THERMAL SLUDGE DRYER DEMONSTRATION
Bird Island Wastewater Treatment Plant, Buffalo, NY

Final Report

Prepared for

THE NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY

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ABSTRACT

The Buffalo Sewer Authority (BSA), in cooperation with the New York State Energy Research and Development Authority (Energy Authority), commissioned a demonstration of a full scale indirect disk-type sludge dryer at the Bird Island Wastewater Treatment Plant (BIWWTP). The purpose of the project was to determine the effects of the sludge dryer on the sludge incineration process at the facility.

Sludge incineration is traditionally the most expensive, energy-intensive unit process involving solids handling at wastewater treatment plants; costs for incineration at the BIWWTP have averaged $2.4 million per year. In the conventional method of processing solids, a series of volume reduction measures, which usually includes thickening, digestion, and mechanical dewatering, is employed prior to incineration.

Usually, a high level of moisture is still present within sewage sludge following mechanical dewatering. The sludge dryer system thermally dewaters wastewater sludge to approximately 26% (and as high as 38%) dry solids content prior to incineration.

The thermal dewatering system at the BIWWTP has demonstrated that it meets its design requirements. It has the potential to provide significant energy and other cost savings by allowing the BSA to change from an operation employing two incinerators to a single incinerator mode. While the long-term reliability of the thermal dewatering system has yet to be established, this project has demonstrated that installation of such a system in an existing treatment plant can provide the owner with significant operating cost savings.

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SUMMARY

The Buffalo Sewer Authority (BSA), in cooperation with the New York State Energy Research and Development Authority (Energy Authority), commissioned a study of sludge incineration heat recovery and process optimization at the BSA's 180 million gallon per day (mgd) Bird Island Wastewater Treatment Plant (BIWWTP). The demonstration project involved installation of a thermal sludge dryer, combustion testing and data gathering, and analysis to determine the unit's effect on the BIWWTP's solids handling process and energy utilization.

The BIWWTP is a conventional activated sludge treatment facility that currently processes approximately 57 dry tons per day of wastewater sludge. As a general rule of thumb, the daily sludge production is approximately one part thickened primary sludge to four parts thickened, digested waste activated sludge.

The facility employs belt filter presses for mechanical dewatering and multiple hearth incinerators as the final step in its solids handling train. Each of the three incineration trains is equipped with an afterburner, waste heat recovery boiler (WHRB), and wet scrubber. The WHRBs are operable only during periods in which the afterburners are operated and, at the time of the demonstration project, the afterburners were not required for the BIWWTP to meet its stack emissions permit. Prior to the sludge dryer installation, typical operations at the BIWWTP included running two partially loaded incinerators 24 hours per day, 365 days per year. The facility's costs for operation and maintenance (O&M) of the incineration system were approximately $2.4 million per year.

The dryer installed under this project was an indirect disk-type sludge dryer that utilizes steam as its heat source. The dryer is an entirely enclosed process and all sludge in the unit is contained in a horizontal stator. Inside the stator, a series of hollow, stainless steel disks are mounted on a hollow rotating shaft. Steam is supplied to the dryer through the shaft and disks, and indirect heat transfer between the steam and the sludge occurs

across the surface of the disks. Sludge enters the inlet end of the dryer and progresses through annular spaces between the disks and the stator wall in plug flow fashion.

Design values for the BSA sludge dryer included an average daily sludge load of 24 dry tons per day applied over a 24 hour operating period; design inlet sludge total solids content is approximately 19%, and design discharge total solids content is 35%. Design steam consumption is approximately 5,800 lbs per hour of operation. The sludge dryer was installed at the BIWWTP between the mechanical sludge dewatering process and the facility's multiple-hearth incinerators. The dryer unit is approximately 24 feet long, 7 feet wide, and 9 feet high. Ancillary equipment installed adjacent to the dryer included sludge inlet and discharge screw conveyors and a condenser system to treat the odorous vapor evaporated from the sludge.

The sludge dryer was installed in 1991, and data gathering was performed throughout the winter and early spring of 1992. Data collection included various sludge management parameters together with several incinerator combustion parameters, including detailed analyses of sludge quality, and continuous measurements of temperatures, combustion air flow rates, and incinerator and afterburner flue gas oxygen and carbon monoxide content. The tests were performed for three different sludge blends and, for each blend, tests were performed with and without the afterburners in operation. During the periods in which the afterburners were operating, steam supply to the dryer was provided via the WHRBs; thus, during the "afterburner on" conditions, the dryer effectively was provided with "free" steam. During "afterburner off" conditions, steam was provided by the plant's auxiliary boilers.

Analyses performed for each test condition included hearth-by-hearth mass and heat balances for the incinerator, and mass and heat balance calculations for the dryer. Statistical data reduction and correlation was performed on the data prior to the engineering analyses. Upon completion of these analyses, cost effective uses for the waste heat generated by the dryer and incinerators were identified.

The following recommendations and conclusions were drawn from this project:

- The dryer achieved its design values. Through thermal dewatering, autogenous combustion (i.e. without the addition of natural gas or other auxiliary fuels) was achieved in the incinerator.

- No significant start-up or operational problems were encountered with the BIWWTP sludge dryer unit. Miscellaneous problems encountered with the ancillary equipment have been rectified since the conclusion of the project. Based on the BSA project, indirect condensers are recommended to treat the dryer vapor.

- The dryer enables the BSA, on occasion, to operate one fully loaded incinerator as opposed to the former operation of two partially loaded incinerators. This was accomplished by recently completed sludge conveyor belt modifications, which allow more sludge to be fed to the dryer. Also, modifications to the dryer's ancillary equipment were required to handle the increased solids load.

- The dryer is capable of operating at higher-than-design evaporation rates, through increased sludge detention times and steam application rates.

- The dryer produces waste heat that may be economically recovered for beneficial use at the BIWWTP. The BSA plans to utilize waste heat recovered from both the dryer vapor and incinerator flue gases to elevate the temperature of the belt filter press belt rinse water, thereby improving the mechanical dewatering process.

- The amount of steam consumed by the dryer during periods in which the afterburners (and, hence, the WHRBs) were off-line necessitated the operation of an additional auxiliary boiler at the BIWWTP. This effectively offset the advantage gained through the autogenous combustion of the sludge in the incinerator and made operation of the dryer cost-prohibitive without the afterburners and WHRBs.

- Due to the 1993 sludge incineration regulations promulgated under 40 CFR 503, operation of the afterburners at the BIWWTP will likely be required on a full-time basis. Thus, the "free" steam generated by the WHRBs renders the dryer an advantageous process in the BIWWTP's solids handling train.

- Thermal drying is recommended for wastewater treatment facilities that employ incineration, so long as a source of relatively cheap steam is available. Economical steam sources include WHRBs and/or the purchase of low-cost steam from cogeneration facilities.

- Thermal drying appears to be a process optimization more economically suited to multiple-hearth incinerators than fluidized bed incinerators. This is due to the fact that fluid bed units typically have lower emissions levels than multiple-hearth incinerators and afterburners are seldom required at fluid bed installations. Thus, the capital and O&M expenses associated with steam generation equipment makes sludge drying less advantageous as a process optimization for fluid bed facilities. However, as a volume reduction method, thermal drying appears to be feasible for any treatment facility which has sufficient steam supply available.

- While sludge dryers appear to be most feasible when used in conjunction with incineration, some wastewater treatment facilities are presently considering the installation of indirect sludge dryers as the final process (exclusive of incineration) in their solids handling streams. However, evaluation of dryers not used in conjunction with incineration was outside the scope of this project.

SECTION 1

INTRODUCTION

BACKGROUND

The Buffalo Sewer Authority (BSA) provides wastewater collection, conveyance, and treatment for the City of Buffalo and surrounding communities. The BSA's modern 180 million gallons per day (mgd) treatment facility is located on Bird Island in the Niagara River, on the west side of Buffalo.

The BSA currently processes approximately 57 dry tons of sewage sludge per day at the Bird Island Wastewater Treatment Plant (BIWWTP). Solids handling is accomplished via a series of unit processes, including thickening, anaerobic digestion, sludge conditioning, and mechanical dewatering. Solids disposal is accomplished using multiple-hearth sludge incinerators, which are equipped with air pollution control equipment (afterburners and scrubbers) and waste heat recovery systems. However, the operation and maintenance (O&M) costs associated with incineration are the highest of all solids handling processes at the BIWWTP.

In an effort to reduce O&M costs, the BSA resolved in 1988 to examine means by which costs associated with solids disposal could be reduced within the framework of the current solids handling system. For this purpose, the BSA retained Nussbaumer & Clarke, Inc., Consulting Engineers, of Buffalo, New York, to perform a comprehensive study and identify cost-effective measures that would optimize the existing solids handling system.

One solids handling option examined by the BSA and the consulting engineer included optimization of the incineration process through the use of a thermal sludge dewatering system or "sludge dryer". Following the comprehensive study and evaluation, *indirect* dryers were recommended over direct dryers due to their higher efficiency, lower O&M costs, and decreased odors. The dewatering alternative recommended to the BSA was the installation of a full-scale sludge dryer.

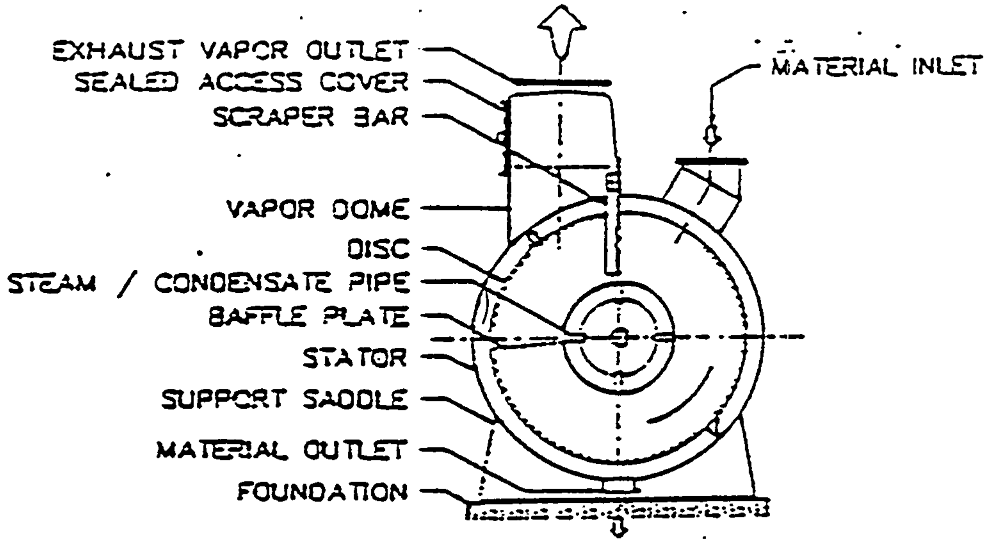
The equipment chosen for the task was a "disk-type" steam dryer marketed and installed by Stord, Inc., of Greensboro, North Carolina. The Stord equipment was recommended based on an evaluation of other manufacturers' sludge dryers, observation of Stord pilot tests at other treatment facilities, and a visit to Stord's manufacturing facility in Norway.

The Stord unit utilizes steam, indirectly applied across a stainless steel plate, to effect the heat transfer necessary to evaporate the water from the sludge and thus perform thermal dewatering. In order to maximize the heat transfer surface, the stainless steel interface between the steam and the sludge is arranged in a series of hollow disks, installed inside a hollow metal horizontal "enclosure" or stator. As sludge moves through the unit in-plug-flow fashion, the vapor produced from the evaporated moisture is routed through a condenser/odor control system. Figure 1-1 shows two cut-away views of the Stord dryer.

Steam for the dryer may be produced in either of two ways. At the BIWWTP, "auxiliary boilers" are maintained for ordinary plant steam production. However, during periods when the incinerators' afterburners are in operation (to meet emissions criteria), the plant's "waste heat recovery boilers" are often utilized for steam production. Therefore, prior to the demonstration project, the BIWWTP had sufficient steam capacity available to supply the indirect dryer.

Early in the solids handling study it was realized that an indirect sludge dryer had the potential to substantially reduce the energy consumption for the incineration process and, perhaps, the steam production process (in spite of the fact that steam demand at the plant would be increased). This was due to several hypotheses which the demonstration project was intended to confirm or deny:

- Thermal dewatering would reduce the volume of wet sludge sufficiently to allow the BSA to go from its then-current two-incinerator operation to a single-incinerator operating mode.



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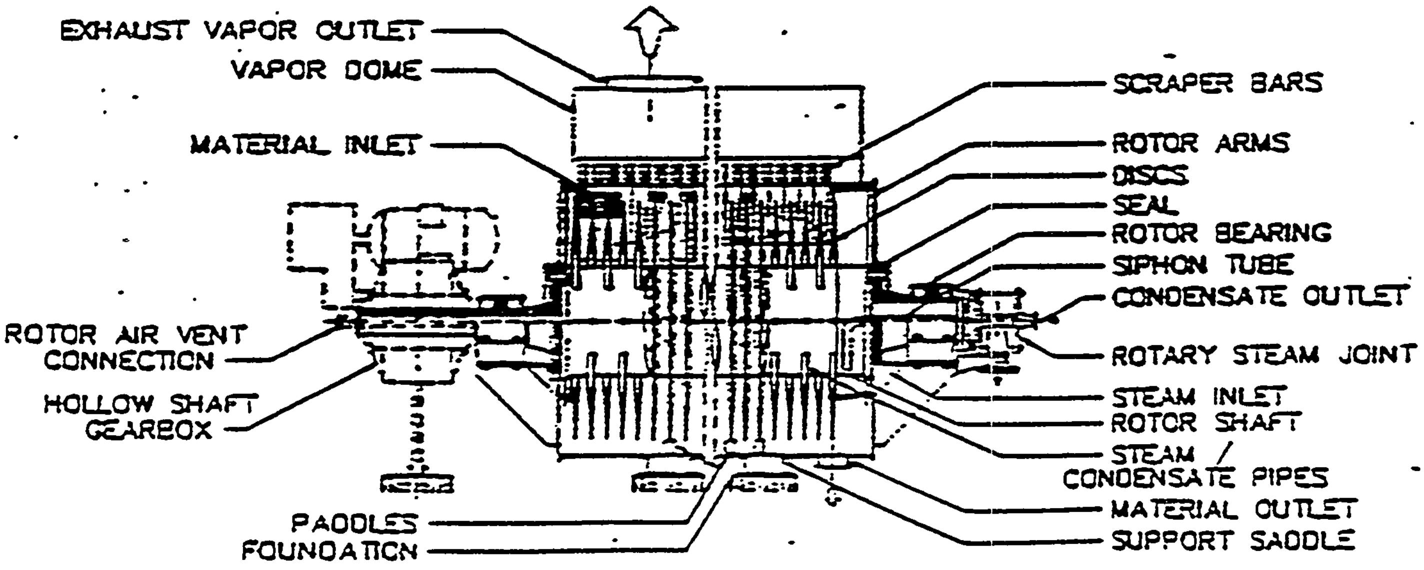

SIDE VIEW SECTION

STORD ROTADISC INDIRECT
HEAT DISK DRYER

FIGURE
1–1

- The elevated temperature of the thermally dewatered sludge fed to the incinerator (as opposed to mechanically dewatered sludge) would reduce incinerator auxiliary fuel required to evaporate water from the sludge prior to combustion.

- The thermally dewatered sludge could produce elevated incinerator exhaust temperatures sufficient to allow operation of the BIWWTP's waste heat recovery boilers during periods when the afterburners were not in use. Thus, the thermal dewatering system would be self-sustaining, in effect, contributing to the production of its own "fuel" (steam).

PROJECT OBJECTIVES

The demonstration project included the following objectives:

1. Determine energy savings in the incineration system obtained through the operation of the indirect dryer. The primary energy savings expected was a reduction in the volume of natural gas required as incinerator auxiliary fuel.

2. Determinate whether the BIWWTP could attain a single-incinerator operation, as opposed to its then-current two incinerator mode. This objective was based on two principles:

    a. The two incinerators were normally loaded well below their design capacity prior to the installation of the dryer. The greatest operating efficiency that can be obtained from a multiple-hearth incinerator is when the unit is loaded at or near its design capacity.

    b. Maintenance costs associated with a single-unit operation are much less than those of a two incinerator operation.

3. Determine whether operating the BIWWTP's waste heat recovery boilers was possible without operating the afterburners, given the anticipated higher burn temperature of the thermally dewatered sludge.

4. Determine the ultimate effect an indirect thermal dryer would have on the incinerators' combustion efficiency, and on the plant's steam production and utilization.

5. Determine appropriate, cost-effective uses for the waste heat generated by the dryer system, and identify cost-effective measures for further recovery of incinerator system waste heat.

PRINCIPLES AND CONCEPTS

Thermal drying of sludge for volume reduction is not a new concept. Other types of thermal drying for wastewater sludge include: utilization of multiple-hearth incinerators as dryers or pelletizers (instead of as combustion units); utilization of rotary dryers and kilns; the Carver-Greenfield process (multiple-effect evaporation); use of electric furnaces; and wet air oxidation.

The particular concept used in this project is a rotary disk dryer, a type of indirect dryer for dewatering municipal wastewater sludge. Prior to the BSA demonstration project, only one other known indirect sludge dryer was operating on municipal sludges in North America, in Youngstown, Ohio. However, indirect steam dryers have been used for years in North America for processing fish meal, animal rendering wastes, and other hard-to-dry materials which require continuous throughput and rugged equipment design. Indirect steam dryers are also in use at municipal wastewater treatment facilities in Germany, Norway, Holland, and Japan.

The concept of the BSA system called for the installation of the dryer between the mechanical dewatering equipment and the incinerators. The dryer would be fed mechanically dewatered sludge produced by belt filter presses. The mechanically dewatered sludge would be diverted (using a mechanical plow) off the existing conveyor belt into a hopper. A screw conveyor would transport the sludge from the hopper to the inlet of the dryer unit. Sludge would progress through the dryer and be discharged at the far end of the unit into a discharge screw conveyor, which would transport the thermally dewatered (or "dried") sludge back to the conveyor belt that fed the incinerator.

The rotary disk dryer utilizes medium-pressure steam as a drying heat source. The steam is contained in a hollow center shaft and multiple hollow disks. The rotating disks present a large surface area for contact with the media to be dried. Rotation of the hollow disks and center shaft allows paddles, affixed to the disk edges, and scraper bars mounted on the stationary stator, to "stir" the sludge and gently move it through the stator, while maximizing the steam/sludge interface.

Moisture probes located at various points along the dryer provide readings to the dryer's programmable logic controller (PLC), which in turn controls the amount of steam admitted to the disks and the amount of sludge admitted to the stator. The PLC controls the speed of the inlet and discharge screw conveyors and the pneumatic controls for the diversion plow on the sludge conveyer belt.

The governing principle behind the indirect steam dryer is simple heat exchange. Steam at approximately 350°F is brought into indirect contact with sludge (at approximately 70°F) across an interface constructed of material (stainless steel) with a high degree of thermal conductivity. Thus, the input to the dryer is composed solely of feed sludge and steam. Resulting byproducts of the thermal heat exchange include partially-dried sludge at a temperature of approximately 185°F, steam condensate, and dryer vapor (which is the water evaporated from the feed sludge). The dryer vapor is a wet, odorous vapor at approximately 212°F that requires separate treatment. For this project, the vapor was routed through a direct venturi condenser. The resulting non-condensible gases were then piped to the incinerators as a secondary source of combustion air.

PROJECT WORK PLAN

The demonstration project involved many different phases and was divided up into the following work tasks:

Task 1: Preparation of a *Summary Report* (BSA/Nussbaumer & Clarke, April 1990) on the proposed system and preparation of the dryer equipment procurement specifications and contract. The dryer equipment was purchased directly from the manufacturer by the BSA, rather than through a construction contractor.

Task 2: Preparation of a report entitled *Combustion Testing Plan and Monitoring Equipment Specifications* (BSA/Nussbaumer & Clarke, February 1991). This plan outlined the required testing protocols and specified the type and location of instrumentation to be used in gathering the project monitoring data. Collection of accurate data was essential. The variables to be monitored were divided into two classifications: sludge management variables and combustion variables. The sludge management variables were read and recorded by plant operators at intervals of either two or four hours (depending on the variable), while all combustion variables except for the "sludge ultimate analysis", which was a series of laboratory tests, were continuously measured by instruments and recorded at intervals of one minute or five minutes (depending on the variable).

Task 3: Preparation of design plans, specifications, and contract documents for the installation of the dryer equipment at the BIWWTP Main Equipment Building, which houses much of the BSA's solids handling systems. In addition to the plans, specifications, and contract documents, a *Design Report* detailing the assumptions and criteria used in the design of the system was prepared (BSA/Nussbaumer & Clarke, February 1991).

Task 4: Bidding and award of the construction contracts and installation of the equipment. The project was awarded in four prime contracts (general/mechanical, HVAC, plumbing, and electrical) at an approximate cost of $1 million (exclusive of the cost of the dryer equipment). Construction included installing the dryer equipment and connecting plant utilities to the new system. This task also included installing instrumentation required to monitor the system for the demonstration project.

Task 5: System start-up and shake-down. This task included preparing a report entitled *Sludge Dryer Installation and Start-up Report* (BSA/Nussbaumer & Clarke, December 1991).

Task 6: Monitoring and data gathering under three separate test conditions, based on the type of sludge feed to the incinerator. Each test condition was further divided into "subconditions" for "afterburners on" and "afterburners off." The monitoring program began in November 1991 and was completed in March 1992.

Task 7: Data reduction and analysis. This task included preparing two reports entitled, *Data Analysis Plan* (BSA/Nussbaumer & Clarke/Gore & Storrie, December 1991), which described the procedures to be utilized in the data reduction and analysis, including descriptions of the hearth-by-heath mass and heat balances to be prepared for several scenarios in each test condition, together with an addendum (BSA/Nussbaumer & Clarke/Gore & Storrie, February 1992); and *Monitoring and Data Analysis Report* (BSA/Nussbaumer & Clarke/Gore & Storrie, January 1993) and addendum (dated August 1993), which described the findings of the analyses.

Task 8: Determination of feasible methods of waste heat recovery, including economic analyses for each alternative examined. This task included preparing a written report entitled, *Waste Heat Recovery Feasibility Study* (BSA/Nussbaumer & Clarke, August 1993).

Task 9: Reporting, including preparation of a Final Report.

Task 10: Technology transfer.

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SECTION 2

EXISTING SYSTEMS

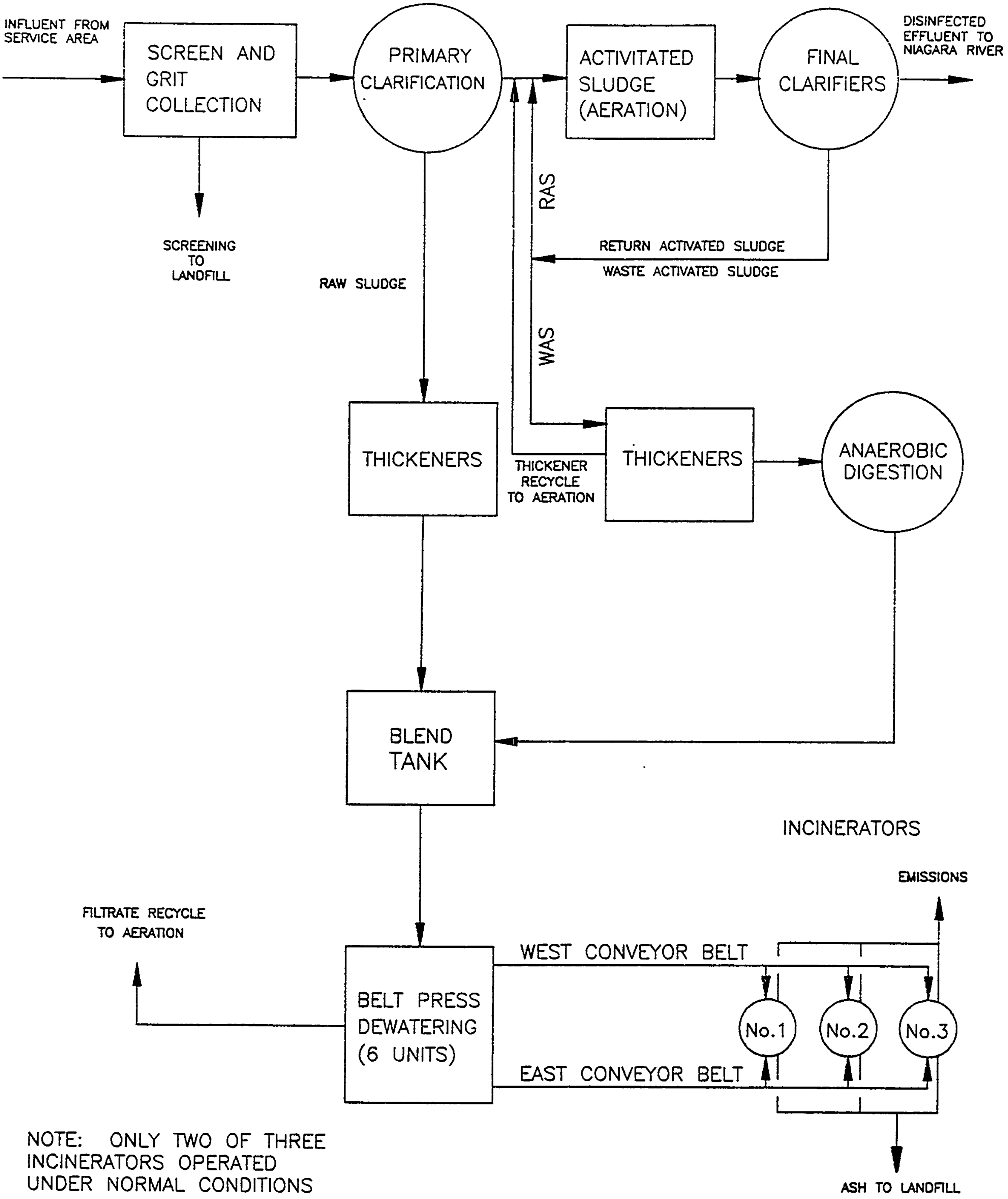
PROCESS CONDITIONS

The BIWWTP is a conventional activated sludge facility which provides full secondary treatment at a design flow of 180 million gallons per day (mgd). The BIWWTP's primary treatment facilities were constructed in 1938, and an extensive program of plant expansion, including construction of secondary treatment and solids handling facilities, was completed in 1979.

The BIWWTP currently treats the wastewater generated in the City of Buffalo and portions of surrounding communities. The plant serves an area of approximately 110 square miles, with a service population of 550,000. Current average daily flows treated at the plant are approximately 165 mgd.

Principal wastewater treatment processes at the BIWWTP (see Figures 2-1, 2-2, and 2-3) include: screening and grit removal, primary clarification, aeration, secondary clarification, and disinfection, prior to discharge to the Niagara River. Solids produced at the treatment plant include primary sludge and waste activated sludge (WAS); solids handling processes include thickening, anaerobic digestion, blending, conditioning with cationic polymer, mechanical dewatering (utilizing belt filter presses), thermal dewatering, and incineration.

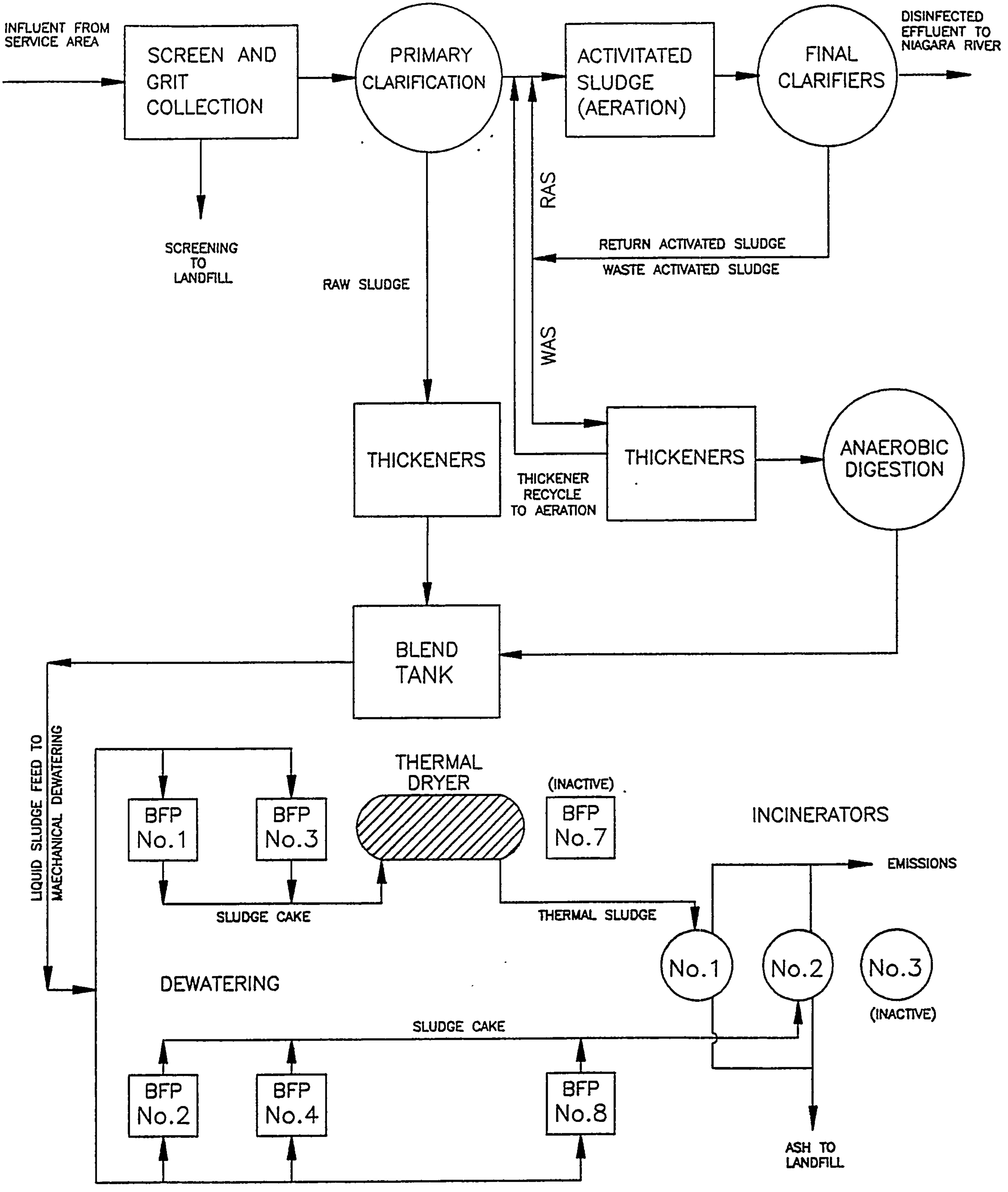
WAS produced in the secondary clarifiers is thickened to approximately 4%-5% solids via dissolved air flotation (DAF), and is anaerobically digested (where a 30%-50% reduction of volatile solids is normally achieved). The digested WAS, with an approximate total solids content of 3.5%, is then conveyed to the blending tanks, where it is combined with raw primary sludge (which is normally not digested), conditioned with polymer, and pumped to mechanical dewatering. As a rule of thumb at the BIWWTP, blended solids conveyed to dewatering are approximately one part primary to four parts digested WAS.



NOTE: ONLY TWO OF THREE
INCINERATORS OPERATED
UNDER NORMAL CONDITIONS

TREATMENT PROCESS FLOW SCHEMATIC
PRIOR TO THERMAL DRYING

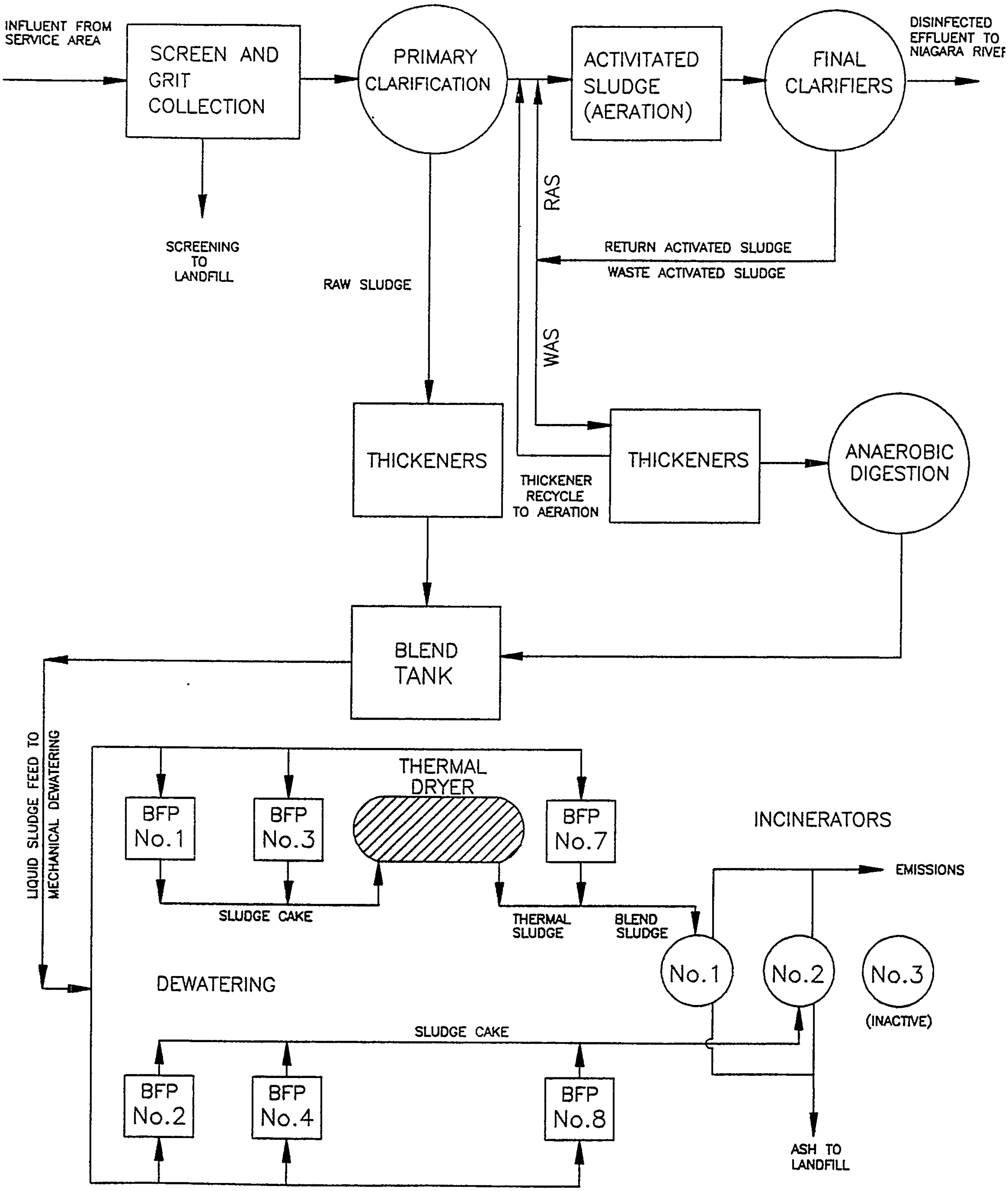
FIGURE
2–1



NOTE: "BFP" = BELT FILTER PRESS

TREATMENT PROCESS FLOW SCHEMATIC ONLY THERMALLY DEWATERED SLUDGE TO INCINERATOR

FIGURE 2–2



NOTE: "BFP" =
BELT FILTER PRESS

TREATMENT PROCESS FLOW SCHEMATIC
BLEND OF THERMALLY
DEWATERED SLUDGE

FIGURE
2-3

Mechanical dewatering is presently accomplished at the BIWWTP by seven belt filter presses, arranged along two conveyor belts (the east belt and the west belt). At present, four presses (units No. 2, 4, 6, and 8) are situated on the east belt, while the west belt is arranged from upstream to downstream as follows: two belt presses (units No. 1 and 3), the thermal dryer, and Belt Press No. 7. Through the use of mechanical plows, each conveyor belt can discharge to any of the BIWWTP's three sludge incinerators. A recent modification of the conveyor belt system also allows transfer of sludge between the east and west belts.

At the time of the demonstration project, however, the east belt had only three presses (units No. 2, 4, and 8), while the west belt was configured as it is at the present; in addition, at the time of the demonstration project, the two conveyor belts were entirely separate, so that transfer of sludge between belts was not possible. Therefore, during the data gathering for the project, at any given time, the dryer was fed by a maximum of two belt presses.

Typical solids content of the mechanically dewatered sludge cake fed to the dryer during the project ranged from 12.9% to 21%, with an average solids content of approximately 16% over all test conditions.

INCINERATION SYSTEM

Incinerators

The BIWWTP is equipped with three multiple-hearth sludge incinerators. The three units, manufactured by Envirodyne Engineering, are typical Herreshoff-type furnaces, and each is 22 feet 3 inches in diameter with twelve hearths. Combustion of sludge is assisted in each incinerator through the utilization of auxiliary fuel; at the BIWWTP, auxiliary fuels are one of the following: natural gas (purchased from a local utility company), biogas produced on-site in the anaerobic digesters (DI-GAS), or fuel oil. The design load for each incinerator is 10 wet tons of sludge per hour at 17% total solids content. The typical volatile solids content of the incinerator feed sludge during the demonstration project was approximately 60%, and moisture/volatiles ratios ranged from roughly 5.5 to 10.5, with the typical value being approximately 7.5-8.0.

Prior to the demonstration project (and periodically after installing the dryer), the mode of incinerator operation was two partially loaded furnaces operating 24 hours per day, 7 days per week, 365 days per year. The third (non-operating) incinerator is either undergoing regularly scheduled maintenance or kept in a "standby" mode.

Typical of multiple-hearth incinerators that burn mechanically dewatered sludge, the BIWWTP units are fed through a hopper at the top hearth, where a temperature of 500°F - 1000°F is maintained. The combustion zone is located in the center hearths where the typical operating temperature is about 1500°F. Incinerator exhaust gases are drawn out of the unit via ducting connected to the uppermost hearth.

Afterburners

Flue gases leaving each incinerator outlet are directed through flue gas breeching to an afterburner. Six burners, of the same type used in the incinerator, are used to heat the incinerator exhaust flue gases from their incoming temperature of 500°F - 1000°F to approximately 1400°F. The burners are located in the periphery of the afterburner shell near the flue gas entry and the flame is directed in such a manner as to give the greatest mixing and agitation of the entering flue gases. The burners are controlled automatically by the signal from a thermocouple which measures the afterburner flue gas outlet temperature.

The general purpose of elevating the flue gas temperature is three-fold: 1) to destroy objectionable odors that may be generated by the drying and burning process in the incinerator; 2) to combust any unburned hydrocarbons in the flue gases; and 3) to oxidize the products of incomplete combustion to a stable condition before discharge to the atmosphere. Hydrocarbons are defined as any compound made up of the chemical elements carbon and hydrogen.

The afterburner and its breeching are sized to provide a minimum detention time of approximately eight-tenths of a second after reaching the desired temperature and before entering the waste heat recovery boiler and/or wet scrubber.

The required final temperature in the afterburner is dependent upon the quality of the incinerator flue gases entering the afterburner unit. Polluting hydrocarbons in the incinerator flue gas can vary considerably, depending on the type of sludge filter cake being burned, the percentage of oil and greases in the filter cake being burned and the operating temperatures in the incinerator. Normally, higher incinerator temperatures, coupled with the presence of sufficient oxygen (air), results in lower concentrations of unburned hydrocarbons and increased oxidation of the flue gases.

Air Pollution Control System

Each incineration train at the BIWWTP is equipped with its own air pollution control (APC) or "scrubber" system. Exhaust gases exiting each afterburner may be routed either through or around a waste heat recovery boiler (see below), before entering the APC system. Each scrubber includes the following: pre-quench, adjustable venturi throat, and impinger trays that provide removal of particulate-laden moisture droplets. The water supply to the pre-quench may be either plant process water or city water. The air flow through each incineration/APC system is provided by a dedicated induced draft (I.D.) fan with an approximate capacity of 30,000 standard cubic feet per minute (scfm). Each of the three I.D. fans exhausts the treated flue gas from the incineration train to a common main stack. In addition to conveying incinerator exhaust, the main stack also serves as the stack for the flue gases generated by the BIWWTP's three auxiliary boilers.

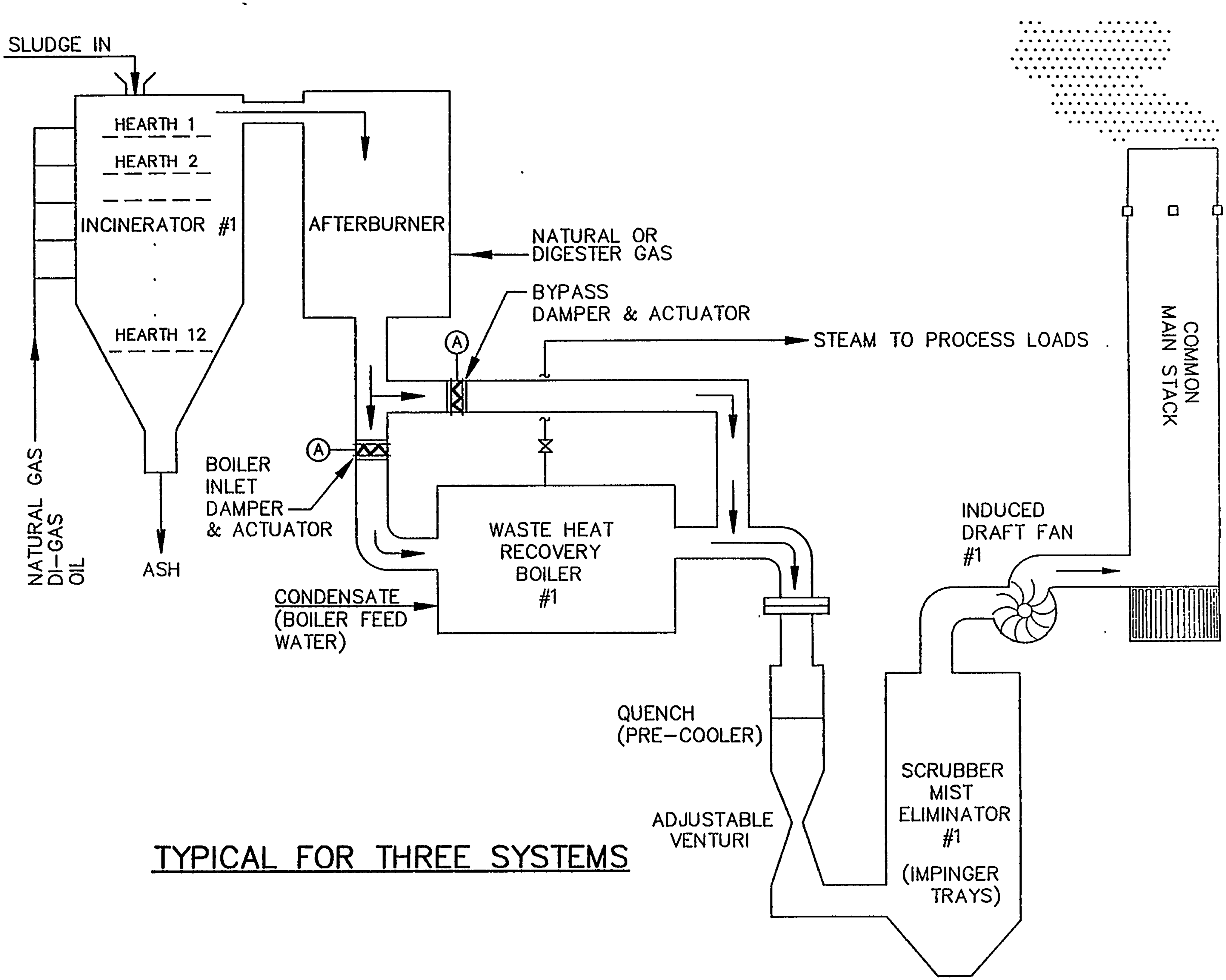
BOILER SYSTEMS

Auxiliary Boilers

The BIWWTP is served by three auxiliary boilers. These boilers are each capable of producing 44,000 lb/hr of steam at 125 pounds per square inch gauge (psig) pressure. They are fire box, water tube-type boilers. At the present time, these boilers serve all domestic hot water, HVAC, and process needs at the BIWWTP. Typically, only one of the three boilers is used to meet the load requirements; however, on a design winter day with the sludge dryer operating, a second auxiliary boiler is required.

Waste Heat Recovery Boilers

There are three waste heat recovery boilers (WHRB) at the BIWWTP. These units are each water tube-type and capable of delivering 22,000 lb/hr of steam at 125 pounds per square inch gauge (psig) pressure. Operation of these boilers is contingent upon the operation of the afterburners. If the afterburners are operating, the flue gas temperatures are sufficiently elevated to operate the WHRBs and prevent condensation (see Figure 2-4). If the afterburners are not in operation, the incinerator flue gases are bypassed around the WHRBs and the auxiliary boilers are utilized to meet the plant's steam requirements.



TYPICAL FOR THREE SYSTEMS

SCHEMATIC OF INCINERATOR/WASTE HEAT BOILER FLUE GAS PATH.

FIGURE 2-4

SECTION 3

SLUDGE DRYER DESIGN CRITERIA

DRYER SYSTEM DESIGN ACTIVITIES

This section summarizes the design activities performed for the project. It includes descriptions of the design considerations for civil/structural, mechanical, electrical, and instrumentation work.

Civil/Structural Design

The initial design problem addressed was the location of the sludge dryer. Several factors were considered in this determination, including accessibility to the existing conveyer belts, provision of ample room for the dryer and ancillary equipment, the load bearing capacity of the existing structure, accessibility of the area for the pre-assembled sludge dryer unit, and accessibility for regular maintenance on the dryer.

It was determined that the dryer would be placed on the third floor of the BIWWTP Main Equipment Building, adjacent to the existing belt presses and the west dewatered sludge conveyor belt. This area was chosen because it had ample space for placement of the pre-assembled dryer adjacent to the west conveyor belt, and required relatively minor changes to the conveyor belt to divert the dewatered sludge cake to the dryer. This area was also in a straight alignment to the west exterior wall of the Main Equipment Building where the dryer would have to be brought into the structure.

Provisions to install a second dryer adjacent to the first at a future date, if desired by the BSA, were also considered. However, during the structural design process, it was determined that installation of two dryers in the available space on the third floor would require extensive structural modifications since each unit would weigh approximately 37 tons when loaded with sludge. Two dryers in close proximity to each other was determined to be unfeasible. However, a second dryer could be added at a later date on the second floor of the Main Equipment Building, with sludge transfer accomplished via high-solids sludge pumps.

The installation of only one dryer provided enough latitude to shift the originally proposed location and greatly reduce the loads transferred to the structural beams. This adjustment eliminated the need for extensive structural framing. A relatively simple foundation frame was designed for the dryer to distribute the loading to beams and columns with available structural load-bearing capacity. The dryer unit installed at the BIWWTP has a dead load (including the structural steel foundation) of approximately 25 tons; the total load of the unit (i.e. when fully loaded with sludge) is approximately 37 tons.

The actual placement of the dryer required transporting it approximately 16 feet across the existing floor. A temporary framing system was used to distribute the heavy point load and allow the dryer to be moved unobstructed along the top of the framing.

To install the dryer into the Main Equipment Building, removal of a portion of the existing exterior wall at the third floor level was incorporated into the design. This included removal of the exterior sandstone wall panels (installed at a height of approximately sixty to eighty feet above the ground) and a masonry wall located adjacent to the exterior panels. It was intended to lift the dryer into the building with a crane; the dryer and its three-ton drive unit were to be installed into the building separately, for ease of construction. Following installation of the equipment, the masonry wall was rebuilt and the exterior wall panels restored. No permanent modifications to the Main Equipment Building were necessary.

The layout of the dryer vapor condenser and the screw conveyers for the sludge was designed to allow maximum space utilization, while leaving ample room for maintenance and operator access.

Modifications to the existing sludge conveyer system were required; these included installing a new mechanical diversion plow, plow controls, and concrete housekeeping pads.

Consideration was given to dryer access for visual monitoring and maintenance. To facilitate such access, a platform and two "ship's ladders" were installed adjacent to the dryer.

MECHANICAL DESIGN

Mechanical design for the demonstration project consisted of integrating the dryer's utility requirements with the existing BIWWTP resources. Several plant-supplied utilities were required to make the dryer operational. The mechanical systems designed were:

- Steam supply and condensate return,
- Selection of a condenser unit and cooling water source,
- Dryer gear box cooling water supply,
- Sludge dryer vapor exhaust location,
- Sludge dryer steam condensate return,
- Non-condensible gas exhaust, and
- A preliminary evaluation of heat recovery alternatives.

These systems are discussed below.

Steam and Condensate. Steam and condensate piping convey the process energy to the dryer. The thermal energy of the steam is used to dewater the sludge cake that composes the dryer feed. Steam condensate piping is necessary to recycle boiler water and maintain a high steam plant efficiency.

Existing 6-inch diameter steam lines were evaluated to determine if sufficient excess capacity was available to service the dryer's potential maximum design steam load of 7,492 lbs/hr. With seasonal loading of the 6-inch diameter steam lines for heating and cooling, it was decided that the additional dryer load on these existing lines would induce excessively high steam velocities. This would have resulted in erosion and noise in the steam piping; consequently, a dedicated steam line was required. A new 6-inch diameter branch main was designed to supply steam to the dryer area.

Existing condensate return lines, which are original plant piping, are schedule 40 steel pipe. Most of the existing piping suffers from erosion and corrosion, which is typical of normal condensate service. At the time of the system design, the existing condensate system required regular repairs to keep it in service. Therefore, new 2-inch and 2.5-inch schedule 80 steel return lines for the dryer system were designed to handle the dryer's condensate and the original plant condensate load.

Condenser Selection and Cooling Water Source. The excess sludge moisture is driven off as vapor within the dryer, condensed, and ultimately piped to a plant drain for disposal. Direct and indirect condensers were both considered for this purpose. A secondary design consideration was whether to use an open or closed recirculating-type of condensing system. Selection of the unit took into consideration available plant resources for condenser coolant. The required design flow of the cooling water supply was approximately 100 gallons per minute (gpm).

City water (potable water) was considered for use as a coolant. Calculations showed that any open-type condensing scheme would require an estimated $60,000 per year to operate because the cooling water would ultimately be sent to a drain.

An indirect condensing unit would permit the establishment of a closed system. Once city water had filled the system, it could continually be recirculated.

A direct-type condensing system cannot be used in a closed loop configuration because of the continual gain of mass within the loop. Initially, a closed loop indirect-type condensing system was considered for maximum heat recovery. However, equipment costs were excessive, projected maintenance costs were high, and operational complexity was extremely high.

To minimize equipment and O&M costs, a direct-type condensing system was required. However, to utilize a direct-type condensing system and ensure reasonable operating costs, an alternate cooling medium (other than city water) was required. The first coolant considered was the liquid sludge feed to the belt presses. However, the sludge feed to the individual belt presses does not flow through a common pipe. Thus, redundancy of pumps and condensing units would have been required to guarantee continuous operational capability of the dryer.

Water from the Niagara River and the Black Rock Canal (respectively located on the west and east side of Bird Island) were both considered for use as condenser coolant. However, the threat of zebra mussel infestation resulted in rejection of these alternatives.

Following considerations of the alternatives discussed above, it was decided that the plant's final effluent water (water diverted from the wastewater treatment process prior to disinfection) could serve as an adequate coolant. Final effluent is not subject to zebra mussel infestation and would have no direct costs associated with its use.

Currently, the plant utilizes final effluent (FE) in its incinerator APC system, for absorption chiller cooling, ash conditioning equipment, and cooling of miscellaneous large motors. The final effluent enters the FE water system from a pump station at the north end of the BIWWTP. The original pumping system has had many additions in cooling loads over the years, so that at the time of the dryer system design, the FE system was utilized to its maximum pumping capacity. Additional demand on this pressurized system was avoided. Alternately, a 36-inch recirculated FE pipe in the sub-basement of the Main Equipment Building was used. This pipe comes from a separate (non-pressurized) effluent source, flows by gravity, and provides FE water to the plant for other utilities.

At the request of the BSA, consideration was given to cross-connecting the recirculated FE water to the BIWWTP's protected water supply. Utilization of condenser cooling water from this source would serve two purposes: 1) eliminating the use of potable city water for plant functions that do not require potable water; and 2) using an existing pumping system, rather than requiring design and construction of a new pumping system specifically for the dryer condenser.

Thus, the protected water supply, augmented by the recirculated FE water system, was chosen as the source for the dryer condenser cooling water. A strainer system was designed to prevent solids in the FE water from carrying over into the revised protected water supply system. For this purpose, a duplex coarse strainer was designed for installation at the existing protected water break tank inlet. A duplex configuration was chosen to permit maintenance on one strainer without a system shutdown. Downstream from the coarse strainers, a motorized automatic, fine scraper/strainer was designed for the outlet of the existing protected water pumps, thus providing continual straining of the fine solids. The 12-inch scraper/strainer would cause a negligible 1.2 pounds per square inch (psi) pressure drop in the protected water system at the estimated peak flow of 2,500 gpm.

A new protected water branch line was installed to the dryer system to minimize water hammer and provide regulated pressure control for the dryer condensing unit. In addition, the protected water from this branch line supplies water to sparge water sprays located at the top of the dryer stator. The sparge water is required for instances in which the sludge in the dryer exhibits "stickiness" and "globs up," inhibiting sludge progression through the unit. Media stickiness has historically not been a significant problem for indirect rotary disk dryers processing wastes from industrial applications. Municipal wastewater sludge processed by indirect disk dryers in Europe, however, tend to exhibit greater stickiness than industrial sludges.

Connecting the recirculated FE water to the protected water supply system required that city water be separated from the current protected water backflow preventer. In addition, city water had to be maintained to plant drinking fountains, sinks, showers, etc. Special provisions were made to continue city water service to the boiler make-up water softeners. Backflow prevention was maintained to all newly configured city water systems to satisfy health codes.

<u>Gear Box Cooling Water</u>. The horizontal central shaft and hollow disks within the dryer stator are rotated by a 75-horsepower (HP) motor; this unit requires cooling water at a rate of approximately 5 gpm.

The dryer manufacturer mandated that only potable water be used as a coolant for this motor, so as not to violate the dryer's warranty. Screened and filtered FE water was proposed; however, the manufacturer continued to maintain that only potable water should be used. A separate source of potable water, complete with backflow prevention, was designed for gear box cooling. This potable water is conveyed through a new 1.5-inch diameter Type K copper line.

<u>Sludge Dryer Vapor</u>. The moisture evaporated from the sludge is transported to the direct condensing unit through the sludge dryer vapor duct, which is schedule 10 type 304 stainless steel. This material was selected due to its high corrosion resistance in the presence of chemical compounds generally found in the sludge dewatering room environment. Schedule 10 pipe was selected because of its light weight and seamless construction in sizes that would handle the required amounts of sludge moisture vapor (approximately 5,550 lbs/hr) between the dryer and condenser. The duct size is 14-inch diameter, per the dryer manufacturer's directions.

<u>Sludge Dryer Vapor Condensate</u>. Condensate piping is required to transport the condensate produced by cooling of the dryer vapor. Downstream from the condenser unit, the drain water flows by gravity through a 4-inch diameter ductile iron pipe to the plant drain. This 4-inch drain line was sized to handle flows of approximately 109 gpm of vapor condensate at a design temperature of 190°F.

Approximately 8-10% of the sludge dryer vapor condensate drain water is actual vapor condensate; the remaining 90-92% is cooling water from the protected water system. Once the condensate is introduced to the plant drain system, it is further diluted and cooled by belt filter press drain water and other process sidestreams, until temperature and chemical content pose no threat to the materials in the existing drain piping system.

Non-Condensible Gases. The sludge dryer vapor is composed of various gases, along with the water evaporated from the sludge, and most, if not all, of these gases are not condensable. During the drying process various "sewer gases" are liberated within the dryer, in addition to the normal inert atmospheric components that would ordinarily carry over in the dryer vapor. Provisions were incorporated into the system design to remove these non-condensible gases by exhausting them to the sludge incinerators, as a source of auxiliary combustion air. Considerations were given to exhausting the gases directly to the atmosphere. However, at the elevated exhaust temperature, the non-condensible gases would be predictably more corrosive or capable of producing objectionable odors. Type 304 stainless steel pipe was chosen as the non-condensible gas duct material due to its high resistance to corrosion. Schedule 10 pipe was originally selected for this duct. However, the costs for the long run of pipe required proved to be very high and alternatives were evaluated. Ultimately, it was decided that 20-gage spiral wound stainless steel duct would be adequate for this application. This type of duct is regularly used for industrial applications and the mechanical seams have low leakage. The non-condensible gas duct was sized at 10-inch diameter for a design gas flow of 250 scfm.

ELECTRICAL/INSTRUMENTATION DESIGN

Instrumentation. Following installation and start-up, the sludge dryer and the existing sludge incineration system at the BIWWTP was extensively tested to assess the impact of the dryer on the solids handling processes, as detailed in the *Combustion Testing Plan and Monitoring Equipment Specifications* (BSA/Nussbaumer & Clarke, February 1991). The tests involved a variety of parameters, including continuous monitoring of flue gas quality, sludge analyses in the laboratory, and continuous temperature measurements. Sampling and testing plan information are provided in Table 3-1 for sludge management variables and Table 3-2 for combustion variables.

The proposed locations of data gathering sensors were originally proposed by the Energy Authority and reviewed by the BSA and its consultant. Following a review of the existing instrumentation available at the BIWWTP, four classifications of instrumentation availability were identified:

- Existing instrumentation in acceptable working order (classification "E");
- New instrumentation which would be installed on existing equipment at the plant (classification "NE");
- New instrumentation which would be installed on proposed sludge dryer system equipment (classification "NP"); and
- Laboratory analysis (classification "L").

Steam production rates of the WHRBs and steam utilization by the sludge dryer were to be measured. Prior to the project, flow-measuring orifice plates and differential pressure sensing devices were in place on the WHRB steam headers, but according to plant instrumentation maintenance personnel, the existing orifice plates were old, inaccurate, and unreliable. Therefore, the existing orifice plates, pressure sensors, and transmitters were replaced with new annubars and differential pressure sensors and transmitters.

Similar equipment was installed on the new sludge dryer steam supply line. The new devices installed on the WHRB steam headers were wired to the incinerator control room and connected to existing chart recorders. The annubar and flow sensor installed on the dryer steam line had a local indicator that provided both instantaneous and totalized data.

To monitor the electricity used by the four motors associated with the dryer and its ancillary equipment, a new kilowatt-hour (kwh) meter was installed at the sludge dryer motor control center. This unit monitored the cumulative electricity usage of the sludge dryer rotor motor, the inlet screw conveyer motor, the outlet screw conveyer motor, and the non-condensible gas fan motor.

TABLE 3-1

SLUDGE MANAGEMENT VARIABLES INSTRUMENTATION CLASSIFICATION

NO.	TEST & UNITS	SAMPLING LOCATION	SAMPLING FREQUENCY	CLASS-IFICATION
A	Sludge Feed Rate (wet tons/hr)	Sludge Dryer Feed ##	4 Hours	L
		Incinerator #1 Feed	4 Hours	E
		Incinerator #2 Feed	4 Hours	E
B	Total Solids (mg/l & % solids)	Sludge Dryer Feed	4 Hours	L
		Sludge Dryer Outlet #	4 Hours	L
		Incinerator #1 Feed	4 Hours	L
		Incinerator #2 Feed	4 Hours	L
		Feed to Belt Press #1	4 Hours	L
C	Volatile Solids Content (%)	Sludge Dryer Feed	4 Hours	L
		Sludge Dryer Outlet #	4 Hours	L
		Incinerator #1 Feed	4 Hours	L
		Incinerator #2 Feed	4 Hours	L
D	Mass/Volatiles Ratio	Sludge Dryer Feed	4 Hours	L
		Sludge Dryer Outlet #	4 Hours	L
		Incinerator #1 Feed	4 Hours	L
		Incinerator #2 Feed	4 Hours	L
E	Sludge Temperature (°F)	Sludge Dryer Feed	4 Hours	L
		Sludge Dryer Outlet #	4 Hours	L
		Incinerator #1 Feed	4 Hours	L
		Incinerator #2 Feed	4 Hours	L
F	Steam Pressure (psi)	Auxiliary Boiler #1	2 Hours	E
		Auxiliary Boiler #2	2 Hours	E
		Auxiliary Boiler #3	2 Hours	E
		Waste Heat Boiler #1	2 Hours	E
		Waste Heat Boiler #2	2 Hours	E
		Inlet to Sludge Dryer	2 Hours	NP
G	Steam Production (lb/hr)*	Waste Heat Boiler #1	2 Hours	NE
		Waste Heat Boiler #2	2 Hours	NE
H	Steam Utilization (lb/hr)*	Sludge Dryer Steam Heater	2 Hours	NP
I	Electricity Utilization (kwk)*	Sludge Dryer Equipment	2 Hours	NE
		Incinerator #1 System (includes all fans & motors)	2 Hours	E
		Incinerator #2 System Includes all fans & motors)	2 Hours	E

TABLE 3-1 (continued)

NO.	TEST & UNITS	SAMPLING LOCATION	SAMPLING FREQUENCY	CLASS-IFICATION
J	Fuel Gas Utilization (cu ft)*	Incin. #1 System (N.G.)**	2 Hours	E
		Incin. #1 System (Meth)	2 Hours	E
		Incin. #1 (N.G.)	2 Hours	E
		Incin. #1 (Meth)	2 Hours	E
		Afterburner #1 (N.G.)	2 Hours	E
		Afterburner #1 (Meth)	2 Hours	E
		Incin. #2 System (N.G.)	2 Hours	E
		Incin. #2 System (Meth)	2 Hours	E
		Incin. #2 (N.G.)	2 Hours	E
		Incin. #2 (Meth)	2 Hours	E
		Afterburner #2 (N.G.)	2 Hours	E
		Afterburner #2 (Meth)	2 Hours	E
K	Condensate Flow Rate (gal/hr)*	Sludge Dryer Venturi Condenser Cooling Water Inlet	2 Hours	NP
		Sludge Dryer Venturi Condenser Condensate Outlet	2 Hours	NP
L	Sludge Flow Rate (gal/hr)	Belt Press #1 Feed	2 Hours	E
		Belt Press #2 Feed	2 Hours	E
		Belt Press #3 Feed	2 Hours	E
		Belt Press #4 Feed	2 Hours	E
		Belt Press #7 Feed	2 Hours	E
		Belt Press #8 Feed	2 Hours	E

** N.G. = Natural gas; "Meth" = digester methane gas

Sampled at this location only if Belt Press #7 is in operation.

To be determined from sludge flow rate to Belt Presses #1 and #3 and Laboratory analysis.

TABLE 3-2
COMBUSTION VARIABLES
INSTRUMENTATION/TESTING CLASSIFICATION

NO.	SAMPLE/TEST	SAMPLING LOCATION	SAMPLING FREQUENCY	SAMPLING PROCEDURE	CLASSIFICATION
A	Oxygen (O_2) (%)	Incinerator Outlet Afterburner Outlet	1 Min. Avg. 1 Min. Avg.	Total Extractive Total Extractive	NE NE
B	Carbon Monoxide (CO) (ppm)	Incinerator Outlet Afterburner Outlet	1 Min. Avg. 1 Min. Avg.	Total Extractive Total Extractive	NE NE
C	RESERVED				
D	Flue Gas Moisture (H_2O)	Incinerator Outlet	15 Minutes	Determined by Calculations	E
E	Temperature °F	Incinerator #1, Hearth #1	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Hearth #2	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Hearth #3	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Hearth #4	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Hearth #5	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Hearth #6	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Hearth #7	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Hearth #8	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Hearth #9	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Hearth #10	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Hearth #11	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Hearth #12	5 Min. Avg.	Thermocouple	E
		Afterburner #1, Outlet	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Cooling Air Outlet	5 Min. Avg.	Thermocouple	E
		Incinerator #1, Shaft Cooling Air Outlet	5 Min. Avg.	Thermocouple	E
		Waste Heat Boiler #1 Exhaust Gas Inlet	5 Min. Avg.	Thermocouple	E

TABLE 3-2 (continued)

NO.	SAMPLE/TEST	SAMPLING LOCATION	SAMPLING FREQUENCY	SAMPLING PROCEDURE	CLASSIF-ICATION
E	Temperature °F	Waste Heat Boiler #1 Exhaust Gas Outlet	5 Min. Avg.	Thermocouple	E
		Sludge Dryer Steam Header	5 Min. Avg.	Thermocouple	NP
		Final Effluent Water Pipe at Entry to Dryer System	5 Min. Avg.	Thermocouple	NP
		Sludge Dryer Exhaust Vapor Outlet	5 Min. Avg.	Thermocouple	NP
		Sludge Dryer Venturi Condenser Condensate	5 Min. Avg.	Thermocouple	NP
		Sludge Dryer Fan Exhaust	5 Min. Avg.	Thermocouple	NP
		Incinerator Air Plenum	5 Min. Avg.	Thermocouple	NE
		Waste Heat Boiler #1 Steam Outlet	5 Min. Avg.	Thermocouple	NE
		Waste Heat Boiler #2 Steam Outlet	5 Min. Avg.	Thermocouple	NE
F	Air Flow Rate (scfm)	Combustion Air Fan (Incinerator #1 Inlet)	5 Min. Avg.	Differential Pressure	NE
		Combustion Air Fan (Afterburner #1 Inlet)	5 Min. Avg.	Differential Pressure	NE
		Auxiliary Combustion Air Fan	5 Min. Avg.	Differential Pressure	NE
		Cooling Air Fan (Incinerator #1 Inlet)	5 Min. Avg.	Differential Pressure	NE
		Centrifugal Fan (Dryer/Cond. Exhaust)	5 Min. Avg.	Differential Pressure	NP
I	Sludge Ultimate Analysis*	Sludge Dryer Feed	2x per Test Condition	Composite Grab Samples	L
		Incinerator #1 Feed	2x per Test Condition	Composite Grab Samples	L

* Ultimate Analysis includes: Carbon (C_2), Chlorine (CI_2), Hydrogen (H_2), Nitrogen (N_2), Oxygen (O_2), Sulfur (S_2), Moisture (H_2O), Ash, sludge B.T.U. content.

To assess the heat recovery opportunities provided by the sludge dryer's waste heat, turbine meters were installed to measure both the cooling water flow rate to the condenser unit and the condenser's drain water flow rate. The turbine meters had a flow rate indicator mounted directly on the meter; the indicator provided readouts for instantaneous flow and total flow.

Several variables monitored for the project were continuously recorded at short (1-minute) intervals by a data acquisition system (DAS). Several alternatives for a DAS were examined during the course of the instrumentation system design. These alternatives included a multi-channel data logger (strip chart recorder), a personal computer (PC)-based DAS, and a mainframe computer-based system that would have utilized the existing BIWWTP computer system. The PC option was chosen as the most desirable alternative from practical and economic perspectives.

Several PC-based DASs were evaluated for the project. The software package "Specifix," a smaller, more economical version of the better-known package "The Fix" and a network-based package, "DMACS," by Intellution, were chosen for the process monitoring software. The "Specifix" package is capable of accepting approximately 100 inputs and has capabilities for data-logging, process control (if desired), and interfacing with popular spreadsheet programs, and the package is capable of elaborate graphics displays.

The PC that was selected was an IBM, industrial design, 286 computer with a math co-processor. The rugged construction of an industrial PC was desired because the PC would be running in a wastewater treatment plant, 24 hours per day. Input signals from the instrumentation to the DAS are converted to digital signals and relayed to the PC using Opto-22 hardware.

A total-extractive continuous emissions monitoring system (CEMS) was designed and installed to monitor incinerator and afterburner combustion quality. Several CEMS manufacturers were investigated during design of the project. Investigations included site visits to view operating CEMSs at cogeneration facilities in Bayonne, New Jersey, and Carson, California; a municipal solid waste incinerator in Niagara Falls, New York; and a municipal sewage sludge incinerator at the Hyperion Wastewater Treatment Plant in Los Angeles, California.

Two separate gas streams were simultaneously monitored by the CEMS: the Incinerator 1 exhaust duct and the Afterburner No. 1 exhaust duct, prior to entry to the WHRB. The CEMS for each location was provided with the following equipment:

- A hastelloy sample probe;
- A heat-traced sample line, including calibration gas lines for automatic system calibration once per day from the "head" of the system through the analyzers;
- Sample conditioning equipment to remove moisture from the extracted gas sample;
- A process controller with an automatic, daily calibration feature;
- A zirconium oxide oxygen analyzer.
- A non-dispersive infrared carbon monoxide analyzer; and
- Sample and condensate vents.

The probes were installed at the locations described above while the analyzers and other equipment were located inside the incinerator control room. Each analyzer provided a 4-20 milliamp (mA) analog output signal capable of interfacing with the DAS.

The CEMS was designed to meet guidelines set forth by New York State Department of Environmental Conservation (NYSDEC), United States Environmental Protection Agency (USEPA), and Northeast States For Coordinated Air Use Management (NESCAUM), and to address operational conditions observed during the site visits. Following installation of the CEMS, system check-out included a variety of testing to ascertain the accuracy and zero-drift span of the CEMS. Following completion of all monitoring for the project, the CEMS was removed from the BIWWTP.

Temperatures at several points in the sludge dryer and incineration systems were monitored. Many of these locations in the incineration system had thermocouples installed prior to the demonstration project. Eight new thermocouples were installed specifically for the project.

In addition to the above instrumentation, air-flow rates for incineration system air flows and the blower for the non-condensible gases were monitored on a continuous basis using annubar (pitot-tube) measuring elements and differential pressure sensors.

Sludge Dryer System Electrical Requirements. The electrical design included furnishing power supply to the 75-HP drive motor that turns the dryer's central shaft and disks; the 5-HP motors on the sludge feed conveyer and discharge conveyer; and the 5-HP non-condensible gas blower. Power for these motors was obtained from an existing motor control center in the Main Equipment Building.

DRYER SYSTEM DESIGN PARAMETERS

Design criteria for the dryer unit and ancillary equipment are summarized below:

Design Throughput Criteria:

• Solids Content of Feed Sludge	18-20%
• Maximum Total Loading Rate	155 WT/D *
• Minimum Solids Handling Capacity	24 DT/D **
• Maximum Capacity of Solids Handling	31 DT/D
• Minimum Solids Content of Discharge Sludge	35%
• Maximum Discharge Rate	89 WT/D
• Maximum Evaporation Rate	5,500 lbs/hr

* WT/D = wet tons per day; one ton = 2,000 lbs

** DT/D = dry tons per day; one ton = 2,000 lbs

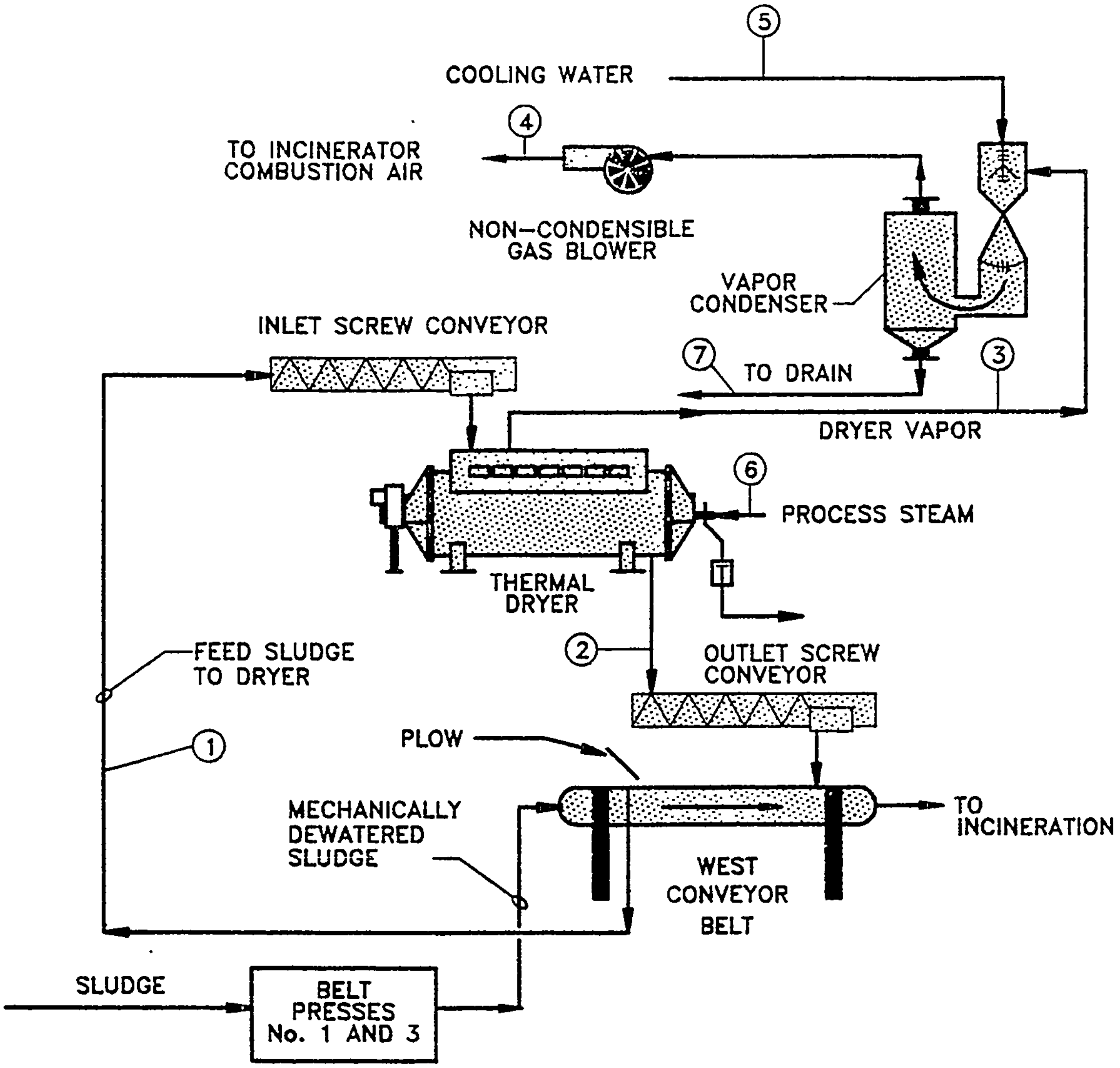
The above design figures were based on a 24-hour per day operating schedule. Thus, the dryer was sized to handle approximately 40%-45% of the solids produced daily at the BIWWTP (total daily plant solids production is approximately 57 DT/D).

A design system mass balance is illustrated in Figure 3-1.

Dryer Unit Physical Specifications:

Manufacturer and Model	Stord TST-30R
Heating Elements	Stainless steel rotor disks
Total Heating Surface Area	1,324 ft^2
Number of Disks	30
Rotor Speed (approximate)	9 rpm
Overall Dryer Length	24.4 feet
Overall Dryer Width	6.9 feet
Overall Unit Height (without structural steel foundation which was 2 feet high)	9.2 feet
Stator Length	16.4 feet
Stator Inside Diameter	6.2 feet
Steam Pressure (normal operating)	125 psig saturated
Steam Pressure (test)	187.5 psig
Specific Steam Consumption	1.25-1.30 lbs steam/lb water evap'd
Design Maximum Steam Consumption	1.30-1.32 lbs steam/lb water evap'd
Weight (empty)	50,710 lbs
Weight (loaded)	74,960 lbs
Shipping Volume	1,275 ft^3

A majority of the dryer's components were fabricated from Type 304 stainless steel for maximum corrosion resistance. System control for the dryer and ancillary equipment is provided by a programmable logic controller (PLC) with



PARAMETER AND UNITS	POSITION DESIGNATION ①	②	③	④	⑤	⑥	⑦
LB/HR DRY MATTER	2000	2000	0				
LB/HR WATER	8000	3715	4285				
LB/HR TOTAL MASS FLOW	10,000	5715	4285			5785	
% DRY MATTER	20	35	0				
% WATER	80	65	100				
TEMPERATURE (°F)	70	200±	212±	190	70	354	180
WATER FLOW RATE (GPM)					100		108.6
LB/HR NCG * FLOW			792	792			

* NON-CONDENSIBLE GAS

SLUDGE DRYER SYSTEM
DESIGN MASS AND
HEAT BALANCE

FIGUR
3–1

a graphical interface, installed in an explosion-proof cabinet adjacent to the dryer. The PLC is programmed for the following alarm conditions:

- Zero speed (any system component)
- Reduction or loss of steam pressure from the set-point
- Reduction or loss of instrumentation air supply
- High draw of motor current
- High or low level of sludge in the dryer
- High or low moisture content in the dryer discharge sludge
- High or low moisture content in the dryer feed sludge
- High or low temperature in the stator
- High inflow rate to the dryer
- High or low cooling water flow

Sludge Dryer Drive Unit Design Data:

• Motor Size	75 HP
• Type	Squirrel cage, induction
• Supply Power	480 volt, 3 phase
• Cooling Water Flow	5 gpm

Inlet Screw Conveyor Design Data:

• Overall Length	16 feet
• Screw Diameter	10-inch
• Screw Speed	20 rpm
• Motor Size	5 HP

Outlet Screw Conveyor Design Data:

• Overall Length	17 feet
• Screw Diameter	10-inch
• Screw Speed	5-15 rpm (adjustable)
• Motor Size	5 HP

The **Direct Condenser Unit** was sized to properly handle the flow and mass loads as shown in Figure 3-1.

Non-Condensible Gas Blower:

Design Flow Rate	250 scfm
Approximate Capacity	400 scfm
Motor Size	5 HP

REFERENCES

BSA/Nussbaumer & Clarke, February 1991, *Design Report.*

BSA/Nussbaumer & Clarke, February 1991, *Combustion Testing Plan and Monitoring Equipment Specifications.*

SECTION 4

INSTALLATION AND START-UP

INTRODUCTION

This section details the problems encountered during installation and system start-up of the dryer, its support systems, and ancillary monitoring equipment. The section also details the alternatives examined, and the eventual solutions to the problems encountered.

EQUIPMENT INSTALLED

The following major equipment items were installed during the construction phase of the project:

- One Stord Rotadisc Sludge Dryer, Type TST-30R, and associated steam services, condensate drains, and wiring.
- One gear reducer/drive unit for the dryer.
- One Allen-Bradley PLC for control of dryer operations.
- One structural steel support frame for the dryer.
- One sludge feed screw conveyer.
- One sludge discharge screw conveyer.
- One mechanical sludge diversion plow.
- One venturi condenser/demister (for dryer vapor) and associated piping.
- One non-condensable gas induction blower and associated stainless steel ductwork.
- Final effluent water strainers and piping modifications
- One sequencing CEMS for measurement of oxygen and carbon monoxide content in the incinerator and afterburner exhaust.
- One PC-based DAS.
- Miscellaneous monitoring equipment instrumentation required to evaluate the performance of the dryer.

All of the above items were installed in the dewatering and incineration areas of the BIWWTP Main Equipment Building, also called "the Megastructure." Several major equipment items (e.g. the dryer, drive unit, both screw conveyers, plow, venturi condenser, PLC, etc.) were installed on the third floor of the building in the sludge dewatering room. Prior to installation of the dryer and its associated equipment, the dewatering room housed six belt filter presses and two sludge cake conveyer belts. The sludge incinerators are located immediately north of the dewatering room.

PREPARATION WORK

The Stord sludge dryer was manufactured on the Island of Stord, near Bergen, Norway, during the winter of 1990-1991; the dryer was delivered to the project site, on the Bird Island railroad spur, on April 27, 1991. Preparation work at the site commenced on April 2, 1991. Throughout the month of April, contractors performed mechanical, plumbing, and electrical work to bring essential utilities to the dryer area. The contractors also installed various instrumentation and sensors on existing piping and process equipment. Other preparation work included structural modifications for the installation of the dryer. The dryer was inserted into the Main Equipment Building through the west wall of the third floor and brought across the existing floor slab to its permanent location between Belt Filter Presses 3 and 7. The general contractor took several precautions to ensure that the installation would proceed smoothly and without cracking or failure of the building wall, windows, or floor slab.

As detailed in the *Design Report* (BSA/Nussbaumer & Clarke, February 1991), one exterior sandstone wall panel, together with the interior concrete block wall adjacent to the exterior panels, was removed. This created a floor-to-ceiling wall opening approximately 10 feet wide to permit entry of the dryer. A temporary shelter constructed of wood and plastic "tarp" covered the wall opening while the dryer was readied for rigging operations. A temporary structural steel frame was installed on the third- floor slab, extending from outside the wall opening to the permanent dryer location. This was constructed in order to prevent cracking/failure of the floor slab and to avoid deflection of the slab near the wall, which could have broken windows on the second floor.

DRYER INSTALLATION

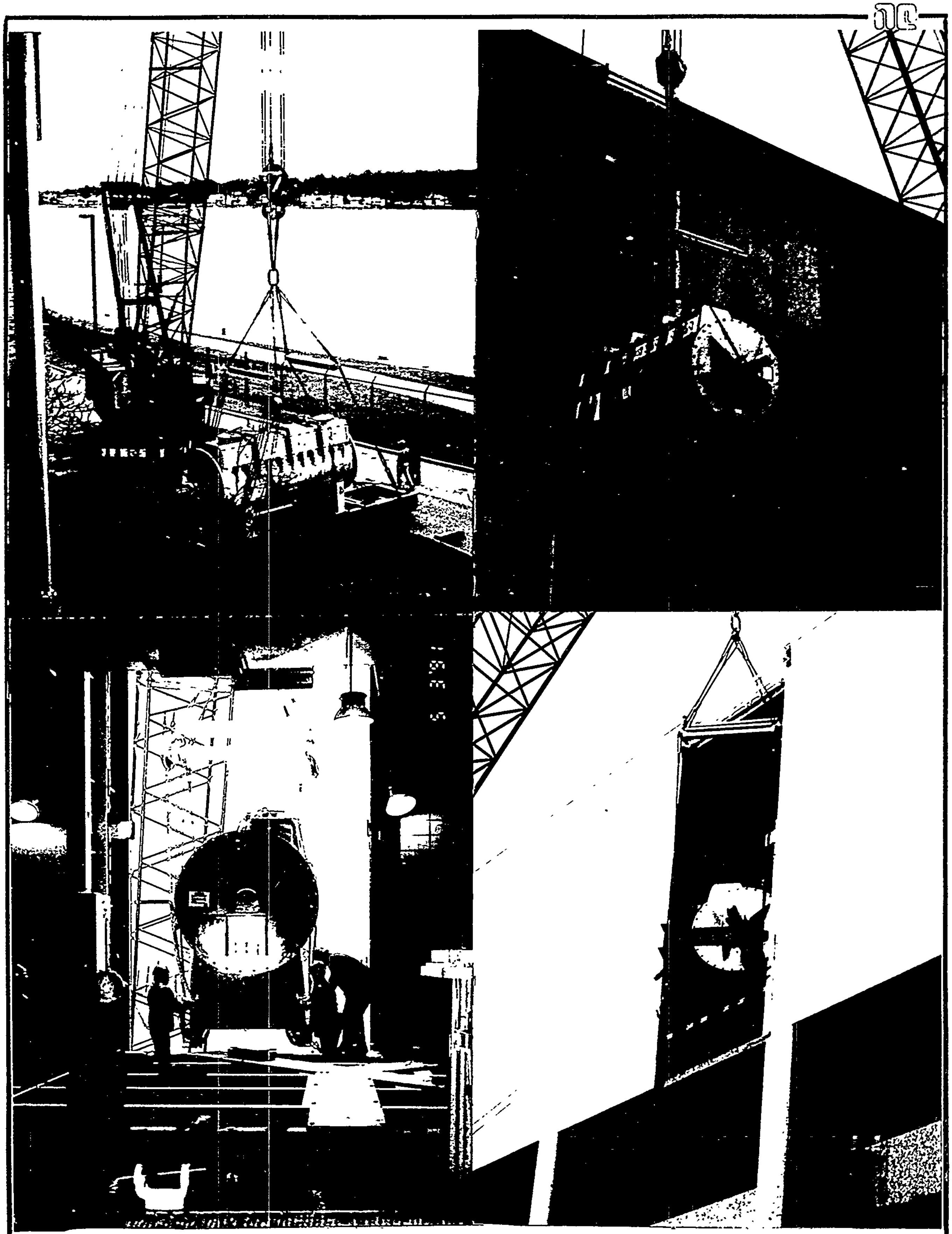
The dryer was loaded onto a flatbed trailer and moved from the railroad spur to the lift staging area on the west side of the Main Equipment Building on May 1, 1991.

Prior to rigging, the dryer was welded to its permanent structural steel frame for ease of installation. The dryer and its support frame were lifted into the third floor on May 3, 1991. A 150-ton crane was used to lift the dryer assembly the 60+ feet into the third floor wall opening. Total time for the lift was approximately 75 minutes. Various stages of the installation process are depicted in Figure 4-1. Following the lift, the dryer was jacked across the temporary support frame and the next day was lowered into its permanent position between Belt Presses 3 and 7. The three-ton drive unit was installed separately and attached to the rotor shaft the day after the lift operation. Following these operations, the temporary steel was removed and the interior and exterior walls restored to their original condition.

SERVICE CONNECTIONS AND OTHER WORK

Installation of process piping and service connections to the dryer and its appurtenant equipment proceeded from April until July, 1991. This work was performed without major problems; minor problems encountered included difficulties with steam line routing and electrical connections. Figures 4-2 and 4-3 illustrate the completed dryer system installation.

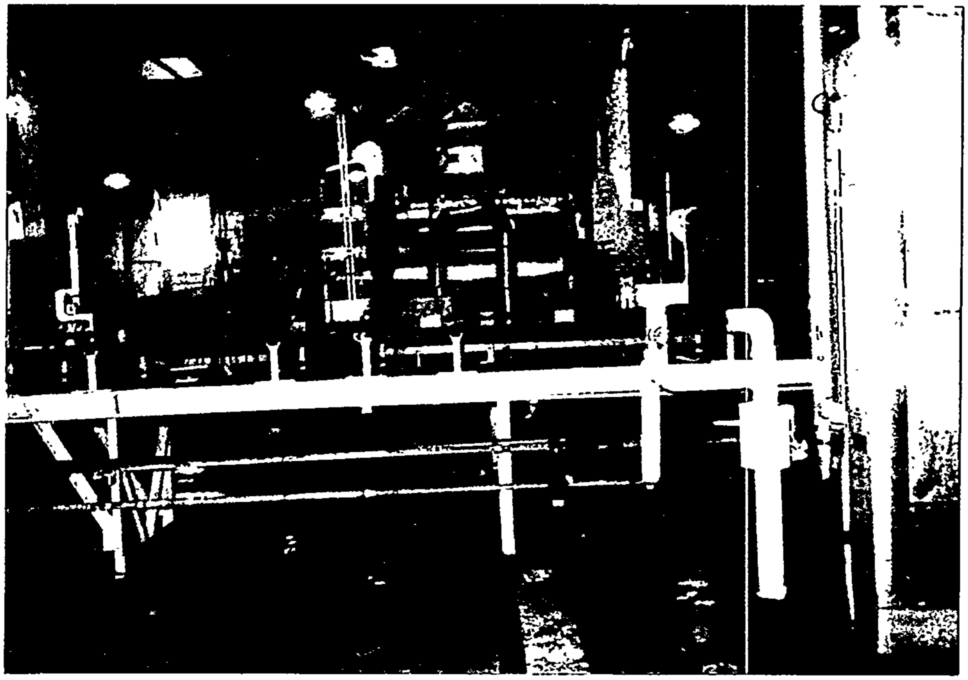
While the service connections were being made, the CEMS, DAS, and the PLC were installed. CEMS work included installing probes on the incinerator exhaust and afterburner exhaust ductwork, sample conditioning equipment, span and calibration gases, and an analyzer/control cabinet in the incineration control room. Work associated with the DAS included installing signal



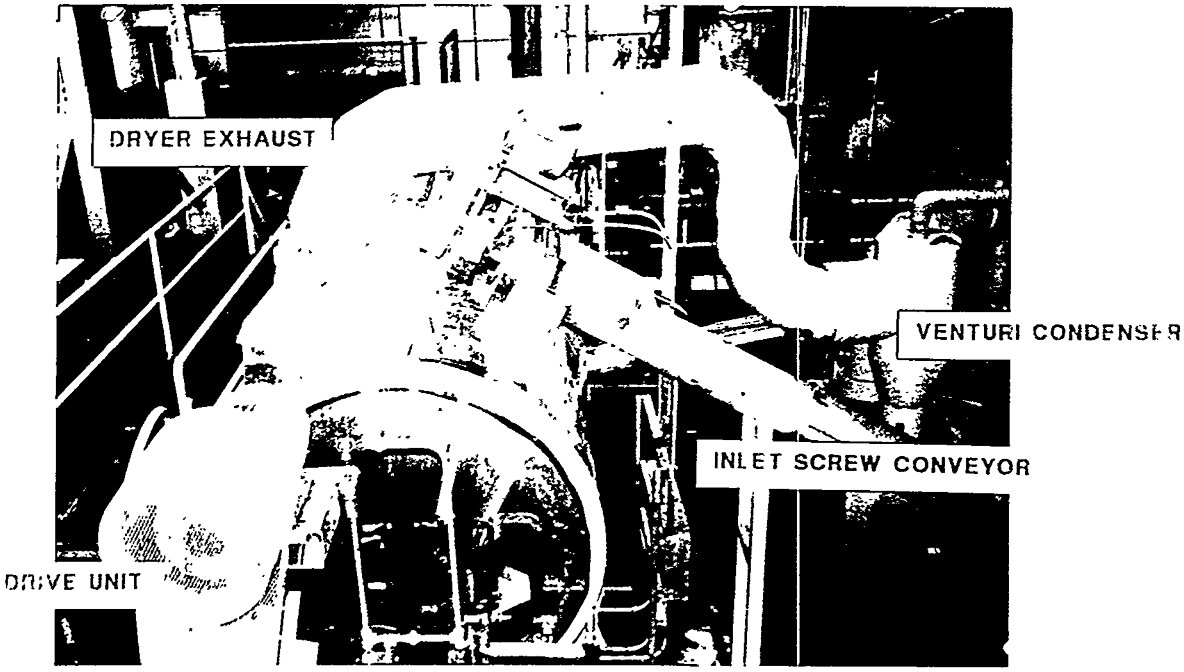
DRYER INSTALLATION INTO BIRD ISLAND MEGASTRUCTURE

(MAY 3, 1991)

FIGURE 4-1



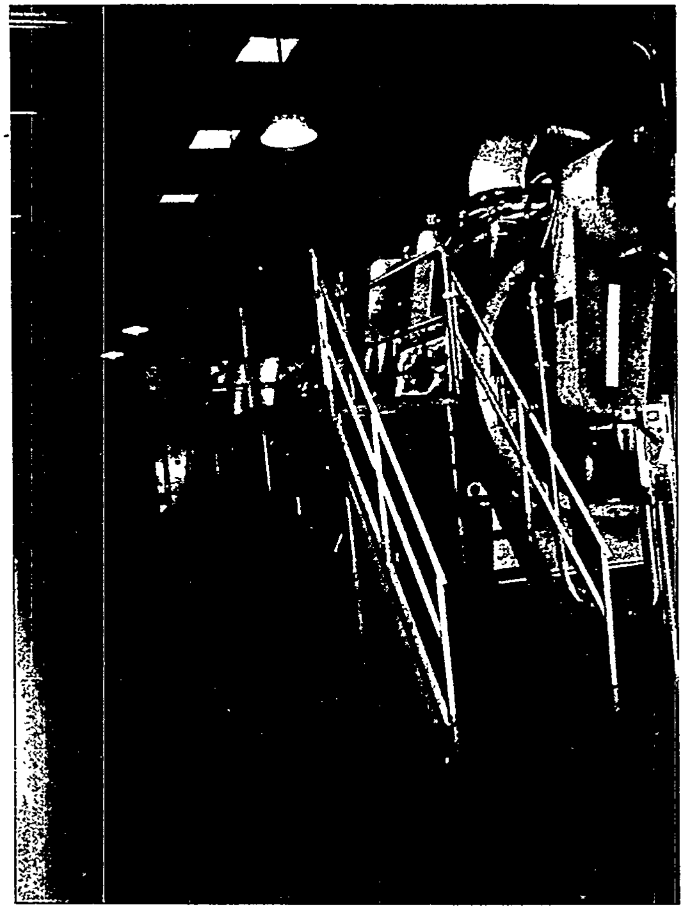
SIDE VIEW, LOOKING WEST



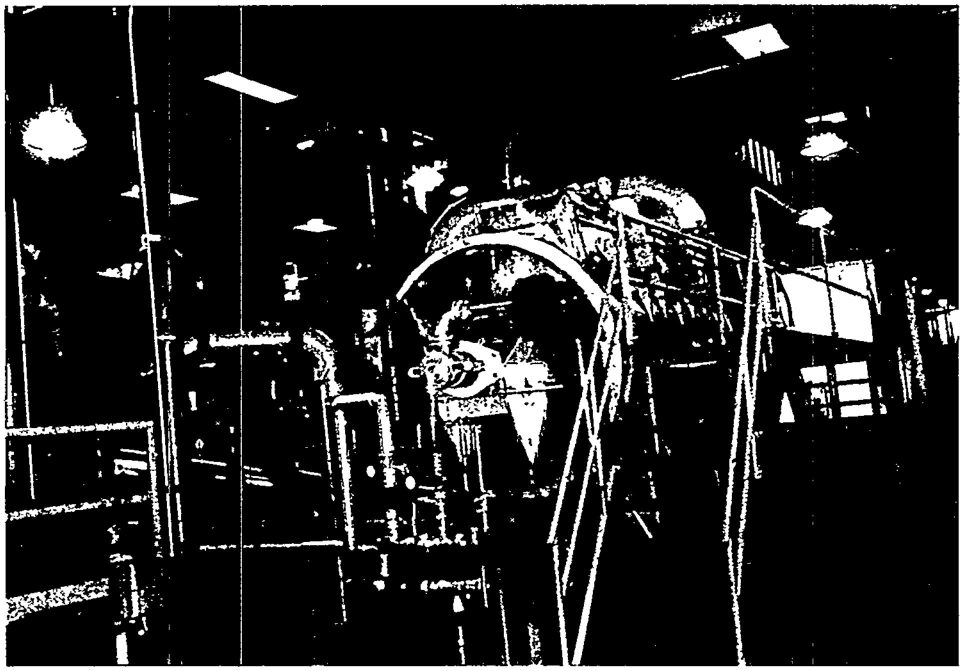
END VIEW, LOOKING NORTH

VIEWS OF COMPLETED INSTALLATION

FIGURE 4-2



(LOOKING NORTH)



VIEWS OF COMPLETED INSTALLATION, 2

(LOOKING SOUTH)

FIGURE 4-3

conditioning equipment in the incinerator control panel that would enable connection of existing thermocouples to the DAS. The DAS computer was installed one floor below the control room in the office of the incineration chief engineer. The PLC was installed in an explosion-proof cabinet adjacent to the dryer. These three equipment items are shown in their final, installed conditions in Figure 4-4.

START-UP OPERATIONS AND PROBLEMS ENCOUNTERED

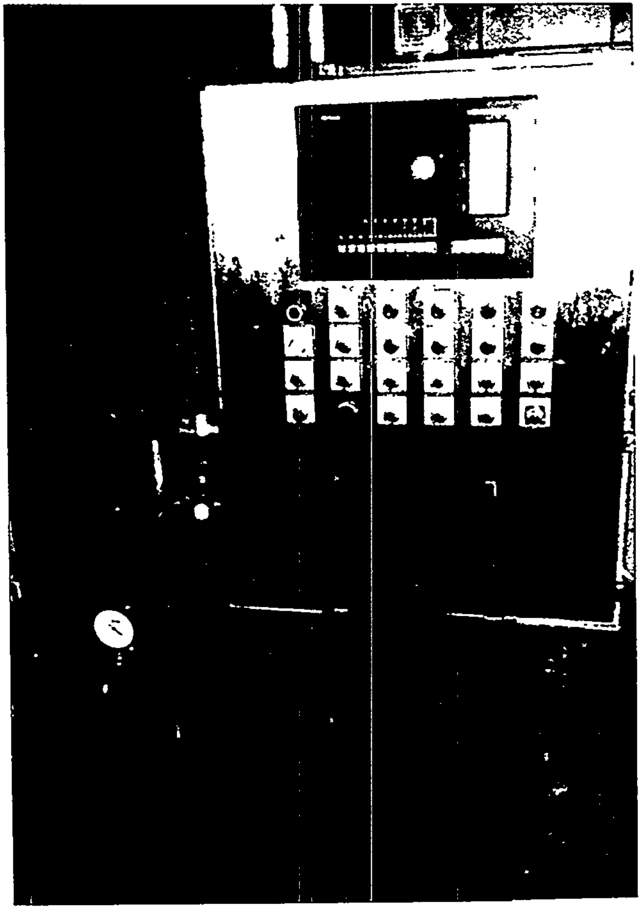
Start-up operations for the thermal sludge dewatering system commenced during the first week of August 1991. During this period, BSA personnel were instructed in the use and maintenance of the new equipment by the dryer manufacturer and other suppliers. The start-up process continued through September, with several minor problems encountered, as detailed below.

A series of "shakedown" operations of the dryer, with interruptions for fine-tuning of various equipment items, characterized start-up activities during the month of September. Full scale operation of the thermal sludge dewatering system was initiated on October 4, 1991.

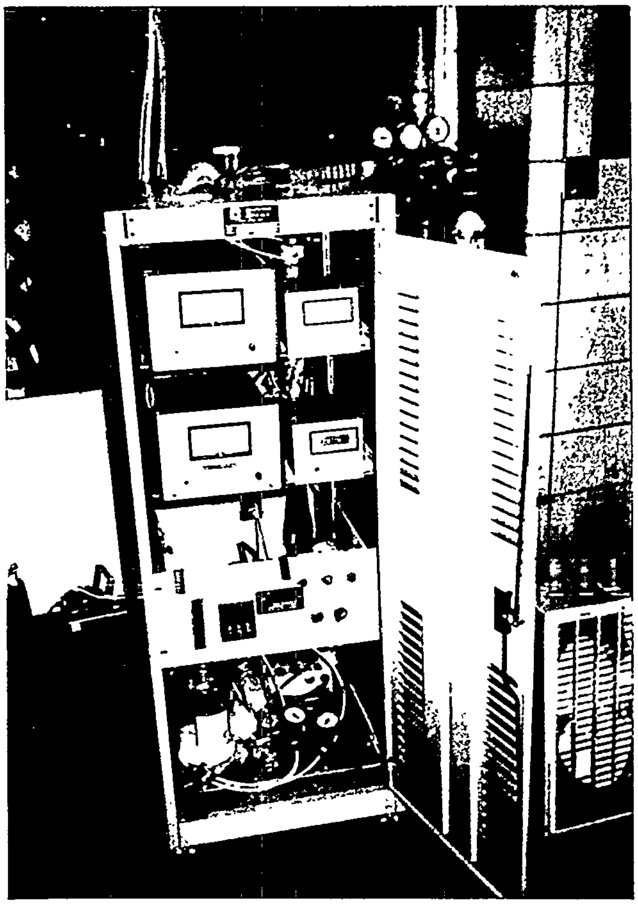
During the months of October and November 1991, a few minor problems were encountered during normal dryer operating conditions. The principal problems were false readings from the sludge level and moisture probes within the dryer stator. The false readings were partially due to inconsistent quantities of sludge being supplied to the dryer. When the sludge level was low, increased heat transfer to the product in the dryer occurred, resulting in sludge adhering to the probes. This gave a false reading of product level and moisture content.

START-UP PROBLEMS AND SOLUTIONS

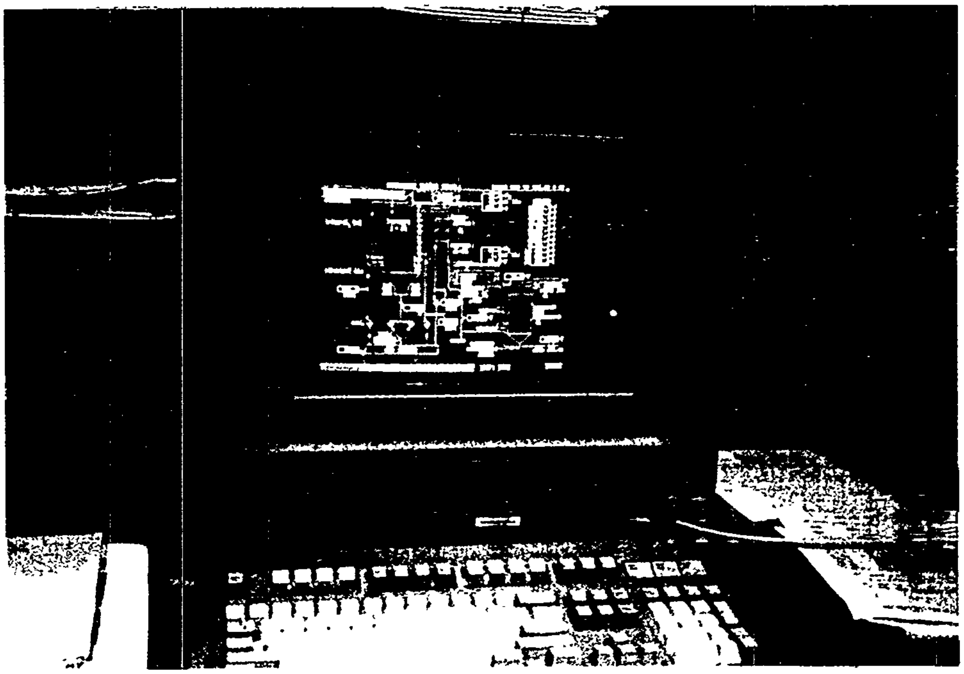
This section presents a summary of problems encountered during installation and start-up of the dryer system. In addition, the remedial solution for each encountered problem is described.



PROGRAMMABLE LOGIC CONTROLLER



C.E.M.S CABINET
WITH ANALYZERS AND CONTROLS



DATA ACQUISITION SYSTEM

FIGURE 4-4

1. Programmable Logic Controller: During the start-up phase of the project, problems with the PLC program were evident. Approximately three weeks were required to find the "bugs" and eliminate them from the programming logic.

2. Extended Start-up Period: The start-up period was longer than originally planed. Approximately six weeks of start-up activities were eventually necessary to get the thermal dewatering system operational. Minor problems with the equipment, rather than a single large problem, were the causes of this delay.

3. Steam Condensate Trap: The trap originally supplied for the project did not operate satisfactorily. A steam parts supplier was consulted and a new steam trap was required. The steam condensate piping to and from the condensate trap was changed to accommodate the redesigned trap.

4. Screw Conveyers: The speed of both the inlet and discharge screw conveyers was low. New sheaves were furnished by the dryer manufacturer and installed, rectifying the problem.

5. Non-Condensable Gas Blower: The design operating capacity for this blower was 250 scfm; however, at the time of start-up, the unit was operating at approximately 400 cfm. A new sheave was installed to reduce the blower output and the unit has functioned according to specifications.

6. Steam Safety Valve: In order to comply with BSA insurance policy guidelines, a steam safety valve had to be installed on the pressure-regulating station. This work was performed directly by BSA personnel.

7. Sludge "Blinding": When the dryer was first tested during a trial drying period, the product would not flow through the stator in the desired manner. Instead, sludge adhered to the paddles, scrapers, and disks, and "blinded" portions of the heat transfer surface. Following

an investigation of this problem, it was found that certain edges and areas of the disks had rough spots and burrs which impeded the normal flow of the sludge product. As an attempted solution, the dryer was filled with incinerator ash that, it was hoped, possessed sufficient roughness to "sand down" the burrs. The ash did not achieve the desired effect and was removed. Mason's sand was then introduced into the dryer and allowed to remain in place while the dryer's rotor was in operation for approximately four hours. Following removal, all rough areas appeared to be smoothed over and sludge was again fed into the dryer, with noticeably improved results.

8. <u>Sparge Water Damage</u>: The sparge water piping, was damaged in transit from the manufacturing site. The entire piping system had been crushed beyond repair. Eventually, the sparge water system was completely removed by the general/mechanical contractor, refabricated, and reinstalled. A small amount of cutting and welding of the top of the dryer stator was required to complete the reinstallation.

9. <u>Moisture Probe</u>: During the attempt to remove the burrs (described in Item 8, above), one of the moisture probes in the dryer was damaged. A spare probe was installed in its place.

10. <u>Cut-Off Plate</u>: A "screen" had to be fabricated and installed at the end of the discharge screw conveyer because dried sludge deposited onto the conveyer belt formed "clinkers" in the incinerator rabble teeth, thus inhibiting effective combustion operations. The cut-off plate reduced the size of the "lumps" of dried sludge discharged to the conveyer belt, creating a more efficient combustion material. Following this modification, the dried sludge did not form "clinkers" and was no longer a problem in the incinerator.

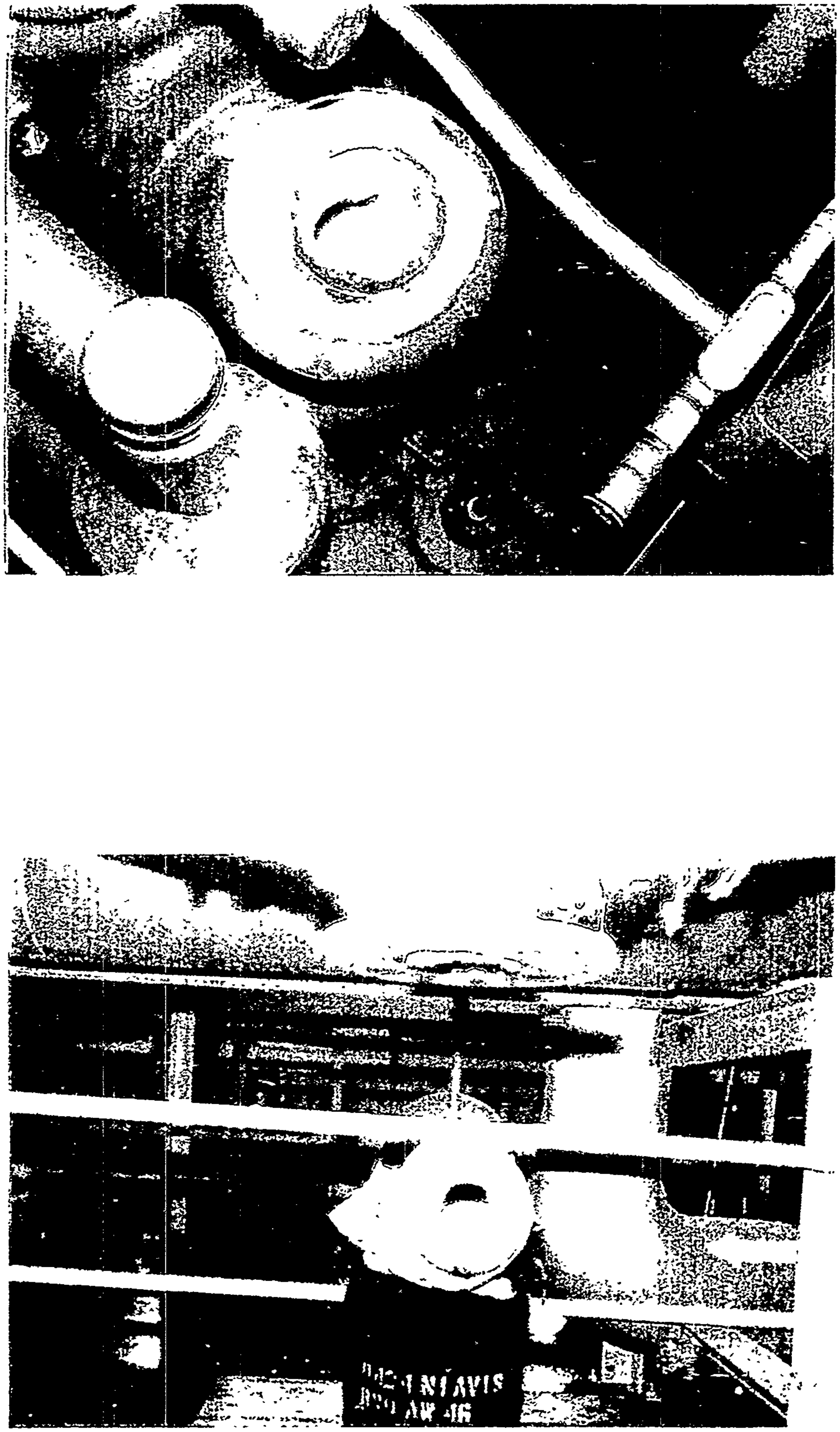
11. <u>Hopper Modifications</u>: The original feed sludge hopper, which was to act as a reservoir between the plow and the inlet screw conveyer, did not effectively feed the inlet conveyer. The hopper was removed and extensively modified. Following this change, sludge diversion from the

conveyer belt to the inlet screw conveyer was accomplished, with no sludge spilled onto the floor.

12. Belt Filter Press Malfunctions: At various times, one or both of the belt presses which supplied sludge to the dryer were out of service due to malfunctions. Therefore, without a sludge supply, the dryer was effectively out of service until the press(es) were repaired.

13. Sludge Dryer Condenser Unit and Derainline Scaling: The condenser and its associated drain piping experienced extensive scaling following start-up of the dryer. The scale was predominantly white in color and was first noticed after approximately three weeks of full-scale dryer operation. The build-up was extensive, constricting the 3-inch-diameter condenser drain to approximately 1.5 inches by late October/early November. Once the scale was noticed during routine maintenance operations, the dryer was deactivated and the entire drain disassembled in order to determine the extent of the problem. Figure 4-5 illustrates the scaling in two sections of the disassembled drain as it appeared in the first week of November 1991. Another problem caused by the scaling was the malfunctioning of the turbine meter installed to measure flows through the drain line. The scale had inhibited the rotation of the turbine propeller, thus rendering the meter inoperable until cleared of the scale.

    The scale was suspected of being either the result of calcium build-up from the cooling water supply (city water) to the condenser, or a polymer-based compound that was evaporated out of the sludge in the dryer and condensed at the lower temperatures in the bottom of the condenser/demister assembly. Following analysis of the scale in the BIWWTP laboratory, it was determined that the substance was calcium carbonate ($CaCO_3$), which was traced back to the city cooling water which made up a portion of the plant's protected water supply. Following discussion with the dryer manufacturer, it was determined that the operating temperatures in the dryer were not sufficiently high to support the conjecture that the scale was evaporated polymer.



SCALING IN VENTURI CONDENSER DRAIN LINE

- NOVEMBER 1991 -

FIGURE 4-5

The hardness of the city water was reputed to be a relatively low value of approximately 32 mg/l as $CaCO_3$. However, it appeared that the volume of cooling water supplied to the condenser was significantly more than the original design value (i.e., up to 150 gpm versus a design figure of 100 gpm), which resulted in a larger daily mass load of $CaCO_3$ than if the design amount of water had been supplied. It is believed that the cooling water entering the top of the condenser unit was partially boiled, which brought some Ca^{2+} and CO_3^{2-} ions out of solution. Also, it is possible that the elevated temperature in the top portion of the condenser, while not enough to vaporize all the influent water, was sufficient to bring other ions out of solution without boiling. It is believed that this resulted in the extensive scaling observed in late October.

Several actions were undertaken to rectify the scaling problem. Under the premise that the ions which came out of solution were attracted to the ductile iron drain piping, and because the scale did not respond adequately to cleansing with sulfamic acid, the entire drain line from the condenser through the turbine meter and the meter's inverted trap (designed to keep the pipe full-flowing) was replaced with 4-inch diameter schedule 80 PVC piping. The turbine meter was cleaned of all scale build-up and reinstalled on the drain line. Also, a plexiglass window was installed in the bottom of the condenser in order to observe potential future scaling.

Dryer operations were restarted on December 19, 1991, to commence data-gathering for the second phase of the demonstration project (testing of a blend of mechanically and thermally dewatered sludge). Within twelve hours of operations, significant scaling was again observed and the turbine meter was again rendered inoperable. Throughout the remainder of the demonstration project, scaling in the condenser drain line was a problem. The effective length of continuous operation for the dryer was approximately three weeks; after a three week operational period, it was necessary to perform the labor-intensive task of manually descaling the condenser and drain line.

Ultimately, in 1993, the direct condenser unit was replaced by an indirect condenser, thus permanently resolving the scaling problem.

Initial results following start-up demonstrated the effectiveness of thermally dewatering sludge using the indirect disk-type dryer. The amount of auxiliary fuel required for incineration operations was reduced due to autogenous sludge combustion (i.e., where the addition of auxiliary fuel to the incinerator was not required to maintain combustion temperatures).

The next phase of work involved testing and analysis of both the efficiency of the dryer and its effect on BIWWTP's multiple-hearth incinerators.

REFERENCES

Buffalo Sewer Authority/Nussbaumer & Clarke, Inc., December 1991, *Sludge Dryer Installation and Start-up Report.*

Buffalo Sewer Authority/Nussbaumer & Clarke, Inc., February 1991, *Design Report.*

SECTION 5

TESTING AND MONITORING

COMBUSTION TESTING PLAN AND SYSTEM MONITORING

Introduction

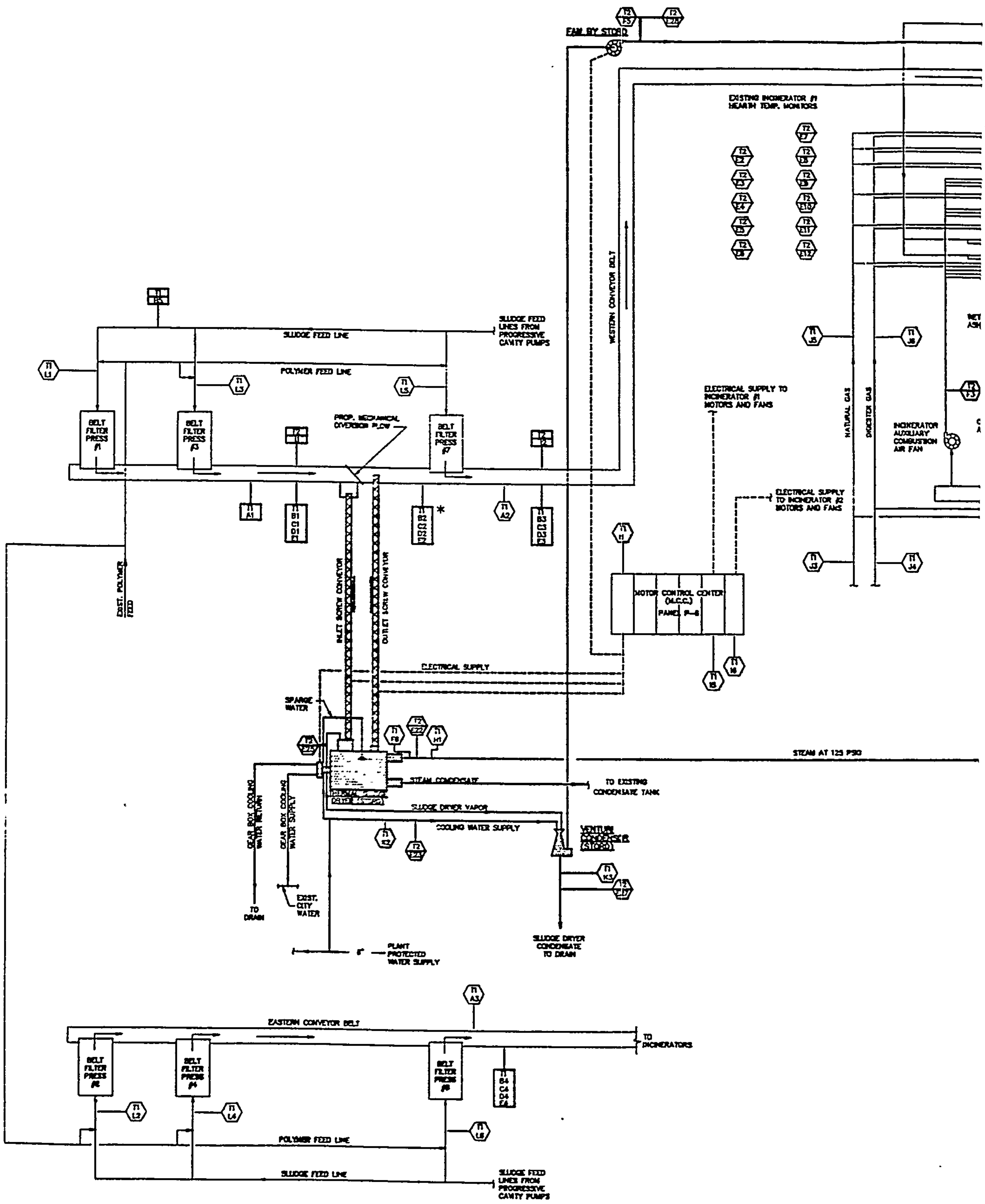
This section describes the plan for monitoring of the dryer and incineration systems. The testing plan was developed prior to the design phase of the project and stipulated the tests and analyses to be performed; it also set forth the frequency at which data was to be gathered or digitally recorded, provided testing protocols, and included specifications for the equipment utilized in the sample gathering, testing, and analysis.

A portion of the solids handling process, following installation of the sludge dryer system, is depicted schematically in Figure 5-1. See sections 2 and 3 for detailed descriptions of the existing sludge incineration system and the sludge dryer system, respectively.

Testing Schedule

Data-gathering for the demonstration project was conducted over a period of approximately three months. Tests were run on several blends of sludge for two principal modes of operation: afterburners on, and afterburners off (i.e., with the incinerator exhaust discharged directly to the scrubber system). The initial stage of the project monitoring was aimed at gathering extensive data on sludge product characteristics prior to installation of the dryer. This provided a "baseline" of data to be used in assessing the effects of the sludge dryer on incinerator operations.

At the time of the demonstration project, the BSA utilized two of the three existing incinerators at the BIWWTP at any given time, with the third incinerator on standby. The demonstration project required that one incinerator (Incinerator 1) receive each of the following sludges in turn:



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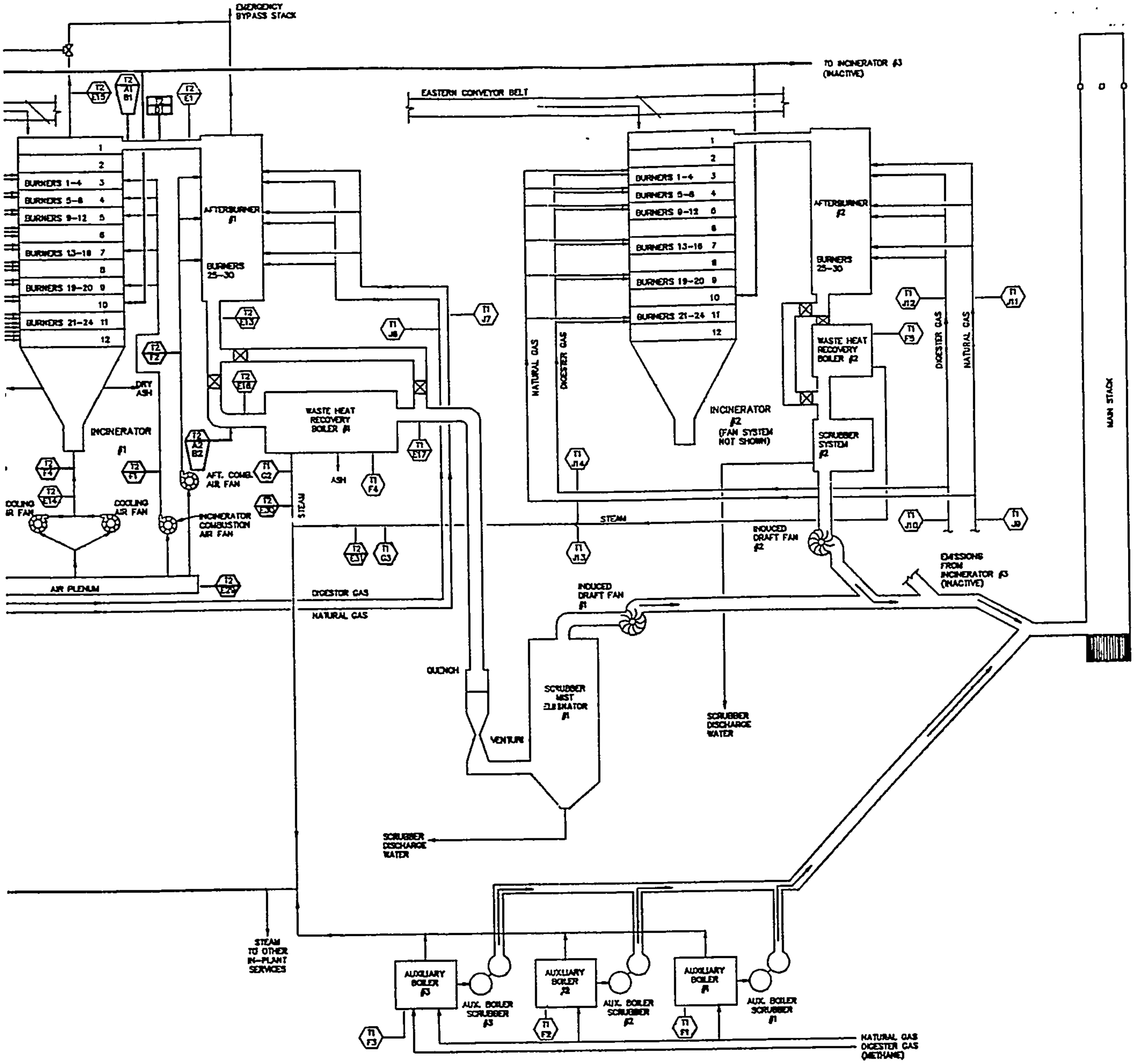


PROPOSED TEST CONDITIONS

A. MECHANICALLY DEWATERED SLUDGE
FEED TO INCINERATOR #1
(BASELINE TESTING)
1. AFTERBURNERS ON
2 AFTERBURNERS OFF

B. BLEND OF MECHANICALLY AND
THERMALLY DEWATERED SLUDGE
FEED TO INCINERATOR #1
1. AFTERBURNERS ON
2 AFTERBURNERS OFF

C. THERMALLY DEWATERED SLUDGE (ONLY)
FEED TO INCINERATOR #1
1. AFTERBURNERS ON
2 AFTERBURNERS OFF

LEGEND

———	EXISTING EQUIPMENT OR PIPING
———	PROPOSED EQUIPMENT OR PIPING
- - - - -	ELECTRICAL SUPPLY
⬡	PROPOSED INSTRUMENTATION (MONITORING POINT)
☐	PROPOSED SAMPLING POINT (LABORATORY ANALYSIS)

* SAMPLING TO BE PERFORMED ONLY IF BELT PRESS #7 IS IN OPERATION. (TEST CONDITION "B" ONLY: BLEND OF MECHANICALLY AND THERMALLY DEWATERED SLUDGE)

REVISIONS				
BY	DATE	DESIGNED BY: K.M.O'B.	CHECKED BY:	
		DRAWN BY: P.J.B.	CHECKED BY:	
		DATE: JAN. 1991	SCALE: NO SCALE	
		JOB NO. 88144/09	REPORT NO:	
		DRAWING NO. 88144/09-FIG5-1		

NUSSBAUMER & CLARKE, INC.
Consulting Engineers, Surveyors
BUFFALO, NEW YORK OSWEGO, NEW YORK

BUFFALO SEWER AUTHORITY
Thermal Sludge Dryer Demonstration Project

COMBUSTION TESTING PLAN
SLUDGE DRYER SYSTEM SCHEMATIC AND
PROPOSED DATA COLLECTION POINTS

FIGURE
5-1

- Mechanically dewatered sludge (the dryer was not operated during this "baseline" phase of the testing),

- Thermally dewatered sludge (only), and

- A blend of mechanically and thermally dewatered sludge.

Blending proportions for the blended sludge condition were determined in the field, based on the BIWWTP's solids inventory and the capacities of the mechanical dewatering, sludge drying, and incineration systems. The second operating incinerator (Incinerator 2) received only mechanically dewatered sludge. It was intended to maintain identical rates of solids loading (measured in DT/D) to both incinerators for the duration of the project.

The six operating conditions that were analyzed for Incinerator 1 are summarized below:

A. Baseline Testing (Mechanically Dewatered Sludge)

1. Afterburners On (test period: 7 days - December 12-19, 1991)
2. Afterburners Off (test period: 7 days - November 13-20, 1991)

B. Sludge Blend

1. Afterburners On (test period: 7 days - March 2-9, 1992)
2. Afterburners Off (test period: 7 days - February 5-11, 1992)

C. Thermally Dewatered Sludge

1. Afterburners On (test period: 7 days - December 28, 1991 - January 8, 1992)*
2. Afterburners Off (test period: 7 days - January 22 - February 9, 1992)*

Total Demonstration Project Test Period: 42 days

* The data gathering for this test condition was performed over seven non-consecutive days.

See Appendix A, Section B, Subsection 1, for details on solids handling procedures for test conditions A, B, and C; data collected during the various test periods are summarized in Table 5-1 (Sludge Management Variables) and Table 5-2 (Combustion Variables). Data for the variables presented in Table 5-1 were collected for both Incinerator 1 and Incinerator 2, while data for Table 5-2 variables were collected for Incinerator 1 only. All data collected for the project was stored on IBM-compatible floppy disks.

Testing Protocols

Tables 5-1 and 5-2 specify the physical locations and temporal intervals at which data was collected. Several variables listed in Table 5-2 required equipment with continuous monitoring capabilities and digital data logging. The variables requiring continuous monitoring were: oxygen, carbon monoxide, temperature, and combustion air flow rates. Data for all variables were collected by BSA operations personnel. Testing protocols and specifications for the equipment utilized by BSA in these analyses are included in Appendix A; equipment specifications for the data acquisition system required for recording data for the combustion variables are included in Appendix B.

An independent testing laboratory was retained for the performance of the sludge "ultimate analysis" (this included analytical determination of: carbon, hydrogen, nitrogen, oxygen, sulfur, chlorine, moisture, ash, and BTU content). Equipment specifications and protocols used for performing the ultimate sludge analyses are included in Appendix C. Sludge samples for ultimate analysis were taken by BSA personnel and shipped via overnight courier to the laboratory.

The locations of individual sampling points are depicted in Figure 5-1. The sampling points indicated in the figure correspond to the table number and test "number" shown in the first column of each table. For instance, sampling point T2-E on the diagram indicates Table 5-2, Test/Sample "E" which in this case is temperature. In addition, each sample point has an associated location number. All sample points are also described in detail in the appendices.

TABLE 5-1

SAMPLING AND TESTING PLAN FOR SLUDGE MANAGEMENT VARIABLES

NO.	TEST AND UNITS	SAMPLING LOCATION	SAMPLING FREQUENCY
A	Sludge Feed Rate (wet tons/hr)	1. Sludge Dryer Feed ## 2. Sludge Dryer Outlet # 3. Incinerator #1 Feed 4. Incinerator #2 Feed	4 Hours 4 Hours 4 Hours 4 Hours
B	Total Solids (mg/1 & % solids)	1. Sludge Dryer Feed 2. Sludge Dryer Outlet # 3. Incinerator #1 Feed 4. Incinerator #2 Feed 5. Feed to Belt Press #1	4 Hours 4 Hours 4 Hours 4 Hours 4 Hours
C	Volatile Solids Content (%)	1. Sludge Dryer Feed 2. Sludge Dryer Outlet # 3. Incinerator #1 Feed 4. Incinerator #2 Feed	4 Hours 4 Hours 4 Hours 4 Hours
D	Moisture/Volatiles Ratio	1. Sludge Dryer Feed 2. Sludge Dryer Outlet # 3. Incinerator #1 Feed 4. Incinerator #2 Feed	4 Hours 4 Hours 4 Hours 4 Hours
E	Sludge Temperature (Degrees F)	1. Sludge Dryer Feed 2. Sludge Dryer Outlet # 3. Incinerator #1 Feed 4. Incinerator #2 Feed	4 Hours 4 Hours 4 Hours 4 Hours
F	Steam Pressure (psi)	1. Auxiliary Boiler #1 2. Auxiliary Boiler #2 3. Auxiliary Boiler #3 4. Waste Heat Boiler #1 5. Waste Heat Boiler #2 6. Inlet to Sludge Dryer	2 Hours 2 Hours 2 Hours 2 Hours 2 Hours 2 Hours
G	Steam Production (lb/hr)*	1. RESERVED 2. Waste Heat Boiler #1 3. Waste Heat Boiler #2	2 Hours 2 Hours
H	Steam Utilization (lb/hr)*	1. Sludge Dryer Steam Header	2 Hours

NO.	TEST AND UNITS	SAMPLING LOCATION	SAMPLING FREQUENCY
I	Electricity Utilization (kwh)*	1. Sludge Dryer Equipment	2 Hours
		2. RESERVED	2 Hours
		3. RESERVED	
		4. RESERVED	2 Hours
		5. Incinerator #1 System (includes all fans & motors)	
		6. Incinerator #2 System (includes all fans & motors)	
J	Fuel Gas Utilization (cu ft)*	1. RESERVED	2 Hours
		2. RESERVED	2 Hours
		3. Incin. #1 System (N.G.) **	2 Hours
		4. Incin. #1 System (Meth)	2 Hours
		5. Incin. #1 (N.G.)	2 Hours
		6. Incin. #1 (Meth)	2 Hours
		7. Afterburner #1 (N.G.)	2 Hours
		8. Afterburner #1 (Meth)	2 Hours
		9. Incin. #2 System (N.G.)	2 Hours
		10. Incin. #2 System (Meth)	2 Hours
		11. Incin. #2 (N.G.)	2 Hours
		12. Incin. #2 (Meth)	2 Hours
		13. Afterburner #2 (N.G.)	
		14. Afterburner #2 (Meth)	
K	Condensate Flow Rate (gal/hr)*	1. RESERVED	2 Hours
		2. Sludge Dryer Venturi Condenser Cooling Water Inlet	2 Hours
		3. Sludge Dryer Venturi Condenser Condensate Outlet	
		4. RESERVED	
		5. RESERVED	
		6. RESERVED	
		7. RESERVED	
		8. RESERVED	

TABLE 5-2

SAMPLING AND TESTING PLAN FOR COMBUSTION VARIABLES

NO.	SAMPLE/TEST	SAMPLING LOCATION	SAMPLING FREQUENCY	SAMPLING PROCEDURE
A	Oxygen (O_2) (%)	1. Incinerator Outlet 2. Afterburner Outlet	1 Min. Avg. 1 Min. Avg.	Total Extractive Total Extractive
B	Carbon Monoxide (CO) (ppm)	1. Incinerator Outlet 2. Afterburner Outlet	1 Min. Avg. 1 Min. Avg.	Total Extractive Total Extractive
D	Flue Gas Moisture (H_2O)	1. Incinerator Outlet	15 Minutes	Determined by Calculation
E	Temperature Degrees F	1. Incinerator #1, Hearth #1	5 Min. Avg.	Thermocouple
		2. Incinerator #1, Hearth #2	5 Min. Avg.	Thermocouple
		3. Incinerator #1, Hearth #3	5 Min. Avg.	Thermocouple
		4. Incinerator #1, Hearth #4	5 Min. Avg.	Thermocouple
		5. Incinerator #1, Hearth #5	5 Min. Avg.	Thermocouple
		6. Incinerator #1, Hearth #6	5 Min. Avg.	Thermocouple
		7. Incinerator #1, Hearth #7	5 Min. Avg.	Thermocouple
		8. Incinerator #1, Hearth #8	5 Min. Avg.	Thermocouple
		9. Incinerator #1, Hearth #9	5 Min. Avg.	Thermocouple
		10. Incinerator #1, Hearth #10	5 Min. Avg.	Thermocouple
		11. Incinerator #1, Hearth #11	5 Min. Avg.	Thermocouple
		12. Incinerator #1, Hearth #12	5 Min. Avg.	Thermocouple
		13. Afterburner #1, Outlet	5 Min. Avg.	Thermocouple
		14. Incinerator #1, Shaft Cooling Air Inlet	5 Min. Avg.	Thermocouple

TABLE 5-2 (continued)

NO.	SAMPLE/TEST	SAMPLING LOCATION	SAMPLING FREQUENCY	SAMPLING PROCEDURE
E	Temperature Degrees F	15. Incinerator #1, Shaft Cooling Air Outlet	5 Min. Avg.	Thermocouple
		16. Waste Heat Boiler #1 Exhaust Gas Inlet	5 Min. Avg.	Thermocouple
		17. Waste Heat Boiler #1 Exhaust Gas Outlet	5 Min. Avg.	Thermocouple
		18. Sludge Dryer Steam Header	5 Min. Avg.	Thermocouple
		19. Final Effluent Water Pipe at Entry to Dryer System	5 Min. Avg.	Thermocouple
		20. Sludge Dryer Exhaust Vapor Outlet	5 Min. Avg.	Thermocouple
		21. Sludge Dryer Venturi Condenser Condensate	5 Min. Avg.	Thermocouple
		22. Sludge Dryer Fan Exhaust	5 Min. Avg.	Thermocouple
		23. Incinerator Air Plenum	5 Min. Avg.	Thermocouple
		24. Waste Heat Boiler #1 Steam Outlet	5 Min. Avg.	Thermocouple
		25. Waste Heat Boiler #2 Steam Outlet	5 Min. Avg.	Thermocouple
F	Air Flow Rate (scfm)	1. Combustion Air Fan (Incinerator #1 Inlet)	5 Min. Avg.	Differential Pressure
		2. Combustion Air Fan (Afterburner #1 Inlet)	5 Min. Avg.	Differential Pressure
		3. Auxiliary Combustion Air Fan	5 Min. Avg.	Differential Pressure
		4. Cooling Air Fan (Incinerator #1 Inlet)	5 Min. Avg.	Differential Pressure
		5. Centrifugal Fan (Dryer/Cond. Exhaust)	5 Min. Avg.	Differential Pressure
I	Sludge Ultimate Analysis*	1. Sludge Dryer Feed	2x per Test Condition	Composite Grab Samples
		2. Incinerator #1 Feed	2x per Test Condition	Composite Grab Samples

* Ultimate Analysis included: Carbon (C_2), Chlorine (Cl_2), Hydrogen (H_2), Nitrogen (N_2), Oxygen (O_2), Sulfur (S_2), Moisture (H_2O), Ash, Sludge B.T.U. content.

DATA GATHERING

Problems Encountered During Data Collection

The actual dates of the testing and monitoring are as provided in the testing schedule, above.

<u>Sludge Feed Rates to the Incinerators</u>. One of the requirements of the monitoring plan was to maintain a constant sludge feed rate, measured in dry tons per hour, to each of the two operating incinerators. However, rarely during the testing was this possible. Typically, sludge feed rates to Incinerator 1 (burning thermally dewatered sludge) were within 15% of the dry feed rate to Incinerator 2 (which burned only mechanically dewatered sludge).

One reason for the difference in feed rates includes mechanical failures of individual belt presses. Most wastewater treatment facilities that utilize belt presses for dewatering experience periodic mechanical failures of belts or other equipment. When such situations occurred during the monitoring program, feed rates to the presses that were still operating would be adjusted as necessary to maintain a constant feed rate. In some cases, belt presses were activated and in other cases were shut down when a mechanical failure occurred.

A second reason for unequal sludge feed rates to the two incinerators was minor hydraulic problems in the belt press feed piping, which resulted in unequal feed sludge distribution to the presses. The hydraulic configuration of the pipes, as well as valve positions at the time of the data gathering, contributed to this problem.

A third reason for unequal feed rates was that the sludge feed rate readings were taken at four-hour intervals; thus, adjustment of the feed rate could only be performed six times per day. Protocols were set up for plant operators to follow during each test condition to attempt to ensure that equal dry feed rates were maintained to each incinerator. When a discrepancy in the feed rates was discovered (using the existing continuous weight scales installed on the east and west conveyor belts), the feed rate to the belt presses on one of the conveyor belts was adjusted, but the system seldom remained in the equal-feed operating mode.

Continuous Emissions Monitoring System Malfunctions. During the course of the data gathering, several problems were encountered with the CEMS. This system was installed to measure oxygen (O_2) and carbon monoxide (CO) concentrations in the flue gases at a location between the incinerator and afterburner, and a location between the afterburner and the WHRB.

The CEMS for this project was not a permanent installation provided by a single manufacturer, but was rental equipment maintained by an instrumentation supplier. Because the plant operators were unfamiliar with the rental equipment and due to the fact that some of the system components were initially improperly integrated, malfunctions in the CEMS occurred during several of the test conditions. In some instances, plant operators did not notice a CEMS malfunction for several hours, and in such cases it took several more hours to get the instrumentation technician on-site to troubleshoot the system and make repairs. Malfunctions and/or inaccurate data reported by the CEMS eventually contributed to problems during the combustion analysis stage of the project.

Differential Pressure Flow Meters. Flow metering instrumentation used to continuously monitor steam flow and combustion air flows were pitot tubes that produced a differential pressure across a sensing device, which was then converted into a flow rate. At various times in different test conditions, problems were encountered with some of these instruments.

There is reason to believe that the steam flow metering unit used to measure the steam consumption of the dryer was not accurate, based on mass and heat balances performed on the dryer for the various test conditions. The reason for this is not known, but the steam consumption of the dryer may have been outside the range of the differential pressure sensing unit used to measure this variable.

One combustion air flow meter in particular experienced some problems. This was the flow meter for the dryer's non-condensible gases. The gases were piped to the incinerators as both an odor-control measure and to serve as an additional combustion air source. However, the non-condensibles in the gas flow plugged the pitot tube openings in the annubar flow element. This was alleviated by the plant operators' occasionally removing the annubar from the duct for draining and cleaning. In the periods just prior to these periodic cleaning operations, the gas flow data recorded by the DAS may not have been accurate.

Dryer Vapor Condensate Turbine Meter Problems. Calcification of the dryer vapor condenser and its drain line was a major problem during system start-up, and continued to be a problem throughout the project monitoring. Throughout Test Conditions B and C (sludge blend and thermal sludge conditions), it was necessary to dismantle the condenser and drain line at least every three weeks, for a complete cleaning by hand and using sulfamic acid.

In order to perform heat balances for the dryer condenser for each test condition, the flow rate of the condensate drain line was needed. A turbine meter was installed on the 4-inch drain line. However, due to the heavy calcification experienced during start-up, the turbine meter was rendered inoperable for the duration of the testing, requiring that assumptions be made as to feed water, drain water, and dryer vapor flow rates. The assumptions were based on the sludge percent solids content in the dryer feed and dryer discharge, as well as the typical pressures in the BIWWTP protected water system.

Data Management. Two problems were encountered with management of the information collected by the PC-based DAS.

The first occurred during routine maintenance of the computer system. When a system technician made a regular examination of the DAS, the personal computer was inadvertently shut off for several hours before the error was discovered. This occurred during Test Condition B (Sludge Blend), resulting in some data not being recorded.

Also, during the process of downloading data to floppy disks for Test Conditions B and C, a required software command to convert the data to a format recognized by the spreadsheet program utilized for data management was not issued. The result was that data collected for these test conditions was not provided at the required one or five-minute intervals but rather was reported as half-hour averages.

Format For Recorded Data

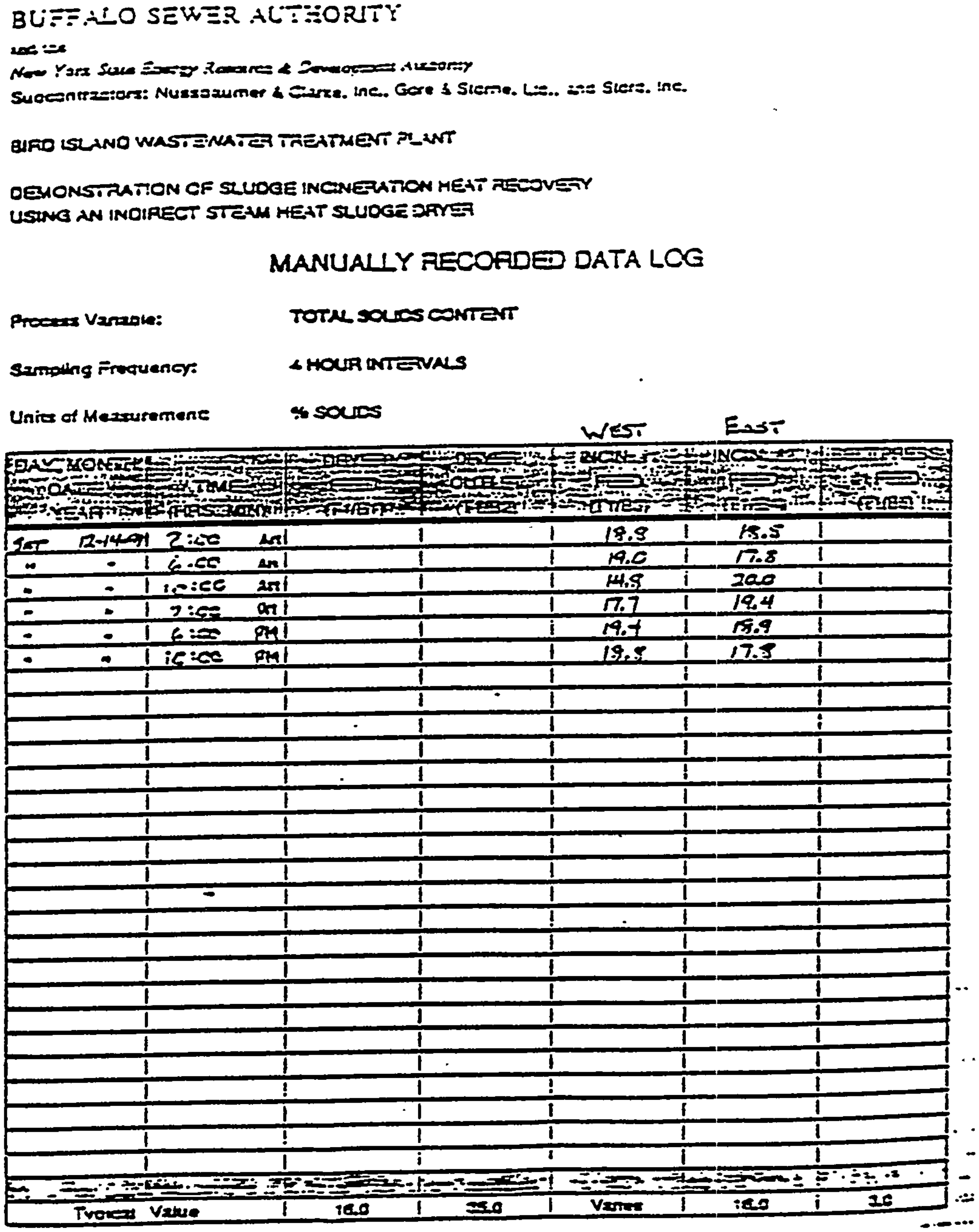
Data recorded for the project was composed of two categories: manually recorded data and data automatically logged by the DAS. The manually recorded data includes all the sludge management variables (see Table 5-1), plus the "sludge ultimate analysis". All combustion variables (see Table 5-2) except the ultimate analysis were connected to the DAS.

Manually recorded data collection included operators "making the rounds" of the project instrumentation and manually recording the indicated data results on log sheets developed for this project. Examples of the manually recorded data format are included in Figures 5-2 and 5-3.

The data collected by the DAS was recorded in the format shown in Figure 5-4. The DAS averaged the continuous readings for the specified time intervals (one or five minutes, depending on the variable) and recorded the averaged data reading. The data was stored on the PC's hard drive and, at the end of each seven-day test condition, the data was downloaded onto a floppy disk in a format compatible with the spreadsheet program used for the data management.

Data Handling And Analyses

Following completion of the monitoring period and data collection, the data was analyzed and heat balances were computed for each of the six test conditions (i.e. three sludge/blend conditions, each with the afterburner on/off subcondition). Heat balances were calculated for conditions monitored on the Incinerator 1 system, only. The "incinerator system" includes: the sludge dryer and associated ancillary equipment, incinerator, afterburner, WHRB, and associated piping and ductwork. Other analyses determined flue gas moisture at the incinerator exhaust, incinerator combustion quality and efficiency, heat recovery opportunities, and the effect of the sludge dryer on fuel consumption for the



BUFFALO SEWER AUTHORITY

and the

New York State Energy Research & Development Authority

Subcontractors: Nussbaumer & Clarke, Inc., Gore & Storrie, Ltd., and Storz, Inc.

BIRD ISLAND WASTEWATER TREATMENT PLANT

DEMONSTRATION OF SLUDGE INCINERATION HEAT RECOVERY
USING AN INDIRECT STEAM HEAT SLUDGE DRYER

MANUALLY RECORDED DATA LOG

Process Variable: TOTAL SOLIDS CONTENT

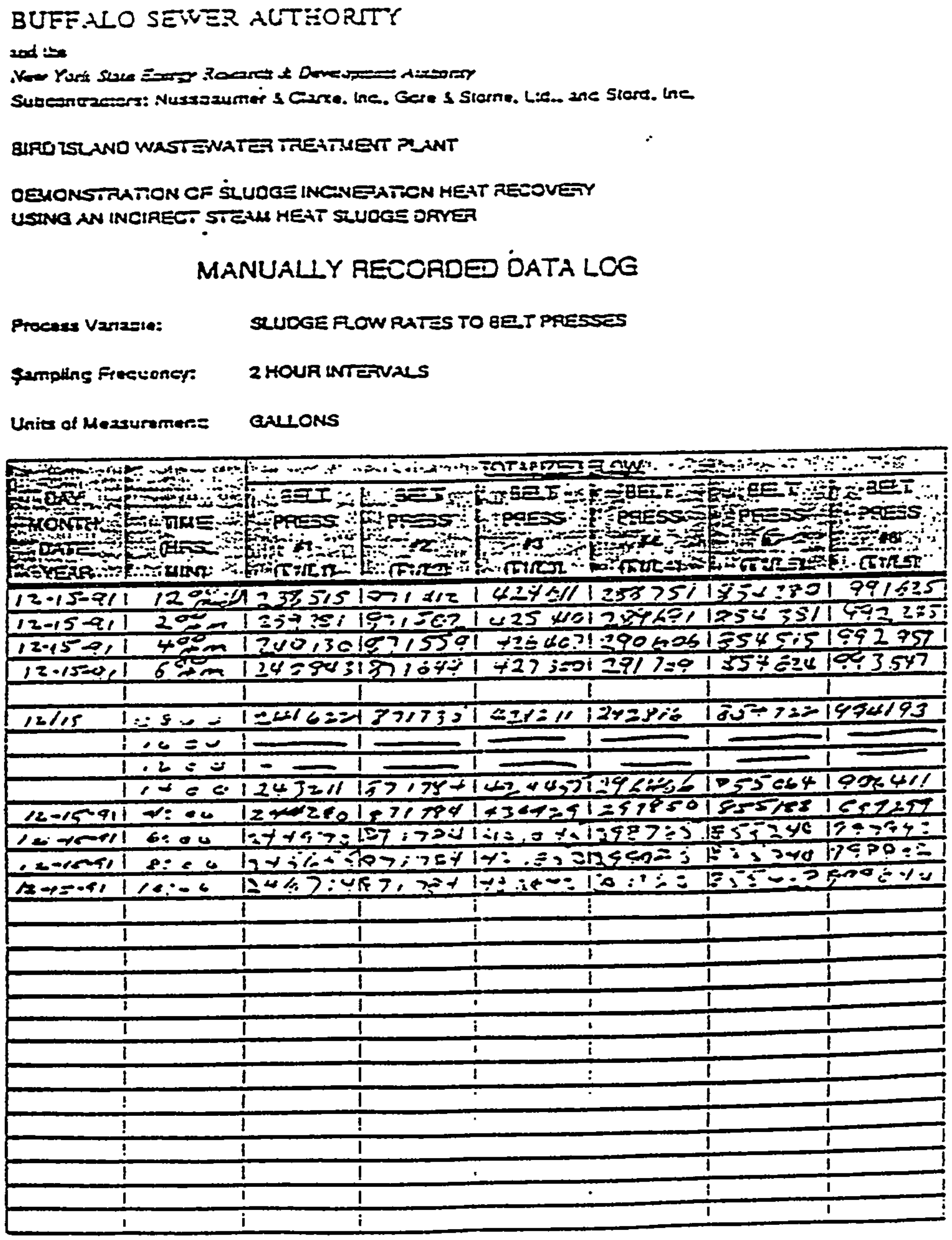
Sampling Frequency: 4 HOUR INTERVALS

Units of Measurement: % SOLIDS

DAY MONTH DAY YEAR	TIME (HRS:MIN)	DRYER [illegible]	DRY [illegible]	INCIN [illegible] WEST	INC [illegible] EAST	[illegible] PRESS [illegible]
Sat 12-14-91	2:00 AM			18.9	15.5	
" "	6:00 AM			19.0	17.8	
" "	10:00 AM			14.9	20.0	
" "	2:00 PM			17.7	19.4	
" "	6:00 PM			19.4	15.9	
" "	10:00 PM			19.9	17.3	
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Typical Value		16.0	35.0	Varies	16.0	3.0

FORMAT OF MANUALLY RECORDED DATA (TYPICAL FOR SLUDGE MGMT. VARIABLES)

FIGURE 5–2



BUFFALO SEWER AUTHORITY
and the
New York State Energy Research & Development Authority
Subcontractors: Nussbaumer & Clarke, Inc., Gore & Storrie, Ltd., and Stord, Inc.

BIRD ISLAND WASTEWATER TREATMENT PLANT

DEMONSTRATION OF SLUDGE INCINERATION HEAT RECOVERY
USING AN INDIRECT STEAM HEAT SLUDGE DRYER

MANUALLY RECORDED DATA LOG

Process Variable: SLUDGE FLOW RATES TO BELT PRESSES

Sampling Frequency: 2 HOUR INTERVALS

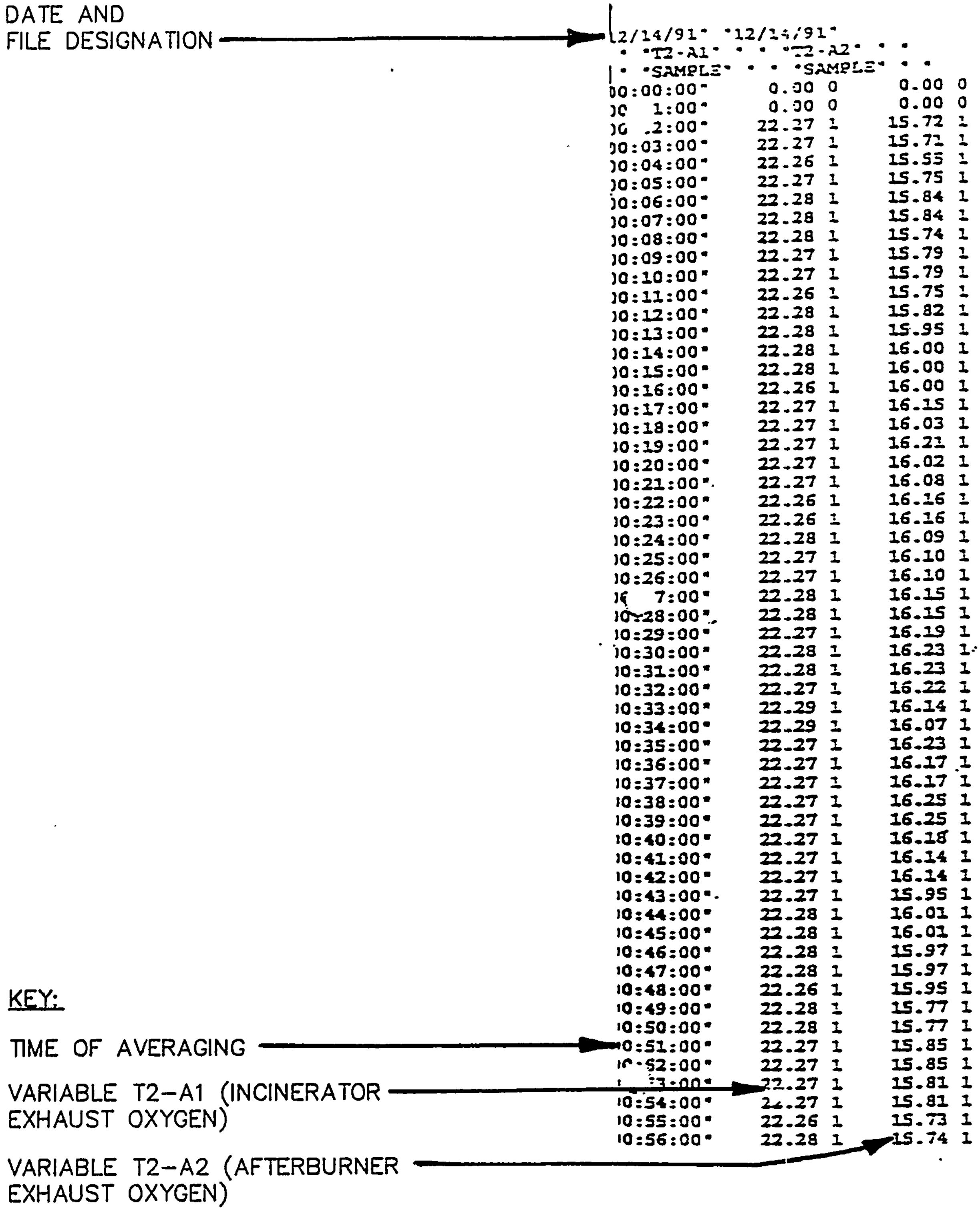
Units of Measurement: GALLONS

DAY MONTH DATE YEAR	TIME (HRS. MIN)	TOTALIZED FLOW					
		BELT PRESS #1 (GAL)	BELT PRESS #2 (GAL)	BELT PRESS #3 (GAL)	BELT PRESS #4 (GAL)	BELT PRESS #5 (GAL)	BELT PRESS #6 (GAL)
12-15-91	12^{00} am	235515	971412	424411	288751	354180	991625
12-15-91	2^{00} am	237251	971507	425410	289691	354351	992235
12-15-91	4^{00} am	240130	971559	426467	290606	354515	992957
12-15-91	6^{00} am	242943	971644	427350	291709	354624	993547
12/15	8:00	246227	971733	431211	292816	354722	994193
	10:00	—	—	—	—	—	—
	12:00	—	—	—	—	—	—
	14:00	243211	971784	424457	296456	355064	996411
12-15-91	4:00	244280	971784	434429	297850	355188	997259
12-15-91	6:00	[illegible]	971724	[illegible]	298725	355246	[illegible]
12-15-91	8:00	[illegible]	971754	[illegible]	[illegible]	355340	[illegible]
12-15-91	10:00	[illegible]	971754	[illegible]	[illegible]	[illegible]	[illegible]

FORMAT OF MANUALLY
RECORDED DATA
(TYPICAL FOR SLUDGE MGMT. VARIABLES)

FIGURI

5–



```
2/14/91"  "12/14/91"
 " "T2-A1" " " "T2-A2" " "
" "SAMPLE" " " "SAMPLE" " "
00:00:00"      0.00 0      0.00 0
0  1:00"       0.00 0      0.00 0
0 .2:00"      22.27 1     15.72 1
0:03:00"      22.27 1     15.71 1
0:04:00"      22.26 1     15.55 1
0:05:00"      22.27 1     15.75 1
0:06:00"      22.28 1     15.84 1
0:07:00"      22.28 1     15.84 1
0:08:00"      22.28 1     15.74 1
0:09:00"      22.27 1     15.79 1
0:10:00"      22.27 1     15.79 1
0:11:00"      22.26 1     15.75 1
0:12:00"      22.28 1     15.82 1
0:13:00"      22.28 1     15.95 1
0:14:00"      22.28 1     16.00 1
0:15:00"      22.28 1     16.00 1
0:16:00"      22.26 1     16.00 1
0:17:00"      22.27 1     16.15 1
0:18:00"      22.27 1     16.03 1
0:19:00"      22.27 1     16.21 1
0:20:00"      22.27 1     16.02 1
0:21:00"      22.27 1     16.08 1
0:22:00"      22.26 1     16.16 1
0:23:00"      22.26 1     16.16 1
0:24:00"      22.28 1     16.09 1
0:25:00"      22.27 1     16.10 1
0:26:00"      22.27 1     16.10 1
0  7:00"      22.28 1     16.15 1
0:28:00"      22.28 1     16.15 1
0:29:00"      22.27 1     16.19 1
0:30:00"      22.28 1     16.23 1
0:31:00"      22.28 1     16.23 1
0:32:00"      22.27 1     16.22 1
0:33:00"      22.29 1     16.14 1
0:34:00"      22.29 1     16.07 1
0:35:00"      22.27 1     16.23 1
0:36:00"      22.27 1     16.17 1
0:37:00"      22.27 1     16.17 1
0:38:00"      22.27 1     16.25 1
0:39:00"      22.27 1     16.25 1
0:40:00"      22.27 1     16.18 1
0:41:00"      22.27 1     16.14 1
0:42:00"      22.27 1     16.14 1
0:43:00"      22.27 1     15.95 1
0:44:00"      22.28 1     16.01 1
0:45:00"      22.28 1     16.01 1
0:46:00"      22.28 1     15.97 1
0:47:00"      22.28 1     15.97 1
0:48:00"      22.26 1     15.95 1
0:49:00"      22.28 1     15.77 1
0:50:00"      22.28 1     15.77 1
0:51:00"      22.27 1     15.85 1
0:52:00"      22.27 1     15.85 1
   3:00"      22.27 1     15.81 1
0:54:00"      22.27 1     15.81 1
0:55:00"      22.26 1     15.73 1
0:56:00"      22.28 1     15.74 1
```

FORMAT OF AUTOMATICALLY RECORDED DATA (DAS)
(TYPICAL FOR COMBUSTION VARIABLES)

FIGURE 5-4

incineration system. Regarding the latter, of special importance were the fuel demands the sludge dryer exerted on the steam generation system. All flue gas quality data was normalized to 7% oxygen prior to analysis in order to account for differing oxygen dilutions (due to variation in the combustion air feed rates) used in the incineration process. Data collected for the Incinerator 2 system was used as a point of comparison in evaluating the advantages and disadvantages of the sludge dryer.

REFERENCES

BSA/Nussbaumer & Clarke, February 1991, *Combustion Testing and Monitoring Equipment Specifications.*

SECTION 6

DATA ANALYSIS

INTRODUCTION

This section of the report details the plan developed for the data analysis, outlines the statistical procedure used to arrange the data into "groups" for analysis, and describes the heat and mass balances performed as part of the engineering analyses. The assumptions inherent to the analyses and the rationale for the assumptions are also presented in this section.

APPROACH TO DATA ANALYSES

Prior to reduction, the data from each phase of the monitoring program were tested for auto-correlation. Following the auto-correlation determination, the data were arranged into groups to facilitate analysis; these groups were based on more-or-less steady state incineration conditions, based on sludge feed rate (measured in dry tons per day, or DT/D). The grouped data were also tested for auto-correlation and the variables within each data group were subjected to statistical T-test procedures. Next, mass and heat balances were performed for each sludge condition (i.e., mechanically dewatered sludge, thermally dewatered sludge, and blended sludge). The resulting data were used to calculate the performance of the dryer and determine energy savings for the solids handling and disposal system.

DATA ANALYSIS PLAN

Sludge Data Analyses

Data Reduction: Six test conditions were defined for the monitoring phase of the project: these were for the mechanical, thermal, and blended sludge conditions, and each sludge blend had an afterburner "on" and afterburner "off" scenario, thereby providing for six separate test conditions. Data was collected over a seven-day period, 24 hours per day, for each of the six test conditions. Due to the large amount of raw data collected during each test period, raw data was subject to data reduction prior to analysis.

Sludge dry feed rate to the incinerators and sludge quality (as defined by the moisture-to-volatiles, or M/V, ratio) varied during the test due to process conditions at the BIWWTP and, therefore, the various data groups were formulated to identify those periods during each test condition which approximated steady-state operations. The tolerance limit for defining steady-state operation of the incinerator was determined following a detailed examination of the collected data. A list of parameters, or "variables", monitored and their sampling locations are included in Tables 5-1 and 5-2.

Raw data for each recorded variable were analyzed for consistent consecutive readings to identify steady-state operating conditions and the duration of each steady state. Operators' daily reports were also utilized to determine steady-state conditions. The primary variables governing steady-state operation (as defined for this project) were;

- Sludge feed rate (in DT/D) to incinerators;
- Sludge volatile solids content (measured as a percentage of the total solids in the incinerator feed). Volatile solids are an approximation of the combustible solids in the feed sludge.

When various steady states were identified, raw data was averaged over the duration of each steady state period to reduce the number of data points. For example, if ten steady state periods were identified for a variable over the course of a certain test condition, then ten reduced data points were identified for that variable for that test condition. These data reduction procedures were applied to each measured variable at each sampling location.

Because the reduced data represents steady state operating conditions, reduced data were used where specific benefits of the sludge dryer were to be identified. Improved or degraded operation of the incineration system during a steady state condition was thus attributed to the sludge dryer and not to a change in independent variables, such as sludge feed rate and sludge quality. If the complete set of raw data were used to identify and quantify the effects of the sludge dryer, the conclusions drawn would include the effect of other causes (e.g. changes in feed rate and/or quality), in addition to the system effects caused directly by the sludge dryer.

For economic analysis, the complete set of raw data was used in order to include non-steady state conditions in the analysis. For actual, long term operation, both steady and non-steady state operations characterize the actual operation of the incinerators at the BIWWTP. The use of all raw data for this analysis generated a realistic estimation of the economic benefits (i.e., a reduction in the overall O&M costs for solids handling at the BIWWTP) that were expected from the sludge dryer.

Initial Analyses: In evaluating the effects of the sludge dryer, analyses were performed to compare the operation of Incinerator No. 1 with the operation of Incinerator No. 2 (for the demonstration project, the third incinerator at the plant was not utilized). For this comparison to be valid, it had to first be proven that Incinerator No. 2 was operating in a mode similar to Incinerator No. 1; or, in other words, that the dependent variables being measured for the two incinerators respond similarly to any changes in the independent variables (sludge feed rate and sludge quality).

In order to investigate the similarity between Incinerators No. 1 and No. 2, a "baseline" test condition was established where both units were operated simultaneously and fed with only mechanically dewatered sludge (test conditions A1 and A2). Data was collected at varying intervals. For example, continuously monitored data was collected at 1-minute and 5-minute intervals, while sludge feed rate was recorded every 2 hours. The data was reduced to 2-hour intervals by averaging each variable over 2 hours. Reduced data of all the dependent variables from Table 5-1 (dependent sludge management variables included the following: steam pressure, steam utilization, steam production, sludge volatile solids content, electricity utilization, auxiliary fuel gas utilization, and sludge dryer vapor condensate flow rate), as well as the independent variable sludge dry feed rate, were plotted for both incinerators versus time for visual screening. In the case of the sludge dry feed rate, both incinerators were operated at similar dry sludge feed rates. Regression analysis and calculations of coefficient of determination (r^2) were performed on baseline data for both incinerators for the sludge dry feed rate, sludge M/V ratio, fuel consumption, and electricity, and the results were plotted against time for visual presentation. Other than dry feed rates and M/V ratio there was poor correlation between the two incinerators. This would suggest that their operations were not similar. However, because of the constantly fluctuating and varying operation of the system, from the sludge dewatering through incineration, incinerators with similar sludge feed quality and feed rates can be considered to be similar for comparison of energy utilization. Thus the incinerators could be compared for other test conditions, if the sludge quality and feed rates were kept similar.

Data were then grouped by dry sludge feed rate for each phase of the monitoring program. All data points that were within ± 10% of the average for each data set were placed in groups for further analysis of energy utilization.

Systems Comparison: The effects of the sludge dryer on the incineration process were studied by comparing incinerator performance when the incinerators were subject to different test conditions. During the thermally dewatered and blended sludge conditions (noted as test conditions B1, B2, C1 and C2) for Incinerator No. 1, the following dependent variables from Table 5-1 were compared for both Incinerator No. 1 and No. 2:

- Percent Volatile Content
- Steam Pressure
- Steam Production
- Steam Utilization
- Electricity Utilization
- Auxiliary Fuel Gas Utilization
- Dryer Vapor Condensate Flow Rate

Field collected data for each of the above variables were reduced. The trend of the reduced data for each of the dependent variables was analyzed for pattern and consistency by plotting all the identified steady states (i.e., the reduced data points) over the duration of each test period. Trends were also compared between

Incinerators No. 1 and No. 2. Median and standard deviation for each reduced data point were calculated and graphically presented on the plots of identified steady states.

To identify the effect of the sludge dryer on each of the seven dependent variables, reduced data obtained from the thermally dewatered and blended sludge conditions were compared for Incinerators No. 1 and No. 2. For each variable, individual reduced data points from Incinerator No. 1 were matched (paired) with corresponding points from Incinerator No. 2, based on similar conditions for the independent variables (incinerator sludge feed rate in DT/D and the sludge volatile solids content). The mean difference of the paired data points and the standard deviation of the mean difference were calculated to quantify the net change in each dependent variable. To verify that the mean difference in each dependent variable was attributed to the sludge dryer, a statistical T-test was performed.

The operation of Incinerator No. 1 under test conditions B1, B2, C1, and C2 was also compared to the operation of Incinerator No. 1 under the mechanically dewatered sludge conditions (A1, A2). For these comparisons, all combustion variables (listed in Table 5-2) and the seven dependent variables listed above were analyzed to estimate the effect of the sludge dryer on the incinerator. Graphical plots similar to those described above were generated to assist in evaluating the effect of the sludge dryer on combustion quality, combustion efficiency, and air pollution control equipment operation.

<u>Test of Confidence Level:</u> To illustrate that the differences in the means of the measured dependent variables between the two incinerators was not due to sampling error, a statistical analysis using a T-test was performed at the 99% confidence level for each of the dependent variables. These tests determined whether the observed effects of the dryer on the Incinerator No. 1 system were due to random chance or if the effects are representative of true improvements in process operation.

Combustion Calculations

General: Heat balances were calculated for the Incinerator No. 1 system for each of the six test conditions; the "incineration system" consists of the incinerator, afterburner, WHRB, sludge dryer, and dryer vapor condensation system.

The heat balance procedure included the formulation of a numerical model of the incinerator operation utilizing the reduced data from the mechanically dewatered sludge tests (test conditions A1 and A2); the model was calibrated from the mechanically dewatered sludge conditions, and then the test runs utilizing the thermally dewatered and blended sludges (test condition B1, B2, C1, and C2) were input into the model and analyzed. The numerical model calculated both energy content and temperature of various system process streams (such as incinerator flue gases and WHRB flue gases). These calculated values were compared with the actual data collected in the field to estimate the efficiency of the WHRB and the dryer vapor system. In addition, the incinerator's combustion quality was analyzed based on data obtained from the CEMS installed in the Incinerator No. 1 exhaust duct.

Incinerator combustion efficiency was also calculated. Incinerator efficiency was defined for this project as the carbon dioxide concentration in the incinerator exhaust (a calculated quantity) expressed as a percentage of the combined carbon dioxide and carbon monoxide concentrations (calculated and field-measured quantities, respectively). This definition is based on the assumption that all organic compounds are converted to carbon dioxide (CO_2) and water (H_2O) in an ideal, complete combustion process. Incomplete combustion would convert some of the organic compounds to carbon monoxide (CO) and water. Hence, the efficiency of a combustion process is determined by the extent to which incomplete combustion occurs. The degree of incomplete combustion is determined by comparison to the ideal condition.

In this project, carbon dioxide concentration of the incinerator flue gas was not field-measured. The combined CO and CO_2 concentrations required for the efficiency calculation were determined by the numerical model of the incinerator;

the numerical model was formulated using a computer program entitled HAM-1. The calculated combined CO and CO_2 concentrations were expressed as the theoretical carbon dioxide concentration. The actual carbon dioxide concentration was calculated by subtracting CO concentration (field-measured) from the theoretical CO_2 concentration for complete combustion.

Numerical Models HAM-1 and HMHEARTH: Mass and heat balances were developed using two proprietary computer programs. The first program, HAM-1, performs mass and heat balances for a combustion system composed of a multiple hearth incinerator, waste heat recovery boiler, and a wet or dry scrubber, or any combination of these principal system components. The program computes mass and heat balances for an entire incineration/air pollution control (APC) system.

HAM-1 does not include options for evaluating a sludge dryer and/or its associated equipment, as part of an incineration/APC system. A computer spreadsheet was used to perform separate heat and mass balances for the dryer and its ancillary equipment. The results of the spreadsheet calculations were incorporated into the HAM-1 input file. In this fashion, the dryer's efficiency, as well as its effect on the combustion process, were evaluated.

A summary of the input data requirements of HAM-1 are included in Appendix F to this report. Appendix F also includes a sample input and output file.

All equations used in HAM-1 are first-order stoichiometric equations (mathematically, these are simple algebraic equations). In some computations, iterations are performed until a specified approximate relative error is reached. Program output is in ASCII file format.

The second program, title HMHEARTH, performs hearth-by-hearth mass and heat balances for a multiple hearth incinerator. The balances are performed for each successive incinerator hearth in order to compute an overall balance for the incinerator unit; this program considers only the incinerator and cannot be used to analyze waste heat recovery boilers or APC equipment. HMHEARTH uses the following input data: hearth temperature profiles, fuel and air injection profiles, and sludge feed rates and quality to each hearth.

A summary of the input data requirements for HMHEARTH and sample output is included in Appendix F. This program also provides output in ASCII file format. Mass and heat balance equations and computation methodology for HMHEARTH are essentially the same as for HAM-1, except that the system "envelope" is smaller.

Waste Heat Recovery: The feasibility of using the WHRB (regardless of whether the afterburners were operating) to extract waste heat from the Incinerator No. 1 flue gas stream was analyzed using both HAM-1 and HMHEARTH. As noted above, the analysis of waste heat availability for the dryer system was performed using a computer spreadsheet. The hypothesis was that steam generated from the WHRB would be more than adequate to satisfy the steam demand of the sludge dryer. Any excess steam could be utilized for to supplement the plant's process steam system. The potential uses of excess steam and other waste heat which may be recovered from the incineration system flue gases and the sludge dryer's sidestreams are addressed in Section 7 of this report.

Economic Analysis

The potential for heat recovery and the benefit derived in reduced incinerator auxiliary fuel gas consumption were used to estimate annual energy and O&M cost savings. In this analysis, reduced data was not utilized; rather, averages of all field collected data were used, which thus incorporated all fluctuations observed in the variables. Hence, long term operation of the Incinerator No.1 system, where system variables are prone to fluctuate due to variations in sludge conditions and mechanical breakdowns, was simulated to provide an accurate analysis of economic impacts of the dryer on the dewatering and incineration systems at the BIWWTP.

DATA ANALYSIS OVERVIEW

Monitoring Program

As noted in previous sections of this report, sludge management variables (see Table 5-1) were recorded manually by BIWWTP operations personnel, and sludge samples for variables such as total solids content and volatile solids content were analyzed in the BIWWTP laboratory. M/V ratios were computed by the laboratory personnel and recorded manually. The M/V ratio is a mass ratio used to track the combustibility of a given sludge. The lower the ratio, the more combustible the sludge, i.e., the fuel in the sludge (volatile content) has less water to evaporate. Earlier work at the BIWWTP established incinerator capacity based on M/V ratios (BSA/Consoer Townsend & Associates, 1982).

Continuously monitored data were automatically recorded by the PC-based DAS in accordance with Table 5-2. Sludge was sampled by BIWWTP operators and ultimate analyses were performed by an independent testing laboratory. Figure 5-1 indicates sampling and monitoring locations.

Monitoring was virtually continuous during each phase of the monitoring program. Shutdowns occurred from time to time and were clearly identified on the manually recorded data sheets. Major gaps in the manually recorded data are summarized in Table 6-1 for each phase of the program. Data that was not recorded generally did not affect the results of the analyses. Some of the missing data is attributable to equipment malfunctions or shutdowns (i.e., belt press problems, etc.); all malfunctions and "gaps" in the data were considered in the analyses. All data electronically recorded by the DAS was complete. In some cases, where inaccuracies were suspected in the monitored data, calculations were performed to check the field-measured data (see also Table 6-2).

The CEMS data were complete except for item T2-D, Incinerator Flue Gas Moisture Content. The flue gas moisture was to be calculated every 15 minutes. The calculation method used was the MHBs, but the MHBs were performed only for selected conditions (as detailed later in this section).

Data Preparation

Manually recorded data were input into a computer spreadsheet to facilitate data analysis.

The incinerator sludge dry feed rate was calculated from two measured variables: the incinerator wet sludge feed rate, and the total solids content of the incinerator feed sludge. While this computation was fairly simple for the mechanically dewatered and thermally dewatered sludge conditions, a more complex operation was required for the sludge blend conditions. The total solids concentration of sludge from Belt Filter Press No. 7 (the mechanical dewatering unit located between the sludge dryer and the incinerators) was recorded. The incinerator feed total solids concentration was first calculated by performing a mass balance around the dryer discharge, Belt Press No. 7, and the incinerator inlet using the measured wet sludge feed rate and total solids concentrations. The incinerator dry feed rate was then calculated. This was required since it was not possible to obtain a representative sample of the blended sludge, since the mechanically dewatered sludge from Belt Press No. 7 was simply discharged onto the conveyor belt on top of the thermally dewatered sludge. No mixing of the two sludges was performed until the product was raked by the rabble arms within the incinerator.

Auxiliary fuel consumption was recorded both as a cumulative value and a flow rate. The recorded values were adjusted by a factor recommended by each meter manufacturer to obtain actual flow rates. Where digester gas was used as the incinerator's auxiliary fuel, prior to analysis the digester gas was numerically converted to equivalent natural gas (based on a heating value empirically determined by BIWWTP operators to be 650 BTU/ft^3) and added to the incinerator's auxiliary fuel consumption.

The steam flow rate from the Incinerator No. 1 WHRB had to be adjusted using the conversion factor for the steam meter. Likewise, the electricity utilization was reported as a cumulative value. Each value had to be adjusted to an hourly rate, and a conversion factor had to be applied for the electrical meter.

The dryer vapor condensate flow rate readings were not recorded due to the previously discussed scale formation in the vapor condenser and its drain pipe. The scale plugged the condensate flow meter on the condenser outlet and this meter was removed from service for the duration of the testing. It is not believed that the removal of this meter from service substantially affected the test results.

TABLE 6.3.2-1-A1 MISSING DATA FOR TEST CONDITION BASELINE WITHOUT AFTERBURNERS

Date	Nov 13, 1991												Nov 14, 1991												Nov 15, 1991												Nov 16, 1991												Nov 17, 1991												Nov 18, 1991												Nov 19, 1991												Nov 20, 1991											
Time	a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.					
Var Name	Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten	
T1/A1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/A2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/A3											*	*																																																																																					
T1/A4											*	*																																																																																				
T1/B1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/B2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/B3																																																																																																			
T1/B4																																																																																																		
T1/B5	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
T1/C1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/C2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/C3																																																																																																		
T1/C4																																																																																																		
T1/D1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/D2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/D3																																																																																																		
T1/D4																																																																																																		
T1/E1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/E2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/E3																			*	*																																																											*	*													*	*				
T1/E4																			*	*																																																													*	*													*	*				
T1/F1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
T1/F2																																																																																																			
T1/F3	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
T1.F4	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/F5	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/F6	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/G2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1.G3	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1·H1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/I1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1.I5																																																																																																			
T1/I6																																																																																																			
T1/J3,J4																									*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
T1/J5,J6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*																																																																									
T1.J7,J8	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1.J9,J10																														*	*	*																	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
T1.J11,J12	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*																																																
T1.J13,J14	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1.K2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1.K3	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1.L1																																																																																																			
T1.L2																																																																																																				
T1.L3																																																																																																			
T1.L4																																																																																																			
T1.L5																																																																																																		
T1.L6																																																																																																			

Notes

* Data missing.

n Data missing but data not required for test condition.

d Different data recorded.

TABLE 6.3.2-1-A2 MISSING DATA FOR TEST CONDITION BASELINE WITH AFTERBURNERS

Date	Dec 12, 1991												Dec 13, 1991												Dec 14, 1991												Dec 15, 1991												Dec 16, 1991												Dec 17, 1991												Dec 18, 1991												Dec 19, 1991											
Time	a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.					
Var Name	Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten	
T1/A1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/A2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/A3																																																																																																			
T1/A4																																																																																																		
T1/B1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/B2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/B3																																																										*	*	*	*	*	*																																					
T1/B4																																																										*	*	*	*	*	*																																					
T1/B5	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
T1/C1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/C2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/C3																																																										*	*	*	*	*	*																																					
T1/C4																																																										*	*	*	*	*	*																																					
T1/D1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/D2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/D3																																																										*	*	*	*	*	*																																					
T1/D4																																																										*	*	*	*	*	*																																					
T1/E1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/E2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/E3																																																							*	*	*	*	*	*	*	*																																					
T1/E4																																																							*	*	*	*	*	*	*	*																																					
T1/F1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
T1/F2																																																																																																			
T1/F3	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
T1/F4																																																																																																			
T1/F5																																																																																																				
T1/F6	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/G2																									*	*	*	*																																																																					
T1/G3																									*	*	*	*																																																																					
T1/H1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/I1	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/I5																																																																																																			
T1/I6																																																																																																				
T1/J3,J4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
T1/J5,J6																																																																																																		
T1/J7,J8																																																																																																			
T1/J9,J10	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
T1/J11,J12																																																																																																	
T1/J13,J14	*	*	*	*																																																																																													
T1/K2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/K3	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/L1																																																																																																			
T1/L2																																																																																																			
T1/L3																																																																																																			
T1/L4																																																																																																			
T1/L5																																																																																																			
T1/L6																																																																																																			

Notes

* Data missing
n Data missing but data not required for test condition
d Different data recorded

TABLE 6.3.2-1-C2 MISSING DATA FOR TEST CONDITION THERMAL SLUDGE WITH AFTERBURNERS

Date	Dec 20, 1991												Dec 28, 1991												Dec 29, 1991												Jan 4, 1992												Jan 5, 1992												Jan 6, 1992												Jan 7, 1992												Jan 8, 1992											
Time	a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.					
Var Name	Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten	
T1/A1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/A2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/A3																																																																																								•	•	•	•	•	•	•	•
T1/A4																																																																																									•	•	•	•	•	•	•	•
T1/B1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•																	•	•	•	•																																																										•	•	•	•	•	•
T1/B2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•																	•	•	•	•																																																										•	•	•	•	•	•
T1/B3	•	•	•	•	•	•	•	•	•	•	•	•																																																																																					
T1/B4	•	•	•	•	•	•	•	•	•	•	•	•																																																																																						
T1/B5	•	•	•	•	•	•	•	•	•	•	•	•																					•	•	•	•																																																										•	•				
T1/C1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•																	•	•	•	•																																																										•	•	•	•	•	•
T1/C2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•																	•	•	•	•																																																										•	•	•	•	•	•
T1/C3	•	•	•	•	•	•	•	•	•	•	•	•																																																																																					
T1/C4	•	•	•	•	•	•	•	•	•	•	•	•																																																																																					
T1/D1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•																	•	•	•	•																																																										•	•	•	•	•	•
T1/D2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•																	•	•	•	•																																																										•	•	•	•	•	•
T1/D3	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/D4	•	•	•	•	•	•	•	•	•	•	•	•																					•	•	•	•																																																										•	•	•	•	•	•
T1/E1	•	•	•	•	•	•	•	•	•	•	•	•									•	•	•	•																																													•	•																							•	•	•	•	•	•
T1/E2	•	•	•	•	•	•	•	•	•	•	•	•									•	•	•	•																																													•	•																							•	•	•	•	•	•
T1/E3	•	•	•	•	•	•	•	•	•	•	•	•																																																									•	•																														
T1/E4	•	•	•	•	•	•	•	•	•	•	•	•																																																																																							
T1/F1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/F2																																																																																										•	•	•	•	•	•	•
T1/F3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/F4																																																																																										•	•	•	•	•	•	•
T1/F5																																																																																										•	•	•	•	•	•	•
T1/F6	•	•	•	•	•	•	•	•	•	•	•	•																					•	•	•	•																																																											•	•	•	•	•	•	•
T1/G2																																																																																										•	•	•	•	•	•	•
T1/G3																																																																																										•	•	•	•	•	•	•
T1/H1	•	•	•	•	•	•	•	•	•	•	•	•																					•	•	•	•																																						•	•	•										•	•	•	•	•	•	•	•	•	•	•
T1/I1	•	•	•	•	•	•	•	•	•	•	•	•										•	•	•																																																																		•	•	•	•	•	•	•
T1/I5																																																																																										•	•	•	•	•	•	•
T1/I6																																																																																										•	•	•	•	•	•	•
T1/J3,J4	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/J5,J6																																																																																										•	•	•	•	•	•	•
T1/J7,J8																																																																																										•	•	•	•	•	•	•
T1/J9,J10	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/J11,J12																																																																																										•	•	•	•	•	•	•
T1/J13,J14																																																																																										•	•	•	•	•	•	•
T1/K2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/K3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T11.1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T11.2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T11.3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T11.4	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T11.5	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T11.6	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

Notes:
- • Data missing.
- n Data missing but data not required for test condition
- d Different data recorded.

TABLE 6.3.2-1-C1 MISSING DATA FOR TEST CONDITION THERMAL SLUDGE WITHOUT AFTERBURNERS

Date	Jan 22, 1992												Jan 23, 1992												Jan 24, 1992												Jan 25, 1992												Jan 26, 1992												Jan 27, 1992												Jan 28, 1992												Jan 29, 1992											
Time	a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.					
Var Name	Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten	
T1/A1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/A2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/A3	•	•	•	•															•	•					•	•	•	•	•	•	•	•																																																															•	•
T1/A4	•	•	•	•															•	•					•	•	•	•	•	•	•	•																																																															•	•
T1/B1	•	•	•	•	•	•													•	•	•	•	•	•	•	•	•	•	•	•																																																													•	•	•	•	•	•
T1/B2	•	•	•	•	•	•													•	•	•	•	•	•	•	•	•	•	•	•																																																													•	•	•	•	•	•
T1/B3	•	•	•	•	•	•																			•	•	•	•	•	•																																																																		
T1/B4	•	•	•	•	•	•																			•	•	•	•	•	•																																																																		
T1/B5	•	•	•	•	•	•													•	•	•	•	•	•	•	•	•	•	•	•							•	•	•	•																																																			•	•	•	•	•	•
T1/C1	•	•	•	•	•	•													•	•	•	•	•	•	•	•	•	•	•	•																																																													•	•	•	•	•	•
T1/C2	•	•	•	•	•	•													•	•	•	•	•	•	•	•	•	•	•	•																																																													•	•	•	•	•	•
T1/C3	•	•	•	•	•	•																			•	•	•	•	•	•																																											•	•	•	•	•	•	•	•	•	•	•	•												
T1/C4	•	•	•	•	•	•																			•	•	•	•	•	•																																											•	•	•	•	•	•	•	•	•	•	•	•												
T1/D1	•	•	•	•	•	•													•	•	•	•	•	•	•	•	•	•	•	•																																																													•	•	•	•	•	•
T1/D2	•	•	•	•	•	•													•	•	•	•	•	•	•	•	•	•	•	•																																																													•	•	•	•	•	•
T1/D3	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/D4																																																																																																
T1/E1	•	•	•	•	•	•													•	•	•	•	•	•	•	•	•	•	•	•	•	•																																	•	•	•	•																							•	•	•	•	•	•
T1/E2	•	•	•	•	•	•													•	•	•	•	•	•	•	•	•	•	•	•	•	•																																	•	•	•	•																							•	•	•	•	•	•
T1/E3	•	•	•	•	•	•																							•	•	•	•																																	•	•	•	•																												
T1/E4	•	•	•	•	•	•																							•	•	•	•																																	•	•	•	•																												
T1/F1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/F2																																																																																																
T1/F3																																																																																																
T1/F4	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/F5	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/F6	•	•	•	•	•	•															•	•	•	•	•	•	•	•																																																																				
T1/G2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/G3	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/H1	•	•	•	•	•	•															•	•	•	•	•	•	•	•	•	•																																																																		
T1/I1	•	•	•	•	•	•															•	•	•	•	•	•	•	•	•	•																																																														•	•	•	•	•
T1/I5																									•	•	•	•	•	•																																																																		
T1/I6																									•	•	•	•	•	•																																																																		
T1/J3,J4	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/J5,J6	•	•	•	•																					•	•	•	•	•	•																																																																		
T1/J7,J8	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/J9,J10	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/J11,J12	•	•	•	•																					•	•	•	•	•	•	•																																																																	
T1/J13,J14	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/K2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/K3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T11.1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T11.2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T11.3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T11.4	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T11.5	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T11.6	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

Notes.
- • Data missing.
- n Data missing but data not required for test condition
- d Different data recorded.

TABLE 6.3.2-1-B1 MISSING DATA FOR TEST CONDITION MIXED SLUDGE WITHOUT AFTERBURNERS

Date	Feb 5, 1992												Feb 6, 1992												Feb 7, 1992												Feb 8, 1992												Feb 9, 1992												Feb 10, 1992												Feb 11, 1992												Feb 12, 1992											
Time	a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.					
Var Name	Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten	
T1/A1	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	•	•	•	•	•	•	•	•	•	•	•	•
T1/A2	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	•	•	•	•	•	•	•	•	•	•	•	•
T1/A3							•	•																																													•	•	•	•																																	•	•	•	•	•	•	•	•	•	•	•	•
T1/A4							•	•																																													•	•	•	•																																	•	•	•	•	•	•	•	•	•	•	•	•
T1/B1																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/B2																																																																																								•	•	•	•	•	•	•	•	•	•	•	•
T1/B3	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	•	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	•	•	•	•	•	•	•	•	•	•	•	•
T1/B4																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/B5																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/C1																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/C2																																																																																										•	•	•	•	•	•	•	•	•	•	•	•
T1/C3	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	•	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	•	•	•	•	•	•	•	•	•	•	•	•
T1/C4																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/D1																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/D2																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/D3	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	•	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	•	•	•	•	•	•	•	•	•	•	•	•
T1/D4																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/E1					•	•	•	•									•	•	•	•																																																																					•	•	•	•	•	•	•	•	•	•	•	•
T1/E2					•	•	•	•									•	•	•	•																																																																					•	•	•	•	•	•	•	•	•	•	•	•
T1/E3					•	•	•	•									•	•	•	•																																																																				•	•	•	•	•	•	•	•	•	•	•	•
T1/E4					•	•	•	•									•	•	•	•																																																																				•	•	•	•	•	•	•	•	•	•	•	•
T1/F1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/F2																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/F3																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/F4	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/F5	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/F6																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/G2	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/G3	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/H1																			•																																																																				•	•	•	•	•	•	•	•	•	•	•	•
T1/I1																																																																																								•	•	•	•	•	•	•	•	•	•	•	•
T1/I5																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/I6																																																																																									•	•	•	•	•	•	•	•	•	•	•	•
T1/J3,J4	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/J5,J6								•																																																																																•	•	•	•	•	•	•	•	•	•	•	•
T1/J7,J8	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/J9,J10	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/J11,J12								•																																																																																•	•	•	•	•	•	•	•	•	•	•	•
T1/J13,J14	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
T1/K2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/K3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/L1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/L2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/L3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/L4	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/L5	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1/L6	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

Notes:

- • Data missing
- n Data missing but data not required for test condition.
- d Different data recorded.
- s Data from sludge dryer log sheet only.

TABLE 6.3.2-1-B2 MISSING DATA FOR TEST CONDITION MIXED SLUDGE WITH AFTERBURNERS

Date	Mar 4, 1992												Mar 5, 1992												Mar 6, 1992												Mar 7, 1992												Mar 8, 1992												Mar 9, 1992												Mar 10, 1992												Mar 11, 1992											
Time	a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.						a.m.						p.m.					
Var Name	Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten		Two		Six		Ten	
T1/A1	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	•	•	•	•
T1/A2	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	•	•	•	•
T1/A3																																																																																																•	•	•	•
T1/A4																																																																																																	•	•	•	•
T1/B1																																																																																																				
T1/B2																																																																																																					
T1 B3	d	d	d	d	d	d	d	d	d	d	d	d	•	•	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
T1 B4																																																										•	•	•	•	•	•																																									
T1/B5																																																																																																					
T1/C1																																																																																																					
T1/C2																																																																																																				
T1/C3	d	d	d	d	d	d	d	d	d	d	d	d	•	•	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
T1/C4																																																																																																					
T1/D1																																																																																																					
T1/D2																																																																																																					
T1/D3	d	d	d	d	d	d	d	d	d	d	d	d	•	•	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
T1/D4																													•	•	•	•									•	•	•	•																																																				
T1/E1																													•	•	•	•									•	•	•	•																																																				
T1/E2																																																																																																					
T1/E3	d	d	d	d	d	d	d	d	d	d	d	d	•	•	d	d	d	d	d	d	d	d	d	d	d	d	d	d	•	•	•	•	d	d	d	d	d	d	d	d	•	•	•	•	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
T1/E4																													•	•	•	•									•	•	•	•																																																				
T1/F1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
T1 F2																																																																																										•	•	•	•	•	•
T1/F3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
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Notes

- • Data missing
- n Data missing but data not required for test condition
- d Different data recorded.
- s Data from sludge dryer log sheet only.

Data missing from tabulated summaries referenced in Section 6.

TABLE 6-2

MISSING DATA SUMMARY & COMMENTS

VARIABLE	DESCRIPTION	COMMENT
T1B5	Total Solids Feed to Belt Press #1	Variable not recorded, did not affect analysis
T1E1	Sludge Temperatures Dryer Feed	Variable not recorded.
T1E2	Sludge Temperatures Dryer Outlet	Variable not recorded.
T1E3	Sludge Temperatures Incinerator #1 Feed	Variable recorded, see Appendices
T1E4	Sludge Temperatures Incinerator #2 Feed	Variable recorded, ass Appendices
T1F1	Steam Pressure Aux. Boiler #1	Recorded where in service, see Appendices
T1F2	Steam Pressure Aux. Boiler #2	Recorded where in service, see Appendices
T1F3	Steam Pressure Aux. Boiler #3	Recorded where in services, see Appendices
T1J3	Fuel Gas Inc. #1 (NG)	Recorded where in service, see Appendices
T1J4	Fuel Gas Inc. #1 (Methane)	Recorded where in service, see Appendices
T1J6	Fuel Gas Inc. #1 (Methane)	Recorded where in service, see Appendices
T1J8	Fuel Gas AB #1 (Methane)	Recorded where in service, see Appendices
T1J9	Fuel Gas Inc. #2 (NC)	Recorded where in service, see Appendices
T1J10	Fuel Gas Inc. #2 (Methane)	Recorded where in service, see Appendices
T1J12	Fuel Gas Inc. #2 (Methane)	Recorded where in service, see Appendices
T1J14	Fuel Gas AB #2 (Methane)	Recorded where in service, see Appendices

TABLE 6-2 (continued)

VARIABLE	DESCRIPTION	COMMENT
T1K2	Condensate Flow Venturi Inlet	Not recorded, malfunctioning meter
T1K3	Condensate Flow Venturi Outlet	Not recorded, malfunctioning meter
T1L1	Sludge Flow BP #1 Feed	Recorded where in service, see Appendices
T1L2	Sludge Flow BP#2 Feed	Recorded where in service, see Appendices
T1L3	Sludge Flow BP#3 Feed	Recorded where in service, see Appendices
T1L4	Sludge Flow BP #4 Feed	Recorded where in service, see Appendices
T1L5	Sludge Flow BP #7 Feed	Recorded where in service, see Appendices
T1L6	Sludge Flow BP #8 Feed	Recorded where in service, see Appendices
T2D	Flue Gas Moisture	Not sampled every 15 minutes, calculated by mass and heat balances, see Appendices
T2A1,A2	O_2 Inc. Inlet, Outlet	For 12/17-19, see Appendices
T2E	Temperatures	For 12/17-19, see Appendices

A separate computer data file containing the raw data was created for each phase of the monitoring program. The data are listed in Appendix E, Tables 2.1-A1, -A2, -B1, -B2, -C1, and -C2, representing the six operating conditions.

Data from the DAS were converted to a format compatible with the computer spreadsheet program used to manipulate the project data, and the DAS data was imported for data reduction. Incinerator flue gas quality data were recorded at one minute intervals, and incinerator temperatures, together with various combustion air flow rates, were recorded at five minutes intervals. Data for the mechanically dewatered sludge conditions were divided into daily files in a spreadsheet-compatible format. The files could not be imported into the spreadsheet program because of their large sizes. Instead, the data were transferred to the spreadsheets using half-hour readings. One-minute and five-minute data were compared to half-hour data to determine whether there were any significant differences. The differences noted were generally less than 0.5% and were therefore considered insignificant.

The data from the DAS for the thermally dewatered and sludge blend test conditions were reduced to two-hour intervals by calculating the average of each two-hour interval. The results are presented in Appendix E, Tables 2.2-B1, -B2, -C1 and -C2. The two-hour values of oxygen and carbon monoxide concentrations, and incinerator and afterburner flue gas temperatures are provided in Appendix E in Tables 2.1-A1, -A2, -B1, -B2 and -C2.

Initial Data Correlation

Regression analyses and calculations to determine the coefficient of determination (r^2) were performed on the mechanically dewatered sludge data from Incinerators No. 1 and No. 2 for the following parameters:

- Sludge Dry Feed Rate
- M/V Ratio
- Auxiliary Fuel Consumption
- Electricity Utilization

These results are summarized in Appendix E, Table 2.3.

Regression analyses and calculations of the coefficient of determination were performed for the thermally dewatered and sludge blend conditions using all data points. Independent variables dry sludge feed rate and M/V ratio were correlated with dependent variables. Dependent variables included: WHRB steam production, incinerator auxiliary fuel consumption, afterburner fuel consumption, steam pressure, steam utilization, and electricity utilization. Volatile solids content was one of the dependent variables, and volatile solids content is included in the M/V ratio. As the M/V ratio is a measure of the variation in combustible (fuel) content of the sludge, it was used as an independent variable in the analysis.

Results of the calculations of coefficient of determination are summarized in Appendix E, Table 2.3. Auto-correlation was tested using Durbin-Watson statistics.

Data Grouping

Data were grouped by sludge dry feed rate within "steady state" portions of each test condition. All data points within ±10% of the average for each data set were placed in groups for further analysis. The average value for each variable was calculated for each group. The results of data groups are summarized in Appendix E, Table 2.4. The grouped data are presented in Appendix E, Tables 2.4-A1, -A2, -B1, -B2, -C1, and -C2.

T-Test Procedures

Dependent variables were compared between Incinerator No. 1 and Incinerator No. 2 for test conditions A1, A2, B1, B2, C1, and C2. Under test conditions A1 and A2, where only mechanically dewatered sludge was incinerated, the inherent differences in dependent variables between the two incinerators were quantified. T-test procedures were then performed for test conditions B1, B2, C1, and C2, with dependent variables corrected for inherent differences. T-test results and the mean differences in dependent variables, with and without the sludge dryer in operation, are presented in Appendix E, Tables 2.5-A1, -A2, -B2, -C1, and -C2.

Incinerator Mass and Heat Balances

Incinerator mass and heat balances (MHBs) were performed for Incinerator No. 1 for each test condition. MHBs using mechanically dewatered sludge test condition data were performed on Incinerator No. 1 to determine the correct input parameters. The *Data Analysis Plan* (BSA/Nussbaumer & Clarke/Gore & Storrie, 1992) called for MHBs to be performed on both incinerators, but since CEMS data was not recorded for Incinerator No. 2, MHBs were not performed for this unit. MHBs were performed for selected data points, as well as for averaged data for each operating condition. Individual data points were selected from the data groupings where there were ten or more similar data points. Results from the MHBs were used to calculate the combustion efficiencies of Incinerator No. 1 for each test condition.

The MHB input data included sludge feed rate and sludge quality from the manually recorded data. Incinerator auxiliary fuel consumption, combustion air flow rates, and WHRB steam production were calculated for comparison with monitored values. A summary of the incinerator MHBs are presented in Appendix E, Tables 2.6-MHB1 and -MHB2.

The sludge "ultimate analysis" (in which the elemental components of the sludge feed to the incinerators was determined by laboratory analysis) results were reported on an as-received basis, except for heating value and chlorine. The values of the elemental constituents (carbon, hydrogen, nitrogen, oxygen and sulfur) reported were obviously incorrect. In particular, the values reported for oxygen were extremely high and inconsistent with typical ultimate analyses for sewage sludge (Technical Practice Committee 1988). Discussions with the independent laboratory which performed the ultimate analysis related that ASTM procedures were followed. However, because of the high moisture content of the sludge samples, the laboratory agreed that the results could have been affected by the capacity of the absorbent used (under capacity). Further tests performed by the laboratory yielded similar results. However, the heating values reported on a dry basis were consistent with typical municipal wastewater sludges.

The heating values, moisture content, and ash content, together with an empirical formula derived by DuLong (Baumeister 1978), were used to determine the values of the elemental constituents for each sludge sample. The elemental constituent values utilized were consistent with those typical of municipal wastewater sludge. The results of the sludge ultimate analyses are presented in Appendix E, Table 2.6-UTI.

Combustion Efficiencies

The method of calculating the incinerator efficiency is described earlier in this section. The method selected calculates the effectiveness of converting carbon in the sludge and gaseous fuels to carbon dioxide. As this is not a direct method of measuring combustion efficiency, it will be referred to as carbon conversion efficiency. Carbon conversion efficiencies were calculated using the following equation (USEPA, no date):

$$\text{Carbon Conversion Efficiency} = \frac{C_{co2}}{C_{co2} + C_{co}} \times 100\%$$

Where:

C_{co} = measured concentration of carbon monoxide in exhaust (ppm)
C_{co2} = calculated concentration of carbon dioxide in exhaust %

Carbon dioxide values were derived from the Incinerator No. 1 MHBs. Values were not corrected to 7% O_2, because both CO and CO_2 were at the same oxygen basis for each calculation.

A summary of the results is presented in Appendix E, Table 2.7-1.

Dryer Performance

A MHB was performed using the dryer design conditions. The results are presented in Appendix E, Table 2.8-Design. The results indicate the distribution of heat used by the dryer.

MHBs were calculated for the dryer to determine the performance. Individual and grouped data derived from the manually recorded data were used as the basis for the dryer's MHBs. Inlet and outlet sludge feed characteristics, and water vapor conditions were used to calculate steam consumption and specific steam consumption (SSC). SSC is a measure of the quantity of steam required to evaporate one pound of water from sludge and is a measure of the dryer's thermal efficiency. The specific evaporation rate (SER) was also calculated. SER is a measure of the evaporation rate per unit area of dryer heating surface. A summary of the dryer MHBs is presented in Appendix E, Table 2.8-MI, -T1.

Additional dryer-related data points reported in the manually recorded data are summarized in Appendix E, Table 2.9. The data was sorted by M/V ratios in descending value. The last column of Table 2.9 shows the calculated values of SSC for each data point.

RESULTS OF DATA ANALYSIS

Initial Data Correlation

The regression analysis results for baseline test conditions indicated coefficients of determination varying from a low of 0.0005 up to 0.78. The mechanically dewatered sludge condition without afterburners indicated reasonable correlation between sludge dry feed rates for Incinerators No. 1 and No. 2 at a coefficient of 0.78 and M/V ratio at a coefficient of 0.65. The other variables showed no correlation. The mechanically dewatered sludge condition with afterburners "on" showed poor correlation between sludge dry feed rates at a coefficient of 0.49, but better correlation for M/V ratios at a coefficient of 0.61. The other variables showed no correlation.

The purpose of the regression analysis for the mechanically dewatered sludge test conditions was to determine whether the operations of the two incinerators were similar. Based on regression analyses, it would appear that their operations were not similar. However, it must be remembered that fuel requirements for each incinerator depend on the total heat input, which is a function of operating temperature, water evaporated, and excess air to be heated. Auxiliary fuel is required to supplement the heat input from the sludge fuel. These operating parameters vary to thermally balance the incinerator. For this study, if the sludge fuel value and feed rate are similar for the two incinerators, their operation will be similar, even though the other parameters, such as auxiliary fuel and operating temperatures, fluctuate. This also holds true for other operating scenarios, such as when a sludge blend is fed to one incinerator.

In summary, the regression analysis for the mechanically dewatered sludge condition without afterburners indicated that, based on sludge feed rates, the two incinerators can be compared for other test conditions. The regression analysis for the mechanically dewatered sludge condition with afterburners "on" does not show a good correlation for sludge feed rate.

Results of regression analyses for the thermal and sludge blend test conditions did not show any significant correlation between the independent variables and any of the dependent variables. In fact, the highest coefficient of determination calculated using all data points was 0.4520 (test condition B2, sludge feed rate versus steam production). All other coefficients of determination calculated were less than 0.2.

All graphs generated showed data points scattered over a wide range. This pattern of scattered data reflects the low values calculated for the coefficients of determination. The reason for this scatter of data is due to the continuous variations in incinerator parameters, including sludge feed rate, sludge quality, combustion air flow rates, and incinerator temperatures.

The presence of auto-correlation tested negative using Durbin-Watson statistics. This indicates that the results of linear regression and calculations of coefficient of determination are valid. The reason for the poor correlation is the wide range of data values recorded. This most likely is a result of the sludge being heterogeneous, with variations in physical and chemical characteristics over time.

Data Grouping

The number of data groupings based on ± 10% of the average sludge feed rate (in DT/D) to the incinerator varied between 5 and 9 for the six test conditions. Average sludge feed rates were as low as 613 dry lbs/hr of sludge for condition A2 and 769 dry lbs/hr for condition C2, to as high as 4,011 dry lbs/hr for condition C1.

Appendix E, Table 3.4, shows the number of data points for each data group. The number of data points ranges from 2 to 48. It is noted that increased number of data points translates to increased confidence in the accuracy of the results.

Data groupings with ten or more data points have been used in the analyses. In the majority of cases of data groupings with more than ten data points, the incinerator feed rate was above 1,000 lbs/hr dry solids. The average design dry feed rate for each incinerator is 2,000 lbs/hr to 2,500 lbs/hr.

Thirty-one percent of the data points for Incinerator No. 1 have dry feed rates above 2,000 lbs/hr. Only 9.5% of the data have ten or more data points in a group where the dry feed rate is above 2,000 lbs/hr. Fifty-five percent of the data points for Incinerator No. 2 have dry feed rates above 2,000 lbs/hr, and 55% of the data points have ten or more data points in these groups. Based on the above, Incinerator No. 1 was operated near the design feed rate about one-third of the time, while Incinerator No. 2 operated at that rate about half of the time.

For the sludge blend and the thermally dewatered sludge test conditions, Incinerator No. 1, had only 3% of data points above 2,000 lbs/hr in groups with ten or more data points, compared to Incinerator No. 2 which had 45% of the grouped data points above 2,000 lb/hr. Therefore, Incinerator No. 1 was under-loaded during most of the test conditions with the dryer in operation. It is noted that an incinerator's highest efficiency is achieved when the unit is loaded at or near it's design capacity.

T-Test Procedure

T-test results show that differences in field-recorded data for the following dependent variables are attributed to the sludge dryer in test conditions B1, C1, and C2:

- WHRB steam production,
- Incinerator electricity utilization,
- Incinerator fuel gas utilization, and
- Afterburner fuel gas utilization.

For test condition B2, differences in the dependent variables of incinerator electricity utilization and afterburner fuel gas utilization were attributed to the sludge dryer. However, T-test results did not confirm that the differences in WHRB steam production and incinerator fuel gas utilization were the direct result of the sludge dryer.

As indicated at the beginning of this report section, the operation of Incinerator No. 1 under the thermally dewatered and sludge blend conditions (B1, B2, C1, and C2) was to be compared to the operation of Incinerator No. 1 during the mechanically dewatered sludge conditions (A1 and A2). After reviewing the raw data, it was apparent that the sludge feed rate for the mechanically dewatered conditions did not correspond to the sludge feed rates for test conditions B1, B2, C1, and C2. Sludge feed rates for the mechanically dewatered test conditions range from 1,610 dry lbs/hr to 3,200 dry lbs/hr, while the sludge feed rates for other test conditions range from 800 dry lb/hr to 2,500 dry lbs/hr. Thus, the majority of the dependent variables cannot be paired (based on dry sludge feed rate) for T-testing.

However, because the operating parameters of Incinerators No. 1 and No. 2 were approximately the same during baseline conditions, it was concluded that it was reasonable to compare the two incinerators under other test conditions on a mass-specific, or per-dry-ton-of-sludge-feed, basis.

Mass and Heat Balances

The results of the MHB calculations performed on Incinerator No. 1 indicate that auxiliary fuel consumption decreased from the mechanically dewatered sludge conditions through the sludge blend and thermally dewatered sludge conditions both with and without afterburners. This agrees with the trend of auxiliary fuel consumption as recorded by the plant operators.

A comparison of auxiliary fuel consumption and total combustion air consumption calculated by the MHBs with the field-measured values for individual and average rates indicates good agreement. However, a similar comparison of flue gas oxygen concentrations between the MHB results and the CEMS data shows no agreement. The oxygen concentration reported by the CEMS was generally 16%-23%, while oxygen concentration ranges of 8%-14% was expected. The high readings were probably due to incorrect instrument measurements, even though the oxygen analyzers were automatically calibrated daily.

Combustion Efficiencies

The carbon conversion efficiency calculations indicate that, without afterburners, the carbon conversion efficiency varies between 97% and 99%. The carbon conversion efficiency is from 99.3% to 99.98% when afterburners are in operation.

There is no noticeable effect on carbon conversion efficiency attributable to the sludge dryer. Combustion efficiency is mainly affected by combustion gas temperature. There is a noticeable increase in combustion efficiency and decrease in carbon monoxide concentration when the exhaust gas temperatures are above 1150°F. Below these temperatures, the combustion efficiency and carbon monoxide concentrations are erratic. However, some high readings of carbon monoxide will occur above 1150°F, indicating that there is still some incomplete combustion at these temperatures. The test data for the blended sludge without afterburners test condition indicates low carbon monoxide levels at relatively low temperatures. This is not typical, and may have been a result of inaccuracies in the CEMS readings.

On February 19, 1993, the USEPA published new rules for the operation of sludge incinerators as part of "Standards for the Disposal of Sewage Sludge," 40 CFR Part 503 (USEPA 1993). One of the requirements of this regulation is that an incinerator's stack emissions (downstream from the APC system) not exceed 100 parts per million (ppm) of total hydrocarbons, corrected to 7% equivalent oxygen. Given the results of this project, it is likely that the BIWWTP will have to continuously operate its afterburners to attain this emissions criterion.

Dryer Performance

The sludge dryer was designed to evaporate 4,285 lbs/hr of water under normal operating conditions, with a maximum of 5,500 lbs/hr of water evaporated with a sludge feed consisting of 20% dry solids. The resulting cake under these conditions would contain 35% dry solids. Standard steam consumption was guaranteed by the manufacturer at 1.25-1.30 lbs steam/lb water evaporated; maximum design steam consumption is 1.30-1.32 lbs steam/lb water evaporated.

Approximately 90% of the heat energy provided to the dryer is used to evaporate the water in the sludge. About 9% of the heat remains in the sludge discharged from the dryer and fed to the incinerator. Another 0.5% of the heat applied to the dryer is contained in the non-condensible gases in the dryer vapor; these are recycled to the incinerator. The remainder of the heat (0.5%) supplied to the dryer is lost through the exterior of the dryer's stator as shell losses. From the 9.5% of the heat supply which is transferred out of the dryer in the sludge and the non-condensible gases, it was assumed that 0.5% of the heat supply is lost from the sludge on the conveyor belt and the non-condensible gases in the ductwork between the dryer's non-condensible gas blower and the incinerator. Thus, about 9% of the dryer's heat supply is transferred to the incineration process but, in order to be conservative, this heat was not accounted for in the incineration MHBs.

The results of the MHBs for the sludge dryer are summarized in Appendix E, Table 2.8-M1 for the blended sludge conditions, and in Table 2.8-T1, for the thermally dewatered sludge conditions. Field data for the drying system are summarized in Appendix E, Table 2.9.

During the tests, the dry solids concentration of the sludge feed to the dryer ranged from 13% to 18%. However, calculations indicate that the dryer was able to evaporate water at or above its design evaporation rate of 4,500-5,500 lbs/hr. For the most part, the steam consumption rate was below the design maximum rating of 1.30-1.32 lbs of steam/lb of water evaporated.

During the thermal sludge condition with afterburners on (C2), the steam consumption rate was calculated as high as 1.71. During these periods of high steam consumption, the sludge solids concentrations at the dryer discharge were extremely low (22%), as was the evaporation rate. It is likely that either the dryer condenser was not operating properly or the steam trap on the dryer was malfunctioning.

Comparing the results of calculations versus field data indicates a discrepancy between the steam consumption calculated based on the MBHs and the manually recorded data. In all cases except one, the field data for the steam consumption was higher that predicted by the MHBs; in some cases the field data was up to 171% higher than the MHB-predicted values. These differences were attributed to a malfunction in the dryer's steam flow meter.

ENERGY ANALYSIS

Overview

One of the primary objectives of the project was to determine whether a sludge dryer processing approximately 40% of the BIWWTP's solids could reduce sludge management costs. Solids handling costs affected by this project include natural gas and electricity costs associated with incineration.

Possible cost savings could be realized by reducing the quantity of natural gas required to incinerate the sludge due to a drier sludge feed. Of course, some of the savings would be offset by the natural gas required to generate steam if the WHRBs are not used and the plant's auxiliary boilers are required to provide steam for the dryer.

The purpose of this section is to review the energy balance of the sludge incineration system to determine whether energy savings were demonstrated during the thermal and sludge blend test conditions.

Energy Evaluation

The fuel used by the incinerator and afterburner, electricity consumption by the incinerator and dryer, and dryer steam consumption were totaled for each data point for Incinerators No. 1 and No. 2 over the six test conditions. When the afterburner was in operation, steam produced by the WHRB was subtracted from the steam requirements for drying to calculate the total energy used by the system. When the afterburner was not in operation, the energy required for drying was increased, assuming that the steam was produced by an auxiliary boiler operating at 80% efficiency. If steam production by the WHRB was less than the dryer's steam consumption, the difference was estimated, assuming use of an auxiliary boiler.

The data was converted to kilowatts/dry ton (kW/DT) prior to calculating energy use. The energy used by each incinerator, the excess energy for each incinerator, and the dryer's energy use were calculated.

The field data results are presented in Appendix E, Tables 4.2-A1, -A2, -B1, -C1, and -C2.

The results indicate a trend toward lower auxiliary fuel utilization by the incinerators as the M/V ratio decreased (i.e., which represents either increasing sludge fuel value and/or decreasing sludge moisture content) for operation both with and without afterburners. When the dryer was in operation, the total energy use increased significantly if the afterburners were not operated. This is a consequence of having to produce steam in the auxiliary boilers. The results are also affected by the apparent high steam consumption of the dryer. This was discussed earlier in this section. The results are also affected by the rate at which solids were incinerated. During the mechanically dewatered sludge conditions, the typical sludge feed rate was 2,000-2,800 lbs/hr dry solids.

During the blend and thermal sludge conditions, the sludge feed rate was typically 1,100-2,000 lbs/hr dry solids.

The results for Incinerator No. 1 from Appendix E, Table 4.2-C1, Thermally Dewatered Sludge Without Afterburner, and Table 4.2-C2, Thermally Dewatered Sludge With Afterburner, indicate a high total energy use that was similar to that of Incinerator No. 2. This is due to the relatively low incinerator sludge loading rate, the high dryer steam utilization, and the low steam production rate exhibited during the "afterburners on" conditions.

Multiple hearth incinerators are typically operated within a heat input range or "envelope". When the sludge feed rate is decreased, auxiliary fuel input is increased to maintain the heat input. This eliminates having to make adjustments for combustion air inputs and allows the incinerator to operate at a relatively large sludge feed turndown rate. It is expected, therefore, that a higher incinerator sludge loading rate would reduce the total energy use of the system.

The results of the MHBs for the incinerator and dryer (when in operation) for the individual and average data points were converted to kW/DT. The fuel consumption, steam consumption, and electrical consumption for the system were totaled, and steam production subtracted to calculate incinerator and dryer energy use, total energy use, and excess energy. The excess energy is the energy in the steam generated by the WHRB after all sludge drying needs are satisfied. With the afterburners operating, there may be a net energy savings if all of the steam produced by the WHRBs is used within the plant.

The results of these calculations are presented in Appendix E, Tables 4.2-IDP1 and -AVG1. The range of energy use is presented in the following Table 6-3.

TABLE 6-3

RANGES OF ENERGY USAGE

Condition	Energy Use By Incinerator kW/DT	Total Energy Use kW/DT	Excess Energy kW/DT
Mechanical Without Afterburners	2,200-3,250	2,000-3,250	0
Mechanical With Afterburners	4,100-6,300	4,100-7,000	2,650-3,475
Blend Without Afterburners	1,000-1,300	3,850-5,300	0
Blend With Afterburners	4,000-6,250	5,900-8,675	250-1,450
Thermal Without Afterburners	1,300-2,375	4,575-6,000	0
Thermal With Afterburners	3,750-7,750	5,300-8,875	1,100-3,475

As may be seen in Table 6-3, the energy used by the incinerators and the total energy is less for the sludge blend condition than that used in the thermally dewatered sludge condition. This is because the sludge loading rate was higher during the sludge blend conditions than it was during the thermally dewatered sludge conditions. Also, in some cases the sludge solids content was the same for the sludge blend condition as it was for thermally dewatered sludge condition; normally, it would be expected that the thermally dewatered sludge would have a higher solids content than the sludge blend condition. The lower sludge feed rate for the thermal condition and occasional parity in the sludge solids content between the thermal and blend conditions resulted in the fuel requirement of the thermal sludge condition being proportionately higher than would be expected, resulting in a higher energy use than was observed during the sludge blend condition. In practice, with a higher sludge loading rate, the thermal sludge condition will result in lower energy utilization by the incinerator and a lower total energy usage.

It can be seen that the incinerator energy use for conditions without afterburners decreases when the sludge dryer is operating. The total energy use, however, increases. Although the savings in incinerator fuel consumption is significant, (as high as 50%, compared to the mechanically dewatered sludge condition), it does not offset the energy required by the auxiliary boilers to provide steam necessary for thermal dewatering.

The incinerator energy use when afterburners are in operation is similar for all test conditions. The total energy use increases with the use of the dryer. This may be due to lower-than-expected steam production in the WHRBs and high steam consumption by the dryer.

The net energy use is affected by the dry solids feed rate to the incinerator. The MHBs for the mechanically dewatered sludge conditions showed that the feed rates ranged from 1,900-3,250 lbs/hr dry solids. The sludge blend and thermally dewatered sludge condition ranged from 1,000-2,350 lbs/hr. The net energy use is also affected by the evaporation rate of the dryer. A higher evaporation rate per unit of dry solids feed to the incinerator translates to higher steam consumption by the dryer. The results derived from this project do not demonstrate that the sludge dryer provides an overall energy savings to the BIWWTP sludge management system when the afterburners are not operating. When the afterburners are operated, there may be a net energy savings if all of the steam produced by the WHRB is used within the plant.

CONCLUSIONS OF THE COMBUSTION ANALYSIS

General

The analyses and results indicate that, in general, the sludge dryer achieved the performance guaranteed by the manufacturer. The performance of the dryer indicates a potential to be operated at a higher-than-design evaporation rate, provided that the ancillary equipment (such as the screw conveyors and vapor condenser) can handle the additional sludge and vapor load.

Data collected during the testing was consistent with the heterogenous nature of sludge, resulting in wide variations in readings.

The following general conclusions can be drawn from the analyses:

- The variations in data were a result of the fluctuating nature of the mechanical sludge dewatering operation and the heterogenous composition and variable characteristics of the sludge.
- Regression analyses of most of the data showed poor correlation.
- The presence of auto-correlation tested negative, indicating that the results of the linear regression and calculations of coefficient of determination are valid.
- T-test results showed that the sludge dryer operation had an effect on parameters such as WHRB steam production and incinerator auxiliary fuel utilization.
- All calculations and analyses were performed using data recorded during the monitoring program. Therefore, results reflect the actual operations and not theoretical scenarios. The wide variations in results are an indication of the constantly changing nature of solids handling and incineration operations, due to the variability of the physical and chemical characteristics of sludge.
- The monitoring program was successful in demonstrating how the sludge dryer would operate within the existing mechanical dewatering and incineration operations.

Incineration

The following conclusions concerning incineration at the BIWWTP were drawn from the analyses:

- Auxiliary fuel consumption decreased as sludge feed solids concentrations increased; feed sludge total solids concentration increases were due to the action of the sludge dryer. Auxiliary fuel consumption decreases of up to 50% were recorded with thermal dewatering.

- Incinerator No. 1 operated at about half of its design load during the thermal and blend sludge conditions, resulting in higher-than-expected energy usage per unit of dry feed solids, compared to mechanically dewatered sludge conditions, which used higher sludge loadings.

- Carbon monoxide concentrations in the exhaust gases decreased with increased incinerator flue gas temperatures. There were still carbon monoxide excursions at the higher temperatures, indicating some incomplete combustion.

- Carbon conversion efficiency increased with increased incinerator flue gas temperatures.

- Sludge drying has no effect on combustion efficiency.

Sludge Dryer

The following conclusions concerning the sludge dryer were drawn from the analyses:

- The sludge dryer operated at or above the performance guaranteed by the manufacturer.

- The sludge dryer appears capable of operating at higher-than-design evaporation rates. However, ancillary equipment (such as screw conveyors and the vapor condenser) would require modification to handle the increased sludge and vapor load.

- Measured steam consumption was higher than calculated. The steam flow meters may have been malfunctioning during the monitoring tests.

Energy Analysis

The following conclusions concerning the energy balance of the project were drawn from the analyses:

- The energy analysis performed indicated that, generally, operation of the sludge dryer decreased incinerator auxiliary fuel consumption by up to 50%.

- Sludge drying and incineration together use more total energy than incineration without thermal dewatering, assuming that afterburners (and, hence, the WHRBs) are not operated.

- The results from the tested conditions indicate that sludge drying with afterburners (and steam generation by the WHRBs) uses about the same total energy as sludge drying without afterburners, but has the potential to provide significant energy savings if the incinerators are operated near their design capacity (which would result in less specific energy losses due to lower excess air and other losses such as radiation, etc.).

- Future operation of the incinerator will likely require afterburning due to the recently promulgated USEPA 503 regulations.

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SECTION 7

WASTE HEAT RECOVERY FEASIBILITY

INTRODUCTION

General

This section of the report details the waste heat recovery options investigated. Throughout the thermal dewatering and incineration processes, there are several opportunities for the recovery of waste heat. In this section, the waste heat sources are described and the available, recoverable energy is quantified; similarly, potential uses for recovered waste heat and the energy requirements associated with each are outlined. Full calculations and assumptions are included in Appendix G.

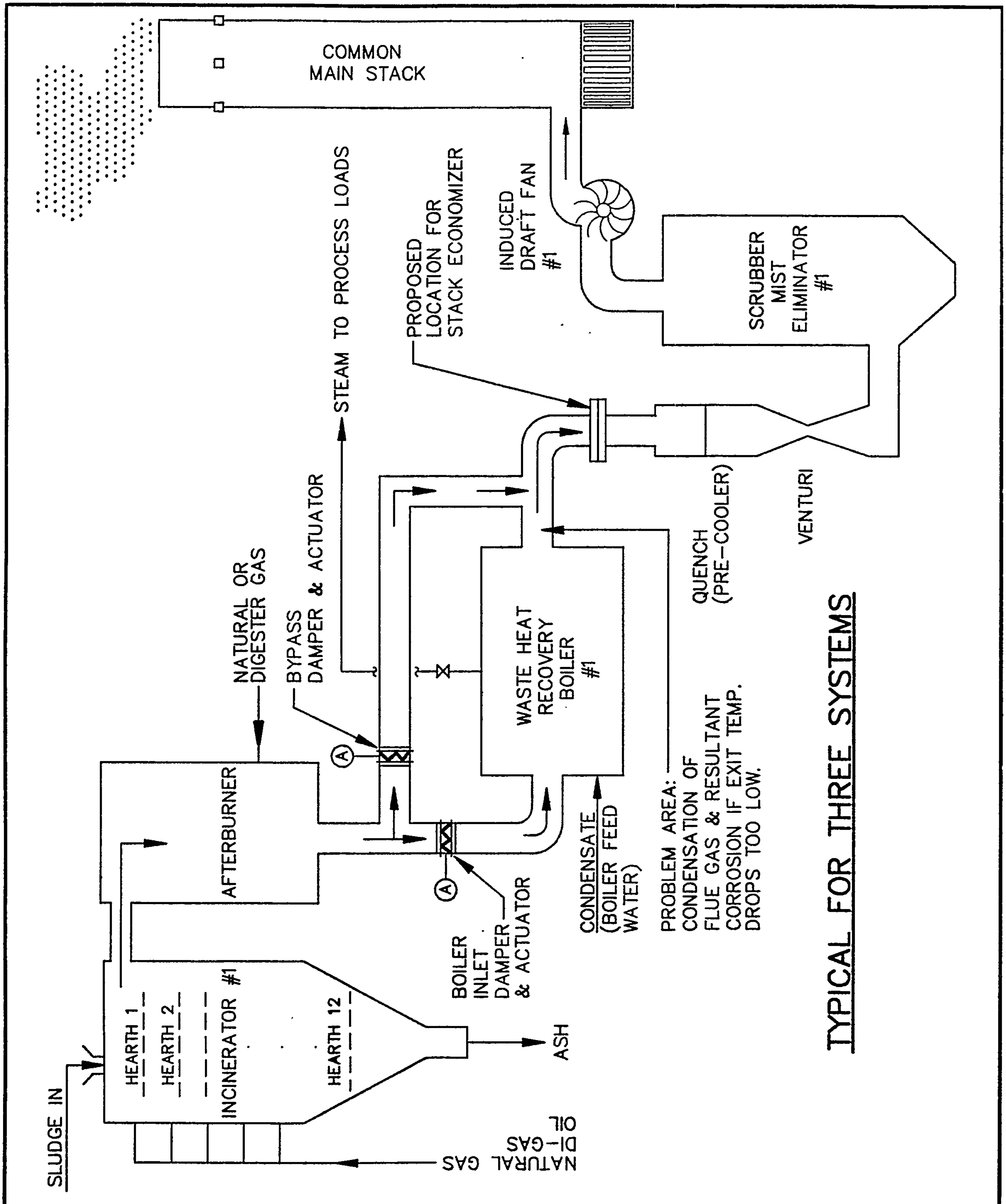
Upon completion of the monitoring and data gathering phase of the project, the sludge dryer commenced normal operations as part of the BIWWTP solids handling train. As such, its typical operating characteristics changed to some extent from the operating conditions prevalent during the demonstration project. Due to process conditions at the BIWWTP, the average total solids concentration in the dryer feed has decreased to approximately 14%, with normal fluctuations within a range of 12% to 18% solids. The current average total solids content of the sludge discharge from the dryer is approximately 32%. The current typical operating mode for dewatering at the BIWWTP is similar to Test Condition B (Sludge Blend). Waste heat recovery opportunities were therefore evaluated based on current sludge characteristics and the experience and data gleaned from the monitoring performed during the Sludge Blend test condition.

Under current operating conditions, flue gases exit the incinerator at temperatures of 850°F to 1,000°F. They enter the afterburner and, if the afterburner is in operation, are discharged to the WHRB at temperatures of 1,350°F to 1,500°F. Prior to the demonstration project, it was not necessary for the BIWWTP to operate the afterburners to maintain compliance with its air emissions permit.

In February 1993, the USEPA promulgated new regulations (40 CFR Part 503) governing wastewater sludge incineration. These shall henceforth be referred to as the "503 regulations." For evaluation of waste heat recovery alternatives, it was assumed that, due to the 503 regulations, the BIWWTP afterburners will have to be operated on a continuous basis in the future. Thus, it was further assumed that all flue gases leaving the afterburner are passed through the WHRB and that the WHRB is operating.

High-temperature dampers control the steam pressure within the WHRBs by modulating the amount of flue gases allowed to pass through the boilers. These dampers do not operate in accordance with their original design and are the subject of a current improvement project. Therefore, due to the problems with the current dampers and control system, and the fact that the BIWWTP has not had to operate its energy-intensive afterburners to attain stack emissions limits, the WHRBs have not been operated on a regular basis for several years. Through the current damper improvement project and due to emissions criteria mandated in the 503 regulations, the BSA is presently working toward reactivating the WHRBs for full-time operation.

Flue gases leave the WHRB at approximately 700°F and are mixed with flue gases that were bypassed around the boiler. The temperature of the mixed flue gas can range from 700°F to 1,500°F, depending on the extent of the bypassing. The dampers are automatically positioned in proportion to the steam demand (as represented by pressure in the steam drum of the WHRB). If more steam is required to meet the steam demand, the drum pressure begins to fall. This decrease in drum pressure proportionally adjusts the inlet and bypass dampers to divert more hot flue gas through the WHRB. At times of zero steam demand (other than normal line condensation), almost all flue gases are bypassed around the WHRB. Figure 7-1 illustrates the schematic relationship between the incinerator, afterburner, and WHRB. Downstream from the WHRB, flue gases proceed into the pre-cooler, where water jets cool the gas flow to approximately 125°F. They then pass through the venturi throat and mist eliminator (impinger trays) and out the main stack.



TYPICAL FOR THREE SYSTEMS

SCHEMATIC OF INCINERATOR/WASTE HEAT BOILER FLUE GAS PATH

FIGURE 7-1

Listed below are the sources of recoverable heat evaluated for this project:

Heat Sources

- Incinerator/Afterburner Flue Gases
  - a. Utilize the existing WHRBs on a full-time basis, following the current damper improvement project.
  - b. Install a stack economizer in the WHRB exhaust gas stream (see Figure 7-1).
- Incinerator Center Shaft (Cooling) Air (CSA) Exhaust.
- Sludge Dryer Sidestreams
  - a. Dryer Vapor Condensate.
  - b. Steam Condensate (Medium Pressure).

Possible uses of reclaimed waste heat evaluated for this project are as follows:

Heat Uses

- Supplement Plant Steam Supply, including satisfying the demands of:
  - Plant HVAC requirements
  - Pre-heating boiler feed water
  - Steam supply to the sludge dryer
- Pre-heating Incinerator Combustion Air
- Pre-heating No. 2 and No. 6 Fuel Oil (used as auxiliary fuel in the incinerators and auxiliary boilers)
- Thermally Condition Belt Press Feed Sludge
- Digester Heating
- Heat Belt Press Belt Rinse Water
- Thermally Condition Polymer Solution

The first item, together with pre-heating of fuel oil and digester heating, are currently part of the "process loads" for the existing steam system, which is supplied by both the auxiliary boilers and, if operating, the WHRBs. None of the other heat uses (pre-heating combustion air, thermally conditioning either the polymer or the belt press feed sludge, and heating the belt press rinse water) are current loads on the plant's energy system.

SOURCES OF WASTE HEAT EVALUATED

Incinerator/Afterburner Flue Gases - General

Figure 7-2 is a schematic illustration of the steam system at the BIWWTP. The production of steam starts at the three auxiliary boilers and/or the three WHRBs. Either or both of the boiler systems is able to satisfy the plant's process steam demand.

Some of the major process loads on the existing steam system are:

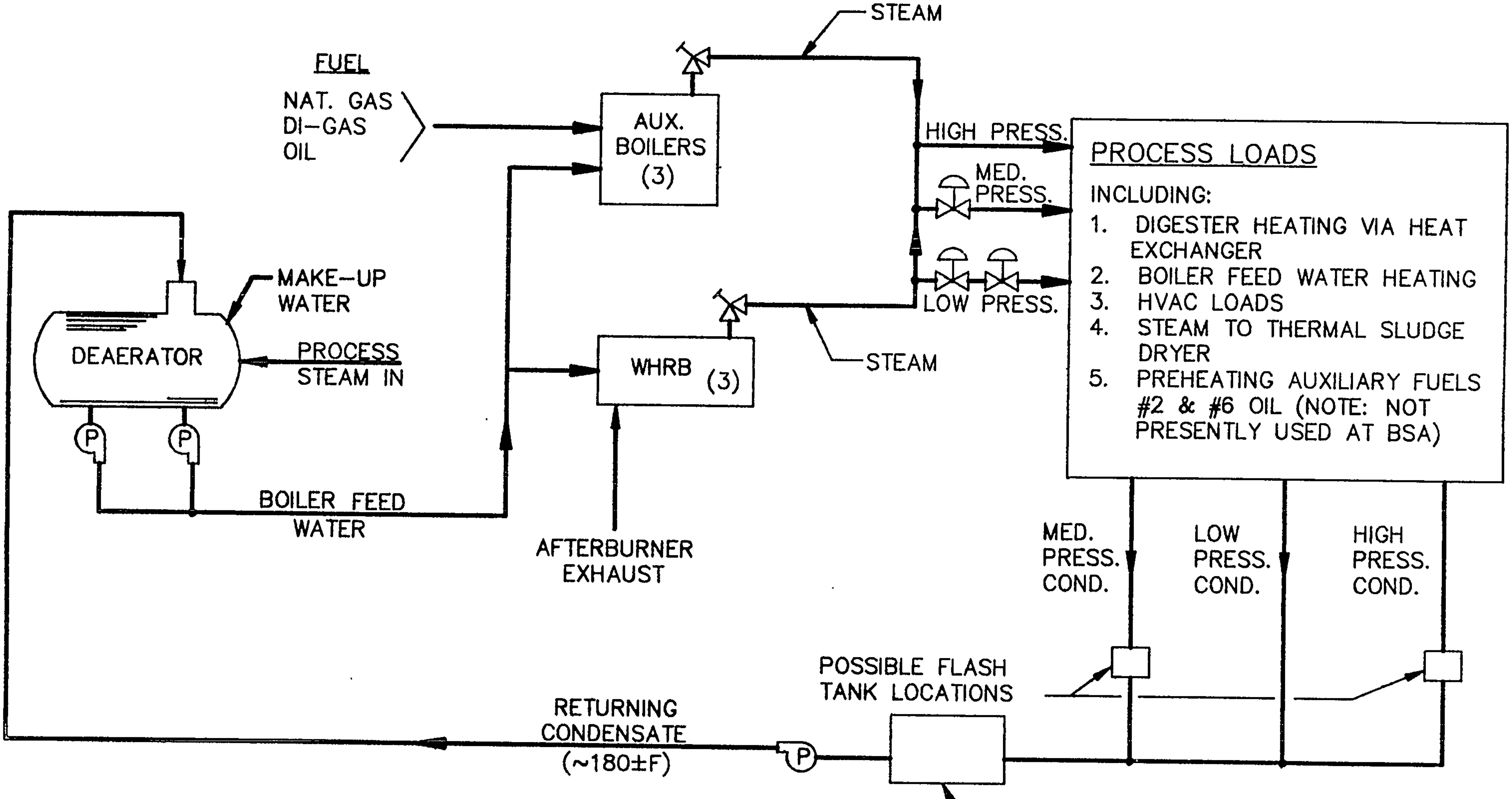
1. Digester heating via a steam-to-hot-water heat exchanger and a hot-water-to-sludge heat exchanger. Digester heating is accomplished by withdrawing sludge from the digester and pumping it through the hot-water-to-sludge heat exchanger and the heated sludge is returned to the digester; this is illustrated in Figure 7-3.

2. HVAC loads for various buildings at the BIWWTP.

3. Boiler feed water heating via a de-aerator unit.

4. Steam to the sludge dryer.

5. Heating of auxiliary fuel oil (for the incinerators and auxiliary boilers) for fluidity and transfer capability. It is noted that, while this heat use is part of the existing process steam load, it is seldom necessary, due to the fact that natural gas is the auxiliary fuel most often used in both the incinerators and auxiliary boilers.



WHRB = WASTE HEAT RECOVERY BOILER

STEAM SYSTEM SCHEMATIC

FIGURE 7–2

Incinerator/Afterburner Flue Gases - Waste Heat Recovery Methods

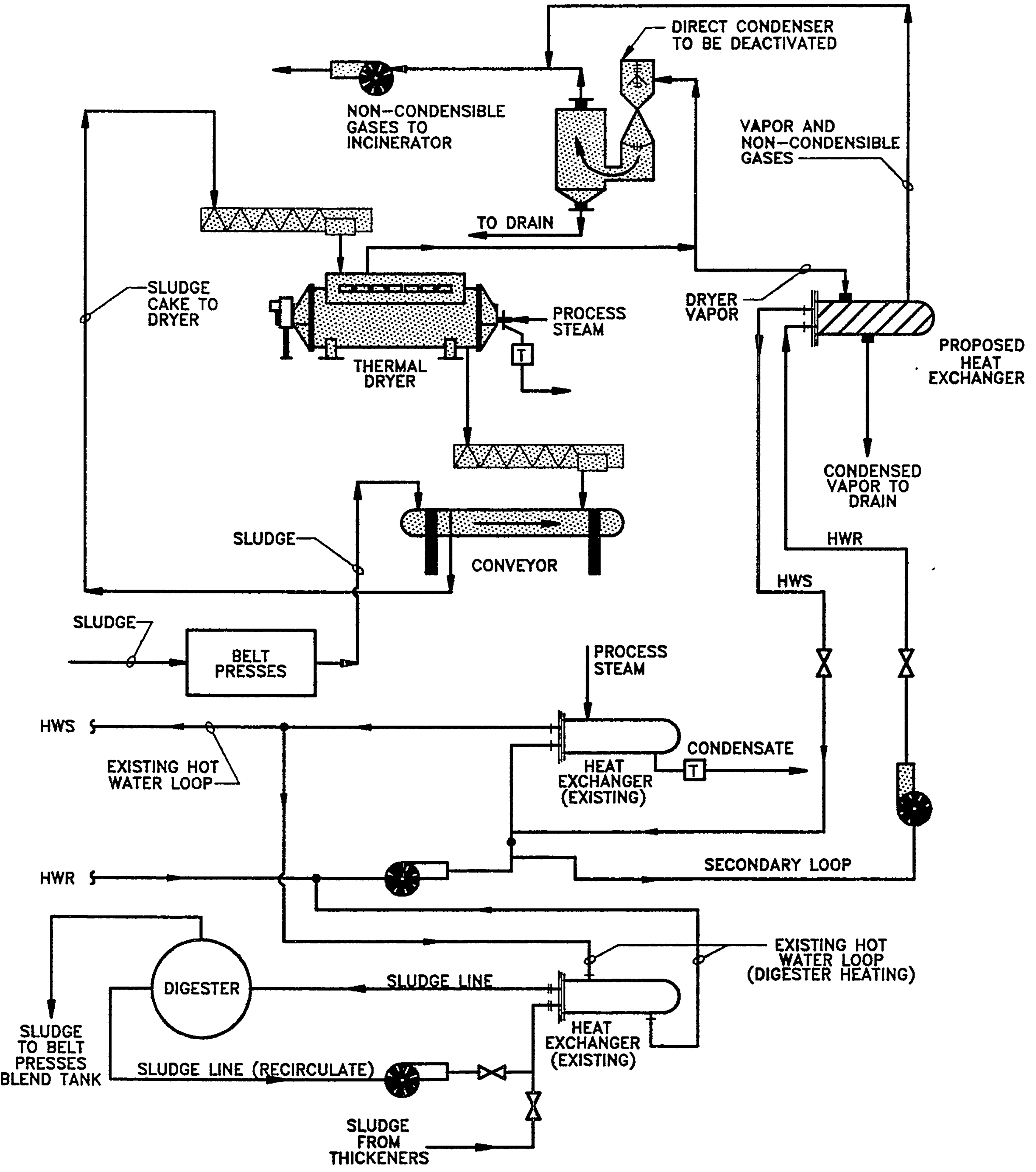
The incinerator/afterburner flue gases contain usable waste heat that can be extracted by two methods:

- A waste heat recovery boiler, or
- A stack economizer (which would be located between the WHRB and the scrubber's pre-cooler).

As noted above, the BSA is presently upgrading the WHRBs' inlet and bypass control dampers so that these boilers can be returned to daily service. All other support systems for the WHRBs are presently on-line and functional (i.e., boiler feed water pumps, de-aerators, steam system control valves, and monitoring controls for the boilers). The incinerators, afterburners, scrubber systems, induced draft fans, and main stack are all presently 100% functional. Therefore, for simplicity and ease of implementation, upgrading and reactivation of the WHRBs is the most economical heat recovery alternative, largely due to the fairly limited capital investment required and the substantial amount of heat available for recovery. As shown in Appendix G, approximately 21.8×10^6 BTU/hr is available from each WHRB (assuming each boiler is operating at 100% capacity with an inlet flue gas temperature of approximately 1500°F); this heat is in the form of 22,000 lb/hr of 125 psig steam.

As stated previously, in order to operate the WHRBs, it is necessary that the afterburners be operating. It has been found from observation of the WHRBs that, if the afterburner is not functioning, the exiting flue gas temperature is below the point at which condensation occurs in the final pass of boiler tubes. Extended operation in this mode would be detrimental to the tubes due to corrosion caused by flue gas condensate.

One additional advantage of upgrading and permanently reactivating the WHRBs for waste heat reclamation is that the stationary engineers in the Main Equipment Building are already familiar with their O&M procedures.



HWR = HOT WATER RETURN
HWS = HOT WATER SUPPLY

PROPOSED DIGESTER HEATING SCHEMATIC (VAPOR)

FIGURE

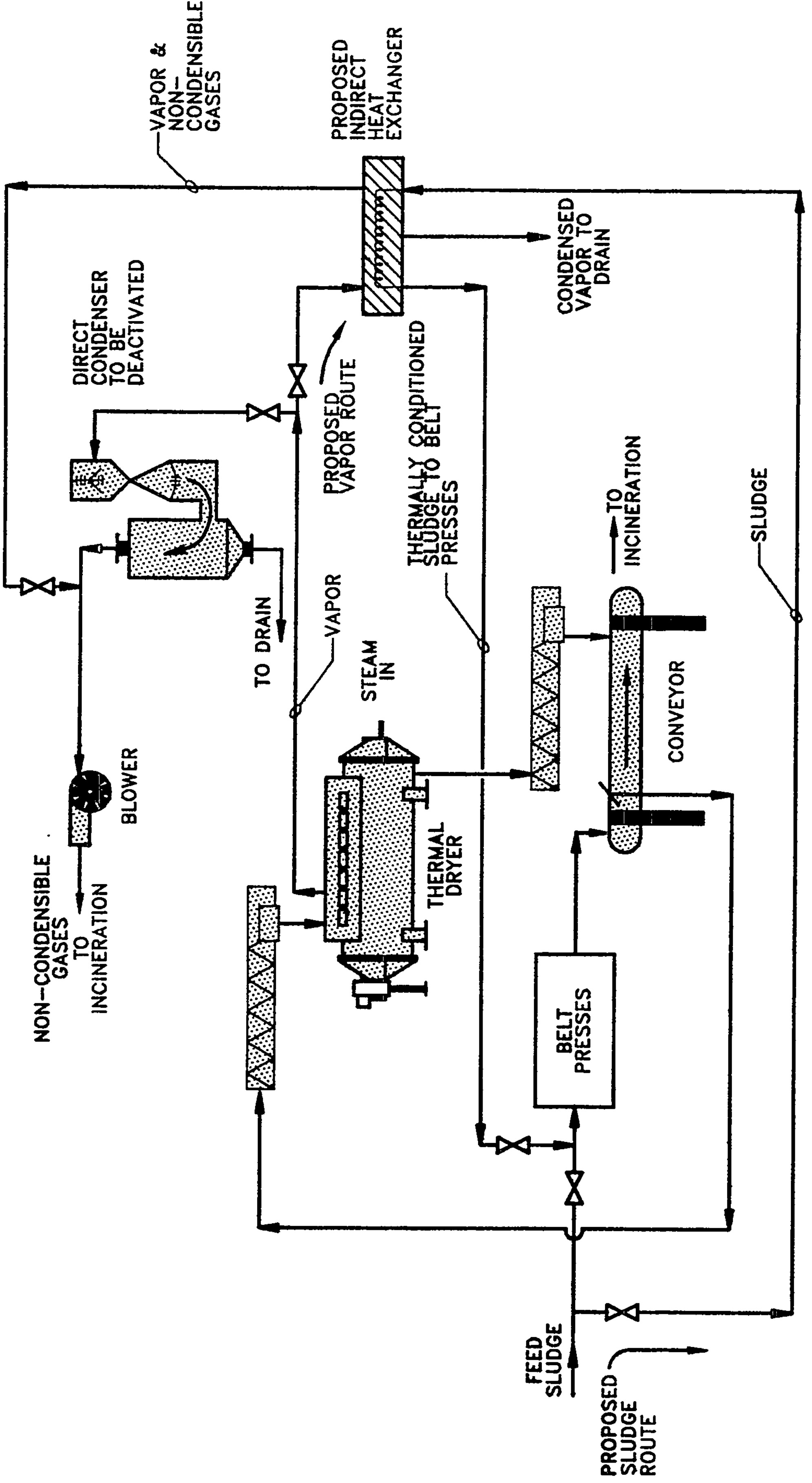
7–3

The second method of waste heat recovery for the incinerator/afterburner flue gases is a stack economizer; the potential location of a such a unit is shown on Figures 7-1 and 7-7. However, the use of a stack economizer in the existing ductwork at the BIWWTP would be difficult due to space considerations and, therefore, it would be necessary to install a economizer off the existing gas stream and "tap into" the existing ductwork. The location shown for the stack economizer taps allow recovery of waste heat regardless of the temperature of the flue gases (i.e., with the afterburner on or off, or the WHRB on or off). In addition to the problem of the physical location of a stack economizer, a second consideration with this particular heat reclamation method is that heat availability would have extremely wide variations depending on which device(s) in the incineration system was (were) in service. Therefore, the control mechanism would have to be fairly sophisticated.

As shown in Appendix G, a stack economizer installed on one operating incinerator train would produce approximately 4.41 x 10^6 BTU/hr (assuming a stack economizer flue gas inlet temperature of 700°F, an outlet temperature of 135°F, and a stack economizer efficiency of 80%). This amount of recoverable waste heat is based on the assumption that on an annual basis, the stack economizer would operate at full load only 67% of the time.

Incinerator Center Shaft Air

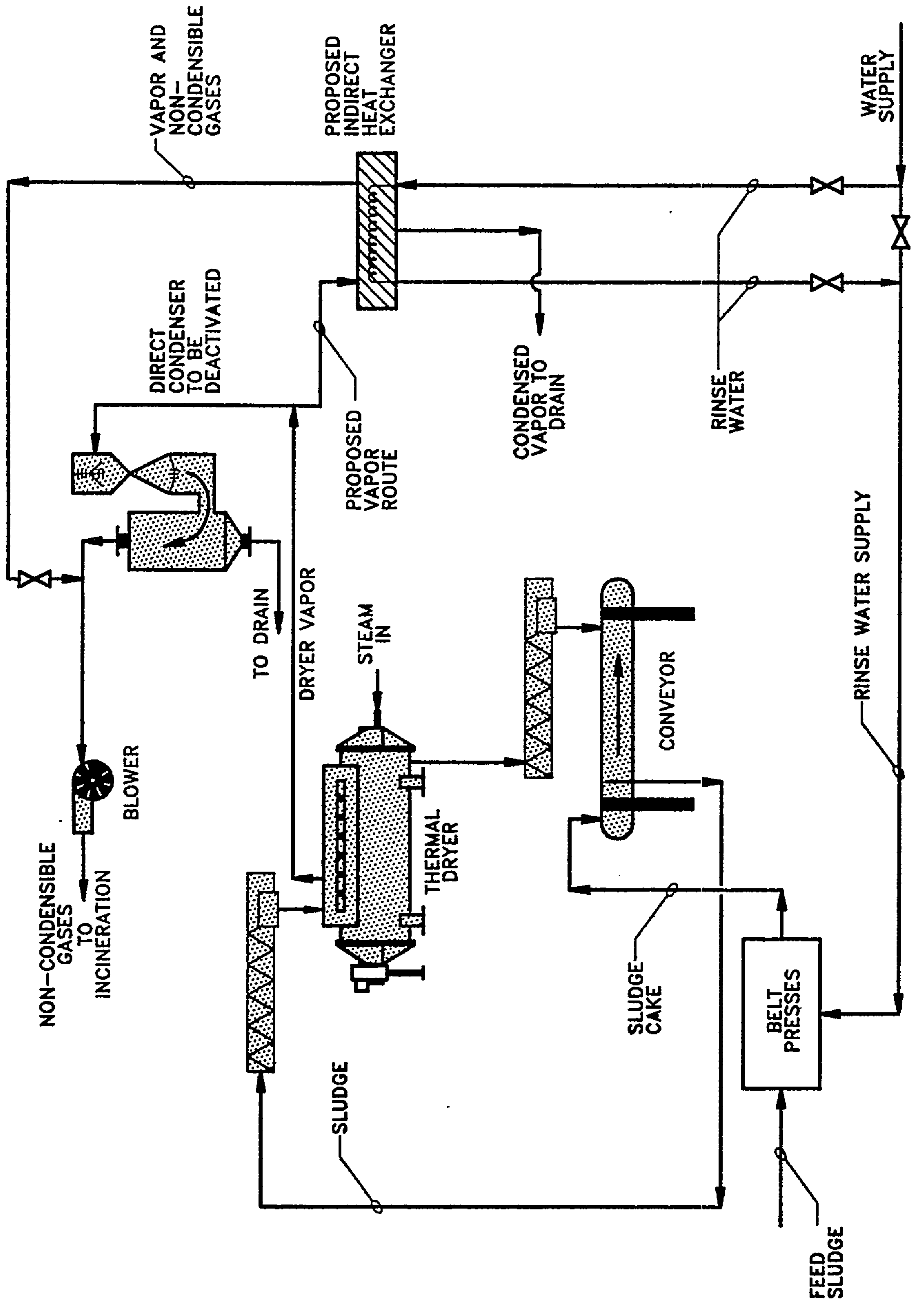
The center shaft air (CSA) exhaust is currently utilized, on a regular basis, as preheated combustion air. If the CSA exhaust was diverted for other heat recovery uses, the amount of ambient outside air required for combustion air needs would increase, resulting in increased incinerator auxiliary fuel consumption. Therefore, since heat in the CSA exhaust is presently being recovered, this heat source alternative was not examined further.



SCHEMATIC FOR THERMAL
CONDITIONING OF BELT PRESS
FEED SLUDGE (VAPOR)

FIGUR

7–



RINSE WATER HEATING SCHEMATIC (VAPOR)

FIGURE 7-5

Sludge Dryer Sidestreams

Condensate from two sludge dryer sidestreams have waste heat available for recovery. The first (and largest) source of waste heat generated during thermal drying is the heat contained in the vapor driven off from the sludge. This vapor is at saturated conditions and atmospheric pressure; therefore, no flash tank is required. Recovering the heat of vaporization is a simple matter of condensing the saturated vapor. However, a problem associated with the dryer vapor is the carry-over of contaminants entrained in the sludge (i.e., non-condensible and some condensible gases, and some solids and chemicals that are somewhat corrosive in nature and usually detrimental to heat exchanger components). The cost of heat recovery devices for this application will be fairly significant due to the need for corrosion-resistant materials. As noted in Section 3, at the time of the demonstration project, the dryer vapor was piped to a direct condenser. The non-condensible gases were piped to the incinerators, both as an odor control method and to provide a minor amount of pre-heated combustion air. The drain water produced by the condenser (approximately 108.6 gpm at 180°F) was sent to a drain and its waste heat was not recovered in the original dryer system design. As shown in Appendix G, approximately 5 x 10^6 BTU/hr are available from this waste heat source.

The second source of waste heat is the condensate resulting from the steam utilized for thermal drying (see Figure 7-5). Medium-pressure steam condenses within the disks of the dryer and exits to a trap at the end of the dryer. Upon exiting the dryer rotor, the condensed steam is still at a pressure of approximately 45 psig. This steam can be "flashed off" in a flash tank as indicated on Figure 7-2. There is a considerable amount of energy available for recovery in this medium-pressure condensate. As shown in Appendix G, approximately 424 lb/hr of flash steam, or roughly 4.07 x 10^5 BTU/hr, is available from this waste heat source.

USES OF RECOVERED WASTE HEAT

Waste heat can be utilized in at least six major systems at the BIWWTP; these are each briefly described below.

Process Steam Demand

The first and most obvious of these uses is supplementing the plant's process steam supply. "Process steam demand" is defined as equipment or systems that utilize the steam produced by the WHRBs and/or the auxiliary boilers. In this heat utilization option there is some overlap between present steam demand (such as building heating, digester heating, preheating boiler feed water, etc.) and new demands that can be supplied with recovered heat. The current steam demand on the BIWWTP boiler system is equivalent to approximately 4.66×10^7 BTU/hr during a design winter day (a design winter day assumes an outdoor air temperature of 6°F, a desired inside temperature of 70°F, a desired sludge digester temperature of 95°F, and a sludge dryer steam utilization of 6,136 lb/hr). Currently, the winter process steam energy requirement of 4.66×10^7 BTU/hr is satisfied by firing natural gas in the auxiliary boilers. Any recovered waste heat applied to this utilization option would go toward reducing this energy requirement.

Pre-heating of Incinerator Combustion Air

The second potential use of recovered waste heat is preheating the incinerators' combustion air. The CSA is presently utilized as preheated incinerator combustion air, therefore only the preheating of that combustion air which is piped directly to the burners was evaluated as a possible use for the waste heat. It is noted that, in the present mode of operation, all combustion air (except the recycled CSA and the non-condensible gases from the sludge dryer vapor) is air drawn from outside the Main Equipment Building; in the winter this air can be as cold as 0°F or colder. When the combustion air is introduced into the incinerator, a significant amount of energy is required to raise its temperature from the outside ambient temperature to the operating temperatures in the hearths (where temperatures range from 500°F to 1500°F).

Options for preheating the combustion air were evaluated for this project. The alternative of air-to-air heat exchangers was evaluated versus installing heat coils in the existing air plenum. The option of air-to-air heat exchangers was discarded due to the capital costs associated with procuring and installing units of sufficient size to handle all the combustion air flows. The second option was also rejected, since the existing air plenum has a very low detention time for air brought in from outside the Main Equipment Building, and a low detention time does not allow adequate time for heat transfer to occur. Further, the Main Equipment Building does not have sufficient space to accommodate a larger plenum.

Pre-heating Auxiliary Fuel

Preheating auxiliary fuel (used for the incinerators and the auxiliary boilers) such as No. 2 or No. 6 fuel oil is also a possible use of recovered waste heat, since No. 6 fuel oil requires heating to maintain fluidity and enable transfer by pump. However, at the time of this report, fuel oil was seldom utilized for firing the auxiliary boilers or the incinerators. Recently promulgated regulations for dual fuel rating units (such as the BIWWTP's incinerators and auxiliary boilers) mandate that oil be fired for at least a few hours per year. This minimum run time with oil is all that is presently anticipated at the BIWWTP. As such, the energy requirement for this item was not quantified for this study.

Thermal Conditioning of Sludge

Sludge at the BIWWTP is not presently heated, or "thermally conditioned", at any location other than in the digester heating system. However, experience at other wastewater treatment facilities has indicated, in some instances, that elevation of sludge temperatures prior to mechanical dewatering provides improved dewatering characteristics, resulting in increased sludge cake total solids content.

For this project, the option of thermally conditioning the sludge feed to the belt filter presses was evaluated. It was assumed for this option that hot-water-to-sludge heat exchangers would be installed downstream from the belt press feed sludge pump discharge manifold. For purposes of evaluation, it was assumed that the feed sludge currently has an ambient temperature of 70°F, and it was desired to raise the temperature to approximately 80°F. Further, it was assumed that six belt presses operate with a feed sludge flow rate of 150 gpm, 24 hours per day. This would require approximately 4.5×10^6 BTU/hr of energy to raise the sludge temperature by the desired amount of 10°F.

An added benefit of thermally conditioning the belt press feed sludge is that the temperature of the sludge dryer's feed sludge would be elevated. This would decrease the amount of energy (steam) required to evaporate the water from the sludge; the energy savings gleaned from this would be approximately 4.16×10^5 BTU/hr. Thus, the net energy requirement for thermally conditioning the belt press feed sludge (computed by subtracting the dryer's energy demand reduction of 4.16×10^5 BTU/hr from the overall energy requirement of 4.5×10^6 BTU/hr) is approximately 4.08×10^6 BTU/hr.

Digester Heating

A potential use of recovered waste heat is digester heating. Currently, the existing anaerobic digesters are heated via a hot-water-to-sludge indirect heat exchanger. Digester heating is accomplished by withdrawing sludge from the digester and routing it through the heat exchanger, where its temperature is elevated to 95°F; the sludge is then returned to the digester. This heat/recycle process is run 24 hours per day.

Sludge is fed to each of the six existing digesters at a rate of 250 gpm for approximately 4 hours per day. The temperature of the feed sludge varies, depending on the season of the year; typical ranges are 34°F to 65°F. The normal operating temperature for the anaerobic digesters at the BIWWTP is 95°F. BIWWTP operational records indicated that, based on an annual average, approximately 3.65 x 10^6 BTU/hr is required to heat one of the existing six digesters; thus, 21.9 x 10^6 BTU/hr is required to heat all six digesters. Due to this high energy requirement, the evaluation of this waste heat utilization alternative was scaled back to examine the feasibility of heating only one digester.

In addition to the average daily energy requirement (based on annual averages) of 3.65 x 10^6 BTU/hr for one digester, the "peak hourly" energy requirement was also evaluated. The peak energy use in digester heating occurs during the period in which new, cool sludge is introduced to the digester; as noted above, this occurs for a period of 4 hours per day. In a worst case scenario, 34°F sludge is pumped into the digester over a 4 hour period. During this time, the energy required to maintain a temperature of 95°F is approximately 7.63 x 10^6 BTU/hr. Thus, any waste heat source utilized for digester heating must be capable of supplying 7.63 x 10^6 BTU/hr.

Heat Belt Filter Press Rinse Water

An alternative use of recovered waste heat is heating the water utilized to rinse the dewatering belts on the belt filter presses. As each belt filter press deposits its dewatered cake onto the conveyor belt, the dewatering belt is partially blinded by solids. If not removed, the belt could eventually be entirely blinded, thus inhibiting the mechanical dewatering process. To avoid this situation, the dewatering belts at the BIWWTP are sprayed with final effluent (FE) water on each cycle through the belt press. This results in improved sludge cake total solids content, and therefore an increased solids content in the sludge dryer feed.

Plant operators at the BIWWTP have found that warm or hot belt rinse water cleans the belt much more effectively than rinse water at ambient temperatures. The hot rinse water is so effective that the BSA is presently planning a capital project to install equipment to heat all the belt press belt rinse water. As such, the option of utilizing recovered waste heat for this purpose (as opposed to the introduction of an additional process load on the existing steam system) was evaluated as part of this project.

It was assumed that the temperature of the FE water used for rinsing the belts varies from approximately 45°F to 70°F, and the desired temperature for rinsing is 115°F. The desired 115°F temperature was selected since it is the maximum temperature which will not cause scalding in the event of a mishap (if a plant operator was sprayed). The belt rinse water is required 24 hours per day, 365 days per year, and approximately 400 gpm is required to rinse all six belt filter presses. If the inlet FE water is 45°F (winter conditions), then approximately 1.4×10^7 BTU/hr of energy will be required; if the feed water temperature is 70°F, then the energy requirement would be reduced to 9.0×10^6 BTU/hr. As can be seen, this is relatively significant energy requirement. A schematic of a proposed heat recovery system, utilizing waste heat in the dryer vapor, is illustrated in Figure 7-5; a second potential heat recovery system, utilizing a stack economizer, is depicted schematically in Figure 7-7.

Thermal Conditioning of Polymer

The final option evaluated under this project for utilizing waste heat was heating, or "thermally conditioning", polymer used in the sludge handling processes. Experience at other wastewater treatment facilities has shown, for some types of sludges and with polymers of certain manufacturers, that thermal conditioning may improve polymer performance and thereby increase the sludge cake solids content. However, it is noted that the polymer used at the BIWWTP experiences inhibited effectiveness at temperatures in excess of 90°F, and exhibits complete breakdown (i.e., the polymer entirely ceases to function) at 120°F; this was confirmed in a bench test performed in the BIWWTP laboratory in October, 1990. It would be necessary, therefore, to consider changing polymers at the BIWWTP in order to implement this option.

At the BIWWTP, polymer is introduced into the solids handling stream at two points: the dissolved air flotation thickener sludge feed and the belt press sludge feed. The polymer is a high-charge cationic polymer which is purchased in solid form and mixed with water in day tanks. The ambient temperature of the polymer solution in the day tanks is approximately 70°F, and 120°F was assumed for the temperature of the thermally conditioned solution.

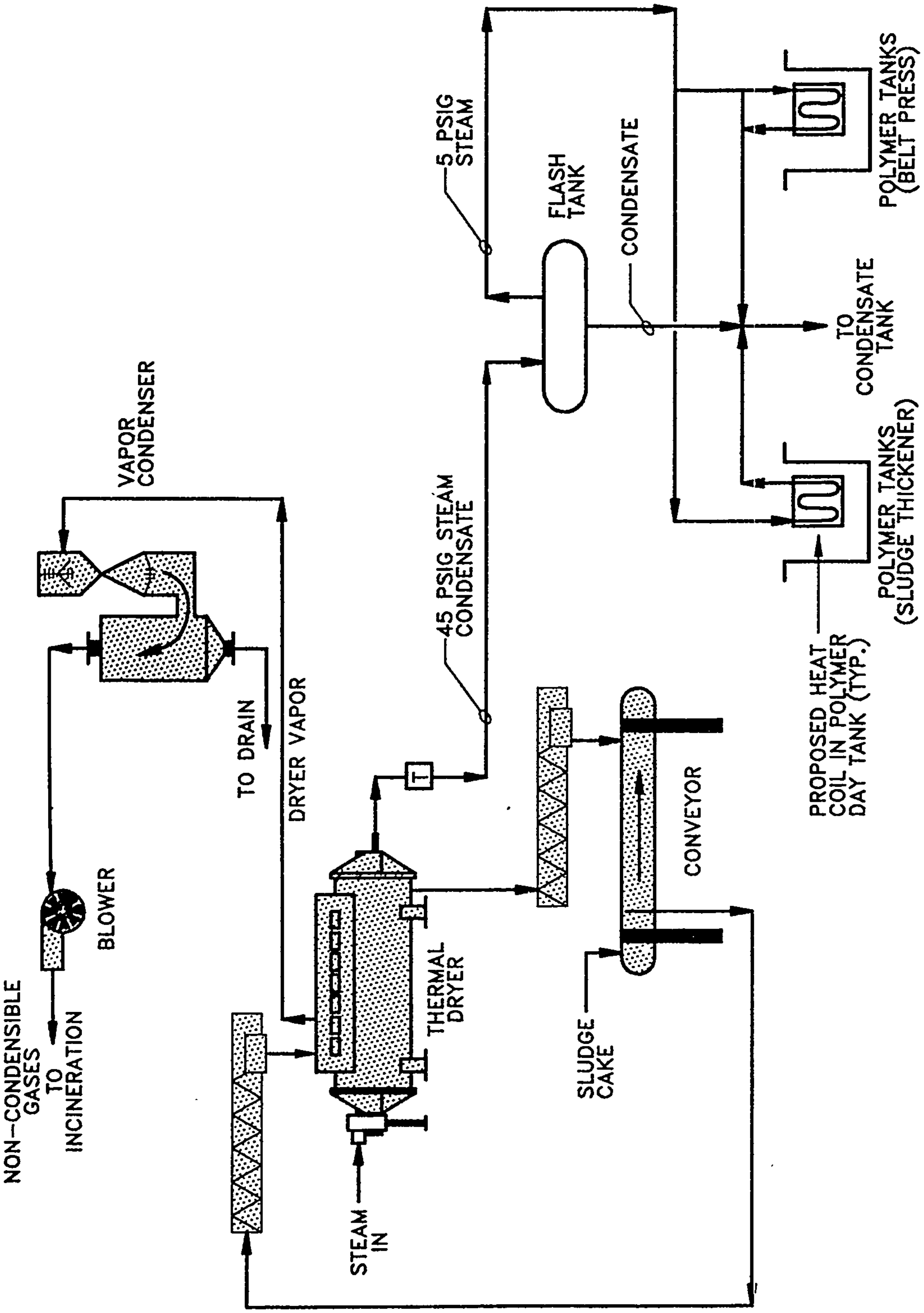
The heat transfer would be via heat exchangers installed in the polymer day tanks. One exchanger would be installed in the thickener day tank and another in the belt press day tank. The hot water supply to the exchangers would be valved to allow local control of the polymer thermal conditioning (see Figure 7-6, which illustrates the sludge dryer steam condensate as the heat source for this utilization option). Based on the above assumptions, approximately 1.125×10^5 BTU/hr would be required to thermally condition the polymer at the BIWWTP.

Summary

Of the seven options investigated for utilizing waste heat, the following options were found to be not feasible: pre-heating auxiliary fuel oil, and pre-heating of incinerator combustion air. Therefore, in the matching of available heat sources with feasible uses, the following were evaluated:

Sources:
  Incinerator/Afterburner Flue Gases
  a. Reactivate the WHRBs
  b. Stack economizer downstream of the WHRBs
  Sludge Dryer Sidestreams
  a. Dryer vapor condensate
  b. Steam condensate

Heat Uses:
  Supplement Existing Plant Steam Supply
  Thermally Condition the Belt Filter Press Feed Sludge
  Digester Heating
  Heat Belt Filter Press Rinse Water
  Thermally Condition Polymer Solution



POLYMER HEATING SCHEMATIC (STEAM CONDENSATE)

FIGURE 7–6

HEAT RECOVERY OPTIONS

The heat sources and options for utilizing recovered waste heat are discussed below. Each heat utilization option is "matched" with potential waste heat sources to determine the optimum utilization for recovered heat.

Utilize Dryer Vapor to Thermally Condition Sludge Feed to Belt Filter Presses

Under this alternative, the heat in the sludge dryer vapor condensate would be utilized to heat the sludge entering the belt filter presses. As noted above, approximately 5 x 10^6 BTU/hr are available from this heat source, while the proposed heat use requires 4.5 x 10^6 BTU/hr; therefore, sufficient waste heat from this source exists for heating the sludge.

The BIWWTP must restrict the maximum temperature of its sludge. The polymer currently utilized by BIWWTP loses its effectiveness at temperatures above 90°F. This maximum temperature represents only a small change in the sludge temperature, since approximately 80% of the sludge processed at the BIWWTP is digested and enters the mechanical dewatering process at about 80°F - 95°F. Based these restrictions and on capital and O&M costs (detailed in Appendix G), this alternative has a relatively long payback period of 6.3 years. Thus, this alternative is impractical for the BIWWTP.

Utilize Dryer Vapor to Heat the Belt Filter Press Rinse Water

Under this alternative, the sludge dryer vapor condensate would be utilized to heat the belt filter press rinse water. It is noted that approximately 5 x 10^6 BTU/hr is available from this heat source, but the energy requirement varies seasonally. The cold weather energy requirement (to raise the rinse water temperature from 45°F to 115°F) is 14.0 x 10^6 BTU/hr; the warm weather energy requirement (to raise the rinse water temperature from 70°F to 115°F) is 9.0 x 10^6 BTU/hr. Thus, this heat source does not have sufficient energy available for this use and, if implemented, an additional heat source would have to be identified.

However, the option of heating the belt filter press rinse water appears to be a feasible one, since the BSA is presently planning on adding this load to the plant's current steam demand. If waste heat can be recovered for this use, then additional steam demand would be avoided. If sufficient waste heat were available for this use, then a substantial savings would be realized. As shown in Appendix G, waste heat from the dryer vapor would be sufficient to raise the belt filter press rinse water temperature by 25°F. Based on an energy cost of $0.42 per therm, utilizing dryer vapor for heating the belt filter press rinse water by 25°F (i.e. to a rinse water temperature of 70°F during cold weather and 95°F during warm weather) would result in a savings of $147,000 per year. Therefore, based on estimated capital and O&M costs, this option has a simple payback period of only 0.41 years. However, as noted, a supplemental heat source is required for this heat utilization alternative to raise the rinse water temperature to the preferred temperature of 115°F.

Utilize Dryer Vapor to Heat Digester Sludge

Under this option, waste heat recovered from the dryer vapor condensate would be utilized to heat the sludge in one of the existing anaerobic digesters; a schematic of this proposal is included in Figure 7-3. As noted above, approximately 5×10^6 BTU/hr is available from the dryer vapor condensate, and heating one digester would, based on an annual average, require between 3.65×10^6 BTU/hr and 7.63×10^6 BTU/hr. Therefore, the dryer vapor condensate has sufficient energy to heat one digester during warm-weather months. During cold weather, it would be necessary to provide supplementary heat from another source for this option. As shown in Appendix G, it is estimated that the dryer vapor would require a supplementary heat source about 12% of the year. The minimum digester influent sludge temperature for which the dryer vapor condensate would be able to heat to 95°F without a supplementary heat source is 55°F.

A consideration in this waste heat utilization option is the distance between the heat source (i.e., the dryer vapor condenser is located on the third floor of the Main Equipment Building) and the point of utilization (the digesters are located outside the Main Equipment Building). As an alternative to piping the condensate, the dryer vapor could be used directly (prior to condensation) for digester heating. However, since the dryer vapor is essentially saturated steam at atmospheric pressure, much of the heat would be dissipated as condensation in the fairly long run of piping required between the dryer and the digesters. Thus, for this option, it is necessary to condense the dryer vapor into hot water near the dryer unit, and then convey the hot water to the existing digester heating system. For this purpose, a new hot water pump near the dryer would be required. It is estimated that such a pump would require a 10 horsepower (hp) motor, and the resulting energy consumption for the pump would cost approximately $6,350 per year. Overall, considering capital and O&M costs, this system would have a simple payback of approximately 4.24 years.

Utilize Dryer Steam Condensate to Heat Polymer

Under this alternative, heat from the steam condensate discharged from the dryer rotor would be used to heat the polymer solution in the existing day tanks (see Figure 7-7). As previously stated, the polymer utilized at the BIWWTP becomes inactive at temperatures above 90°F and breaks down above 120°F. As noted above, roughly 4.07×10^5 BTU/hr (in the form of low pressure flash steam) is available from the dryer's steam condensate, and polymer heating requires approximately 1.125×10^5 BTU/hr. As such, more-than-sufficient energy exists from this source for this heat utilization option.

However, since the polymer temperature is limited to 90°F, the amount of heat required to heat the polymer is likewise limited. This, coupled with the relatively high cost of the necessary heat exchanger equipment, results in a 16.9 year payback period for this option. Also, thermal conditioning of the polymer solution would likely require that the BIWWTP change its current polymer to one that is not susceptible to breakdown at temperatures above 90°F. Also, the process benefit that would be obtained at the BIWWTP through thermal conditioning of polymer could not be quantified under the scope of this study. In order to determine the advantage to the thickening and dewatering process, a pilot test or, at minimum, a detailed bench testing program would be required. The scope of such testing would include evaluating various polymers at various temperatures, applied to the typical blends of raw primary sludge, raw WAS, and digested WAS processed at the BIWWTP. The scope of the testing required, coupled with the extremely long payback period, eliminates this waste heat recovery option from further consideration at the BIWWTP.

Other wastewater treatment facilities that might choose to use this alternative should investigate how their polymer reacts to elevated temperatures through a pilot test or detailed bench test, as mentioned above. If a polymer used in wastewater treatment is stable, and is as cohesive at elevated temperatures as it is at ambient room-temperature, the sludge will likely exhibit improved dewatering characteristics, allowing a drier cake and, consequently, improved thermal dewatering and incineration.

Supplement Existing Steam Supply by Reactivating the WHRBs

Under this alternative, heat from the incinerator flue gas would be recovered and used to supplement the existing steam supply system (i.e., the auxiliary boilers) through the reactivation of the existing waste heat recovery boilers. As shown in Appendix G, any remediation that would allow the existing WHRBs to operate on a full-time basis would yield significant savings. As noted in the introduction to this section, this conclusion assumes that the afterburners will be required full-time to attain the total hydrocarbons stack emissions limits mandated in the 503 regulations. The annual energy savings for this option would be approximately $622,000, with a payback period of 0.24 years.

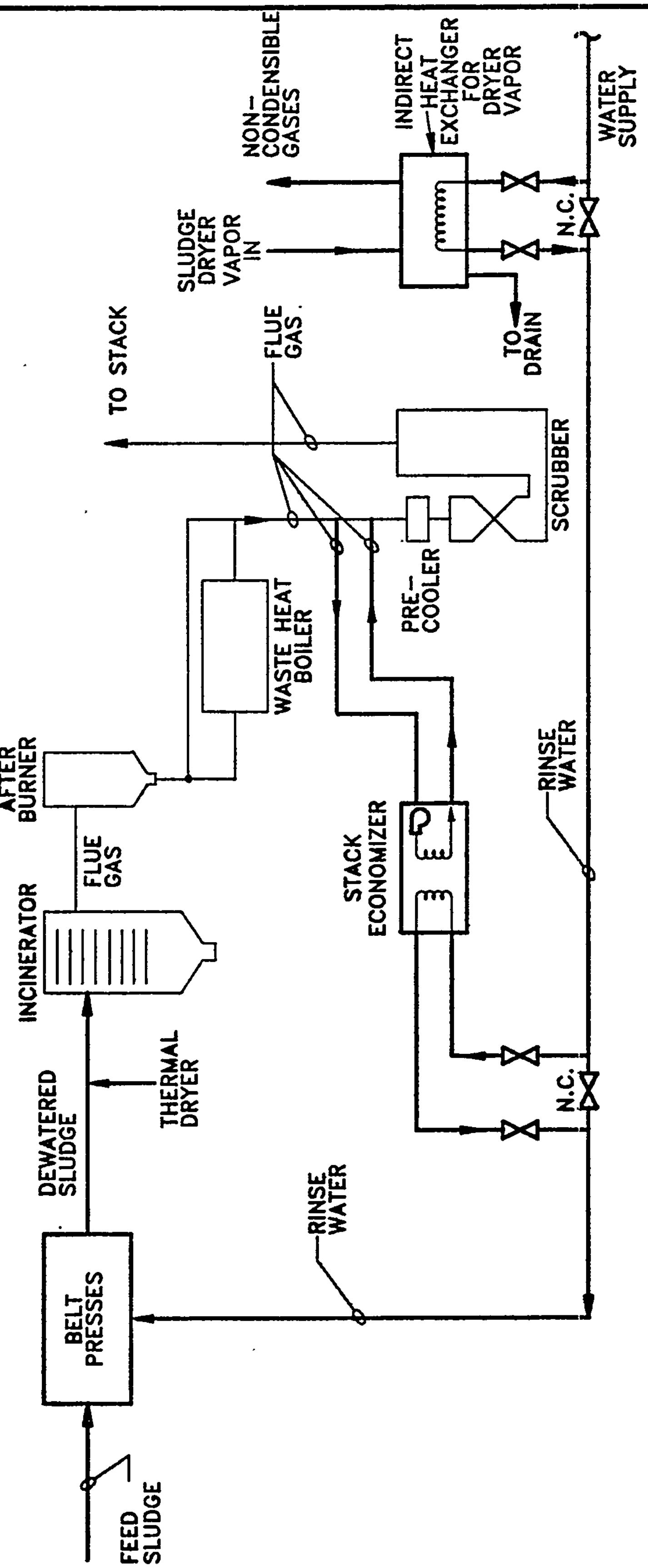
Utilize Stack Economizers to Heat Belt Filter Press Rinse Water

As described above, the amount of waste heat available in the dryer vapor is not sufficient to elevate the belt filter press rinse water to the desired temperature. As noted above, the temperature of the FE water which would be used as belt filter press rinse water ranges from 45°F (cold weather) to 70°F (warm weather), and the waste heat available from the sludge dryer vapor condensate is only sufficient to raise the temperature of the FE water to 70°F (cold weather) and 95°F (warm weather); the preferred belt filter press rinse water temperature is 115°F. A stack economizer, installed downstream from the WHRB, could be used to supplement the heat shortfall. As mentioned above and as shown in Appendix G, approximately 4.41 x 10^6 BTU/hr of energy may be recovered and reused from this heat source. This system is depicted schematically in Figure 7-7.

If the primary energy source for heating the belt filter press rinse water is the sludge dryer vapor condensate, then the energy requirement of the supplemental heat source (required to raise the belt press rinse water from 70°F (cold weather) or 95°F (warm weather) to the preferred temperature of 115°F) will range from 4 x 10^6 to 9 x 10^6 BTU/hr. Therefore, if the belt filter press rinse water is heated using both the sludge dryer vapor condensate and the waste heat recovered using a stack economizer, a total of 9.41 x 10^6 BTU/hr of heat is available, assuming that only one incineration train is in operation.

The total available energy of 9.41 x 10^6 BTU/hr is sufficient to elevate the belt filter press rinse water to 115°F in warm weather, and to 111°F in cold weather; as such, it is not quite sufficient to raise the rinse water to the desired temperature of 115°F when the FE water supply temperature is at 45°F, plant process steam could be used to elevate the water temperature during periods of cold weather; alternatively, the belt filter press rinse water could be heated only as far as the dryer vapor and stack economizer sources allow (i.e., to a temperature of somewhat less than 115°F). Conversely, during warm weather, excess waste heat (beyond the energy requirement for heating the rinse water) will be available from these two sources. In such situations, the excess waste heat available from a stack economizer (or economizers, if two incinerators are operating) may be used to reduce the digester heating requirements.

In either case, the option of heating the belt filter press rinse water using recovered waste heat is an attractive one for the BSA, since it currently plans to heat the belt filter press rinse water using process steam. Based



N.C. = NORMALLY CLOSED

RINSE WATER HEATING
SCHEMATIC (STACK ECONOMIZER)

FIGURE
7-7

on the anticipated capital and O&M costs, the simple payback for installing a stack economizer to heat a portion of the belt filter press rinse water is approximately 3.47 years.

Other Alternatives

A number of additional alternatives were considered but rejected as impractical. These are summarized below:

Utilize a Stack Economizer to Preheat Boiler Feed Water: This alternative was rejected because of the relatively small temperature difference between the return condensate temperature and the boiler feed water temperature. The boiler feed water temperature is approximately 230°F, while the condensate temperature is approximately 190°-200°F. The stack economizer would be better suited to the belt filter press rinse water option.

Utilize the Stack Economizers to Heat Domestic Water: The domestic hot water load serving office lavatories and employee welfare areas (showers, lavatories, etc.) is significantly lower than the available capacity of the stack economizer. This alternative would mean an extremely large capital cost with a very small return.

Utilize Sludge Dryer Sidestreams for HVAC Loads: Reactivation of the WHRBs will satisfy all the HVAC and process loads, except for approximately 7 to 10 days during the year. The expense of providing additional heat exchangers and piping necessary for recovery of dryer vapor or dryer steam condensate for HVAC use versus the energy savings would provide a poor return and result in a long payback period.

Replace Existing Boiler Feed Water Pre-heating System: Preheating of boiler feed water was eliminated because an existing preheating system is already in place. The existing preheat system directly injects steam from the boilers into the boiler feed water. Since steam is directly injected, there is no increased energy efficiency to be gained by replacing the existing preheat system.

SUMMARY

A summary of options investigated is presented in Table 7-1. The options representing waste heat sources are designated as A through E, and waste heat utilization alternatives are numbered below each heat source option.

TABLE 7-1

SUMMARY OF OPTIONS

Options Investigated	Capital Cost	Payback Period
A. Dryer Vapor Waste Heat		
1. Heat Feed Sludge to Belt Presses	$ 70,000	6.30 years
2. Heat Belt Press Rinse Water	$ 60,000	0.41 years
3. Heat Digesters	$ 74,000	4.24 years
4. Plant HVAC Load	Rejected	N/A
B. Dryer Steam Condensate Waste Heat		
1. Heat Polymer Solution	$ 56,000	16.9 years
2. Plant HVAC Load	Rejected	N/A
C. Upgrade Waste Heat Recovery Boilers for Daily Operations	$150,000	0.24 years
1. Supply Steam to Existing Distribution System		
D. Install Stack Economizers on Incinerator System Flue Gas Duct		
1. Heat Belt Press Rinse Water	$609,000	3.47 years
2. Pre-heat Boiler Feed Water	Rejected	N/A
3. Heat Domestic Water	Rejected	N/A
E. Incinerator Center Shaft Air Waste Heat	Rejected	N/A

RECOMMENDED WASTE HEAT RECOVERY ALTERNATIVES

The three most viable waste heat recovery and utilization options are:

1. Utilization of the dryer vapor to raise the temperature of the belt filter press rinse water, supplemented by,
2. Installation of stack economizers in the incineration flue gas stream downstream from the WHRBs.
3. Reactivation of the WHRBs for continuous operation.

The first and third options are the most cost-effective, and would result in a net energy savings of approximately 18.32 x 10^{10} BTU/year (for both options combined), annual energy cost savings of about $147,000 and $622,000 respectively, and payback periods of 0.41 and 0.24 years, respectively. The second option would result in a net energy savings of roughly 4.32 x 10^{10} BTU/year, with an estimated annual energy cost savings of approximately $181,440.00/year with an associated payback period of 3.47 years.

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SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

The BSA sludge dryer project demonstrated, in full-scale operation, the advantages and disadvantages associated with thermal dewatering of municipal sewage sludge via application of indirect steam heat. Further, the project was the first full scale evaluation in the United States of sewage sludge drying utilizing an indirect rotary disk steam-heated unit.

PERFORMANCE OF THE SLUDGE DRYER AT THE BIWWTP

The following conclusions on the dryer unit were drawn from this project:

- The dryer achieved its design values. Further, the dryer appeared to be capable of thermally dewatering sludge at feed rates in excess of the design values, although at the expense of increased steam application rates, increased sludge detention times in the stator, and decreased total solids (in tons per hour) capacity. As a next step, the BSA will experiment with the dryer to determine optimum solids feed rates, from the perspective of steam utilization and incineration operations.

- No significant start-up or operational problems were encountered with the BIWWTP sludge dryer unit. Miscellaneous problems encountered with the dryer's ancillary equipment have been rectified since the conclusion of the project. Based on the BSA project, indirect condensers are recommended to treat the dryer vapor.

- Since the BSA resolved to determine the optimum operational point(s) for the dryer, modifications to the dryer's ancillary equipment (such as the inlet and discharge sludge screw conveyors, and the condenser unit) were required to handle increased solids loads.

- The dryer produces waste heat which may be economically recovered for beneficial use at the BIWWTP. The BSA plans to utilize waste heat recovered from the dryer vapor to elevate the temperature of the belt filter press rinse water, thereby improving the mechanical dewatering process.

- The amount of steam consumed by the dryer during periods in which the afterburners (and, hence, the WHRBs) were off-line necessitated the operation of an additional auxiliary boiler at the BIWWTP. This effectively offset the advantage gained through the autogenous combustion of the sludge in the incinerator and made operation of the dryer cost-prohibitive without the afterburners and WHRBs.

- Based on the experience gained through the Buffalo project, the availability of plant utilities will be strong factor in determining the feasibility of installing indirect steam heated sludge dryers in other wastewater treatment facilities.

INCINERATOR OPERATION AT THE BIWWTP

The following conclusions regarding the BIWWTP's incinerators and the dryer's effects on the incinerators and boilers were drawn from this project:

- Through thermal dewatering, autogenous combustion (i.e. without the addition of natural gas or other auxiliary fuels) was achieved in the incinerator, thereby sharply curtailing the amount of auxiliary fuel required for the incinerator. However, due to variations in the incineration and dewatering processes, over the long-term auxiliary fuel use was not entirely eliminated, but was substantially reduced, with several operational periods in which no auxiliary fuel was required.

- The dryer enables the BSA, on occasion, to operate one fully loaded incinerator as opposed to the former operation of two partially loaded incinerators. This was accomplished by recently completed sludge conveyor belt modifications, which allow more sludge to be fed to the dryer. Also, modifications to the dryer's ancillary equipment were required to handle the increased solids load.

- Due to the 1993 Federal sludge incineration regulations promulgated under 40 CFR 503, operation of the afterburners at the BIWWTP will likely be required on a full-time basis. Thus, the "free" steam generated by the WHRBs renders the dryer an advantageous process in the BIWWTP's solids handling train.

- Flue gases downstream from the waste heat recovery boiler contain significant amounts of economically recoverable waste heat. This waste heat could be recovered by installation of a stack economizer at a location off the existing flue gas duct work. The BSA plans to utilize waste heat recovered from the incinerator flue gases to elevate the temperature of the belt filter press rinse water, thereby improving the mechanical dewatering process.

- The greatest source of waste heat available for recovery is in the afterburner flue gases. While the existing WHRBs are, to some extent presently serviceable, upgrades and improvements to their dampers and controls are currently being performed by the BSA to return the WHRBs to full-time service.

- Combustion of thermally dewatered sludge, or a blend of thermally and mechanically dewatered sludge, resulted in increased incinerator flue gas temperatures (as compared to the incineration of mechanically dewatered sludge). The average increase in incinerator flue gas temperatures ranged from 100°F to 150°F.

- In the event it may not be necessary to operate the afterburners full-time to meet the requirements of 40 CFR 503, it may be possible to operate the WHRBs off the incinerator flue gases if the incinerator exhaust temperature were significantly elevated. While this is not presently possible, due to the fact that elevated temperatures in the top hearth of the incinerator (at the point where the sludge is fed to each unit) would cause flashing (uncontrolled flames) through the sludge feed hopper, it may be feasible to introduce sludge into the incinerator in a lower hearth (say, Hearth No. 2 or 3) and block off the existing feed hopper on Hearth No. 1. Thus, exhaust temperatures may be sufficiently elevated to allow operation of the WHRBs without operating the afterburners. However, a detailed investigation of this option was outside the scope of this study.

SUGGESTIONS FOR FURTHER STUDY AT THE BIWWTP

Now that a new cross-feed conveyor belt and a new indirect condenser are in operation at the BIWWTP, further tests could be performed using larger quantities of sludge input to the thermal dryer. The ultimate goal of such a study would be to determine the optimum operational point for the sludge dryer/incineration/WHRB system.

The testing and monitoring program completed under this project could be repeated after the current WHRB damper and control upgrade project is completed. Such a test would determine the amount of "free" steam that can be produced by the heat from the incinerator flue gas. Thermal dewatering, with afterburning and the use of the WHRBs, has the potential to provide significant energy savings (assuming that operation of the afterburners is required to attain the emissions limits mandated in 40 CFR 503), especially if the incinerator(s) are operated near their design capacities.

INDIRECT STEAM DRYING AT OTHER MUNICIPAL WASTEWATER TREATMENT PLANTS

The results of the demonstration project performed at the BIWWTP may be extrapolated to some general conclusions on the feasibility of using an indirect sludge dryer at other wastewater treatment plants. The conclusions outlined in this section of the report were based on analysis of the results of the Buffalo project, visits to treatment facilities with operating steam dryers (specifically, facilities located in Stuttgart and Karlsruhe, Germany), and the results of selected pilot tests performed using smaller versions of the indirect disk dryer. These tests included pilot programs at the Niagara Falls, New York WWTP, Naugatuck, Connecticut WWTP, Alleghaney County, Pennsylvania (Pittsburgh) WWTP, and the Joint Meeting of Essex and Union Counties WWTP, in Elizabeth, New Jersey.

Overall, thermal drying appears to be an improvement to the solids handling method at the BIWWTP, but only during periods in which the afterburners (and, hence, the waste heat recovery boilers) are in operation. While sludge drying significantly improves the operation of the incinerators (including such benefits as decreased auxiliary fuel utilization and, potentially, the ability at the BIWWTP to consolidate incineration operations from two units to one), it requires a substantial amount of steam. If a treatment facility employing incineration already has afterburners/waste heat recovery boilers (or some other source of "free" or low-cost steam), then sludge drying is recommended. However, if steam must be generated specifically for the sludge dryer then, based on the experience at the BIWWTP, the process may increase the operating cost of sludge management.

Thermal drying may be more attractive for treatment facilities equipped with multiple-hearth incinerators rather than fluidized bed incinerators. Multiple-hearth units typically have exhaust gas temperatures that are not conducive to the operation of waste heat recovery boilers without the expensive process of afterburning. However, under the recently promulgated 40 CFR 503 Regulations, it is likely that many multiple-hearth incineration facilities (such as the BIWWTP) will be required to either activate their afterburners, or if they are not presently equipped with afterburners, it may be necessary to install them to meet required emissions limits for total hydrocarbons. In such cases, most facilities with an operating afterburner will implement some form of waste heat recovery, possibly involving the generation of steam. For most treatment plants, there are three alternative uses for steam: in-plant HVAC needs; cogeneration of electricity (which can be capital-intensive with fairly limited returns); or the installation of an indirect steam heated sludge dryer to optimize the incineration process.

While the effectiveness of an indirect dryer at a facility employing fluidized bed incineration cannot be discounted, such facilities often have much more efficient combustion, so that afterburning is not necessary. Therefore, facilities with fluidized bed units may not stand to gain as much through the outlay of capital required for the installation of an indirect dryer. However, the exhaust temperature of fluid bed incinerators is often much higher than that of multiple-hearth units, and if steam generation from this available waste heat is economically feasible, then the owners of such facilities should consider introduction of a steam dryer into their solids handling train to increase incineration system capacity.

As observed at a 1990 Niagara Falls, New York, pilot test (Stord-Bartz, 1990) and the Joint Meeting of Essex and Union Counties pilot test (Wormald, 1993), it is feasible to install a steam dryer at a wastewater facility that does not employ incineration in the solids handling train. The dryer would likely be very expensive to operate, however, unless a low-cost source of steam were available. Wastewater treatment plants located in proximity to commercial cogeneration facilities should examine the option of steam drying. As observed at Niagara Falls and the Joint Meeting of Essex and Union Counties, with the appropriate detention time, number of drying units, and steam application rate, it is possible to dewater sewage sludge (even sludge that has not been dewatered using mechanical means) to a solids content in excess of 90% (a consistency similar to incinerator ash) using steam dryers.

Since the performance of the Buffalo demonstration project, the use of indirect steam dryers for dewatering of sewage sludge has gained increased popularity in North America. In addition to the pre-1992 installations at municipal wastewater treatment plants in Buffalo and Youngstown, Ohio, the following treatment plants now have installed, or are planning to install indirect steam dryers: City of Los Angeles, California (two dryers at the 400 mgd Hyperion WWTP); County of Los Angeles, California (with a total of six dryers); Pittsburgh, Pennsylvania; Hoboken, New Jersey; the Joint Meeting of Essex and Union Counties, New Jersey; and Seattle, Washington, among others.

Each of the above facilities is employing (or will employ) indirect steam drying of sewage sludge from primary and/or secondary treatment processes. This is perhaps the most difficult application for steam drying, due to the "stickiness" of the product and its tendency to adhere to any burrs within the dryer (see section 4 of this report). An "easier" application of indirect steam drying of municipal sewage sludge is to use a drying unit to separate sludge from the carrier oil utilized in the multiple-effect evaporation (Carver-Greenfield) dewatering process. Several such indirect thermal dryers are in operation in the United States.

RECOMMENDATIONS

It is recommended that the BSA implement the heat recovery opportunities defined in Section 7, namely; repair of the waste heat recovery boilers, and installation of the equipment required to heat the belt filter press rinse water, using the waste heat from the dryer process. It is also recommended that further study be performed to evaluate increased dryer/incinerator throughput, along with monitoring the effects on incinerator operations and efficiencies.

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