3] Thieme does not use a foam cutter. Foam overflows aeration inductor cone and is educted into aerator.

[4] Exhaust blower is used to carry off gas to odor control process.

Annual operating costs have been estimated for nine Fuchs systems. Labor requirements were reported by the facility operators to be low and did not appear to vary significantly based upon the size of the facility. Labor requirements were estimated at 1.5 hr/d as shown in Table 8-4, based on discussions with operating personnel and review of the facilities.

Table 8-2. ATAD Capital Cost Summary[1]

Facility	Population Equivalent	Cost (DM)	Cost Year/ (ENR-CCI)[3]	1990 Cost ($)[2,4]	MARCH 1989 Through-put (kg/d)	Cost ($/kg)[5]
Isenbüttel	12,000	242,000	1982 (3721)	191,000	800	239
Schöntal	12,500	130,000	1979 (2886)	132,000	1,000	132
Fassberg	22,000	366,000	1981 (3384)	318,000[6]	1,600	199
Nettetal-Viersen	80,000	450,000[7]	1983 (4006)	330,000	2,540	130
Gemmingen	6,000	166,000	1980 (3159)	154,000	425	362
Vilsbiburg	25,000	285,000	1977 (2513)	333,000	700	476
Meinersen/Leiferde	4,000	338,000[10]	1989 (4568)	217,000	450	482
Walheim	5,000	362,500	1989 (4568)	233,000	400	582
Trebur	8,000	410,500[10]	1989 (4568)	264,000	1000	264
Neckarwestheim	10,000	350,500	1989 (4568)	225,000	1050	214
Wesendorf	12,000	393,000[10]	1989 (4568)	253,000	800	316
Lachendorf	15,000	601,300[10]	1990 (4701)	376,000	1350	278
Rheinhausen[8]	5,000	280,000	1984 (4118)	200,000	291[9]	687
Römersberg[8]	20,000	450,000	1984 (4118)	321,000	899[9]	357

[1] Based on data received from system engineers or manufacturers. Costs for pre- or post-thickening and storage not included in Fuchs cost data. Fuchs costs confirmed as installed costs. Post-thickening and storage not included in Thieme costs.

[2] Assumes an exchange rate of 1.60 DM/$.

[3] Engineering News Record-Construction Cost Index, for March of indicated year.

[4] ENR-CCI = 4701 (March 1990).

[5] Nonamortized unit costs based on annual throughput capacity.

[6] Includes cost of heat recovery equipment.

[7] Cost does not include tankage. This project was a retrofit into existing tankage.

[8] Industrial applications.

[9] These facilities loaded three times per week. Weekly loading rates have been divided by 7 to develop a daily loading rate for comparison purposes.

[10] Includes "biofilter" odor control system cost.

Table 8-5 includes a summary (translated from early 1980s [5]) of costs determined for the Gemmingen facility during the period of study (early 1980s). These costs (1980 base) compare favorably with the estimated costs in Table 8-2.

8.3 Literature Source Cost Data

Capital cost data have been derived from several sources (25, 53, 54) and updated to 1989 basis. Figure 8-2 illustrates the ATAD capital costs as a function of installed reactor volume.

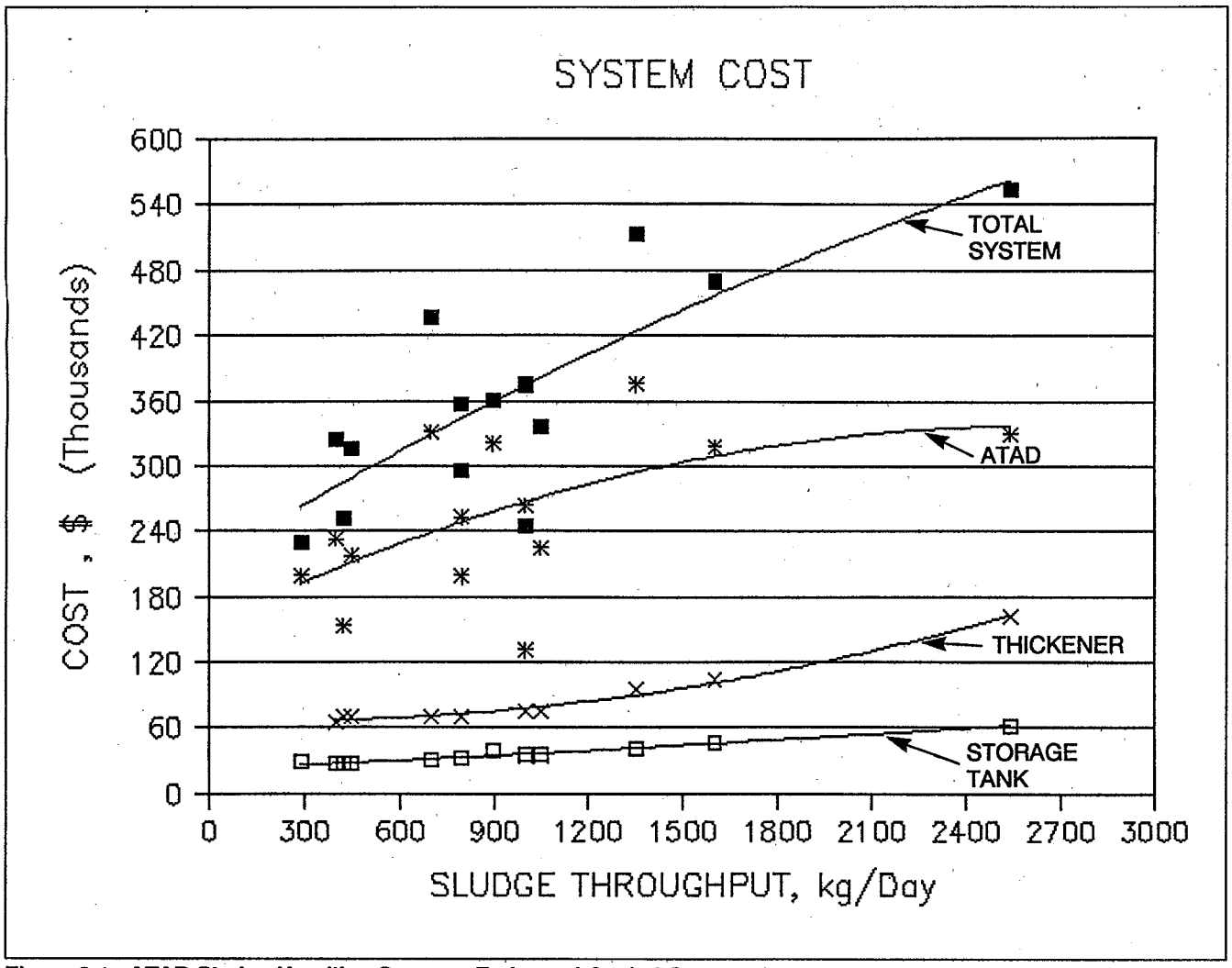

Figure 8-1. ATAD Sludge Handling Systems Estimated Capital Costs.

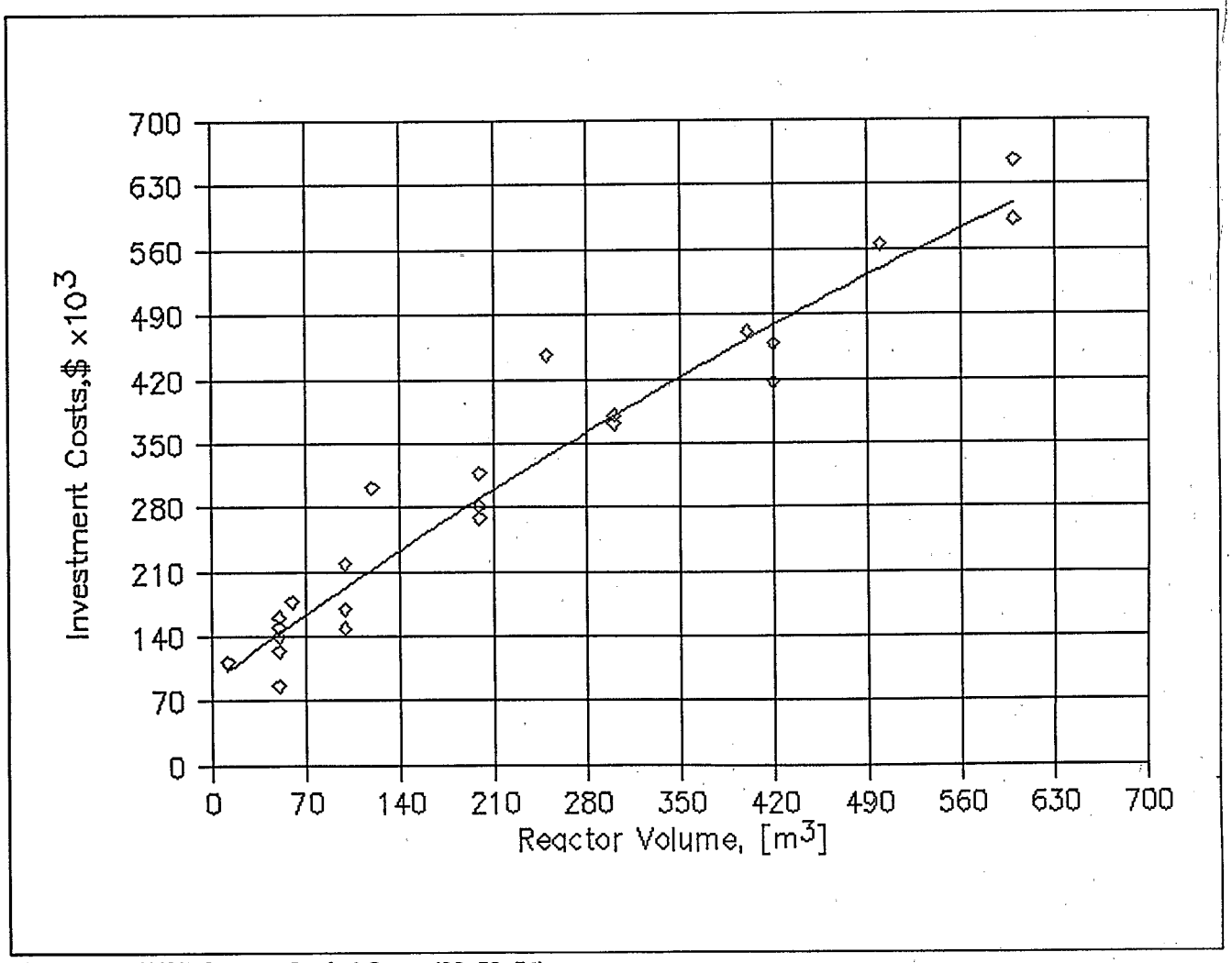

Figure 8-2. ATAD System Capital Costs (22, 53, 54).

Table 8-3. Estimated Sludge Handling Capital Cost

Facility	Throughput (kg/d)	ATAD Cost ($)[1]	Pre-Thickener Estimated Cost ($)[2]	Post-Thickener Storage Cost ($)[3]	Total ($)	Unit Cost ($/kg)[4]
Isenbüttel[5]	800	199,000	71,000	33,000	295,000	369
Schöntal	1,000	132,000	76,000	36,000	244,000	244
Fassberg[5]	1,600	318,000	105,000	47,000	470,000	218
Nettetal-Viersen[5]	2,540	330,000	161,000	62,000	553,000	218
Gemmingen	425	154,000	71,000	27,000	252,000	593
Vilsbiburg	700	332,000	71,000	32,000	436,000	623
Meinersen/ Leiferde	450	217,000	71,000	28,000	316,000	702
Walheim	400	233,000	65,000	27,000	325,000	813
Trebur	1,000	264,000	76,000	36,000	376,000	376
Neckar-westheim	1,050	225,000	76,000	36,000	337,000	321
Wesendorf	800	253,000	71,000	33,000	357,000	446
Lachendorf	1,350	376,000	95,000	42,000	513,000	380
Rhein-hausen[6]	291	200,000	N/A	29,000	229,000	787
Römersberg[6]	899	321,000	N/A	39,000	360,000	400

[1] ATAD costs from Table 8-2.

[2] Cost estimated using MCD-53 construction cost curve, adjusted to ENR 4701.

[3] Cost estimated assuming the following condition: 40% VSS destruction, 20-day storage volume, 5% TSS concentration for Fuchs, 9% TSS concentration for Thieme, circular tank design (1-ft-thick concrete side walls, 1.2-ft-thick slab, 15-ft tank height), $342 per cubic yard (installed) concrete cost. Cost includes $4,600 for pump station to discharge final product to vehicles.

[4] Nonamortized unit costs based on annual throughput capacity.

[5] These facilities do not include dedicated pre-thickening units, but are costed for example and comparison purposes.

[6] Cost does not include tankage for the ATAD system.

Table 8-4. Estimated Annual Operating Costs for Nine Fuchs Systems in the FRG[1]

Facility	Through-put (kg/d)	Labor ($)[2]	Power ($)[3]	Miscel-laneous Parts and Supplies ($)	Total ($)	Unit Cost ($/kg)4
Isenbüttel	800	5,500	9,500	600	15,600	19.5
Fassberg	1,000	5,500	19,200	1,200	25,900	16.2
Nettetal-Viersen	2,540	5,500	38,600	2,200	46,300	18.2
Gemmingen	425	5,500	5,100	2,800	13,400	31.5
Vilsbiburg	700	5,500	13,800	900	20,200	28.9
Schöntal	1,000	5,500	—	—	—	26.5 to 35.8
Walheim	400	5,500	4,500 to 8,200	600	10,600 to 14,300	20.7
Neckar-westheim	1,050	5,500	14,500	1,700	21,700	21.4

[1] Cost does not include disposal.

[2] Labor cost estimated at 1.5 hr/d labor cost at $7.5/hr.

[3] Design power consumption (calculated) with power cost at 6.5 cents/kWh. Power cost estimate is based on aeration and foam cutter power requirements.

[4] Nonamortized unit costs based on annual throughput capacity.

Table 8-5. Summary of Costs for the Gemmingen ATAD System[1]

Cost Item	Cost - 1980 DM ($)[2]	Remarks
Capital Cost	133,000 DM (48,900)	Mechanical-electrical (concrete slab not included in cost). Pre- and post-thickeners not included.
- 2-24 m^3 reactors	62,700 DM (23,050)	
- Installation		
TOTAL INSTALLED	195,700 DM (71,950)	
Operating Cost	6,132 DM/yr (2,250)	112 kWh/d x 0.15 DM/kWh; 0.5 k/g x 20 DM/hr; 1% structures; 2 % mechanical/electrical
- Power	3,650 DM/yr (1,340)	
- Personnel	2,584 DM/yr (950)	
- Upkeep		
TOTAL OPERATING	12,366 DM/yr (4,540)	
Fixed Cost	9,709 DM/yr (3,570)	4% structures, 7% mechanical/electrical; i = 10%
- Depreciation	9,785 DM/yr (3,600)	
- Interest		
TOTAL FIXED	19;494 DM/yr (7,170)	
TOTAL ANNUAL COST	31,860 DM/yr (11,710)	
Cost Factors	28.40 DM (10.44)	Capital cost - 6,900 P.E.
- DM/Pop. eq.	67.02 DM (24.64)	Capital cost - 8 m^3/day
- DM/m^3 of sludge/yr	1.79 DM/yr (0.66)	Operating cost
- DM/Pop. eq.	4.23 DM/yr (1.56)	Operating cost
- DM/m^3 of sludge	4.62/yr (1.70)	Total annual cost
- DM/Pop. eq.	10.91/yr (4.01)	Total annual cost
- DM/m^3 of sludge	181.85/yr (66.86)	Total annual cost (480 kg/day)
- DM/t TS (metric)		

[1]Translated from Reference [5].

[2]Assumes an exchange rate of 2.72 DM/$.

Chapter 9.
Thermophilic Pre-Stage Process

9.1 Introduction

Pre-stage systems also provide thermophilic digestion and are normally incorporated in the treatment process ahead of conventional anaerobic digestion. Pre-stage systems differ from ATAD systems in several respects, including:

- Normally only one prestage reactor is used. If more than one reactor is installed, they operate in parallel.
- Detention time is 1 d or less, with sludge added several times per day.
- Pre-stage systems require supplemental heating. Heat exchangers are used in all systems.
- Aeration is limited.
- Sludge leaving the prestage system has not been stabilized.

Pre-stage systems are classified as a process that meets the FRG criteria for the production of a disinfected sludge (see Appendix). Pre-stage installations in the FRG are summarized in Table 9-1 and located as shown in Figure 9-1.

In 1989, 31 pre-stage systems were being constructed or operated in the FRG. Design capacities range from 3,500 to 120,000 P.E. (0.16 to 5.5 MGD). Twenty systems were furnished by Umwelttechnik Buchs (UTB), a Swiss company, and eleven by German companies: seven by Roediger, three by Oswald-Schulze, and one by Fuchs.

The Swiss company has a relatively strong market position because pre-stage systems have been used in Switzerland for some time. The Swiss ordinance regulating the land application of sewage sludge and the required pathogen reductions was enacted in 1981 (55). The UTB system was originally developed for the purpose of pathogen reduction and weed seed control (56). UTB reports that more than 70 UTB installations are under construction or in operation; most of these are in Switzerland and the FRG.

In the United States the UTB pre-stage system is marketed by CBI Walker.

9.2 System Design and Operation

A typical pre-stage configuration (see Figure 9-2) consists of a storage/thickening tank, a heat exchanger (sludge/sludge), the pre-stage reactor with aeration, mixing and foam-controlling equipment, an equalizing tank to adjust the pre-stage effluent and the anaerobic feed cycle, and an auxiliary heating device (usually a sludge/water heat exchanger). The basic design parameters for the pre-stage system are shown in Table 9-2.

Pre-stage conversion of COD is limited by the system HRT and the availability of oxygen. Air input into the process is typically less than stoichiometric requirements for digestion, and at no time is a dissolved oxygen residual maintained in the reactor. Although pre-stage systems are referred to as aerobic, "aerated" is probably a better descriptor. Because of the limited oxygen supply, the concentration of soluble degradable organic compounds such as volatile acids is normally high (57, 58, 59).

Most systems use an injector system (venturi) to provide air to the process, and an external recycle pumping loop to accomplish mixing. In UTB and some other systems, waste gas from the reactor is partially recirculated back through the venturi injector to increase oxygen transfer and minimize vent gas heat loss. No full-scale measurements to determine oxygen transfer efficiency are known (60), but values of 70-80% have been claimed (60, 61).

The exhaust air can be particularly foul due to the presence of large quantities of organic (volatile) acids. As a result, it has to be treated and is typically diffused into the activated sludge aeration tank.

The design limits on detention time and oxygen transfer limit the amount of heat generated by the microbial reactions in the pre-stage. COD reduction is reported to range from 5% to 15%. As a result, heat development is not sufficient to achieve a temperature level above 60°C, and an auxiliary heating device is required. The UTB system typically has 50% of the thermal input supplied with external heat. Supplemental heat is supplied by the auxiliary heat exchanger fueled by methane produced in the anaerobic digesters. This additional heat require-

Table 9-1. Summary of Pre-Stage Installations in the FRG

No.	Name	Size (P.E.)	Vendor	Design Load (m^3/d)	Years of Operation
1	Bad Aibling	47,000	Roediger	94	
2	Bad Tölz	52,000	UTB	105	1
3	Chiemsee	62,000	Roediger	125	
4	Detmold	92,000	UTB	185	
5	Dilligen/Bayern	15,000	UTB	30	0.5
6	Dilligen/Saar	24,000	UTB	49	3
7	Duisburg		OS		1
8	Ebersdorf	6,500	UTB	13	
9	Grüneck		Roediger	135	4
10	Bundelfingen	17,500	UTB	35	
11	Günzburg	60,000	Roediger	120	3
12	Heroldsberg	12,500	UTB	25	
13	Holzkirchen	35,000	UTB	70	3
14	Hückelhoven	57,000	UTB	115	5
15	Hünfeld	36,000	Fuchs	43	3
16	Itzgrund	4,500	UTB	9	
17	Linkenheim	8,000	UTB	16	1
18	Marl-Ost		OS	140	1
19	Mitterteich	19,000	UTB	38	
20	Nabburg	13,500	UTB	27	0.5
21	Nellingen	42,000	Roediger	85	0.5
22	Oberteuringen	4,500	UTB	9	
23	Raubling	15,000	Roediger	30	
24	Rosenheim	120,000	UTB	240	1
25	Saarlouis	86,000	UTB	173	0.5
26	Schuttorf		OS	120	
27	Schwabmunchen	29,000	UTB	58	3
28	Schwarzach	27,500	UTB	55	3
29	Weiershagen	20,000	UTB	40	3
30	Werne	85,000	Roediger	170	
31	Wilhelmstal	3,500	UTB	7	0.5

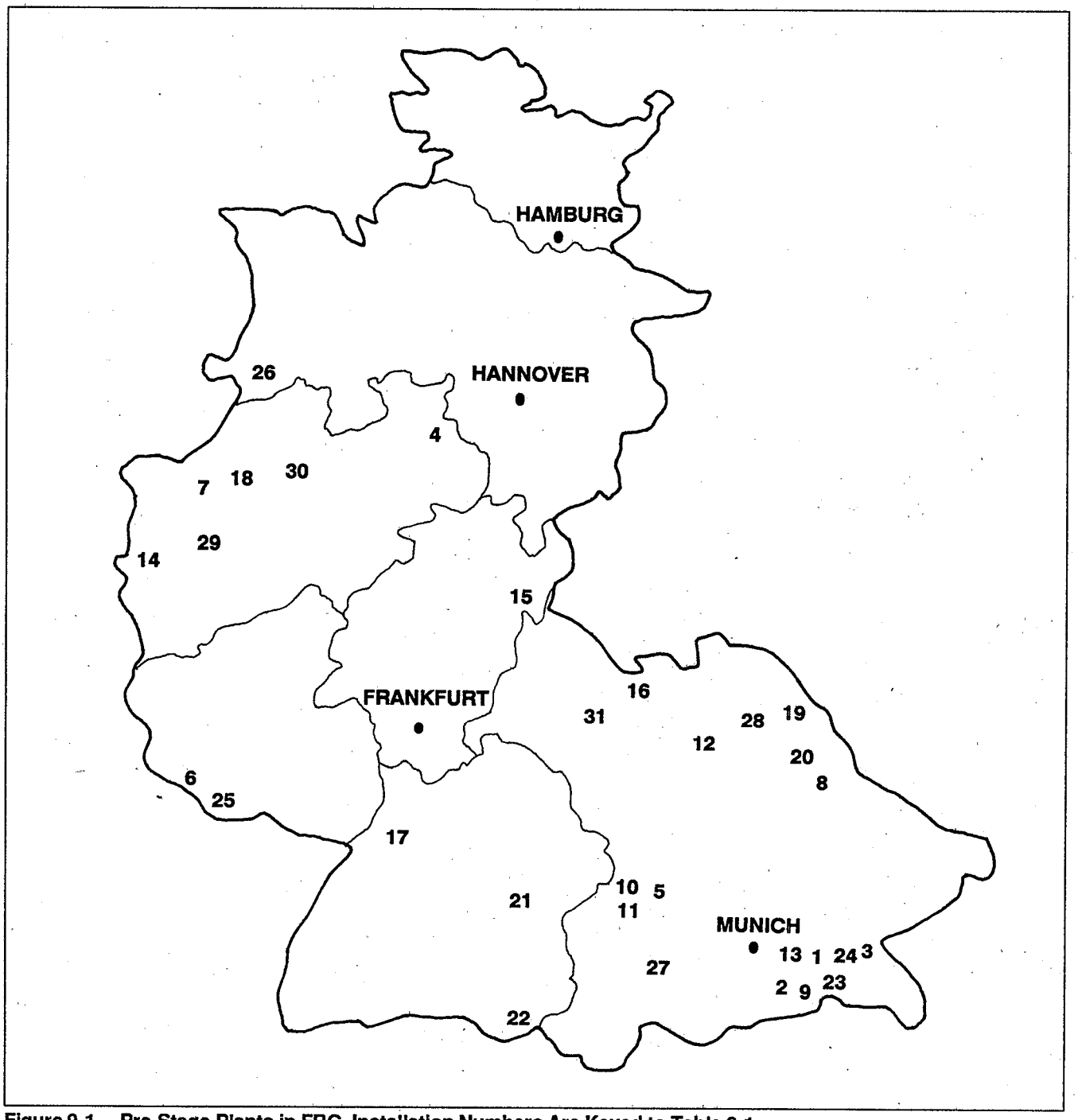

Figure 9-1. Pre-Stage Plants in FRG. Installation Numbers Are Keyed to Table 9-1.

ment is reportedly satisfied by the digester methane production under most operating conditions. Dual-fuel boilers (typical for anaerobic digester installation) provide startup and backup heating capacity as required.

The operation cycle is discontinuous. A normal operating cycle begins when hot effluent from the aerated pre-stage is discharged to the sludge/sludge heat exchanger. Thickened, cold raw sludge is fed to the second chamber of this exchanger. There the raw sludge is preheated while the pre-stage effluent cools down to mesophilic temperatures (40°C). Oswald-Schulze installs an emergency cooler to protect the mesophilic anaerobic digester. After temperature equalization, the preheated raw sludge is transferred to the pre-

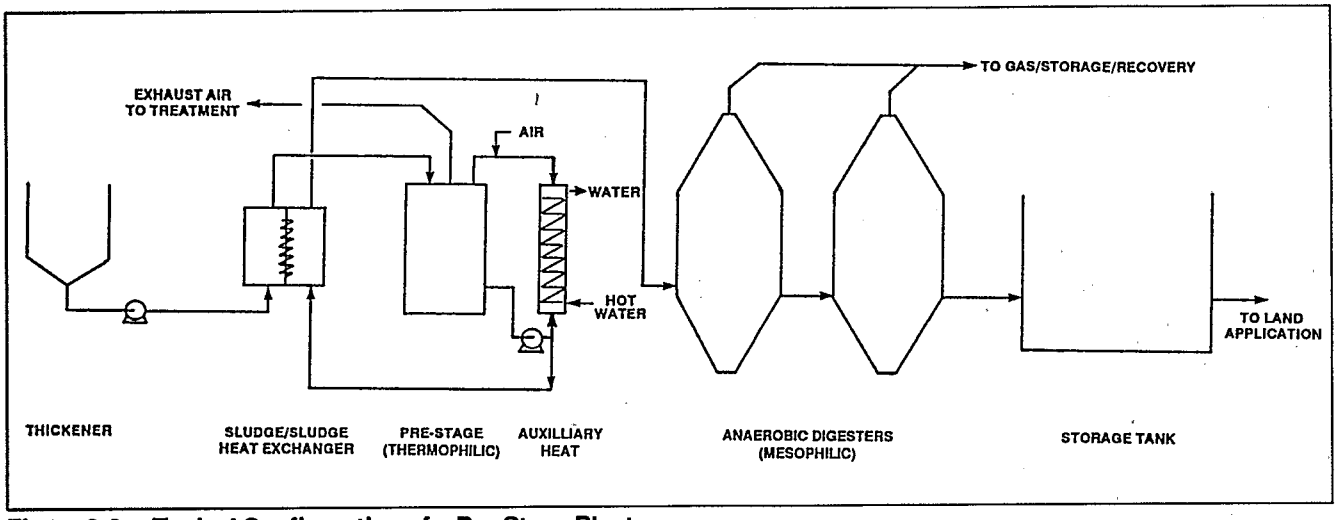

Figure 9-2. Typical Configuration of a Pre-Stage Plant.

stage reactor where aeration and mixing start again. No additional raw sludge is fed for 1 to 2 hr in order to maintain the undisturbed detention required for disinfection. Temperature in the pre-stage reactor is controlled to 60°C to 65°C as a function of the time-temperature requirements for disinfection.

Typically the displaced volume in the pre-stage system amounts to 10% of the reactor volume, resulting in 10 cycles per day. Variations in the daily waste sludge quantity can be compensated for by adjusting the number of cycles. The batch volume itself is fixed by the compartment volume of the heat exchanger.

9.3 Process Evaluation

As of 1990, the EPA has not thoroughly reviewed the cost, performance and benefits of pre-stage systems. Clearly, these systems offer a process suitable for pathogen reduction where existing anaerobic digestion facilities provide most of the sludge stabilization. Since the discharge from pre-stage systems is not stabilized, further sludge processing is required whenever the pre-stage process is used.

Some reports (56, 62) claim that the pre-stage process improves sludge thickening and dewatering, increases sludge degradation, and increases methane production during anaerobic digestion. The reported improvement in thickenability and dewaterability is controversial. Swiss investigations at full-scale plants showed distinct improvements as compared to a one-stage anaerobic digestion system: 9-13% TS with gravity thickening and 35-45% TS with belt filters (57, 63). German sources do not entirely confirm these results (62, 21, 52) and believe the Swiss results to be influenced by the use of iron salts for phosphorus removal, which may contribute a much denser chemical sludge to the system.

Table 9-2. Design Parameters for Pre-Stage Systems

Reactors:	One or more stages, depending on plant size, operating in parallel semi-continuous operation
Type of sludge:	— Primary or secondary (activated sludge, tricking filter) — Sedimentation or flotation — Mixed or separate — Domestic, industrial origin — Manure
Usual TS range:	40-60 g/L (4-6%)
Required VSS:	$\geq$ 25 g/L (2.5%)
Detention time:	Average 12-24 hr
Minimum reaction time:	1-2 hr
Temperature and pH:	60°C - 65°C, pH $\geq$ 7.2 in final sludge
Reactor:	Cylindrical; height/diameter ratio: 2-5
Air input:	1 $m^3/(m^3$ reactor hr) [1-3 (37)]
Specific power:	~ 100 W/m^3 reactor (50)
Energy requirement:	No design data available; reported are 3.5-12 (29) and 5 kWh/m^3 sludge (54); measured value for a plant with 21-m^3 sludge loading (design load 31 m^3): 4.9 kWh/m^3

Appendix

Criteria for Agricultural Use of Sludge in the Federal Republic of Germany

Agricultural utilization of sewage sludge in the FRG is regulated by the Ordinance on Sewage Sludge (OSS) enacted on April 1, 1983. As of January 1, 1987, only "hygienically safe" sewage sludge can be applied to fields used for vegetable and fruit growing or for pasture or forage land. The OSS defines a sludge to be "hygienically safe" if appropriate technologies have eliminated all pathogenic organisms (64). The Ordinance does not cite the relevant pathogens nor does it define the appropriate technologies to use. The federal OSS is regulated on a state (Lander) level through incorporation in state decrees. Here the term "hygienically safe" has been interpreted to mean "disinfected," but the state decrees provide no clear definition of this term.

A joint working group of the ATV (Abwassertechnische Vereinigung, Water Pollution Control Federation) and the VKS (Vereinigung kommunaler Stadtereinigungsbetriebe, Association of Public Cleansing Enterprises) assembled for the first time in 1986. The working group is composed of engineers and human and veterinary medicine experts. The working group has proposed a definition of "disinfected" and has recommended appropriate sanitizing technologies (65, 66). It is expected that the working group's proposals will be incorporated into an administrative regulation for "disinfection" and will then become legally binding (66, 67, 68).

According to the working group, a sewage sludge can be considered disinfected if it meets the criteria of the following three-stage control concept.

1. Treatment Process Qualification

The sludge must be treated by an approved technology. An approved technology is one in which adequate investigations have shown that:

- The indigenous or seeded *Salmonella* have been reduced by at least 10^4.
- Indigenous or seeded eggs of *Ascaris* are rendered noninfectious.

2. Treated Sludge Performance Criteria

Directly after treatment there shall be:

- No *Salmonella* in 1 g of sludge.
- Not more than 1,000 enterobacteriaceae/g of treated sludge.

3. Process-Specific Operational Control Criteria

Operational control criteria must be established specifically for each process. These criteria define those conditions that result in disinfection as required above. As of 1989, six treatment processes had been evaluated and control criteria established. The operational control criteria for ATAD and pre-stage systems are summarized below.

a) Autothermal Thermophilic Aerobic Digestion (ATAD)

- At least two stages must be used to avoid short-circuiting.
- The undisturbed reaction time, t_{min}, for given temperature T must be:

$t_{min} \geq 23$ h @ $T = 50^oC$

$t_{min} \geq 10$ h @ $T = 55^oC$

$t_{min} \geq 4$ h @ $T = 60^oC$

The temperature requirements take into consideration the drop in temperature resulting from intermittent (batch) feeding occurring once per day.

- Total detention time (t_d) must be ≥ 5 d (two equal-sized tanks).

Operational controls include:

- Continuous on-line measurement and recording of the temperature of each tank in at least two locations.
- Measurement of raw and final sludge pH values.
- Continuous on-line measurement of sludge feed volumes to allow for calculation and control of detention time.

b) Aerated Thermophilic Digestion Pre-Stage Before Anaerobic Digestion (PREST):

The temperature in the aerobic stage must be maintained with additional heating. The requirements are the same as for a pre-pasteurization:

$t_{min} \geq 10$ min @ $T = 80^oC$

$t_{min} \geq 20$ min @ $T = 75^oC$

$t_{min} \geq 25$ min @ T = 70°C

$t_{min} \geq 30$ min @ T = 65°C

Operational control includes the measurement of:

- The time of undisturbed reaction (contact time) t_{min}.
- The temperature in at least two locations, in the aerobic as well as in the anaerobic stage.

In addition, the temperature of the subsequent anaerobic stage must be kept above 30°C to maintain disinfection.

In summary both the ATAD and pre-stage processes have a sufficient data base and operating history to be classified as processes that meet the FRG criteria for agricultural use of sludge. The relation of documented ATAD performance and the proposed U.S. regulations is discussed in detail in Chapter 6.

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