Start-up Experience at the Robbins Resource Recovery Facility while Focusing on the Environment

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PEER-REVIEW

INTRODUCTION

In early November, 1996, a new generation of advanced combustion technology using circulating fluidized bed (CFB) boilers began continuous operation in Robbins, Illinois, a suburb of Chicago.

The Robbins Waste-to-Energy and Recycling Facility processes a minimum of 1,600 Tons-per-day of Municipal Solid Waste. Approximately 400 tons-per-day of waste will be recycled with the remaining 1200 tons fed to one of two 600 ton-per-day circulating fluidized bed steam generating units.

The Robbins Facility is designed and operates with the most advanced pollution control equipment. Foster Wheeler and facility personnel, in conjunction with the Illinois Environmental Protection Agency and Cook County Department of Environmental Control, have undertaken a number of programs to optimize environmental performance at the facility, including an on-going, aggressive ambient air monitoring program using a chemical mass balance model and ambient air mercury testing.

This paper provides an overview of the design, approach to start-up, actual experiences to date, and the overall operations of the Robbins Facility with emphasis on the monitoring programs and environmental controls.

FACILITY DESCRIPTION

Overview

The Robbins Resource Recovery Facility, as shown in Figures 1 and 2, is a resource recovery plant that is located in the Village of Robbins, southern Cook County, Illinois. The recovery processes involve the separation of recyclable materials (e.g., aluminum, ferrous, glass, compost feed) from the waste stream and the conversion of the remainder to electrical energy. These processes are accomplished in the facility's (RDF) Refuse Derived Fuel Plant and Power Plant. In order to have a high level of reliability and availability, the Plants were designed and constructed with redundant systems and supporting equipment.

The RDF Plant will receive about 2,050 tons of municipal solid waste (MSW) per day (Monday to Friday and half a day on Saturday) from surrounding communities via approximately 200 refuse collection and transfer trucks. The MSW (about 500,000 Tons per year) will be inspected and processed through an automated recovery system to separate out the recyclable materials (about 125,000 tons per year) which will be sold to recycling companies. The material that is larger than 2.5" will be shredded in order to produce RDF (about 375,000 tons per year). The RDF will be screened to recover any ferrous material.

The Power Plant will then burn the RDF in two state-of-the-art circulating fluidized bed (CFB) boilers which will produce steam to power a steam turbine and drive a 55 MWH/hr. electric generator. A simplified process flow diagram of the Facility is shown in Figure 3.

RDF Plant

The RDF Plant consists of the tipping floor, two parallel processing systems, RDF storage building and two truck weigh scales. Each processing line is designed to handle 85 tons of MSW per hour.

MSW collection and transfer trucks will be weighed at the inbound truck weigh scale and then proceed directly to the tipping floor. The trucks will dump the MSW directly on the floor where there is a two (2) day storage capacity. The waste composition of the MSW which was used for design purposes is described in Table 1.

The MSW is inspected with unprocessable materials (e.g. white goods, large furniture, carpet, etc.) removed with mobile grapples and loaded into trailers for disposal to a landfill. Front-end loaders will be used to manage the MSW for efficient storage. The grapples will also be used to mix and load the MSW onto the feed conveyors to the processing lines. The processing lines include primary and secondary trommels. The trommels are large cylindrical drums with thousands of holes of uniform size. The primary trommels have 5.5" diameter holes. The secondary trommels have 1.75" diameter holes at the input end and 2.5" diameter holes at the outlet end. The trommels are on a three (3) degree angle sloping from the inlet to the outlet.

As the trommels rotate, the materials that are less than the size of the holes fall through to the conveyor below. This material from the primary trommel is run under a magnet to remove ferrous material and then is conveyed to the secondary trommel. There the material less than 1.75", is dropped out and is conveyed to the glass system for further segregation and processing. The remaining material that is greater than 1.75" but less than 2.5" is separated out and is conveyed directly to the RDF storage building. The oversize material from the secondary trommels is processed under the eddy current separators to remove aluminum cans. With respect to the glass recovery system, it will yield an organic-free glass product and a compostable organic material. The glass product will be sold for use in concrete aggregate, and the organic material will be processed off-site into compost for use as a soil amendment.

The oversize material from both the primary and secondary trommels is conveyed to the heavy-duty shredders. The shredders reduce the material to 3.5" or smaller. The shredders are enclosed in reinforced concrete structures with a fire suppression and protection system, explosion venting through the roof and relief panels. The shredder enclosures are located outside and adjacent to the processing building. A simplified process flow diagram of the materials recovery and fuel preparation system is shown in Figure 4.

The shredded material is then conveyed to the RDF storage building where it can be used immediately or stored until needed. The RDF storage building provides a 3-day inventory of fuel.

In order to minimize dust and odors within the MSW tipping floor, processing areas and RDF storage area, combustion air for the boilers is drawn from these areas. This causes a slight negative pressure in the buildings which results in air always being drawn in.

Power Plant

The Power Plant consists of two (2) parallel, 600 tons per day (based on a design RDF heat content of 6,170 Btu/lb.) circulating fluidized bed boilers, each producing 229,000 pounds per hour of superheated steam. They will be operated 24 hours per day, 345 days per year. It is estimated that 20 days of maintenance will be performed on each boiler per year. However, even during periods of major maintenance, one of the boilers will remain in service so that the plant will effectively be in operation 365 days per year.

At the maximum continuous rating (MCR) of the boilers, 458,000 pounds per hour of high pressure superheated steam (900 psig @ 830° F) are generated and directed to one 55 MW turbine generator. The electricity generated by the condensing turbine that is not required for in-plant use is exported to Commonwealth Edison. The furnace system within each boiler is capable of handling fuel with a higher heating value (HHV) range of 4500-7000 Btu/lb. In each boiler, the RDF furnace is fed through the front wall of the furnace. The top supported boiler walls are water-cooled, welded-tube-and-fin construction. During start-up, bed inventory will be sand. The bed inventory silo will later be filled with screened bed ash material and sand, which will be used thereafter to make up lost material.

Following each furnace is a single high-efficiency steam-cooled cyclone. The design effectively handles the thermal variations which occur when burning RDF and will give reliable operation for many years. The cyclone separates entrained solids including unburned carbon from the flue gas and returns them to the furnace, providing excellent carbon burn-out. A cross-section of the boiler is shown in Figure 5.

Downstream of the cyclone is a vestibule that encloses the steam-generating boiler bank and the pendant finishing superheater. The heat-recovery area (HRA) is the final segment of the steam generator. It encloses the primary superheater and economizer. All tubes in the HRA are designed on a large clear spacing with a low inter-tube velocity to minimize any accumulation of sticky ash deposits. Flue gas leaving the economizer will pass through the air emissions control system prior to discharge to the exhaust stack.

Flue gases are cleaned in an air emissions control system which includes dry scrubbers and fabric filters. The air emissions are continuously monitored in accordance with the facility's Air Quality Permit issued by the Illinois Environmental Protection Agency (IEPA). Lime and activated carbon are injected to control the acid gasses and mercury levels. A selective, non-catalytic reduction (SNCR) system, using Urea, is also injected for NOx reduction.

Due to the highly efficient combustion characteristics of the CFB technology at relatively low combustion temperatures (1500° - 1700°F) and high gas residence time, together with staged combustion, NOx emissions have been extremely low. So low that Urea injection has not been necessary to meet permit limits.

To meet the hydrogen chloride and sulfur dioxide emission permit limits, each boiler is equipped with a dry flue-gas scrubber in combination with a fabric-filter baghouse. In the dry flue-gas scrubbers, lime slurry is atomized and injected into the flue-gas stream, neutralizing the acid-gas components. The water in the slurry is evaporated by the hot flue gas producing dry powder reaction products. Additionally, small quantities of activated carbon are mixed with the lime slurry and sprayed into the flue-gas scrubber to reduce emissions of mercury.

The particulate matter, consisting of flyash, dry scrubber reaction products and unreacted lime, is collected on an array of fabric filter bags contained in multiple modular units (with redundant capacity). Approximately 99.6% of the particulate is being removed.

The continuous emissions-monitoring system is being used to control and record flue-gas opacity, sulfur dioxide, carbon dioxide, carbon monoxide, nitrogen oxide, and total hydrocarbons ensuring compliance with applicable environmental standards. All of this data is also available to be telemetered to the IEPA.

Overall, the advanced combustion technology available by using the CFB boilers, coupled with the front end processing of all waste into RDF, and the highly efficient air emissions control system, have resulted in air emissions well below permit limits. The results of recent stack testing, which were performed in mid January, 1997 are compared to the regulatory limits in Table 2. The continuously monitored pollutant values and their limits, are summarized in Table 3.

That portion of bottom ash which is not recycled for use in maintaining CFB inventory, and flyash, are conveyed to their respective storage locations. The flyash can either be conditioned with water, loaded into covered trucks and sent to an approved ash disposal site, or transported dry for possible use by a local cement company. All ash streams are periodically tested and have been classified as non-hazardous.

APPROACH TO START-UP

On November 23, 1994 upon completing financing and with the necessary permits issued, the Project was provided with its official Notice to Proceed. This notice initiated a thirty-three (33) month schedule which was the original duration planned for the engineering, procurement, construction, and start-up of the Facility. As with other Foster Wheeler facilities, which relies on its own family of companies for the engineering, boiler supply, construction and start-up, this project was aggressively pursued and fast tracked to assure on-time completion. This proven approach resulted in completing the Facility seven (7) months ahead of schedule with Commercial Operation declared on January 22, 1997.

Preparation for the Start-up and Operation was initiated by Foster Wheeler Illinois (FWI), a wholly owned subsidiary of Foster Wheeler Power Systems (FWPS), during the early engineering phase of the project. This consisted of reviewing all applicable technical specifications and drawings to assure lessons learned at other FWPS Plants were incorporated. Also, a detailed review of all permits were undertaken to summarize the various programs, plans and reports for which FWI would be responsible. These, along with the programs and plans normally incorporated by FWPS, were then all logically placed into an overall Start-up Activity Schedule. This particular schedule consisted of over 190 tasks. Primary activities included:

- Staffing Plan
- Training Program
- Operations and Maintenance Manual
- Test and Turnover Manual
- Subsystem Startup Schedule
- Startup Plan

- Equipment Purchases and Plant Supplies
- Plant Normal and Emergency Procedures
- Outside Services and Sub-Contractors

The original staffing plan called for 79 employees organized as depicted in Figure 6. Operating Supervisors were placed at the Facility a full year prior to Start-up.

FWI and FWPS developed for the Robbins Resource Recovery Facility a detailed Start-up Plan and Operations and Maintenance Manual. This in-depth set of documents was prepared in accordance with the Construction Permit/PSD, Solid Waste Permit and an environmental Consent Decree with the Illinois Attorney General's Office, along with Foster Wheeler's standard programs and procedures. The manual serves as both a technical and administrative reference and contains the necessary information to assist the plant staff in the start-up, operation and maintenance of the facility. In addition, an entire volume has been dedicated to an overview of all permits with a compliance summary to assure a proper understanding of the permits that exist and their operating criteria. In total, seventeen (17) volumes were required. The Table of Contents for the Robbins Resource Recovery Facility Start-up Plan and Operations and Maintenance Manual is shown in Table 4. The major parts of the manual are listed below and are followed by a brief description of their purpose and contents.

1) System Operating Procedures

The System Operating Procedures are designed and written in accordance with Foster Wheeler's operating philosophy and are based on the plant's unique design as defined in the drawings and equipment specifications. They are also based upon the operating instructions furnished by the various equipment vendors. Each operating procedure contains as a minimum, the following sections:

- System Overview
- Major Components
- Control of Major Components
- System Operating Instructions (SOI)
- Troubleshooting
- Appendix - System Operating Instructions
- Appendix - Initial Valve and Switch Alignment

The system operating, maintenance and start-up procedures presented in volumes 1 to 3 were developed specifically with the end user or plant staff in mind and are a plant specific document. Each section describes a system with an overview, annotated list of components and description of the control system. These are purposely kept concise and when coupled with the Engineering Flow Diagrams in volumes 12 to 17, provide an understanding of each system and its operation. The next part, the system operating instructions (SOI), coupled with the initial valve and switch alignment in the section's appendix explains exactly how each system is to be prepared, started-up, operated (normal), and shutdown. Finally, the last part, the troubleshooting guide, provides the necessary information to analyze and correct malfunctions, abnormalities, etc. to assure the continuous operation of the system.

2) Maintenance

The Maintenance program contained in the manual was designed to provide an effective inspection, maintenance, repair and parts replacement program. Through the implementation of this program, equipment within the plant will receive the appropriate maintenance to assure maximum productivity and reliable performance. Because of the number and complexity of equipment and parts and the need to assure that an organized maintenance program exists, a computerized maintenance management system was implemented. This system allows all necessary information about equipment, including parts, warranties, vendors and labor to be organized and easily accessed. In addition, the system provides the best means of planning for and completing all preventive and predictive maintenance, routine testing and reporting, inspections, etc.

3) Safety

Emphasizing Foster Wheeler's policy to maintain safe working conditions for employees, subcontractors and visitors, accident prevention can only be achieved by taking a structured approach through a formal plant safety program. Within the Safety Program Manual, the following information and procedures are included:

- Safety Policy
- Safety Program Outline
- Safety Organization and Responsibility
- Safety Miscellaneous Memos/Focus Topics
- Safety Handbook
- Safety Inspections
- OSHA Inspections
- Record Keeping and Reporting
- Medical Exams
- Substance Abuse Program
- Alternate Work Program (Light Duty)
- Employee Training Summary
- Personnel Protective Equipment
- Emergency Planning
- Safe Work Permits
- Electrical Safety Program
- Lock Out/Tag Out Clearance Program
- Confined Space Entry Program
- Contractor Orientation & Safety
- Hazardous Communication Program
- Respiratory Protection Program
- Exposure Monitoring and Control Program
- Hearing Conservation Program
- Bloodborne Pathogens Exposure Control Prog.
- Chemical Hygiene Plan for Chemistry Lab.
- Fall Protection Program
- Walking-Working Surfaces Safety Prog.
- Cranes
- Safe Sling Use
- Industrial Vehicles
- Process Safety Management
- Special Conditions
- Torch Cutting and Welding
- Portable Power Tools
- Abrasive Grinding Machinery
- Signs and Tags

4) Training

To prepare newly hired personnel to assume positions at the Robbins Resource Recovery Facility, a comprehensive training program was developed and implemented. The program consists of several different curriculum, each combining formal classroom instruction with hands-on and on-the-job training. The training program for the Robbins Resource Recovery Facility is comprised of three major areas:

- Operator Training, including appropriate portions of classroom and hands-on instructions.
- Maintenance Training, including specialized classroom instruction and hands-on training.
- Supervisor Training, including specialized training as well as classroom instruction at various times with their respective groups.

The operations training course was designed to cover the theory of plant operation, safety and fire protection, and design and operating principles of the individual equipment, including environmental considerations. Also included was instruction regarding start-up, routine and emergency operation, and shutdown of all systems and components. Similarly, the maintenance courses are developed from material covering subjects such as tools, work practices, methods, safety and fire protection.

These basic training courses which also include specialized safety videotapes and materials are enhanced by the addition of facility specific vendor training during and following start-up of the facility. Within the Training Manual the following topics were included:

- Plant Orientation
- Safety, Security and Emergency Response Plan
- First Aid and CPR
- Fire Fighting and Protection Systems
- Supervisor Training
- Power Plant Principles
- System Operating Procedures
- Maintenance Training
- Vendor Training

5) PERMITS

The Permit Overview and Compliance Summary contained within the manual was developed to help the Robbins Resource Recovery Facility's staff to more easily understand the applicable regulatory compliance issues. Each summary section is based on operation of the facility. Therefore, pre-construction and construction activities are considered completed within the scope of this section. By having the compliance information summarized in a user friendly format, additional emphasis will be placed on always adhering to permit requirements. An actual copy of each permit is included in the manual, each under its own tab, and is periodically used for compliance evaluation. The following permits have been included:

- IEPA Construction Permit/PSD Approval
- IEPA Solid Waste Construction Permit
- NPDES-Storm Water Permit
- Water Pollution Control Permit
- Federal Aviation Administration Permit
- Illinois Department of Transportation Permit (IDOT) - Roadway
- Wetland Permit - Construction
- Sewer Related Permits
- Endangered Species
- Hazardous Waste
- Illinois Historic Preservation Review

In addition to the permits, other documents, which will assure the safe and proper operation of the facility while minimizing the impact on the environment, include:

- Hazard and Operability Study (HAZOP)
- Emission Test Plan
- Continuous Emissions Monitoring Procedures
- Mercury Optimization Plan
- NOx Abatement/Optimization Plan
- Remedial/Corrective Action Plan
- Ash Management Plan
- Noise Survey
- Ambient Air Monitoring Program

STARTUP ACCOMPLISHMENTS

Through proper planning and the proper allocation of resources, coupled with working very closely with the IEPA and Illinois Attorney General's office, the Robbins Resource Recovery Facility was commissioned and started up ahead of schedule. With construction starting in February, 1995 the electrical switchyard was completed with the back-feeding of power on June 12, 1996. Overall mechanical completion from a construction perspective occurred on September 20, 1996. Through the sequential turnover of subsystems and systems prior to mechanical completion an effective and orderly startup was possible. On September 9, 1996 MSW was first delivered to allow for check-out and startup of the RDF Plant. In parallel with this effort the Power Plant was commissioned with natural gas firing, via the auxiliary burners provided on both boilers, on September 19, 1996. This was followed shortly thereafter by the blowing of steam lines and the initial synchronization of the turbine generator, using natural gas, on October 31, 1996.

With the facility properly commissioned, and all major systems and equipment proven reliable, RDF was introduced and properly fired within the boilers beginning on November 8, 1996. Prior to the introduction of RDF the boilers are first fired using natural gas via auxiliary burners to obtain a cyclone outlet gas temperature of greater than 1500°F. This assures that the RDF will be properly combusted with sufficient temperatures to destroy any organics. A cold start can be accomplished in less than 6 hours with a hot start in under 1.5 hours.

After completing all final checks as the boilers were fired on RDF, the plant was raised to full load operation to allow tuning of the control system for full automatic operation. Once completed, a seven (7) day Facility Acceptance Test was undertaken. This test started on January 14, 1997 and was successfully completed 7 days later on January 21, 1997. Acceptance criteria consisted of:

- RDF Processing Capacity
- RDF Processing Recovery (greater than 25%)
- Boiler/Power Plant Availability
- Boiler/ Power Plant Capacity
- Electrical Generating Rate
- Boiler Residue Rate
- Environmental Compliance

With respect to the RDF plant, recovery overall has exceeded the 25% minimum requirements. Recovery rates for specific recyclable materials are shown below.

Ferrous Material	90%
Aluminum Cans	65%
Glass Material	90%
Compostable Organics	55%

CONCLUSIONS

Although only recently started and placed into commercial operation, the Robbins Resource Recovery Facility has not only established new benchmarks of environmental performance, it has already benefited the Village of Robbins. The Robbins Facility by accepting, separating and processing all residential and commercial waste delivered to the plant has allowed the village, and surrounding communities to reduce or eliminate the cost of separate recycling programs and disposal of materials prohibited in landfills.

The pretrommeling of MSW and the glass-recovery system, combined with the proven high efficiency, stable combustion and low emissions of the CFB combustion design give the Robbins Facility several unique attributes when compared to other waste-to-energy projects. These attributes are:

- Low Air Emissions
- High Materials-Recovery Capabilities
- Superior Energy-Recovery Efficiency
- Low Ash Generation
- Low Overall Waste-Disposal Cost

The ambient air monitoring program, which has been in operation at various locations around the suburbs of Chicago for over a year, will continue to collect and analyze air samples now that the facility has been placed into service. Based on the extremely low air emissions from the facility, its impact on the ambient air is expected to be truly non-existent.

As additional operating data and information from the facility and the various programs become available, future papers will be published to allow all interested parties to keep informed on this next generation resource recovery facility.

Table 1. Design Waste Composition.

Material	Percent
Newspaper	10.1
Corrugated Cardboard	8.7
Other Paper	27.3
Plastics	8.1
Wood	4.8
Textiles	3.3
Rubber and Leather	1.5
Food Waste	7.2
Yard Waste	9.7
Glass	9.3
Ferrous	5.2
Aluminum Cans	1.1
Other Aluminum	0.3
Non-Ferrous	1.0
Sand, Stones, etc.	2.4
Total	100.0

Table 2. Comparison of Compliance Stack Test results to the Emission Permit Limits.

Burning 100% RDF

Pollutants		Unit A	Unit B	Robbins permit
Particulate	gr/dscf	0.0015	0.0056	0.01
SO_2	ppm	1.0	0.5	30
HCl	ppm	4.6	6.2	25
CO	ppm	4.4	2.2	100
NO_x (1)	ppm	73.1	90.4	130
VOC	ppm	1.5	0.6	10
Total dioxin-furans	ng/dscm	2.1	4.9	30
Total TE (89 EPA)	ng/dscm	0.05	0.13	NA
Arsenic	μg/dscm	0.2	0.2	10
Cadmium	μg/dscm	<detection limit	0.3	40
Chromium	μg/dscm	4.8	5.6	120
Lead	μg/dscm	3.6	30.9	490
Mercury	μg/dscm	15.8	2.9	80
Nickel	μg/dscm	3.1	3.1	100

All concentrations are at 7% O_2
NA-Not applicable
(1) NO_x values are without SNCR system in operation

Table 3. Comparison of Continuously Monitored Pollutants to the Emission Permit Limits.

Pollutants		Unit A/B Average	Emission Limit
SO_2	ppm	0.9	30 ppm @ 7% O_2 -24 hr. block average
CO	ppm	3.85	100 ppm @ 7% O_2-4 hr. block average
NO_x	ppm	80.25	130 ppm @ 7% O_2-24 hr. block average
THC	ppm	1.55	10 ppm @ 7% O_2- 24 hr. block average
Opacity	%	2.50	10% over a 6 min. block average

Table 4. Start-up Plan and Operations and Maintenance Manual Table of Contents

Volume	Description
1	Introduction
	Description of Manual
	Manual Revision Requests
	Matrix of Vendors Manuals
	List of Enclosed Drawings
	Test/Turnover Program
	Plant Black Start Procedure
	Plant Cooling/Circulating Water System
	Plant Compressed Air System
	Demineralized Water System
	Scrubber, Lime & Activated Carbon Systems
	Bag House
	Plant Control System
2	Feedwater System
	Boiler/Steam Generator
	Combustion Air and Flue Gas
	No_x Control/UREA Injection System
	Steam Turbine and Condenser
	Plant Electrical System
3	Waste/Raw/Potable Water
	Plant Fire Water System
	Bottom and Fly Ash Handling Systems
	Refuse Receiving and Processing
	RDF Fuel Feed
	Blowdown System
	Main Steam System
	Sampling
	Natural Gas System and Burners
4	Mercury Optimization Plan
	Emissions Test Plan
4	Continuous Emissions Monitoring Procedures
	Remedial/Corrective Action Plan
	NO_x Abatement/Optimization Plan
	Ash Management Plan
5	Contingency Plan
	Inspection Plan
	Waste Management Plan
	Record Keeping
	Community Relations Plan
	Facility Staffing Plan
	IEPA Notification Procedure
	Fugitive Particulate Control Program
6	Safety Program Manual
7	Safety Program Manual
8	Preventive Maintenance & Spare Pts.
9	Training Program Manual
10	Permit Overview & Compliance Summ.
11	Hazard and Operability Study
12	Engineering Flow Diagrams (4261-1-50-1 to 4261-1-50-203)
13	Engineering Flow Diagrams (4261-1-50-204 to 4261-1-50-510)
14	Electrical Power One-Line Diagrams (4261-173-1 to 4261-1-73-18)
15	Electrical Power One-Line Diagrams (4261-1-73-19 to 4261-1-73-37)
16	Electrical Power One-Line Diagrams (4261-1-73-38 to 4261-1-73-59)
17	Site Preparation Plan Drawings (4261-1-51-100 and 4261-1-41-3 to 4261-1-41-22)

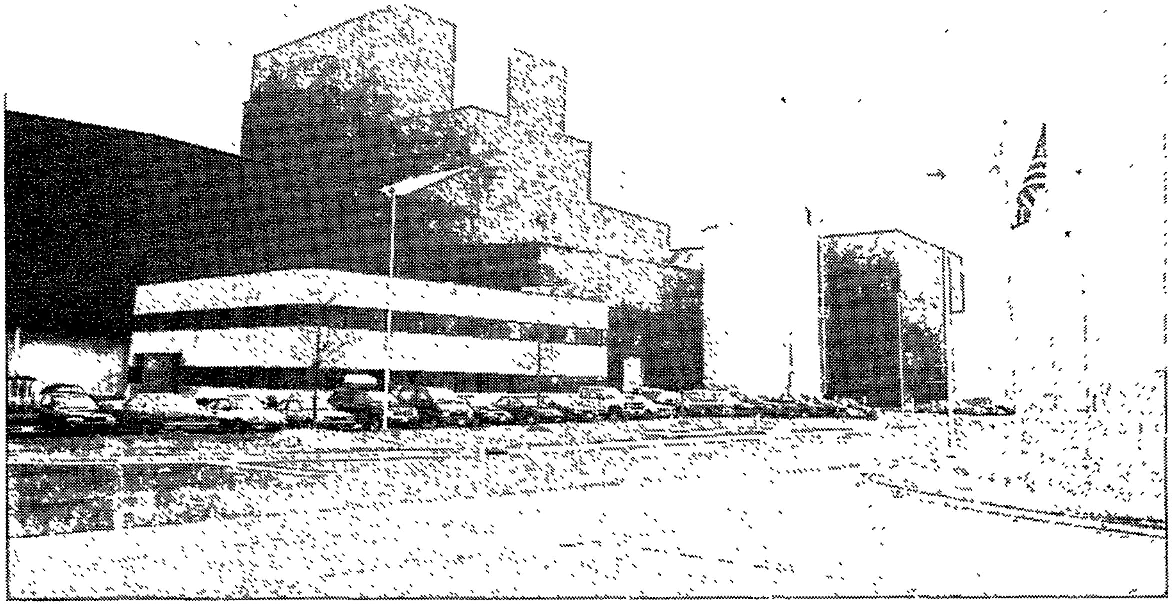

Figure 1. Photograph of the Robbins Resource Recovery Facility.

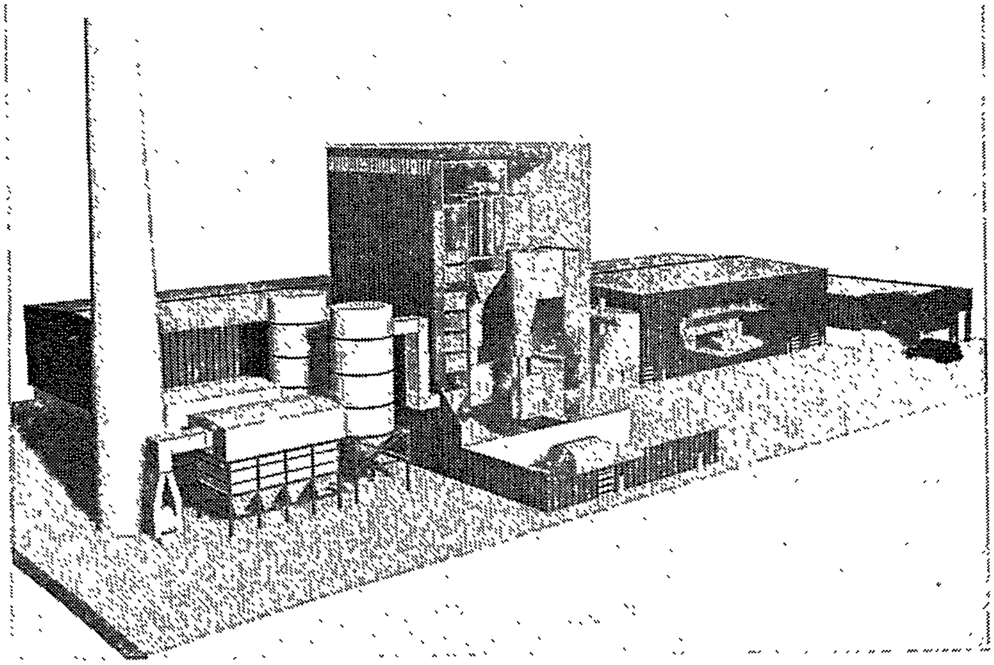

Figure 2. Computer Model of the Robbins Resource Recovery Facility.

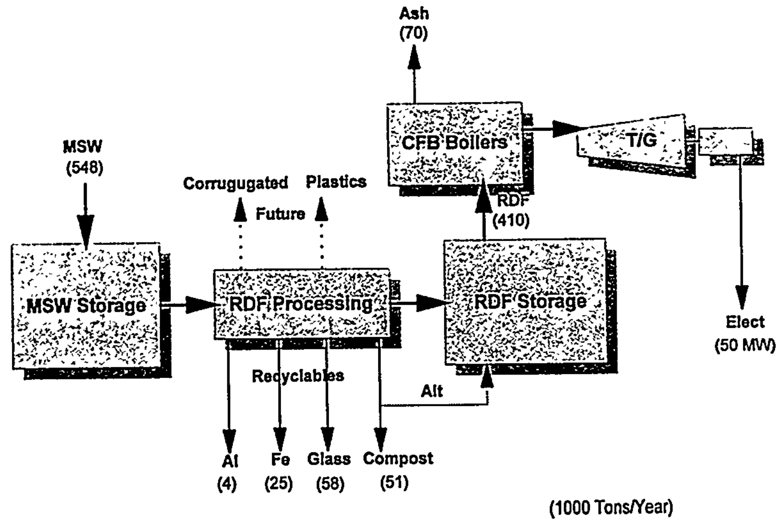

Figure 3. Robbins Process Flow Diagram

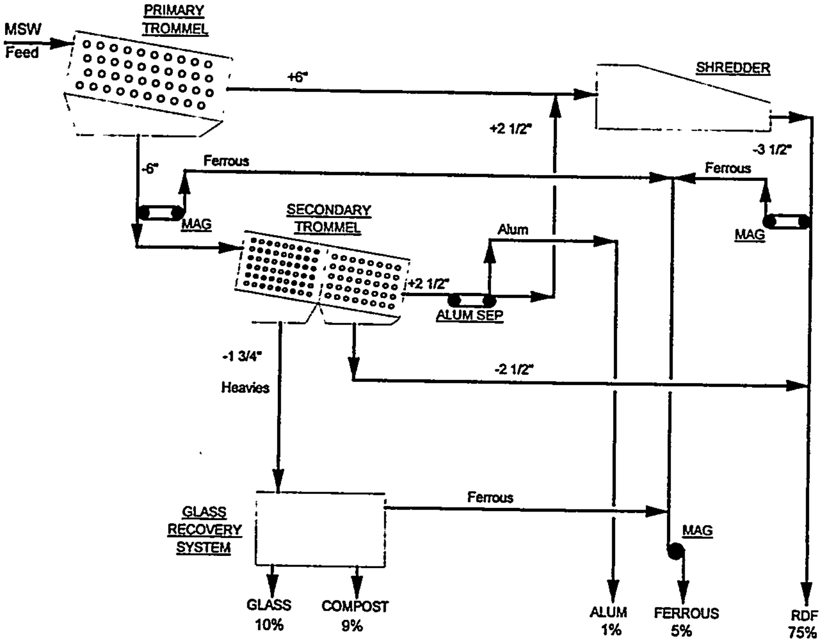

Figure 4. Robbins Fuel Preparation System

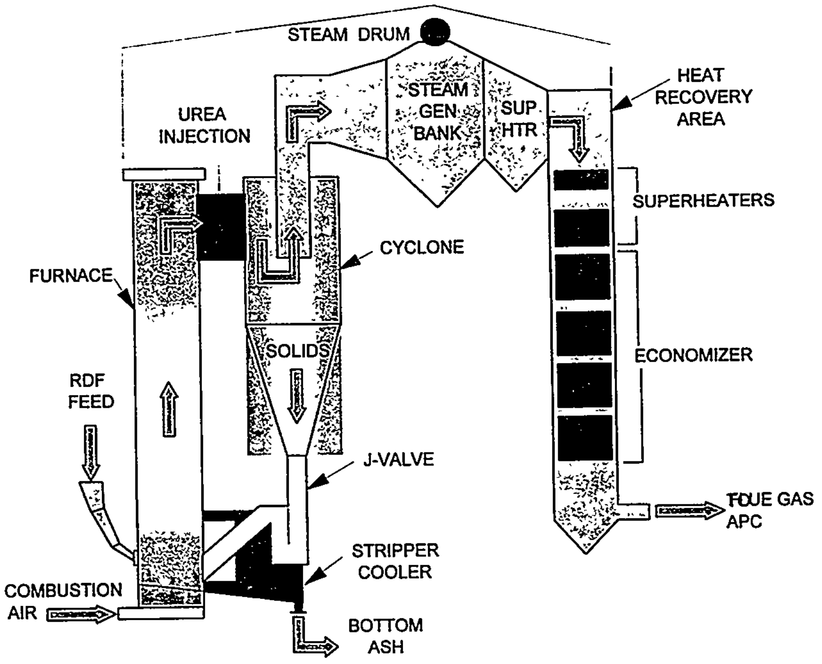

Figure 5. Robbins CFB Boiler

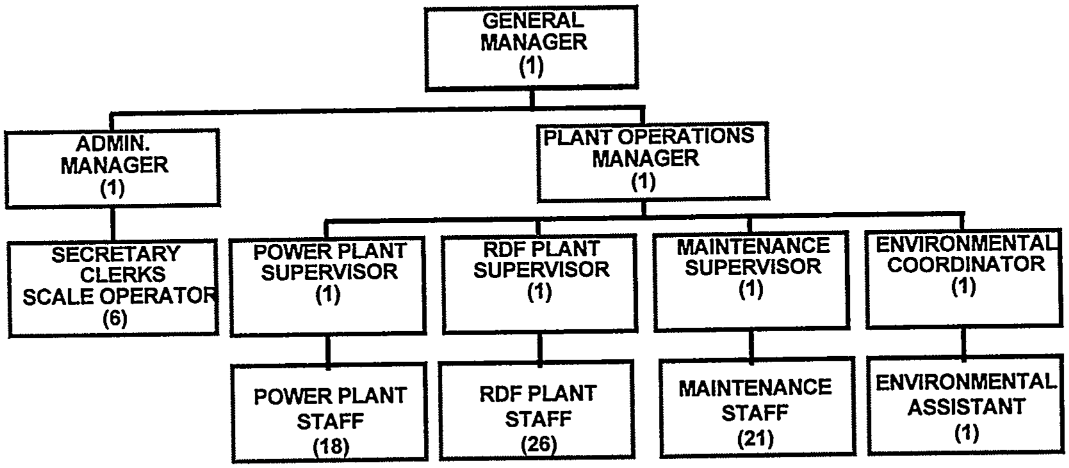

FIGURE 6. ROBBINS ORGANIZATION CHART

TECHNICAL SESSION III

Emissions Control

Mercury Emissions - Trends and Control Effectiveness

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INTRODUCTION

Emissions of mercury from municipal waste combustors has been an item of interest in the 1990's. Standards have been established by the USEPA[1] (MACT Standard) and by state regulatory agencies such as the New Jersey Department of Environmental Protection[2]. As the owner and operator of facilities that combust over 3.5 million tons per year of municipal waste, American Ref-Fuel has been very active in following the trends in waste mercury content, promoting the recycling of mercury containing wastes, and understanding and applying technologies to minimize mercury emissions from waste combustors.

Mercury emissions from waste combustors is determined by the mercury content of the waste stream, combustion efficiency, and the efficiency of the air pollution control equipment at removing mercury. In this paper we review some encouraging trends in waste mercury levels, and discuss the performance of several different combustor/air pollution control configurations for controlling mercury emissions.

CONCERN ABOUT MERCURY IN WASTE

Concern for mercury in the environment was highlighted in Clean Water Action's 1990 report termed Mercury Rising[3]. The principal argument in the report was that MSW incinerators emit mercury to the atmosphere and that mercury then enters the food chain, thereby increasing the potential health effects due to biomagnification. In this vein, another study[4] found increased levels of mercury in sphagnum moss near a Waste-to-Energy facility. Other studies[5] have placed modern atmospheric deposition rates and sedimentation rates at 3-4 times historical rates, with fresh water lake accumulation being proportional to catchment surface area.

In response to these and other studies, the United States Environmental Protection Agency commissioned a characterization study[6] on mercury containing wastes for the period 1990 to 2000, and the New Jersey Department of Environmental Protection established a Task Force on Mercury Emissions. The NJDEP Task Force report[2] and USEPA study[6] both listed batteries as the principal mercury-containing waste source today. The USEPA study concluded that mercury in waste peaked in 1986 (estimated at 770 tons) and would continue on a downward trend to the year 2000 (to an estimated 173 tons), based primarily on the removal of mercury from alkaline batteries and the elimination of mercury-based biocides in paints, for an overall reduction of over 70%. While we are on a definitive downward trend in mercury use, there will be individual product increases, such as mercury-containing fluorescent bulbs and mercury switches. New product applications, like sneakers with mercury switch activated lights, may also alter the dynamics of the decline.

American Ref-Fuel has seen the results of these mercury reduction efforts at its facility in Essex County, New Jersey. Figure 1 presents the change in uncontrolled mercury levels in the flue gas exiting the boilers, prior to the air pollution control equipment, from 1990 to 1996. In 1990 and 1991, the uncontrolled mercury averaged about 600 μg/dscm, and ranged from about 300 to over 1100 μg/dscm. In 1996, the uncontrolled mercury had dropped significantly, averaging about 200 μg/dscm, and ranging from about 100 to 300 μg/dscm. (Note that all mercury concentrations presented throughout the paper are at 7% O_2.) While Ref-Fuel had developed and implemented a battery recycling program in Essex

County over this time period, the primary cause for this dramatic decrease is believed to be due to decreased mercury entering the waste stream, particularly from batteries. Battery manufacturers have sought to reduce the mercury content in batteries due to public pressure and legislative initiatives like New Jersey's. This downward trend in uncontrolled mercury levels has also been seen in data from other American Ref-Fuel facilities, although the trend is less pronounced and the database is less extensive.

MERCURY CONTROL IN MODERN WASTE-TO-ENERGY SYSTEMS

American Ref-Fuel operates five large municipal waste combustors in the United States employing a number of different combustion and air pollution control technologies. Reviewing the mercury emissions from these facilities illustrates the importance of both the combustor design and the type of air pollution control equipment, in determining the mercury control performance.

Ref-Fuel's first three facilities employ Deutsch Babcock's center-flow combustor design (see Figure 2) and operate with approximately 90% excess air. The air pollution control technologies, however, differ in each facility, as follows:

Essex, NJ	-	SDA / ESP
Hempstead, NY	-	SDA / Reverse-Air FF (low air/cloth ratio)
SE Connecticut	-	SDA / Pulse-Jet FF (high air/cloth ratio)

The average mercury emission and control performance of each of these facilities is presented in Figure 3. While these are commercial facilities, and do not operate identically, they do employ the same furnace design and boiler configuration, and operate with similar combustion conditions and SDA temperatures, which are thought to be the most important operating parameters affecting mercury control. The difference in mercury control between the facilities is believed to be primarily due to the different air pollution control technologies, which is consistent with the current industry knowledge. The SDA/ESP at Essex yields the worst performance, with mercury emissions averaging greater than 200 μg/dscm, and mercury reduction across the air pollution control equipment of about 65%. (This facility recently installed a supplemental mercury control system which will be discussed below.) The reverse-air fabric filter (RA-FF) at Hempstead achieves the best performance, with mercury emissions of about 30 μg/dscm, and reductions of about 95%. This performance rivals that of carbon enhanced systems, and easily meets MACT standards of 80 μg/dscm emission or 85% reduction. This superior mercury control performance is believed to be due to a combination of the large fabric filter, and the quantity and nature of the residual carbon on the fly ash. SE Connecticut, with the smaller pulse-jet fabric filter (PJ-FF), also performs well with mercury emissions of about 60 μg/dscm, and reductions in excess of 80%, but is inferior to the larger reverse-air system at Hempstead.

American Ref-Fuel's SEMASS facility, in Rochester, Massachusetts, provides another comparison of the SDA/FF vs. SDA/ESP for mercury control. The SEMASS facility contains three units, all with the shred-and-burn technology developed by Energy Answers Corporation. Two of the units have SDA/ESP air pollution control systems, while the third unit, which was constructed more recently, has an SDA/FF system. While mercury reduction data is not available for all three units, a comparison of the mercury emission levels again shows SDA/FF systems to be superior to SDA/ESP systems. The unit with the SDA/FF averages mercury emissions of about 20 μg/dscm, while the SDA/ESP units averages about 75 μg/dscm.

American Ref-Fuel's facility at Niagara was recently retrofitted with a new combustor, boiler, and air pollution control system. The combustor is Deutsch Babcock's new parallel-flow design (see Figure 4), which operates with just 60% excess air, and is designed for increased turbulence in the combustion zone relative to the center-flow design. The higher combustion temperature resulting from the reduced excess air, coupled with the improved mixing, result in improved combustion efficiency and lower residual carbon on the fly ash exiting the boiler. The new air pollution control system at Niagara is a SDA/reverse-air fabric filter, with a low air/cloth ratio, similar to that at Hempstead. The strategy in using this design was to seek to achieve the superior emissions control, including mercury, that was demonstrated at Hempstead.

The actual mercury control performance for the retrofitted Niagara facility, however, has turned out to be quite poor. The average mercury emissions and control performance for this new facility is presented in Figure 5, and compared to that of Hempstead. The average mercury reduction across the SDA/RA-FF at Niagara averaged just 35%, and the mercury emissions averaged about 170 μg/dscm. This is considerably worse than the 95% reduction, and 30 μg/dscm emission achieved at Hempstead. The reason for this poor mercury control performance is believed to be due to the reduced, and possibly altered carbon content (due to the higher combustion temperature) of the fly ash at Niagara. Although based on a very limited database, analysis of the carbon content of Niagara fly ash shows it to be about 25% less than that of Hempstead. This alone, however, does not seem significant enough to explain the large difference in mercury control between Niagara and Hempstead. The chemical form of the mercury in the flue gas is also known to affect its adsorption potential on the carbon containing fly ash[7]. The different furnace and boiler configuration at Niagara may alter the speciation of mercury containing compounds in the flue gas entering the SDA/RA-FF, affecting its propensity for removal. However, no data has been collected to support this theory. The new Niagara facility is currently undergoing an evaluation for the addition of a supplemental mercury removal system to reduce the mercury emissions to less than MACT standards.

SUPPLEMENTAL MERCURY CONTROL TECHNOLOGY

While several technologies have been developed and tested to improve the removal of mercury in the primary air pollution control equipment, the injection of powdered activated carbon provides the best fit with the SDA/FF and SDA/ESP systems commonly used in the United States, achieving high mercury reduction at an affordable cost of approximately $1 per ton of MSW. Activated carbon injection has been identified as the Best Available Control Technology by the USEPA, and has been repeatedly demonstrated in tests and commercial applications to easily meet the MACT standards of 80 μg/dscm or 85% reduction. American Ref-Fuel has followed the development and commercialization of activated carbon injection for mercury control, has tested the effectiveness of various methods of carbon injection in their facilities, and has recently installed a commercial system in their Essex County facility.

In the early 1990's, American Ref-Fuel tested two methods of activated carbon injection at its Essex facility. In the first method, the activated carbon was injected "wet", by adding it to the lime slurry being sprayed into the SDA units. The second method injected the carbon "dry", by adding it in powdered form to the flue gas exiting the boiler, upstream of the SDA units. At about the same time, similar tests were being conducted by the USEPA at the Stanislaus County, California facility[8], which employs an SDA/FF system, and at the Camden County, New Jersey facility[9], which uses an SDA/ESP system similar to Essex. The results of these tests provide an interesting comparison of "wet" versus "dry" carbon injection in these different air pollution control systems.

Figure 6 presents mercury reduction data from the three tests for "wet" carbon injection. In the SDA/FF system at Stanislaus, mercury reductions ranging from about 83 to 97% were achieved at carbon injection rates between 60 and 100 mg/dscm. Essex and Camden, with similar SDA/ESP systems, yielded similar mercury reduction performance, but as expected, were inferior to the Stanislaus SDA/FF performance. Essex and Camden achieved only 70 to 80% mercury reduction at carbon injection rates of 80 to 90 mg/dscm.

Figure 7 presents mercury reduction results from the three systems for "dry" carbon injection. Although the data is very scattered at low carbon injection rates, at carbon rates above 50 mg/dscm the SDA/FF system again showed superior performance, with mercury reductions ranging from 88 to 98%. The SDA/ESP system at Essex was only able to achieve 78 to 89% mercury reduction at higher carbon rates of about 90 mg/dscm.

A comparison of the "wet" and "dry" injection results at Stanislaus (Figures 6 and 7, respectively), shows little difference in the mercury reduction performance with their SDA/FF system, as was concluded from the study[8]. However, this was not the case in the SDA/ESP systems at Essex and Camden. Figure 8 presents the "wet" and "dry" carbon injection results for both Essex and Camden. "Dry" carbon injection achieved significantly better mercury reduction performance in these SDA/ESP systems, reaching reductions of about 95% at carbon rates above 200 mg/dscm. While this carbon injection rate is significantly higher than that needed in the Stanislaus SDA/FF system, it does demonstrate that high mercury reductions can be achieved in SDA/ESP systems with "dry" carbon injection. "Wet" carbon injection at Essex and Camden was limited to between 80 and 90% mercury reduction, even at carbon rates above 200 mg/dscm, leaving some doubt as to whether "wet" injection in a SDA/ESP system can consistently meet the MACT standard of 85% mercury reduction. Some industry sources have reported that "wet" injection of carbon with enhancers may perform similarly to "dry" injection systems. If proven true, this may change the relative performance of "dry" vs. "wet" in SDA/ESP systems.

The results of these analyses formed the basis of American Ref-Fuel's evaluation to find the best carbon injection method for a permanent system to be installed at Essex last year. The system installed is a "dry" carbon injection system designed by Norit Americas, Inc. The system is designed to pneumatically convey and inject the activated carbon directly into the side wall of the SDA unit. The system has been in operation since January 1996, and performance to date has been very good, allowing the carbon injection rate to be optimized to maximize both mercury reduction and carbon utilization. The system has achieved 90 to 95% mercury reduction, and emissions of less than 15 μg/dscm, at carbon injection rates of about 75 mg/dscm[10].

SUMMARY AND CONCLUSIONS

The available data suggest that facilities equipped with dry injection activated carbon systems, as part of an SDA/FF or SDA/ESP can easily achieve the MACT standards of 85% mercury reduction or 80 μg/dscm mercury emission. While a number of factors influence the emissions of mercury from a waste-to-energy facility, reverse-air fabric filters appear to have slightly better mercury removal performance when compared to pulse-jet fabric filters, and both types of fabric filters are superior to ESP equipped facilities. The relative performance of the Hempstead and Niagara facilities suggests the importance of the combustor configuration, in conjunction with the air pollution control equipment, for determining mercury control. Improved combustor designs with higher combustion temperatures and better mixing, yield higher combustion efficiency and lower residual carbon on the fly ash, which negatively impacts mercury control in the downstream fabric filter. The mercury control in these more modern designs can easily be recovered, however, by adding a dry injection activated carbon system. Ultimately, facility designers may find a combustor/air pollution control configuration that achieves good combustion and minimal mercury emissions, without requiring the addition of activated carbon. Combustion efficiency and residual carbon quantities alone do not appear to explain the differences between Niagara and Hempstead; other factors related to carbon or mercury speciation may explain more with regard to removal dynamics.

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FIGURE 1
Downward Trend in Uncontrolled Mercury at Essex County

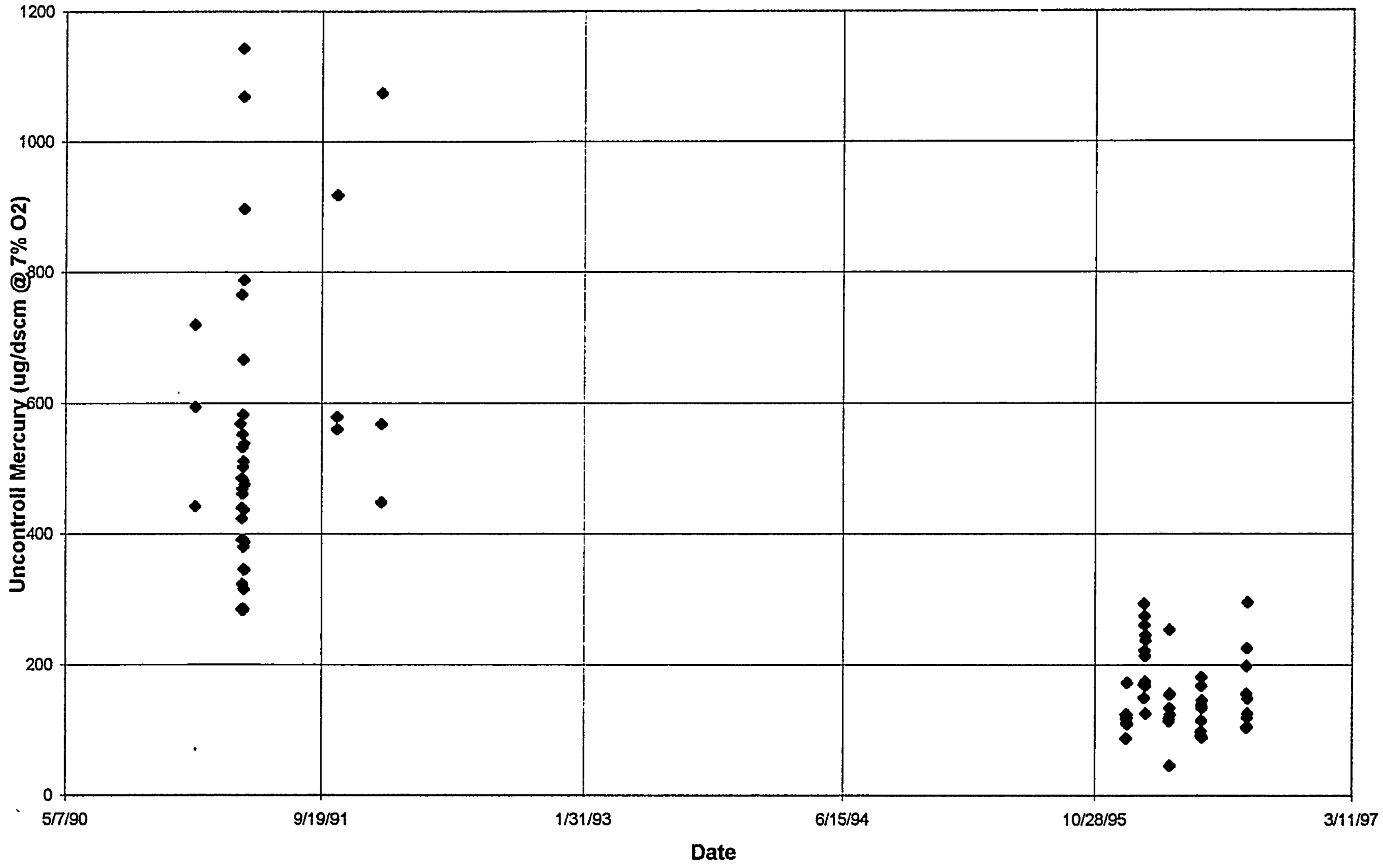


Figure 2
Center-Flow Combustor Design

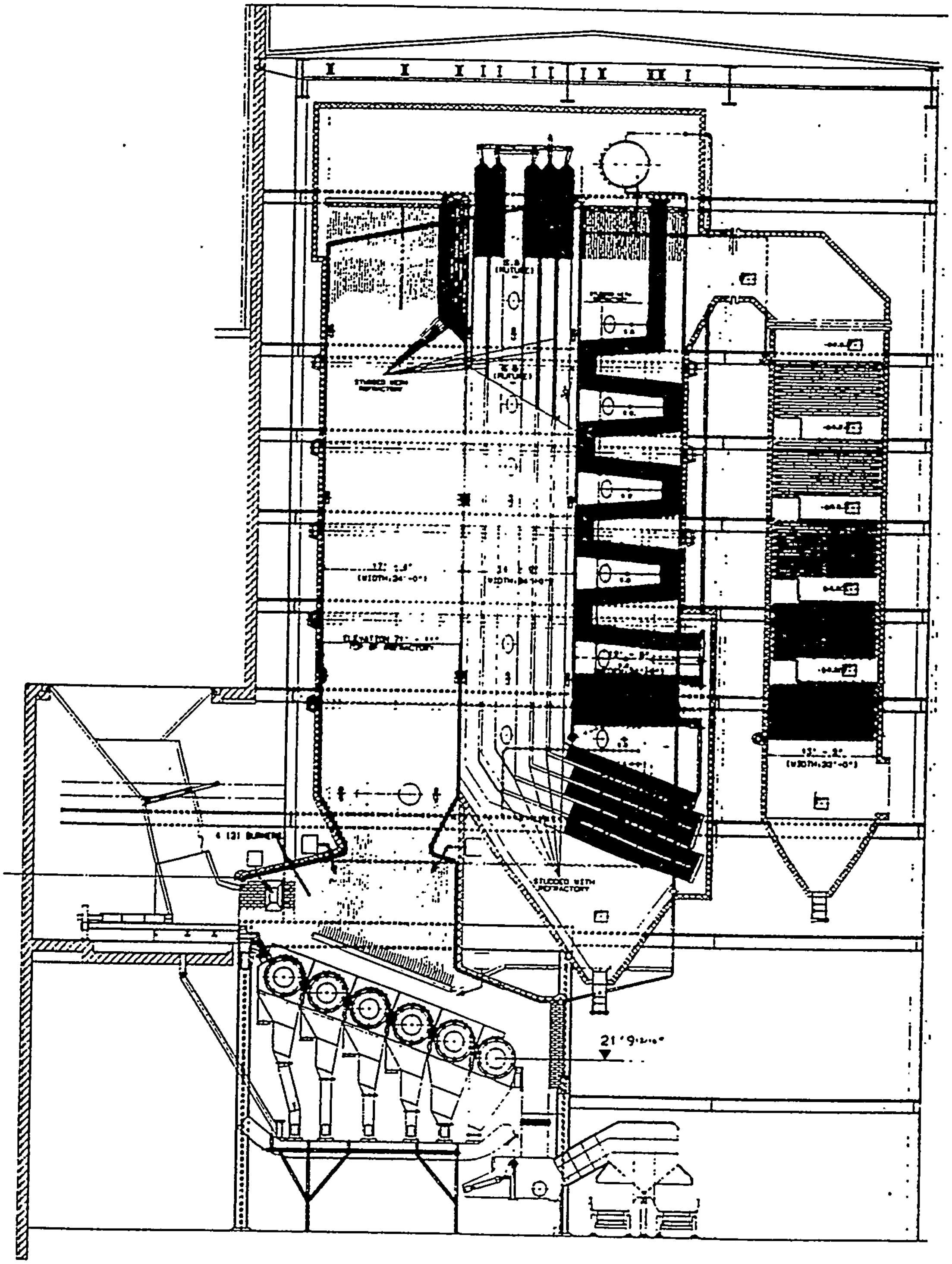


FIGURE 3
Comparison of Air Pollution Control Technology

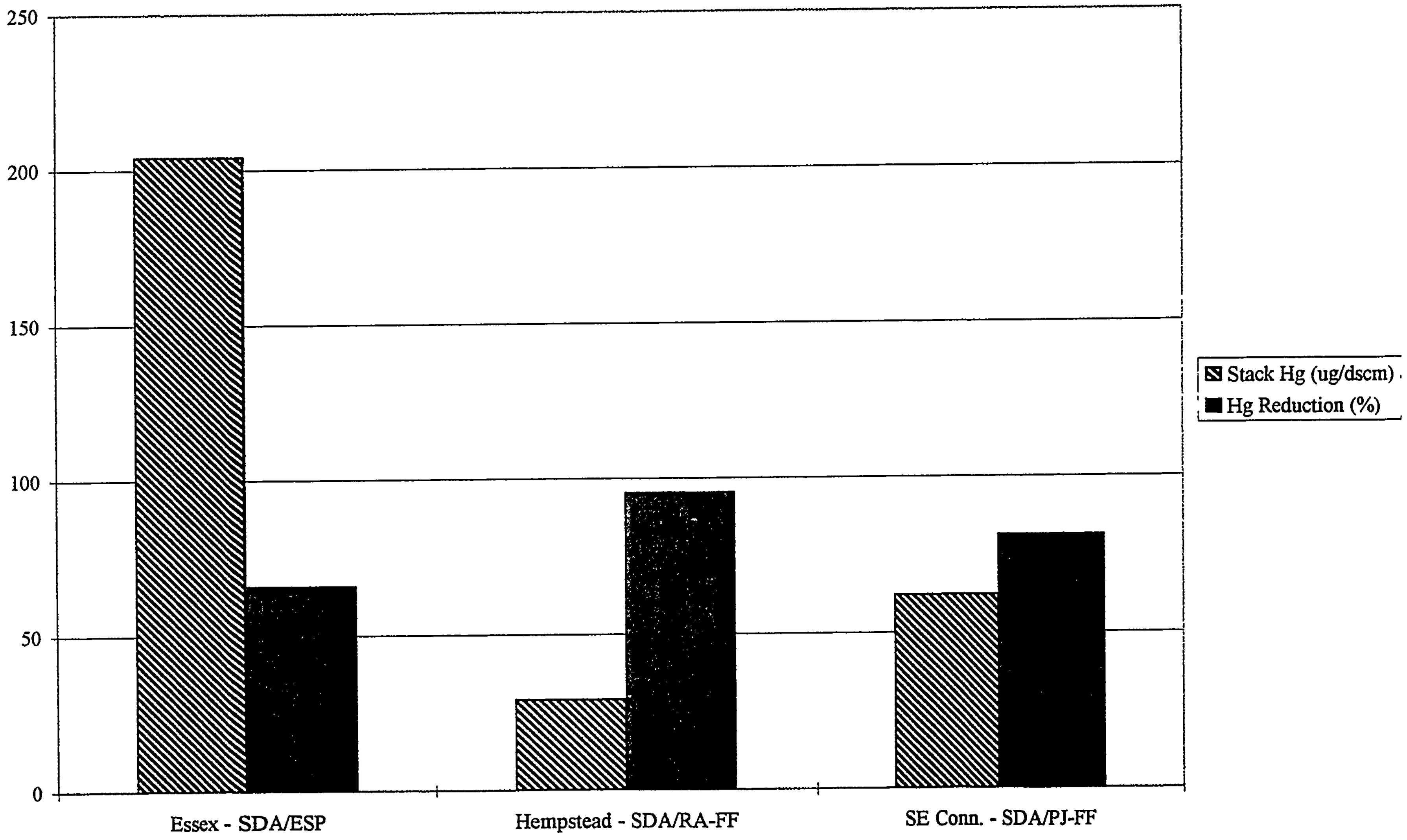


Figure 4
Parallel-Flow Combustor Design

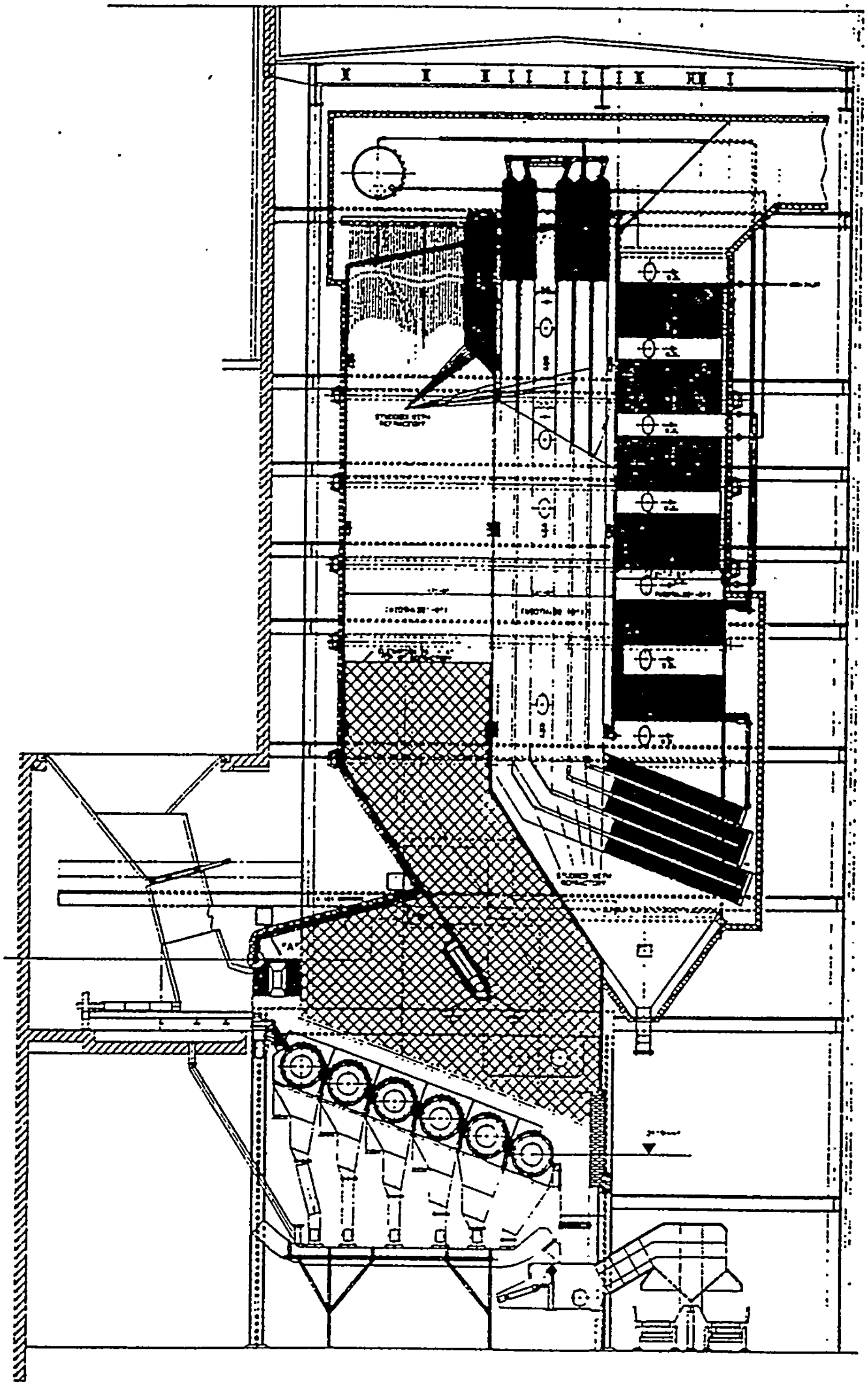


FIGURE 5
Comparison of Combustor Technology

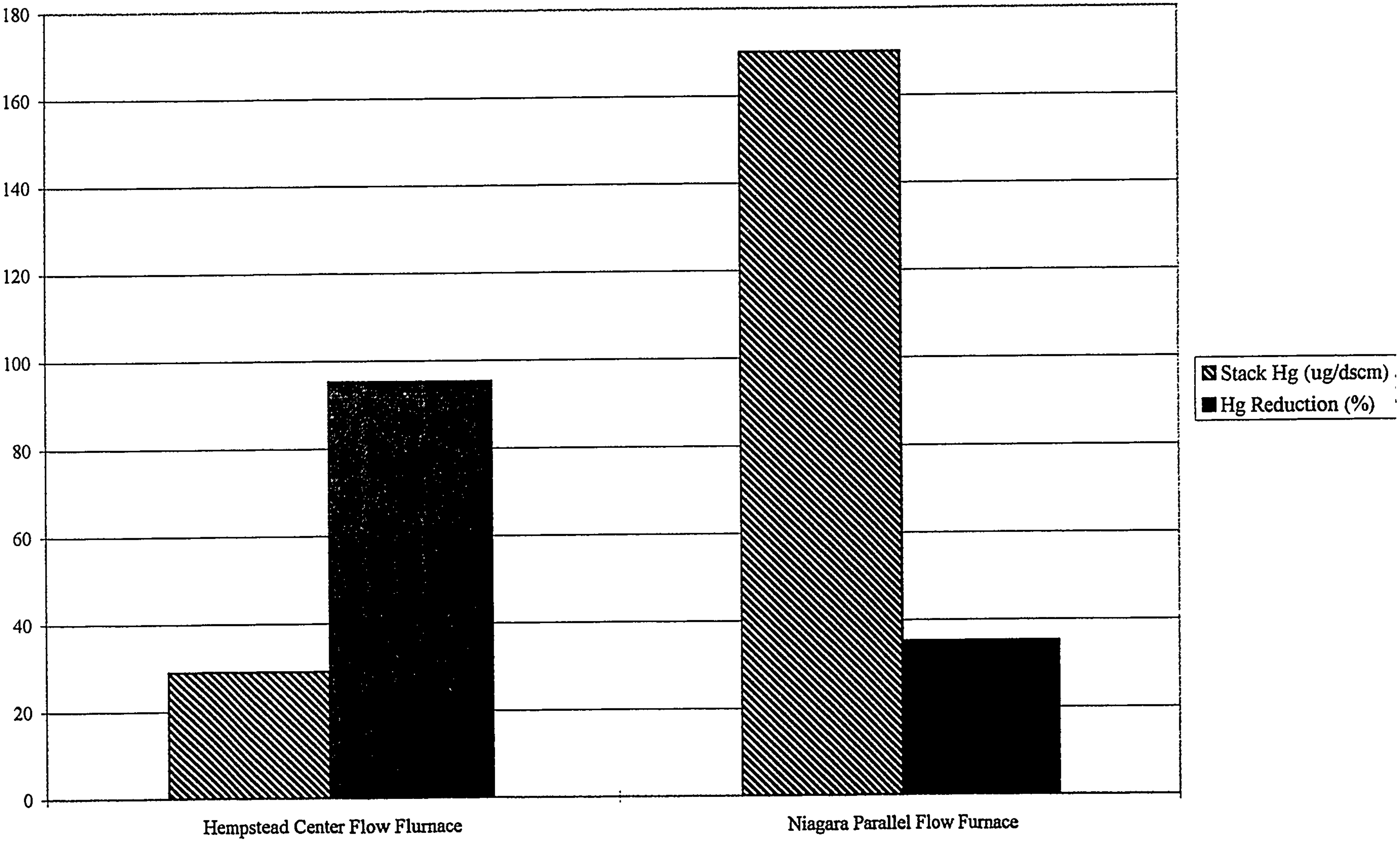


Figure 6
"Wet" Activated Carbon Injection Performance Data

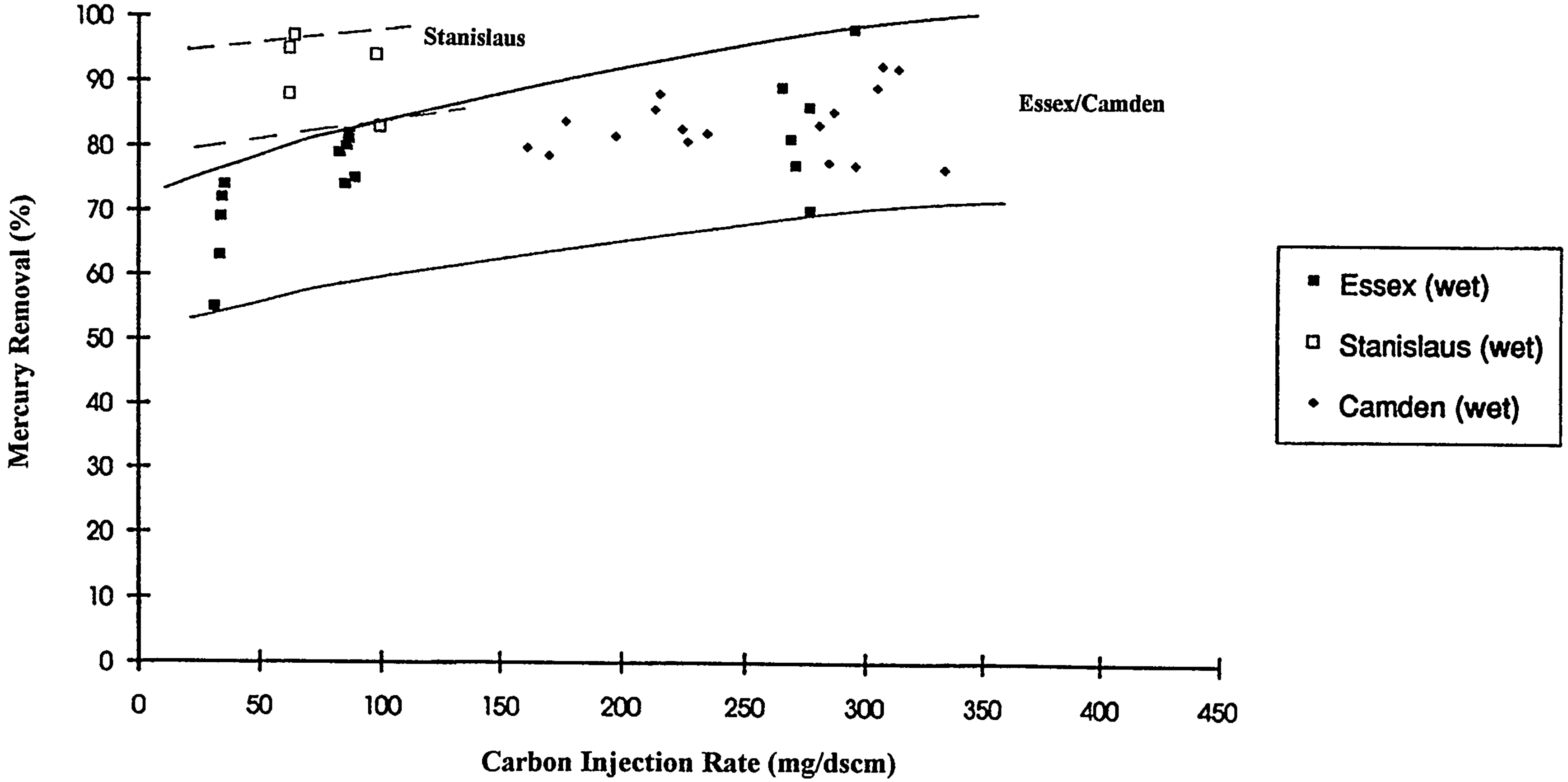


Figure 7
"Dry" Activated Carbon Injection Performance Data

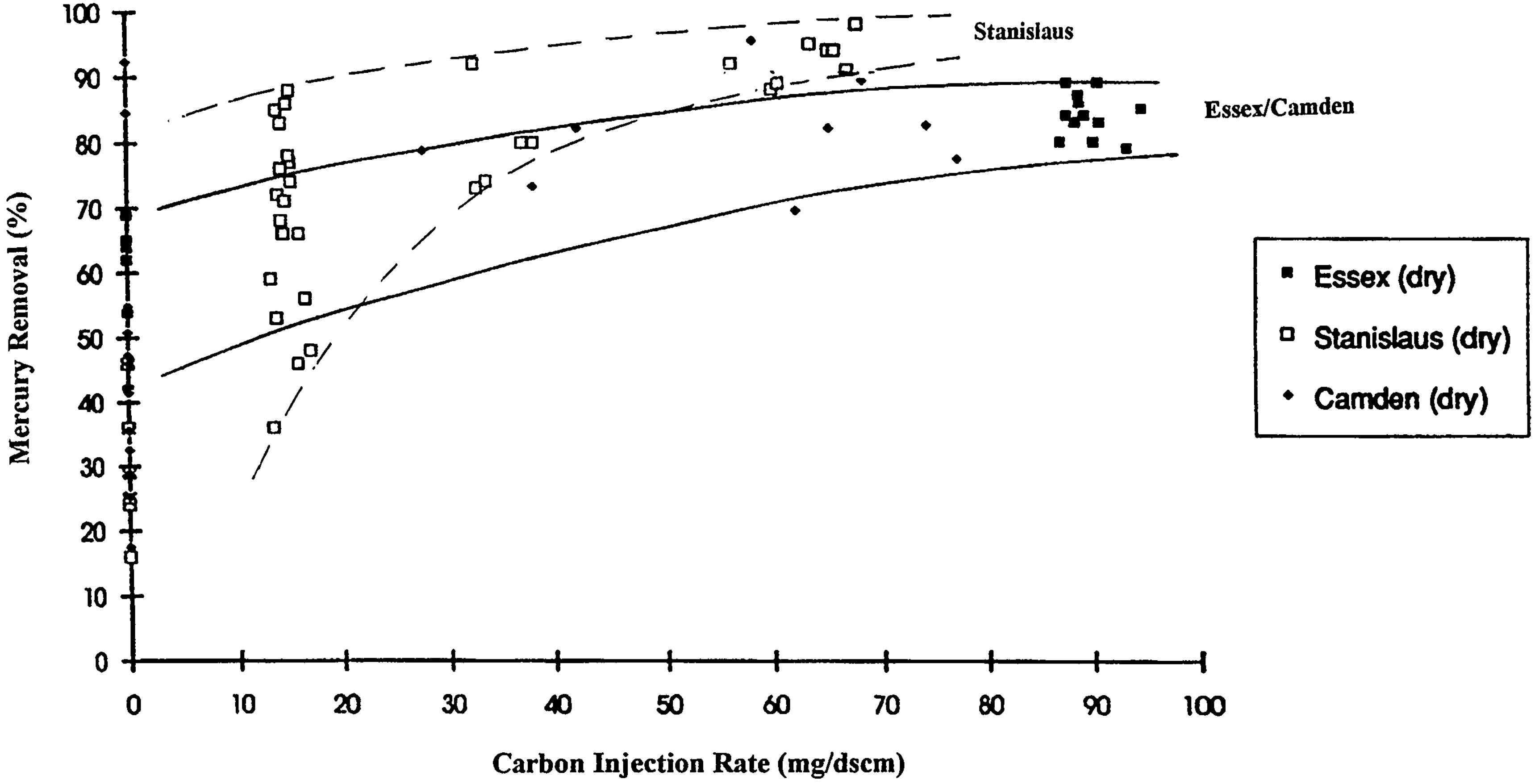
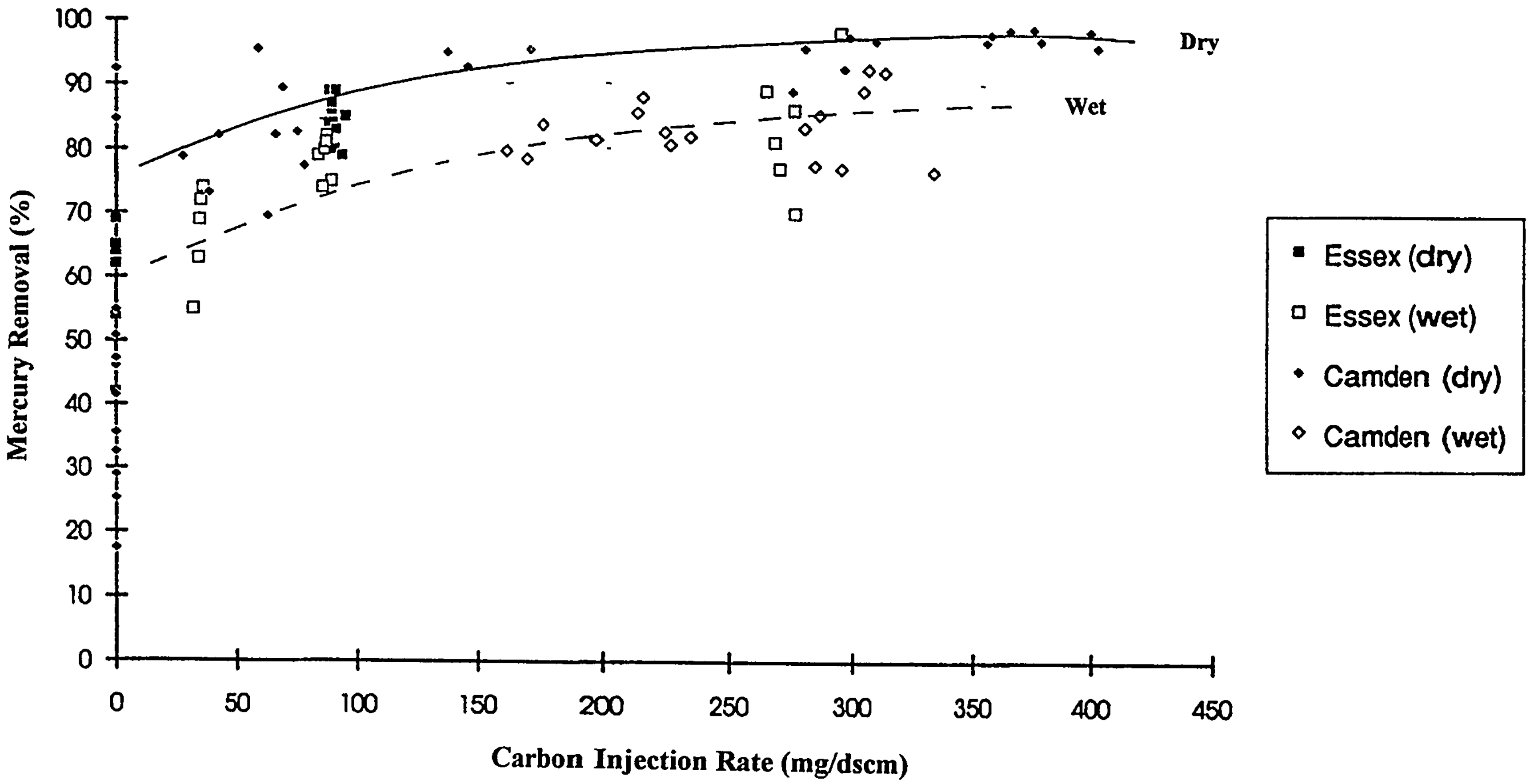


Figure 8
Comparison of "Dry" and "Wet" Carbon Injection for SDA/ESP Systems



Environmental Performance of the Robbins Resource Recovery Facility

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INTRODUCTION

For many years there has been incremental improvement in the environmental performance of Municipal Waste Combustor (MWCs) facilities. These improvements were obtained by additional control hardware and additional chemical additives being applied to traditional grate combustion systems. This paper presents early environmental results from a new and different combustion system for MSW, the Circulating Fluidized Bed (CFB) boiler. These results indicate a significant improvement in the environmental performance of waste to energy facilities.

DESCRIPTION OF FACILITY

The Robbins Resource Recovery Facility located in southern Cook County, Illinois, went commercial in January, 1997. It is designed to recover material for recycling and produce energy in the form of electricity from 1,600 tons per day (TPD) of municipal solid waste. The plant consists of two materials-recovery and fuel-preparation processing lines, two Refuse Derived Fuel (RDF)-fired CFB combustion systems, two state-of-the-art air pollution control systems, and a single turbine generator designed to produce more than 50,000 kW (gross) of electric power. The Robbins facility is a 24 hour-per-day, 365 day per year operation. The annual throughput of municipal solid waste (MSW) will be approximately 500,000 tons, assuming an 85% capacity factor.

This facility incorporates a combination of proven waste-conversion technologies in an innovative manner to exploit their inherent advantages, and the overall design builds on the industry's current experience.

Materials-Recovery and Fuel-Preparation System

Two processing lines, each designed to process 85 tons per hour of MSW, operate at a nominal throughput of 64 tons per hour, 16 hours per day, five-and-one-half days per week.

Trucks deliver the waste to the MSW tipping building, where plant personnel direct the dumping onto the concrete tipping floor and inspect the waste for unacceptable and unprocessible material. Front-end loaders are used to separate unprocessible items, such as large appliances, and push the waste onto the in-feed conveyors. The MSW is conveyed past a picking station located ahead of the primary trommel, where personnel inspect the waste stream and remove additional unprocessible waste. The MSW tipping building is capable of storing 3,000 tons of MSW, or nearly two days of system feed requirements.

The fuel preparation system is shown schematically in Figure 1.

The primary trommel opens trash bags, breaks glass, and separates any material under six inches in size. The fraction of MSW not removed by the primary trommel is shredded using a horizontal hammermill to a particle size of 3.5 inches or less, and sent to RDF storage after passing a magnet for ferrous recovery.

Material removed by the primary trommel is conveyed first past a magnet for ferrous recovery then to a two-stage secondary trommel screen for separation into three streams:

- Glass and organics (yard and food wastes); (19% of waste stream)
- An aluminum-rich fraction (1%); and,
- A fuel fraction of burnable material (75%).

The glass-recovery system yields organic-free glass product (10% of waste stream) and a compostible organic material (9%). The glass product is sold for use as concrete aggregate and the compostible material is processed off-site into compost for use as a soil conditioner. Each processing line incorporates several overhead belt magnets strategically located and designed for the recovery of 90% of the ferrous metals, or approximately 5% of the total MSW throughput. RDF produced is conveyed to the RDF-storage building where an almost three-day (3,500 tons) intermediate storage capacity is provided. Direct-feed conveyors or front-end loaders transfer RDF to the CFB boiler feed system.

CFB Boilers

Each of the two CFB combustors is designed to burn 600 tons per day of RDF with a higher heating value (hhv) of 6,170 Btu/lb (3482 Kcal/kg) and produce 229,000 pounds per hour of superheated steam at 830° F and 900 psig. The furnace system is capable of handling fuel with hhv range of 4500-7000 Btu/lb (10,460-16,320 KJ/kg).

In each boiler, the RDF is fed through four feeders located on the front wall of the furnace. The top-supported furnace walls are water-cooled, welded tube-and-fin construction.

Following each furnace is a single high-efficiency cyclone completely cooled with saturated steam from the drum. The cyclone is constructed of Monowall™, a welded tube and fin construction. The cyclone separates entrained solids including unburned carbon from the flue gas and returns them to the furnace, providing excellent carbon burn-out. A cross-section of the boiler and associated air pollution control equipment is shown in Figure 2.

Downstream of the cyclone is a vestibule that encloses the steam-generating boiler bank and the pendant finishing superheater. The heat-recovery area (HRA) is the final segment of the steam generator. It encloses the primary superheater and economizer. All tubes in the HRA are designed on a large clear spacing with a low inter-tube velocity to minimize any accumulation of sticky ash deposits. Flue gas leaving the economizer passes through the air pollution control system prior to discharge to the exhaust stack.

The use of CFB-combustion technology provides the Robbins project with several conceptual advantages over conventional grate-type combustors and contributes to the high energy conversion and low pollutant emissions achieved by the facility. CFB combustors do not burn the solid waste on a grate or hearth as in conventional municipal waste combustors (MWCs). Rather, the waste is burned in a hot, fluid suspension of material, entrained in a substantial upward flow of gas. This fluid suspension, the "fluidized bed," consists of the RDF mixed with intensely hot particles (1600°F) of an inert bed material (a mixture of screened bed ash and sand).

Because of the inherent differences in the combustion process of conventional grate-type combustors and CFB combustors, several important advantages are realized with the use of CFB technology. These advantages include high combustion efficiency, low combustion temperature, reduced NO_x formation, stable combustion, and clean stack emissions.

High Combustion Efficiency. The CFB's turbulent mixture of hot inert bed particles, fuel, and air results in excellent combination of the three T's of combustion: time, temperature, and turbulence.

Vigorous mixing of RDF with air, uniform combustion temperature within the entire furnace, and long residence time of the gases in the furnace contribute to high combustion efficiency.

The CFB's combustion capability is further enhanced by a highly efficient cyclone, which removes elutriated ash along with any unburned carbon from the flue gas. This ash, which normally would drop out into hoppers or be caught in the baghouse in a conventional combustor, is returned to the furnace for further carbon utilization.

Loss on ignition (LOI) testing show less than 1% carbon in the ash, giving 99% plus combustion efficiency, exceeding that of conventional solid-waste combustors, where only 97%-98% is achieved.

Low Combustion Temperatures. The CFB combustor typically operates in the range of 1525°-1675°F (829°-913°C). Besides reducing the potential for ash slagging and tube fouling, these relatively low temperatures reduce high temperature chlorine corrosion.

Reduced NO_x Production. The low furnace temperature of the CFB combustor produces lower nitrogen oxide (NO_x) emissions than conventional high-temperature combustion. In addition, the introduction of combustion air in stages (different elevations) suppresses the generation of NO_x even further. NO_x emissions average under 100 ppmv in the CFB as compared with 200 to 350 parts per million volume (ppmv) typically achieved with grate combustors.

Stable Combustion. The CFB combustion process allows a large thermal mass to circulate between the furnace and cyclone. More material resides in the furnace at any given time than would be possible in a similar-sized grate type unit. A tremendous amount of heat is absorbed and retained by this large mass of inert particles. This gives the furnace a thermal inertia, maintaining a stable temperature throughout the furnace.

The intimate mixing of fuel and air due to the extreme turbulence greatly reduces the potential for hot spots or a localized reducing atmosphere. Thus, CFB technology is particularly able to effectively combust RDF that may vary dramatically in composition and heating value.

Dioxin Emissions. The highly turbulent mixing and prolonged gas-residence time in the CFB combustor provides for nearly complete destruction of dioxin precursors even at the lower combustion temperature.

AIR POLLUTION CONTROL

Air emissions are controlled by the efficient combustion characteristics of the CFB boilers, a selective non-catalytic reduction (SNCR) system, and a semi-dry fluegas scrubber/baghouse system.

Due to the highly efficient combustion characteristics of the CFB technology at relatively low combustion temperatures (1500°-1700°F), together with staged combustion, NO_x emissions are extremely low.

Acid gas and particulates are controlled by a combination semi-dry scrubber/fabric filter. The spray dryer reactor is a parallel downward flow type that utilizes multiple two-fluid nozzles for atomization of the lime and activated carbon slurry.

The fabric filter baghouse is a pulsejet with eight modules. Net/net (two modules out of service) air to cloth ratio is 4 to 1.

A continuous emissions monitoring system is used to control and record flue-gas opacity, sulfur dioxide, carbon dioxide, carbon monoxide, volatile organic compounds, and nitrogen oxide, ensuring compliance with applicable environmental standards. Tables 1 and 2 are daily summaries of the hourly averages from the CEM system for each unit for one day during the acceptance testing.

HISTORY OF PERMIT REQUIREMENTS

Although the original permit to construct (PSD) was issued by the Illinois Environmental Protection Agency (IEPA) in June 1990, construction was not begun until 1994. The units are therefore regulated by the 1990 USEPA new source performance standards. A court order settling a procedural dispute in 1992 added Powdered Activated Carbon injection and a 80% mercury removal rate (below the previous requirement). An ambient monitoring program designed to show the effect of the facility on ambient pollutant levels was also instituted.

As a result of USEPA regulatory action in 1995, new federal requirements were added. Although the 1995 Emission Guidelines (40CFR60, subpart Cb) have been vacated by court order, the facility has submitted an application for an operating permit which contains those requirements.

Finally, in order to comply with a 1991 IEPA regulation concerning MWC metals, limits were placed on three additional metals: arsenic, nickel and chromium.

In the subsequent section, the emission test results are compared to the permit requirements. Since there are duplicative requirements for some pollutants, the permit requirements are a compilation of the above requirements and are the most stringent of the requirements.

RESULTS OF TESTING

Compliance test results are compared to the regulatory limits in Table 3. While overall comparisons are favorable, a few results stand out. First, the CO concentration is extremely low, and has been continuously confirmed in this range by the CEM system. This is directly attributable to CFB combustion, as can the continuously low NO_x emissions. This NO_x result presented in Table 3 is without the urea injection system in operation, and again shows the low NO_x potential of this firing method. The beneficial effects of the fuel processing system are evident in the low levels of heavy metals emission. The Mercury emissions data is with Powdered Activated Carbon being injected.

The CFB combustion process provides for increased fuel flexibility. This is shown in Table 4, which provides the air emission test results from burning an MSW mixture of 50% residential waste and 50% wood waste.

Although new construction activity for WTE plants is low in the U.S., European bidding opportunities are actually increasing. Table 5 presents the results in Table 3, converted to usual European convention. This Table also presents results from additional testing performed to begin a database on various other pollutants, which are a concern in Europe. Test results are compared to the required guarantees for a recent European request for proposals.

POLLUTANT LOADINGS INTO THE APC

The most interesting aspect of the system performance is the contribution of CFB technology to the reductions in pollutant levels. Table 6 shows CFB outlet emissions for selected pollutants. As previously discussed, the NO_x emission level shows the effect of limiting thermal NO_x production during combustion and the staging of combustion air. Mercury levels reflect fuel processing, which eliminates practically all batteries and electrical components. The SO_2 emission is particularly notable. Emissions average a few ppm until the ash bed builds up, when SO_2 emissions drop near to zero. Keep in mind that this is a sand bed, not limestone as is usual with CFBs. (Limestone is usually added to the CFB bed material in order to capture sulfur. Because of the level of chlorine in the MSW, which is not captured at bed temperature, a traditional semi-dry scrubber is used for acid gas control.) As a matter of fact, SO_2 emissions on natural gas firing are higher than waste firing. This is thought to be the result of refinery gas (with low levels of H_2S) being blended into the natural gas pipeline. Absorption of the sulfur by the bed material also has an effect on the ash, as discussed below.

RESULTS OF ASH TESTING

Robbins is unusual in the U.S., in that fly and bottom ash are not combined prior to disposal, but are handled separately. Also, due to the CFB combustion process, the ratio of bottom to fly ash is roughly the reverse of grate firing (recent testing shows 80% flyash, 20% bottom ash leaving the facility.)

Bottom ash is moved through the furnace area to an outlet location by a combination of an angled bed plate and the use of directional nozzles. Directional nozzles deliver the fluidizing combustion air, but in such a manner as to move the heavy bed material towards the discharge point. After cooling, the ash is screened and returned to the sand silo for bed make-up.

Fly ash is picked up from various boiler, scrubber and fabric filter hoppers and moved by drag conveyors to one of the fly ash storage silos. This ash is wetted during gravity loading into trucks, or can be transported dry if desired.

Table 7 provides results from TCLP testing of the bottom ash and flyash/scrubber residue. The excellent results are probably a combination of two factors. First, lower overall metals in the fuel, compared to mass burn, because of the fuel processing. Second, it appears that the conditions are right in the circulating fluid bed to form mineral combinations.

Because the ash in the bed is absorbing the sulfur, chemical reactions occur which appear to be binding metals in various sulfite and sulfate combinations. Future research includes looking for potential additives to improve the characteristics of the ash, increasing its market value.

CONCLUSIONS

The environmental benefits of using CFB technology are fully realized at the Robbins facility. One quarter of the waste stream is recycled. Air emissions to the atmosphere are very low, both for criteria pollutants and for those considered a health risk. Electrical power is produced which replaces the use of coal at the local utility, reducing overall air emissions.

The CFB ash stream has the physical and chemical properties which can be utilized by industry. This not only reduces disposal costs, but reduces impact on the environment caused by the ash transportation and disposal.

This fully integrated facility has the potential for a 100% reduction in waste.

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Table 1. CEM daily log, Unit A

Robbins Resource Recovery Facility.
Robbins, Ill. Unit A
Daily Summary Report-Stack

Date	Time	No_x ppm	SO_2 ppm	CO ppm	THc ppm	SO_2Remove%
01/16/1997	00:59	60	0	0	0	1.000
01/16/1997	01:59	64	0	1	0	1.000
01/16/1997	02:59	62	0	5	0	1.000
01/16/1997	03:59	56	0	6	0	1.000
01/16/1997	04:59	74	0	2	0	1.000
01/16/1997	05:59	76	0	4	0	1.000
01/16/1997	06:59	75	0	3	0	1.000
01/16/1997	07:59	65	3	1	0	0.785
01/16/1997	08:59	77	3	8	0	0.575
01/16/1997	09:59	73	0	1	0	1.000
01/16/1997	10:59	73	0	2	0	1.000
01/16/1997	11:59	66	0	1	0	1.000
01/16/1997	12:59	67	0	2	0	1.000
01/16/1997	13:59	72	0	3	0	1.000
01/16/1997	14:59	77	0	1	0	0.983
01/16/1997	15:59	61	0	1	0	1.000
01/16/1997	16:59	64	0	1	0	1.000
01/16/1997	17:59	83	0	12	0	0.862
01/16/1997	18:59	97	0	6	0	0.954
01/16/1997	19:59	91	0	35	0	0.916
01/16/1997	20:59	76	0	1	0	1.000
01/16/1997	21:59	77	0	5	0	1.000
01/16/1997	22:59	74	0	0	0	1.000
01/16/1997	23:59	74	0	0	0	1.000
AVERAGE		72	0	4	0	0.961

- Corrected to 7%O_2

Table 2. CEM daily log, Unit B Robbins Resource Recovery Facility.
Robbins, Ill. Unit B
Daily Summary Report-Stack

Date	Time	No_x ppm	SO_2 ppm	CO ppm	THc ppm	SO_2Remove%
01/16/1997	00:59	74	0	6	0	1.000
01/16/1997	01:59	81	0	6	0	0.968
01/16/1997	02:59	75	0	7	0	0.996
01/16/1997	03:59	78	0	8	0	0.973
01/16/1997	04:59	86	0	10	0	0.947
01/16/1997	05:59	83	0	10	0	0.946
01/16/1997	06:59	86	3	8	0	0.836
01/16/1997	07:59	73	0	5	0	0.964
01/16/1997	08:59	79	1	4	0	0.882
01/16/1997	09:59	82	0	7	0	0.959
01/16/1997	10:59	77	0	4	0	0.977
01/16/1997	11:59	82	0	6	0	1.000
01/16/1997	12:59	76	0	3	0	0.979
01/16/1997	13:59	77	0	3	0	0.968
01/16/1997	14:59	89	0	5	0	0.894
01/16/1997	15:59	89	0	6	0	0.707
01/16/1997	16:59	89	0	5	0	0.647
01/16/1997	17:59	92	0		0	0.872
01/16/1997	18:59	91	0	8	0	0.612
01/16/1997	19:59	97	0	6	0	0.992
01/16/1997	20:59	93	0	4	0	0.986
01/16/1997	21:59	89	0	2	0	0.981
01/16/1997	22:59	98	0	6	0	0.994
01/16/1997	23:59	90	0	4	0	0.994
AVERAGE		84	0	6	0	0.920

- Corrected to 7%O_2

Table 3. Comparison of Compliance Stack Test Results to the Emission Permit Limits.

Burning 100% RDF

Pollutants	Units	Unit A	Unit B	Permit Limit
Particulate	gr/dscf	0.0015	0.0056	0.01
SO_2	ppm	1.0	0.5	30
HCl	ppm	4.6	6.2	25
CO	ppm	4.4	2.2	100
NO_x (1)	ppm	73.1	90.4	130
VOC	ppm	1.5	0.6	10
Total dioxin-furans	ng/dscm	2.1	4.9	30
Total TE (89 EPA)	ng/dscm	0.05	0.13	NA
Arsenic	μg/dscm	0.2	0.2	10
Cadmium	μg/dscm	<detection limit (0.01)	0.3	40
Chromium	μg/dscm	4.8	5.6	120
Lead	μg/dscm	3.6	30.9	490
Mercury	μg/dscm	15.8	2.9	80
Nickel	μg/dscm	3.1	3.1	100

- All concentration are at 7%O_2, dry.
- NA = Not Applicable
- (1) NO_x values are without SNCR system in operation.
- Average of 3 test runs
- 3-hr. test runs for all pollutants, except 4-hr. for PCDD/F

Table 4. Comparison of Compliance Stack Test Results to Emission Permit Limits.

		Burning 50% Residential Waste and 50% Wood	
Pollutants	Units	Unit B	Permit Limit
Particulate	gr/dscf	.0047	0.01
SO_2	ppm	0.6	30
HCl	ppm	2.4	25
CO	ppm	1.9	100
NO_x (1)	ppm	82.5	130
VOC	ppm	0.9	10
Total dioxin-furans	ng/dscm	2.1	30
Total TE (89 EPA)	ng/dscm	0.053	NA
Arsenic	μg/dscm	0.3	10
Cadmium	μg/dscm	0.1	40
Chromium	μg/dscm	5.9	120
Lead	μg/dscm	22.1	490
Mercury	μg/dscm	0.5	80
Nickel	μg/dscm	3.1	100

- All concentration are at 7%O_2, dry.
- NA = Not Applicable
- (1) NO_x values are without SNCR system in operation.
- Average of 3 test runs
- All test runs 3-hr., except 4-hr. for PCDD/F

Table 5. Robbins RRF's Compliance Stack Test Results vs. European Air Emission Requirements.

Pollutants	Unit A	Unit B	Recent European Requirement
Total Particulates	2.62	9.76	15 (hourly)
Hydrochloric Acid	5.34	7.2	10 (daily av.)
Sulfur Dioxide	1.89	1.02	50 (daily av.)
Carbon Monoxide	3.92	1.96	50 (daily av.)
Volatile Organic substance, given as total carbon (THC)	0.07	0.3	5 (daily av.)
Nitrogen Oxide	107	132	200 (daily av.)
Ammonia	<1.9	<1.9	10 (daily av.)
Hydrogen Fluoride	<.06	<.06	1 (daily av.)
Cadmium + Thallium	.001	.002	0.05
Mercury (Hg)	0.01	.002	0.05
Pb + Cr + Cu + Mn + Ni + As + Cd + Hg	.08	.06	2
* Dioxins and Furans (ITE)	.039	.10	0.10
Polynuclear Aromatic Hydrocarbon (PAHs)	.0007	.0008	0.05
Chlorophenol	<.0006	<.0006	.001
Hydrogen Cyanide (HCN)	<.004	<.004	0.50
Chlorobenzene	<.00005	<.00005	.001

- All concentration are mg/Nm^3 at 11% O_2 except noted otherwise.
- *ng/NM^3 at 7% O_2
- Average of 3 test runs
- All tests 3-hr. duration, except 4-hr. for PCDD/F
- Ammonia detection limit with CEM

Table 6. Emission at the CFB Boiler Outlet

Pollutant	Units	Unit A	Unit B
CO	ppm	4.4	2.2
NO_x	ppm	73.1	90.4
SO_2	ppm	6.6	1.7
HCL	ppm	357.5	351.2
Mercury	μg/dscm	60.7	141

- All concentrations corrected to 7% O_2.
- Average of 3 test runs

Table 7. Summary of Ash Analytical Results.

Flyash Performance Test Samples

Parameter	Regulatory Limit	Sample 1	Sample 2	Sample 3
TCLP arsenic	5	<0.05	<0.05	<0.05
TCLP barium	100	<5	<5	<5
TCLP cadmium	1	0.2	<0.05	<0.05
TCLP chromium	5	<0.5	<0.5	<0.5
TCLP lead	5	<0.5	<0.5	<0.5
TCLP mercury	0.2	<0.05	<0.05	<0.05
TCLP selenium	1	<0.05	<0.05	<0.05
TCLP silver	5	<0.5	<0.5	<0.5
Putrescibles	NA	<0.01%	<0.01%	<0.01%

Bottom Ash Performance Test Samples.

Parameter	Regulatory Limit	Sample 1	Sample 2	Sample 3
TCLP arsenic	5	<0.05	<0.05	<0.05
TCLP barium	100	<5	<5	<5
TCLP cadmium	1	0.05	<0.05	<0.05
TCLP chromium	5	<0.5	<0.5	<0.5
TCLP lead	5	<0.5	<0.5	<0.5
TCLP mercury	0.2	<0.05	<0.05	<0.05
TCLP selenium	1	<0.05	<0.05	<0.05
TCLP silver	5	<0.5	<0.5	<0.5
Putrescibles	NA	<0.01%	<0.01%	<0.01%

- TCLP metals concentrations are in PPM.
- NA = Not Applicable
- Putresicible not detected at indicated concentration

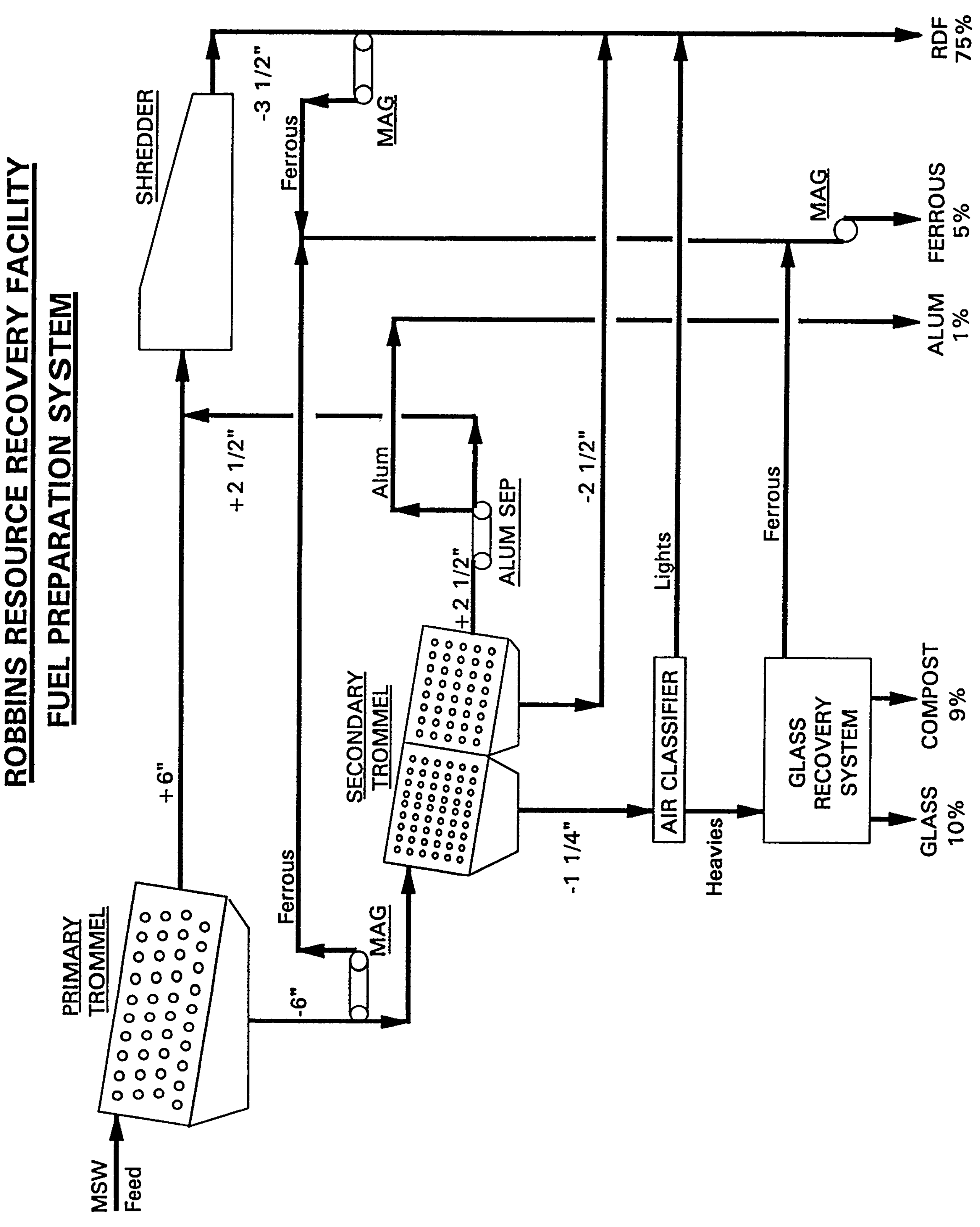

Figure 1. Fuel Preparation System

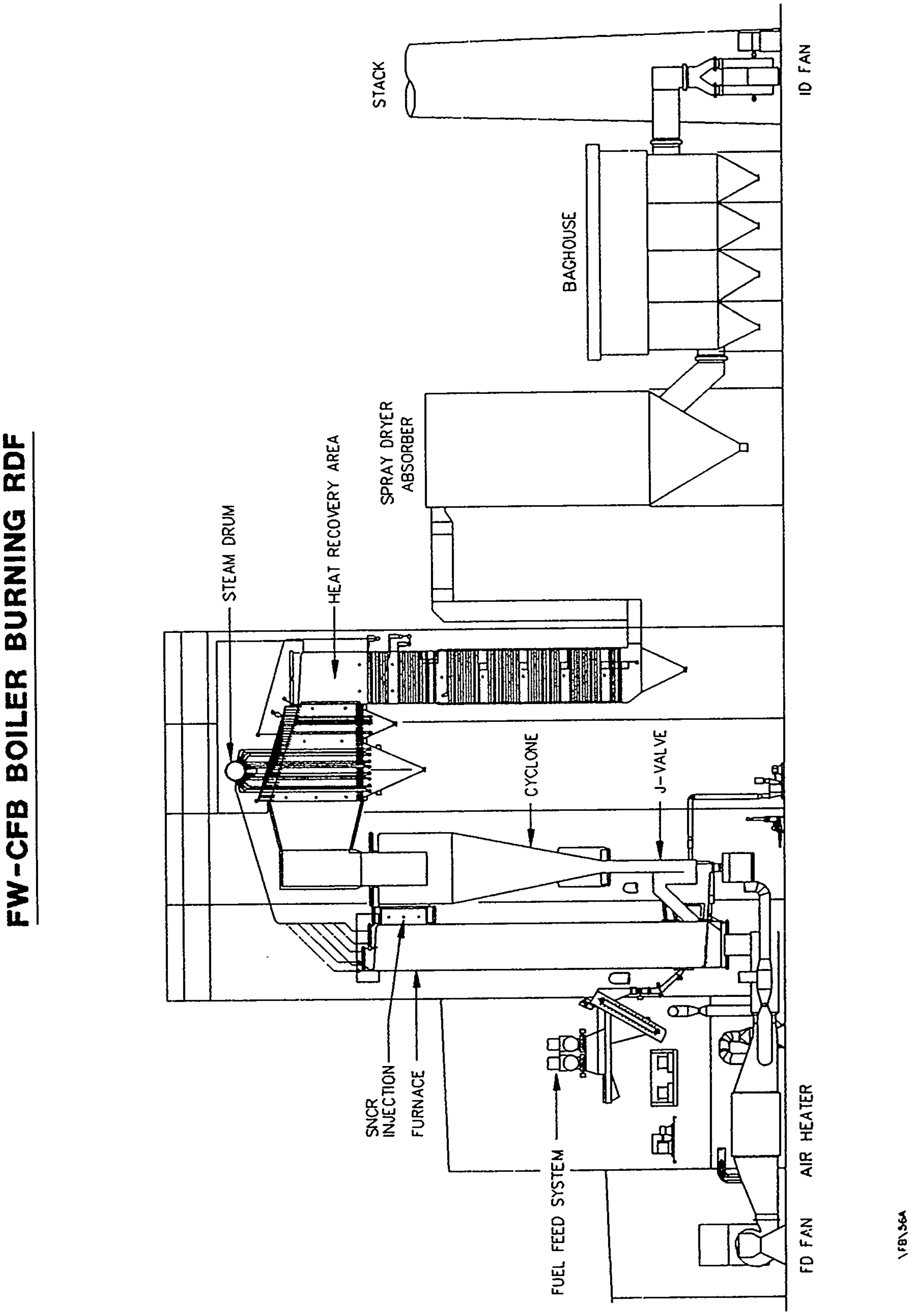

Figure 2. Cross-section of CFB and Air Pollution Control Equipment.

New Mercury Control Technology for the Ft. Dix Waste-to-Energy Plant

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INTRODUCTION

Mercury emissions from waste-to-energy plants, municipal solid waste incinerators, and other industrial processes have come under increased regulatory scrutiny. National Emission Guidelines were recently promulgated for municipal incinerators eventually requiring either 85% mercury removal or compliance with an 80 µg/Nm^3 emission standard.[1]

The ability of air pollution control equipment to remove mercury from a gas stream has been found to be largely a function of the particular mercury species present, their concentrations, and the gas temperature. Mercury chloride ($HgCl_2$) tends to be found in incinerator flue gases and this species may be well-removed by activated carbon injection,[2] wet scrubbing,[3] or even hydrated-lime injection at low temperatures.[4] When the gas streams are relatively small, as with incinerators, fixed beds of mercury sorbents are also feasible. Beds of granular activated carbon have long been used to remove mercury vapors from small gas volumes in chloro-alkali plants and from other industrial processes.[5] The co-absorption of water and SO_2, leading to bed-soaking and corrosive sulfuric acid production, however, can limit this method of control. And activated carbon beds can spontaneously combust. However, very thick carbon beds have been applied in Europe in recent years on incinerator streams for the adsorption of mercury and other toxic species.[6]

Finer activated carbons can also be injected into the gas stream and removed in a particulate removal device.[6,7] Activated carbons can do a good job capturing high concentrations of mercury chloride, particularly when injected at relatively low temperatures. However, once the carbons are injected, they are lost; they become mixed in with large masses of acid gas sorbents and/or fly ash, which goes to disposal. Any sorbed mercury is not recovered.

The elemental form of mercury, unfortunately, has proven to be much more difficult to control. Elemental mercury is not soluble in water, and even iodine-impregnated activated carbons[8] and lime at extremely-high injection rates[4] may do little to remove it at temperatures above 300 F.

The operators of some incinerators need to be concerned about elemental mercury capture. While the mercury in most incinerator streams is predominantly $HgCl_2$, this is not always the case. Prior compliance measurements from the Ft. Dix municipal waste-to-energy plant in New Jersey, for example, indicate a high degree of elemental mercury.[9] And some sites, like that at Ft. Dix, do not have a cool-side baghouse for activated carbon injection. Moreover, to meet the new 85% mercury removal requirements, some sites will have to remove a significant amount of elemental mercury. For example, if 90% of the mercury in a gas is in the form of $HgCl_2$ and activated carbon injection removes 90% of that, the 81% net removal is less than the 85% minimum.

After promising early experiments, the U.S. EPA and Air Force awarded Sorbent Technologies Corporation contracts to develop and demonstrate granular elemental mercury sorbents for incinerator use. The target was a recoverable-mercury sorbent that would last for from six-months to two years on a concentrated incinerator stream in a thin, simple, panel-bed arrangement. Two sorbent materials have been developed in this effort: a low-temperature version from which the mercury can be recovered, and a high-temperature version for upstream applications. This paper describes some of the work that has been done on these sorbents. Sorbent Technologies is scheduled to demonstrate the new mercury sorbent technology at the Fort Dix incinerator later in 1997.

PANEL-BED SORBENT PELLETS

Laboratory Screening

A laboratory test stand was constructed to evaluate the elemental mercury capture performance of various sorbent chemistries and a large number of screening runs were conducted. While the majority of treatments gave little evidence of any mercury sorption, two chemical combinations showed excellent potential.

The test stand used in the screening program included bottled gases, mass flow controllers, a constant-temperature oil bath, laboratory oven, mercury analyzers, and a computer data acquisition system. Elemental mercury was introduced into the simulation gas from permeation tubes. These tubes emit highly-constant elemental mercury vapor at rates strictly dependent on their temperature. A certified permeation tube, traceable to NIST standards, was used to calibrate the analyzer. During testing, the permeation tubes were placed inside a glass container that was maintained at a constant temperature using a constant-temperature oil bath. The permeation rate of mercury was varied by using multiple permeation tubes or by changing the temperature of the bath.

To test the various materials, a small fixed-bed of the candidate sorbent material was held in a custom-fabricated glass chamber which was heated in a laboratory oven to the simulation temperature. To prevent the absorption of mercury by the test apparatus, all components exposed to the mercury-laden gas stream were constructed of Teflon or glass and heated. The mercury-laden gas was pre-heated in an inert, glass-bead-loaded preheater before it entered the sorbent bed.

A data acquisition system allowed long-term, unattended system operation. The elemental mercury measurements were made using a Jerome 431-X gold-film mercury analyzer, manufactured by Arizona Instruments, and/or a Jupiter cold vapor atomic adsorption (CVAA) analyzer. The Jerome analyzer uses a gold-film sensor to measure elemental mercury vapor. The gold-film sensor is inherently stable, selective to elemental mercury, and has a detection range from 0 to 999 $\mu g/Nm^3$. The sensor is periodically regenerated. The Jupiter CVAA instrument has a dual-beam design that decreases zero-drift and improves the way in which the sample gas is refreshed in the sample cell. By altering the feed line configuration, this CVAA instrument is capable of providing continuous elemental mercury measurement with no interference from acidic gases, such as SO_2.

Low-Temperature Sorbents

After screening many potential chemistries, a good low-temperature elemental mercury sorbent was found. We call this material low-temperature "Mercsorbent." The new material can be pelletized for low-pressure-drop application in panel-beds and shows good potential for long-term mercury capture at temperatures from about 130 F to 220 F. Importantly, once the Mercsorbent is saturated, the captured mercury is easily recovered with simple thermal treatment.

The new sorbent's potential for long-term elemental mercury-capture is suggested in Figure 1. With a mercury inlet concentration of 150 $\mu g/Nm^3$, a space velocity of 2400 hr^{-1}, and a 7.6-cm deep sorbent bed, a removal rate of over 95% was obtained with no diminution in performance in a 70-hour run. The ultimate capacity of the sorbents has not yet been determined.

Mercury Desorption Tests

Effectively sorbing the mercury from the exhaust gas is not enough; it must be assured that it no longer threatens human health or the environment. Consequently, leachability and thermal desorption tests were conducted to explore the safety and mercury recovery potential of the new sorbent. Saturated sorbent containing approximately 0.12 wt% of mercury from a long-term utilization test run was used in these studies.

If a waste material like the saturated sorbents is easily leachable, heightened precautions are necessary in its storage and transport, and disposal can be expensive. Two 5-gram samples of the partially-saturated sorbent, containing approximately 6.000 mg of mercury, were sent to an independent testing laboratory, Electro-Analytical Laboratories of Mentor, Ohio, for standard Toxic Characteristic Leaching Procedure (TCLP) extraction analysis. Two identical samples were subjected to an 18-hour extraction with a 20:1 solution-to-solids ratio using an acetic acid solution with a pH of 2.9. The detection limit of the process was 0.010 mg Hg/liter. The first sample had a TCLP extraction test result of 0.082 mg Hg/liter; the second sample had a result of 0.080 mg Hg/liter. The TCLP mercury leachate level to qualify as hazardous wastes is 0.200 mg Hg/liter. Thus, these saturated sorbent samples would not be classified as a hazardous waste.

It is not ultimately helpful to remove mercury from the gas phase if it is simply transferred to another medium. Mercury captured by activated carbon injection, for example, becomes mixed in with other fly ash that is ultimately sent out for land disposal. The mercury is not recovered, but left to become a potential groundwater pollutant. The sorbents examined in this research, however, present the possibility of mercury recovery.

A growing secondary source of mercury supply is its recovery from mercury-containing wastes, which are roasted in retort furnaces to recycle their mercury. Today there are five secondary mercury recovery facilities around the country, supplying about half of the U.S. needs for mercury by retorting mercury wastes and condensing out and purifying the mercury for sale.[10] Nine U.S. gold smelting and refining operations, which supply about 60 tons of by-product mercury per year, could also be used for this purpose.

Experiments were performed to examine the new sorbent's thermal recovery potential. A 0.50 g sample of partially-saturated sorbent, with a known quantity of sorbed mercury, was heated under a flowing gas stream and the elemental mercury content of the off-gas was continuously measured. In order to accurately measure the mercury, a low desorption temperature of 450 F and was selected. Integrating under the desorption curve revealed that after six hours fully 85% of the mercury had evolved from the sorbent.

Mercury recovery retort furnaces and ore roasters operate at a temperature of about 1100 F.
A desorption test was carried out at this temperature also. Under these conditions, however, the mercury desorbed from the materials so quickly and in such quantities that the initial exit mercury concentration was far over the upper detection limit of the analyzer, even with 80:1 dilution sampling. The mercury concentration of the off-gas rapidly dropped to zero after a period of two minutes, indicated a very fast desorption process at this temperature. Thus, the mercury captured by the new sorbents should be desorbed very quickly and completely by the furnaces of mercury recovery facilities.

High-Temperature Sorbents

A second elemental mercury sorption chemistry was also discovered which operates at higher temperatures, from 220 F to over 450 F. This composition can also be easily pelletized into granular, low-pressure-drop, panel-bed sorbents. However, while this sorbent material is capable of operating under more extreme conditions, unlike the low-temperature version, its mercury is not thermally recoverable.

At higher temperatures, elemental mercury is difficult to capture. For example, the performance of an activated carbon at higher temperatures is plotted in Figure 2. One gram of a granular activated carbon (Calgon CPG; 12x40 mesh) was tested over the range of 280 F to 400 F with gas containing 40 $\mu g/Nm_3$ mercury. The test was run with air also spiked with SO_2 and moisture. Measurements were simultaneously taken on both the Jupiter and Jerome instruments.

With dry air, 1.0 g of this carbon in a 2.5 cm bed was capable of sorbing about 45% of the mercury at 400 F. However, when 0.06 lb-of-moisture-per-pound-of-dry-air was added to the gas stream, the mercury removal level dropped to zero. Apparently with carbon, water molecules compete for the same sites as the mercury. After the gas temperature was lowered to 300 F, a small amount of mercury sorption began to occur, perhaps to 10% removal. At high temperatures, this carbon does not appear to be a good candidate for elemental mercury capture.

In contrast, a run with a 3.8 cm bed of the new high-temperature Mercsorbent pellets is shown in Figure 3. Here the gas flow and face velocity were the same as the previous test, but the mercury concentration was twice as high. This gas was spiked with 200 ppm each of SO_2 and HCl. For over 65 hours at 230 F, the Mercsorbent removed over 95% of the elemental mercury in the gas stream. When the temperature was raised to 300 F for the last three hours of the experiment, the removal rate increased to nearly 100%.

These Mercsorbents can work well at even higher temperatures. Figure 4 contains a plot of a short-term test of a 2.5 cm bed of pelletized sorbent as a function of temperature. The data from this test indicate the potential for 90+% elemental mercury removal up to 700 F.

Bench-Scale Testing

Based on the earlier laboratory runs, sorption testing of the low-temperature sorbents was then scaled up to a large 150 m^3/hr (90 acfm) simulation system. This bench-scale system included a propane burner, elemental mercury spiking system, dilution air intake for temperature control, 24 m of ducting, an orifice plate for flow measurement, three heated sample lines for gas analysis at various points, and a variable speed ID fan. The spiking system was capable of adding 50 $\mu g/Nm^3$ of elemental mercury to the hot gas stream.

A thin filter of the new sorbent was inserted into the end of the ducting. Sitting in a drum, the conically-shaped, flat filter was 1 m high, 0.5 m at its maximum diameter, and 7.5 cm thick. It held 15 kg of the new sorbent. See Figure 5. At a gas flow rate of 150 m^3/hr, with a space velocity of 2700 hr^{-1}, the pressure drop across the filter was only 0.5 cm of water column. When operated in multi-hour tests, the sorbents removed from 80% to 100% of the mercury passing through them, depending on the operating conditions.

POWER PLANT SLIP-STREAM TESTING

The low-temperature Mercsorbents were also tested in the field on actual flue gas from the Ohio Edison Company's R.E. Burger station near Shadyside, Ohio. A test rig was constructed that drew off a slipstream of the plant flue gas after the electrostatic precipitator and divided it between six small test beds. Approximately 550 lpm of gas with approximately 3.5 $\mu g/Nm^3$ of elemental mercury was drawn through each of the sorbent test beds, 13-cm in diameter and 15-cm deep, for nine days. A blower returned the gas to the ductwork.

Each sampling train consisted of a particulate pre-filter, ice bath, two acid-gas filters in series, two gold-coil dosimeters, a mass flow controller, and a pump operating at 90 cc/min. The acid-gas filters were to eliminate any hydrogen sulfide or other acidic gases. The gold-film dosimeters are made to sorb very low concentrations of elemental mercury, concentrating it for more accurate measurement. Two dosimeters in series were used to insure that all of the elemental mercury was collected. They are designed not to sorb any mercury chloride that may be in the gas. After 90 minutes, the dosimeters were removed and analyzed using the Jerome instrument. The elemental mercury concentrations of the gas is the mass of mercury collected divided by the total gas volume sampled. To save time, three sampling lines, with a total of six dosimeters, were run simultaneously.

The mercury content of gas from power plants is about two orders of magnitude lower than that of waste incinerators and some measurement difficulties were experienced. An interferant gas appeared to affect our measurements at these levels. By using a plain vermiculite dummy bed, however, a method was developed to correct the readings. Using the dummy-bed correction, the elemental mercury removal rates measured after nine days varied from between about 75% and 97%, similar to what was seen in the laboratory. These numbers are approximate because the mercury sampling at the power plant was episodic and the inlet mercury would be expected to vary over the nine days.

To do a mass balance, a sample from one of the Burger beds was thermally desorbed at a low temperature of 400 F. A plot of the results appears in Figure 6. Integrating under this curve provides a value for the amount of mercury sorbed. The consistent mercury removal efficiencies for this sorbent observed in a laboratory test, field slipstream test, and calculated based on the desorption test, are shown in Figure 7. Combining the desorption result with measurements of mercury in the Burger plant gas stream suggests an average mercury removal rate of about 80 to 90% for the new sorbent under the actual flue gas conditions.

FABRIC FILTER BAGS

Research is also underway to examine other possible ways of applying the Mercsorbent chemistries to flue-gas applications. For example, many municipal waste incinerators have spray dryers and fabric filters in their air pollution control trains. At these facilities an additional strategy is available. First, activated carbon injection would remove the majority of the oxidized mercury species, such as mercury chloride. Then, the large surface area in the baghouse would be exploited by treating the fabrics with the mercury-reactive substances to create a polishing filter for elemental mercury.

Low-Temperature Fabrics

Initial laboratory tests of the mercury-sorbing baghouse fabrics have been promising. So far, the treatments have been successfully applied to samples of commercial baghouse fabrics of acrylic, polyester, and Ryton, and to both felts and weaves.

In one example, a 5.4-cm diameter polyester fabric filter sample was treated with the new low-temperature chemistry and dried. A simulated flue gas at 1 lpm, spiked with elemental mercury to about 170 $\mu g/Nm^3$, was then passed through the fabric. The gas temperature was held at 160 F, a temperature representative of spray dryer baghouses.

Over 95% mercury removal was achieved for nearly 24 hours under these conditions. This sample was then further saturated at higher gas flow rates for 108 more hours, in 5 additional tests examining changes in various conditions. Although still not saturated and removing most of the mercury passing through it, the testing was stopped with the sample having sorbed 4.1 mg of mercury, or almost 2 g Hg/m^2 of fabric. A photograph of the fabric, with its captured mercury coating very evident, appears in Figure 8. Like the low-temperature Mercsorbent pellets, the baghouse application allows for simple recovery of the sorbed mercury. When the fabric filter bags have met their useful life, the mercury-laden fabrics could be shipped to a mercury recovery facility.

When operating on a pulse-jet baghouse, the mercury-laden stream would pass through the fabric at a high rate. To examine such conditions, a treated fabric was tested at a very high air-to-cloth ratio of 8 ft/min. The results of this run appears in Figure 9. The elemental mercury concentration into the fabric was 150 $\mu g/Nm^3$ and the gas temperature was 160 F. Even at this high gas-flow rate, mercury removal averaged about 90% in this 50 hour test.

High-Temperature Fabrics

The high-temperature sorbent composition can also be applied to baghouse fabrics. In the next example, a high-temperature Teflon® baghouse fabric (Pyro-Tex®) was treated with the high-temperature Mercsorbent. The fabric was then was then tested in the laboratory test stand with a 200 $\mu g/Nm^3$ mercury simulation gas at 375 F and an air-to-cloth ratio of 4.0 ft/min. The performance of this material leveled off at about 70% elemental mercury removal at about 40 hours. See Figure 10.

Of course, much more development and testing of this concept is required, with much longer run times, lower concentration mercury streams, and frequent bag pulsing. Disposal of the mercury-containing bags must also be addressed. However, the sorption capacities of the samples has been high and no breakthroughs have yet been achieved. The concept deserves further work.

FUTURE PLANS

Laboratory and bench-scale testing and optimization of the sorbents at Sorbent Technologies Corporation is an ongoing activity.

Like many incinerator facilities around the country, the refuse incinerator at Fort Dix in New Jersey has a mercury emission problem. Prior compliance sampling at this unit suggests that a significant amount of its mercury is in the elemental form. While it complies with other emission regulations, this Army incinerator has been unable to meet its operating permit mercury limit (0.00093 lb/hr) or the new statewide mercury standards (65 µg/dscm now and 28 µg/dscm later) on a regular basis. The facility has been fined by the State of New Jersey for its mercury emissions. Sorbent Technologies Corp. is scheduled to demonstrate the new recoverable-mercury sorbent technology at this Fort Dix incinerator in later 1997.

ACKNOWLEDGEMENTS

This work was largely funded by the U.S. Air Force, through their Armstrong Laboratory, and the U.S. Environmental Protection Agency. The authors would like to thank Dr. Joseph Wander and Lt. Tammy Abbett of the Environics Division of the Air Force Civil Engineering Support Agency and Donald Carey of the U.S. EPA for their support and advice. They would also like to thank Frank Nolan of the U.S. Army Environmental Division and Scott Spurlock of United Cogenerators for access to the Ft. Dix waste incinerator.

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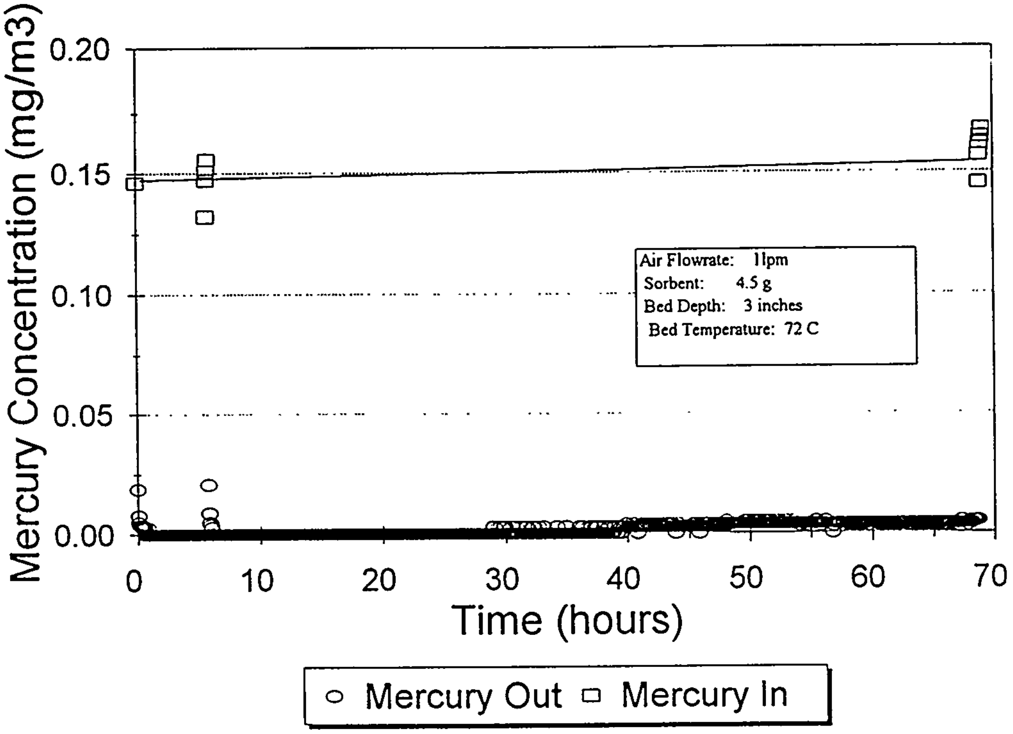

Figure 1. Elemental mercury removal of low-temperature Mercsorbent.

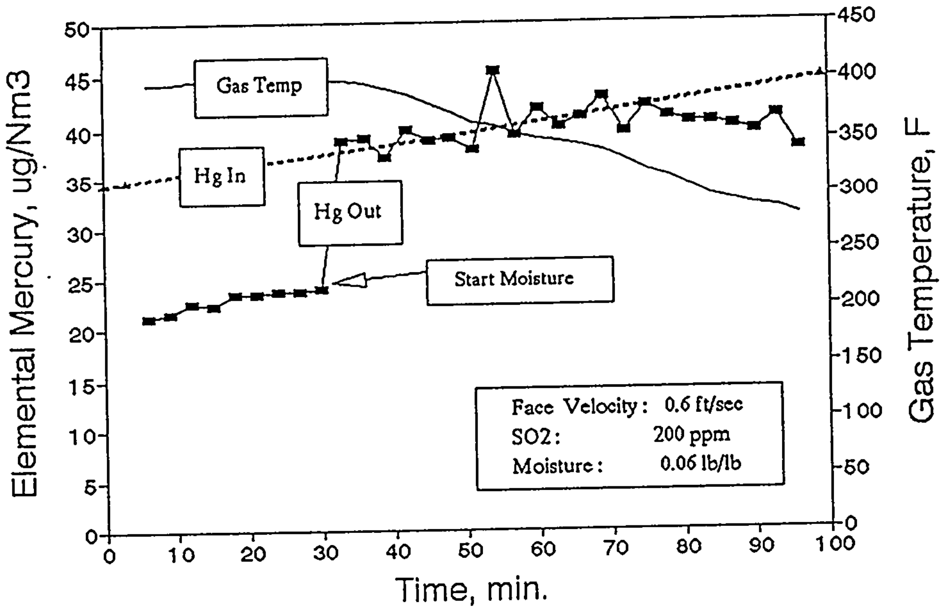

Figure 2. Elemental mercury removal of an activated carbon at high temperatures.

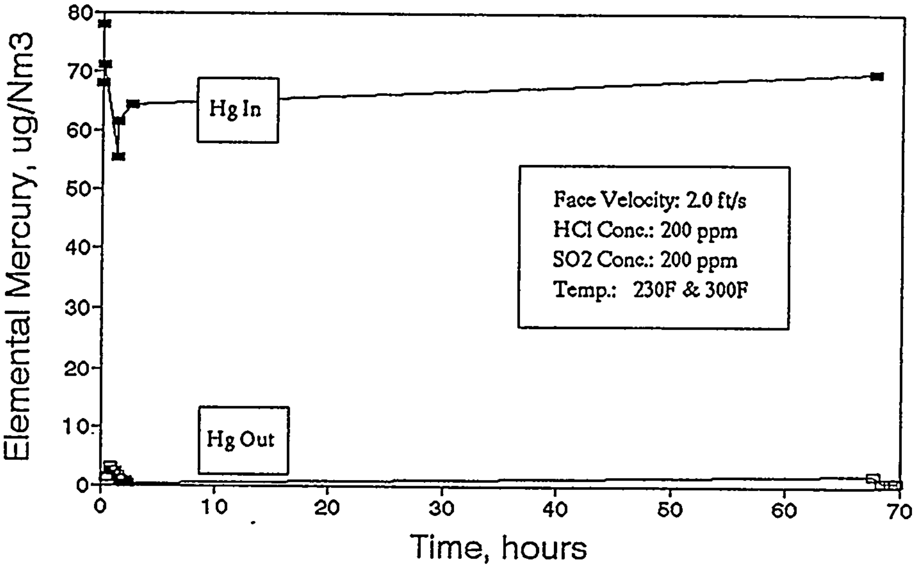

Figure 3. Elemental mercury removal of high-temperature Mercsorbent.

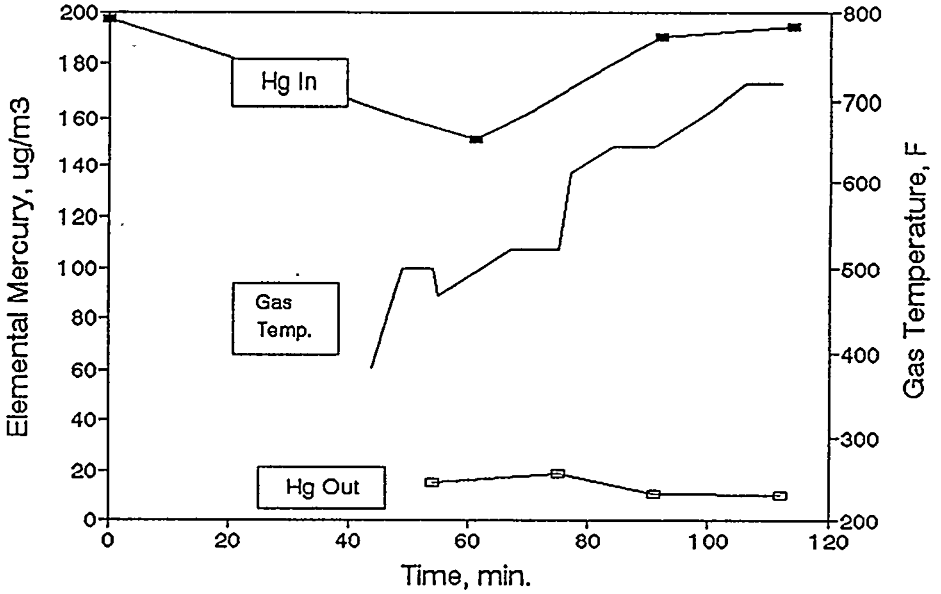

Figure 4. High-temperature range of Mercsorbent.

Figure 5. Small conical panel-bed filter of mercury sorbents.

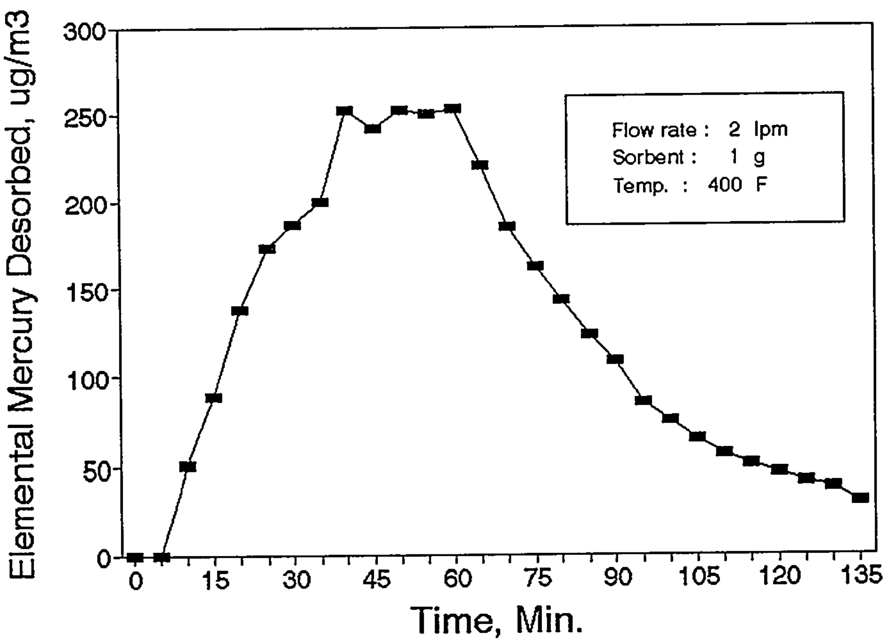

Figure 6. Desorption of elemental mercury from the Burger station Mercsorbent.

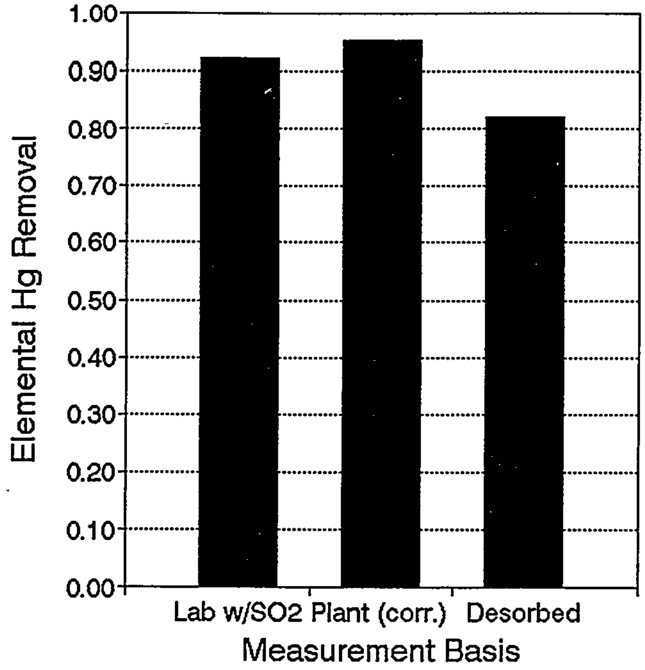

Figure 7. Low-temperature performance of Burger plant Mercsorbents.

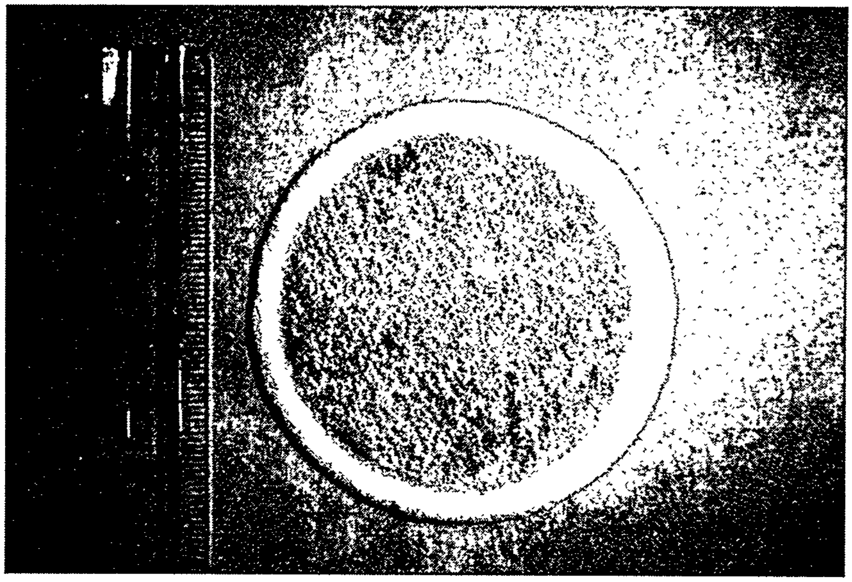

Figure 8. Mercury captured on a low-temperature Mercsorbent baghouse fabric.

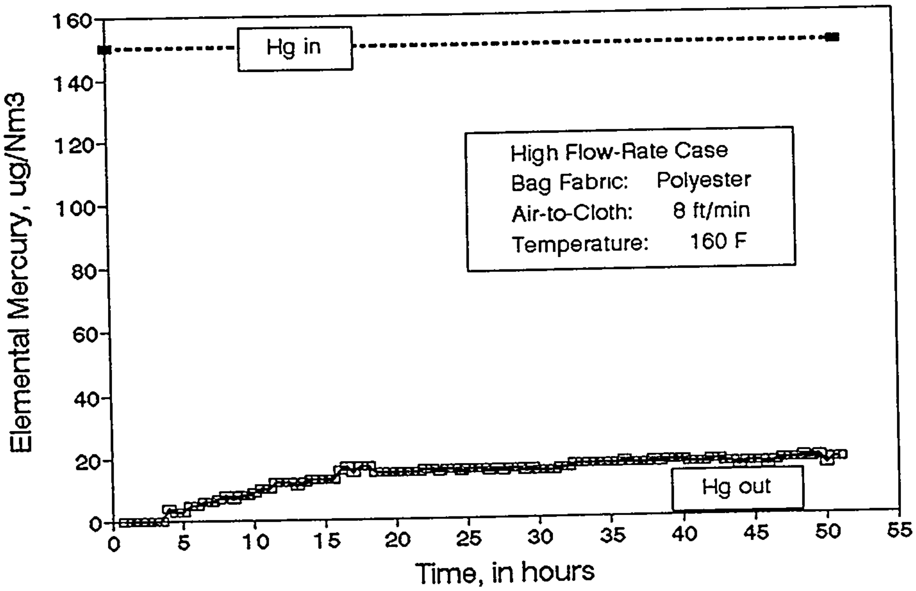

Figure 9. Results of a low-temperature Mercsorbent baghouse fabric test.

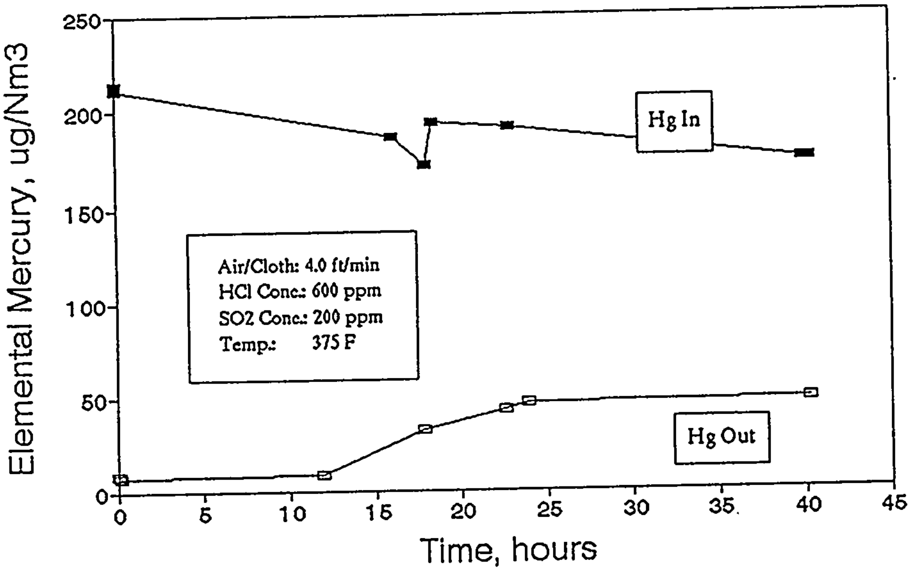

Figure 10. Results of a high-temperature Mercsorbent baghouse fabric test.

Is There a Meaningful Relationship Between Chlorine Feed and Non-Dioxin Stack Emissions?

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PEER-REVIEWED

INTRODUCTION

The American Society of Mechanical Engineers' Center for Research and Technology Development (ASME/CRTD) published an extensive analysis and tabulation of available dioxin and chlorine in late 1995[1]. The preponderance of that data produced no meaningful relationship between dioxin stack emissions and chlorine feed across a broad range of commercial waste combustor types. In the Preamble to the April 1996 proposed Hazardous Waste Combustor Rule, EPA acknowledged that changes in chlorine feed have little effect on dioxin emissions[2], but the text goes on to speculate that reducing chlorine input is still a good idea because fewer metals and chlorinated organics might be emitted.

Given that the conventional wisdom — reducing chlorine input to full scale facilities will reduce dioxin emissions — proved groundless when the available data were examined in a consistent manner, what does the available data tell us about the relationship between chlorine feed rate and municipal waste combustor (MWC) stack emissions in general? Product substitution and waste component diversion programs are expensive and economically disruptive at current levels. So, the likelihood of achieving any benefit needs to be determined before public policy changes are made. If there is no significant relationship between chlorine feed rate and stack emissions, then efforts to reduce chlorine feed are unlikely to reduce the trace levels of contaminants that leave state-of-the-art MWCs. Interventions to reduce chlorine feed rate would simply cause society to squander its scarce resources chasing ghosts.

APPROACH

The ASME/CRTD analysis used a segment of a much larger emissions database that contains emitted concentrations for a host of non-dioxin pollutants. These data can be subjected to the same analysis used in the ASME/CRTD report to determine if there is a meaningful relationship between chlorine input and MWC stack emissions.

Database Characteristics

All database entries are from the most reliable information available. Whenever possible, emitted concentrations are calculated directly from analytic laboratory reports and field data sheets to avoid intermediate transcription, rounding and interpretation problems. The databased values are brought to USEPA standard reference conditions (dry, 20°C, 1 atmosphere, 7% O_2) and compared to reported concentrations as a quality assurance check. In addition, the database is routinely screened for outliers — unusually large or small results. Potentially aberrant results are checked and corrected whenever possible. Remaining outliers are flagged so that their effect on subsequent data analysis can be determined.

Metals, volatile and semivolatile organics and criteria pollutant concentrations are covered to varying degrees in the database. The metals include those in the Clean Air Act Sections 112 and 129 lists along with additional environmentally sensitive metals listed in 40 CFR 266, the Boiler and Industrial Furnace Rule, and the European Union standards. Trace organics include much of the Section 112 Organic Hazardous Air Pollutants (HAPs) list along with data on other trace organics collected as part of broad-scope emissions assessments and research programs.

Below Analytic Laboratory Detection Limits Results

Much of the trace organics data are below analytic laboratory detection limits (ADL). Traditional analytic laboratory practice involves establishing the detection limit for their instruments. An instrument response that is less than 2.5 to 3 times the noise (variability) established by repeatedly analyzing samples without the pollutant present is not distinguishable from a sample with the pollutant absent. Analytic laboratories report these values as below detection limits (BDL). Some labs go a step further following ASTM[3] practice and identify results between the ADL and a value 3.33 times higher as tentative since the variability is too large to provide reasonable assurance that the measured value is within 30 percent of the true value. When the ADL is converted into an equivalent emitted concentration using standard data reduction procedures, it is called the analytic laboratory detection limit equivalent concentration or ADLE.

When two below ADLE results are compared, source characteristics are not involved. Rather the comparison is between the low level quantitation capabilities of the instruments and laboratories involved. Such results must be excluded from the statistical data analysis since they provide no useful information on the relationship between MWC stack emissions and chlorine. Below ADLE results are excluded so that relationships are neither caused nor hidden by laboratory detection limit differences and random chance.

A fully correct analysis should also exclude data that are below the Reference Method Practical Quantitation Limit (RMPQL). The ADL inherently considers only analytic laboratory procedures and instrument responses. Emitted concentrations, on the other hand, have a whole host of additional sources of variability — for example, spatial differences within the stack, velocity pressure and flue gas molecular weight determination errors, residual sampling train contamination, recovery losses, matrix differences, sample volume and diluent measurement errors, laboratory concentration procedure and sample clean-up errors, etc. — in addition to the instrument limitations considered by the ADL. These sources of variability raise the concentration that can be accurately quantified.

EPA Method 301[4] describes the practical quantitation limit (PQL) as "the lowest level above which quantitative results may be obtained with an acceptable degree of confidence." A reasonable degree of confidence is defined in Method 301 as 99 percent of replicated results being within 30 percent of the average value. The PQL is determined by analyzing paired test results obtained by operating, recovering and analyzing two or more simultaneous sampling trains. The "lower limit of the test method" is, by definition, equal to the PQL.

Results that are between the ADLE and the PQL are too variable to provide any meaningful information. They are so noisy that any relationships uncovered between the ADLE and the PQL are as likely to be attributed to data noise (random chance) as they are to the phenomena being investigated. Unfortunately, EPA has not determined the PQL for Methods 23, 26 and 29. Consequently, all results above the ADLE have been treated as valid numbers in this analysis.

Analysis of dual and quad train testing sponsored in part by the ASME Research Committee on Municipal and Industrial Waste indicates that the median PQL to ADLE ratios are 10, 3,000 and 120 for Methods 23 (dioxins, chlorobenzenes, PAHs and other semivolatile compounds); 26 (HCl, Cl_2, HF and HBr); and 29 (Section 112, BIF and EU) results respectively. The controlled metals data are probably sufficiently accurate for this analysis; the uncontrolled HCl and trace Organic HAPs analyzed may be sufficiently noisy that really firm conclusions are not possible.

Chlorine Input

Determining the chlorine concentration of a particular batch of MSW burned during a test run is virtually impossible. Previous analysis of MWC data shows, however, that there is a strong correlation between chlorine feed measurements and uncontrolled flue gas HCl concentrations. The starting amount of chlorine available of participation in organic chlorination reactions and formation of metal chlorides is the amount released from the MSW (not bound up with the bottom ash). Also, the uncontrolled HCl concentration is usually large compared to the amount of chlorine that is associated with uncontrolled MWC fly ash. Consequently, uncontrolled HCl is used as a proxy for chlorine feed rate.

Statistical Techniques

The techniques used in the ASME/CRTD study to investigate the relationship between dioxin feed rate and dioxin stack emissions can be applied to these as well. Those analyses included: Spearman Rank-Order and Partial Correlation Analysis, Analysis of Variance (ANOVA) and Factor Analysis to find whatever relationship might exist between chlorine input and stack dioxin concentrations.

The major parametric studies which required ANOVA techniques to sort out confounding effects do not generally include metal or other trace organics emissions. Instead, partial correlation techniques were employed to sort out the effect of readily discernible differences like the type of air pollution control device (APCD) and designed interventions (e.g., purposely running the afterburner at low temperature for research purposes), from whatever effect chlorine feed might have on non-dioxin pollutant emissions. Factor Analyses were not performed due to the sparse nature of the data. To be reliable, Factor Analysis requires that all the parameters being investigated be complete. When there are significant data gaps, the analysis can still be mathematically performed, but the interaction terms are not fully characterized and the results can be misleading.

Spearman Rank-Order Correlation techniques were used to perform most of the analyses. Here, rank orders rather than absolute values of data sets are compared. This method has the advantage of not requiring precise knowledge of the underlying data distribution. Regardless of whether the data are normally, lognormally or otherwise distributed, the rank order of each data point remains the same. Sidestepping the distribution type question simplifies the analysis without loosing any ability to uncover a relationship if one exists. Whenever Spearman Rank-Order Correlations could not be performed, the natural logarithms of the data were used, since it is well known that emissions data are usually lognormally distributed.

Statistically significant correlations are ones whose significance level are less than 5 percent. This is a way of saying that we are 95 percent confident that the correlation is significant. Since this is an exploratory data analysis, we have to be aware that one in 20 comparisons will be "significant" due to chance alone. To avoid the problem of finding false positive results while minimizing the chance of declaring there is no relationship when one is really present, we used the False Discovery Rate (FDR) procedure[5]. This is a refinement of Bonferroni which scales the significance level from $\propto = 0.05$ found in most EPA regulations by the total number of comparisons (n) to be made and the rank order (i) of the significance level determined for a specific comparison:

$$\propto^* = i\propto/n \tag{1}$$

The FDR criteria effectively increases the required level of significance as the number of less significant comparisons already made increases. The advantage compared to other techniques that use a single threshold value is an increased potential for finding meaningful relationships that could otherwise be lost using a more conservative screening criteria while still avoiding the problem of finding a large number of false positives.

Just because a relationship is statistically significant does not mean that it is practically significant. The amount of change seen in one variable as a result of a change in the other is explained by the square of the correlation coefficient. As a result, with large data sets, statistically significant relationships can explain practically inconsequential portions of the total observed response.

For each statistically significant relationship, a scattergram was produced and a loess line — a <u>lo</u>calized regr<u>ess</u>ion fit through the nearest 25 percent of the data on each side of an uncontrolled HCl concentration — was added to determine if a threshold is apparent. A loess line that is flat at one end followed by rapid rising is evidence of a threshold effect. When the loess line flattens out again, this is an indication that different mechanisms are at work. A continuing straight line indicates the relationship is valid over the data range. Separate loess lines were fit through data from facilities equipped with high efficiency particulate control devices and those that were not to separate that effect in the plots.

RESULTS

The 28 databased HAPs and pollutants found in other country's regulations with enough simultaneous uncontrolled HCl and emitted concentration data to support analysis are tabulated in Table 1. The number of paired data points and the strength of the relationship (squared partial correlation coefficient) with uncontrolled HCl as a chlorine feed surrogate are included along with available melting and boiling temperatures for metal chlorides.

Scatterplots contrasting Section 112 HAP and uncontrolled HCl emissions are provided for all pollutants displaying a statistically significant relationship.

Metal Emissions

Figures 1 through 7 are scatterplots for analyzable Section 112 and 129 metal emissions versus uncontrolled HCl concentrations that show a statistically significant relationship. In each plot, data collected at facilities equipped with high efficiency particulate control devices (fabric filters and large electrostatic precipitators) are plotted as solid points. The balance of the data, principally from low efficiency electrostatic precipitators, are plotted using open symbols. While some plots show roughly an order of magnitude difference between these two data sets, the majority of the results are interleaved. This indicates that either the volatilization and condensation mechanism often ascribed to chlorine is not applicable to commercial scale systems or state-of-the-art air pollution control devices are efficient enough that this mechanism becomes essentially irrelevant.

The lack of applicability of the volatilization mechanism to MWCs is illustrated by the metal chloride boiling point data in Table 1. For metals showing a statistically significant relationship with uncontrolled HCl, after controlling for known confounding factors, the metal chlorides boil between 130 and >1,600°C while those that show no such relationship have metal chloride boiling points between 12 and 1,560 °C. There is no obvious relationship between increased releases and the metal chloride boiling point.

Most of the loess curves show either a hockey stick or a S-type pattern. Metal concentrations are initially flat, rising rapidly between 600-800 $\mathrm{ppm_{dv}}$ @ 7% O_2 uncontrolled HCl concentrations and then flatten again. This indicates that there is either a change in mechanism taking place or, alternatively, this effect could be a data artifact. A data artifact could be caused by distinct plant or test method differences above and below 600-800 $\mathrm{ppm_{dv}}$ @ 7% O_2.

Inspection of source descriptions and test reports indicates that design differences are probably not the cause, but the possibility cannot be ruled out. Interestingly, the majority of the higher uncontrolled HCl data tend to be from European MWCs. Thus, sampling method variations are a credible explanation. For the purposes of this paper, this possibility will be ignored.

Even though statistically significant relationships exist between chlorine and some metals, those relationships are not practically significant. For example, only 11 percent of the variability in cadmium concentrations, the most strongly related Section 129 HAP, is explained by changes in uncontrolled HCl concentration after design and location differences were accounted for in the partial correlation analysis. For lead, only 7 percent of the variability is accounted. Mercury is not statistically related to uncontrolled HCl concentrations in this data set even though it is believed that mercury chloride is more readily captured than elemental mercury. These observations provide a strong indication that other mechanisms predominate.

Turning to the other Section 112 metals, antimony and selenium are the most strongly related. Here around 50 percent of the variability is explained by changes in uncontrolled HCl concentrations. The other Section 112 metals exhibiting statistically significant relationships also have practically insignificant relationships.

Trace Organic HAPs

Figures 7 and 8 display the simultaneous data for Section 112 trace organic HAPs that are statistically significantly related to uncontrolled HCl concentrations. The strongest relationship is for 1,4 dichlorobenzene, and that relationship is negative. That is, increasing uncontrolled HCl concentrations is associated with reduced 1,4 dichlorobenzene concentrations. This entire relationship could be nonsense since 1,4 dichlorobenzene is a contaminant in the North American supply of dichloromethane used in the laboratory extraction and clean-up technique.

Total chlorobenzenes, as a surrogate for the Section 112 HAP monochlorobenzene, on the other hand, are statistically significantly related to uncontrolled HCl concentrations after accounting for confounding effects. As a practical matter, however, they are found at environmentally insignificant stack concentrations and only 24 percent of the variability in this pollutant is explained by changes in uncontrolled HCl. Interestingly, 2,3,7,8 TCDD shows neither a statistically significant (significance level 0.2 for a statistical confidence level of 80 percent) nor a practically significant relationship (5 percent of the variance is explained after controlling for confounding factors) to uncontrolled HCl. So, while total chlorobenzenes are sometimes used as surrogates for dioxin emissions, they probably should not be.

CONCLUSION

The same techniques that found no statistically significant relationship between dioxin and chlorine in combustor stack emissions have found a transition in emitted concentrations when uncontrolled chlorine concentrations are around 600 ppm_{dv} @ 7% O_2. On either side of this bound, there is no significant relationship. Since there is no theoretical reason to expect a step-type threshold effect, these conclusions may be a data artifact caused by differences in European (much of the high uncontrolled HCl concentration data) and North American (much of the low uncontrolled HCl concentration data). In any case, the metals showing a statistically significant relationship that is also practically meaningful are not environmentally significant. So, interventions to reduce MSW's chlorine content for the purpose of reducing metal emissions are unlikely to improve the environment. The same finding is reached for trace organic HAPs.

Analysis of the information in our database and review of the Regulatory Docket for the 1995 Emissions Guidelines indicates that current uncontrolled North American HCl concentrations are on the order of 550 ppm_{dv} @ 7% O_2. Consequently, it appears that little benefit would result from interventions to reduce the chlorine content of MSW, even if there were a meaningful chlorine—HAP link. No intervention for the purpose of reducing metal or trace organic HAPs emissions is indicated.

It must be realized, however, that the database employed in this analysis, as extensive as it is, only has a small amount of applicable data. Further work is needed to reach very strong conclusions. The available information indicates that such an effort is unlikely to discover that significant reductions in metal emissions will be realized by reducing the level of chlorine in North American MSW. Nevertheless, such research is encouraged to minimize the chance that erroneous public perceptions rather than sound science will drive regulatory efforts.

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2. Federal Register, V. 61 NO77, April 19, 1996.
3. ASTM, Method D4210-83, Standard practice for Interlaboratory Quality Control Procedures and a Discussion on Reporting Low-Level Data.
4. Method 301—40 CFR 63, 9.1.2, Appendix A. Method 301 Field Validation of Pollutant Measurement Methods from Various Waste Media.
5. V. Williams, L. Jones and J. Tukey, "Controlling Error in Multiple Comparisons," with Special Attention to the National Assessment of Educational Progress, National Institute of Statistical Sciences, Technical Report, #33, December 1994.

Table 1. Correlation results for uncontrolled HCl versus metals and HAPs.

Pollutant	n	significance (2-tail)	RDF significance criteria	result significant?	signed squared correlation coefficient	metal chloride melting point	metal chloride boiling point
Silver	36	0.0028	0.013	yes	25%	455	1500
Aluminum	34	0.0000	0.005	yes	52%		177.8
Arsenic	52	0.0124	0.021	yes	13%	-8.5	130.2
Boron	37	0.0533	0.027	no	11%	-107.5	12.5
Barium	35	0.4391	0.043	no	-2%	963	1560
Beryllium	14	0.6528	0.046	no	-2%	405	520
Calcium	23	0.0000	0.007	yes	64%	752	>1600
Cadmium	65	0.0149	0.023	yes	11%	568	960
Cobalt	25	0.7109	0.048	no	1%	742	1049
Chromium	62	0.0031	0.014	yes	15%	824	
Copper	38	0.1109	0.032	no	8%	620	993
Iron	37	0.0000	0.002	yes	69%	674	
Mercury	101	0.0955	0.030	no	3%	276	302
Nickel	56	0.0099	0.020	yes	13%	1001	976
Lead	83	0.0222	0.025	yes	7%	501	950
Antimony	35	0.0000	0.004	yes	54%	283	602
Selenium	25	0.0004	0.011	yes	43%	305	288
Tin	26	0.0000	0.009	yes	54%	246	652
Zinc	93	0.1981	0.039	no	2%	283	732
Total Chlorobenzenes	35	0.0056	0.016	yes	24%		
1,2 Dichlorobenzene	12	0.1616	0.034	no	26%		
1,3 Dichlorobenzene	18	0.9718	0.050	no	0%		
1,4 Dichlorobenzene	17	0.0069	0.018	yes	-44%		
Total Hexachlorobenzene	33	0.5454	0.045	no	1%		
4 Methylphenol	11	0.1937	0.038	no	18%		
Napthalene	13	0.0694	0.029	no	32%		
Total Pentachlorophenol	33	0.2294	0.041	no	5%		
2,3,7,8 Tetrachlorodibenzo-p-dioxin	44	0.1899	0.036	no	-5%		

Figure 1. Relationship between antimony and uncontrolled HCl concentrations.

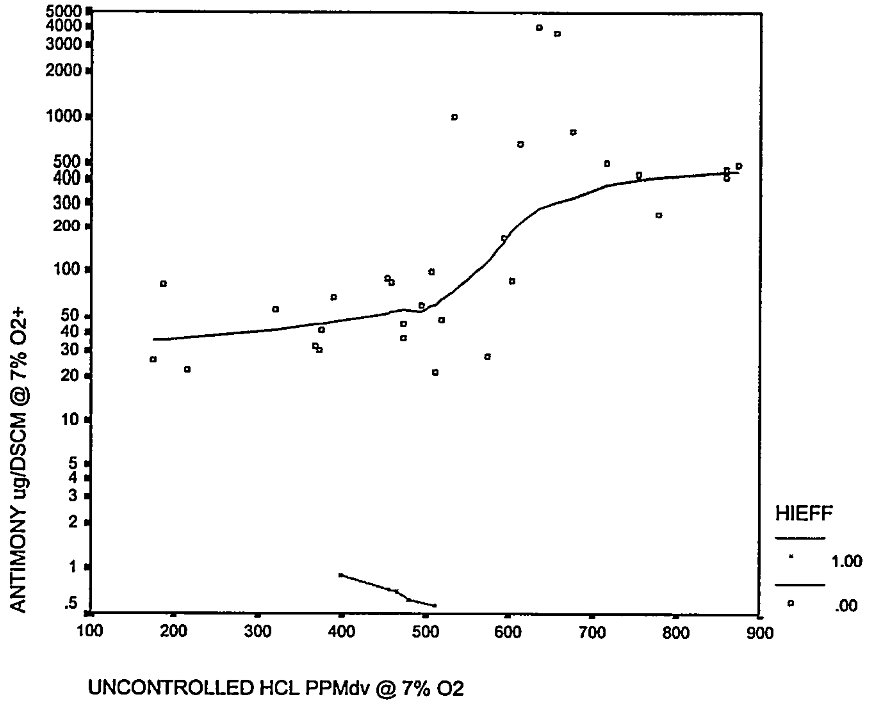


Figure 2. Relationship between selenium and uncontrolled HCl.

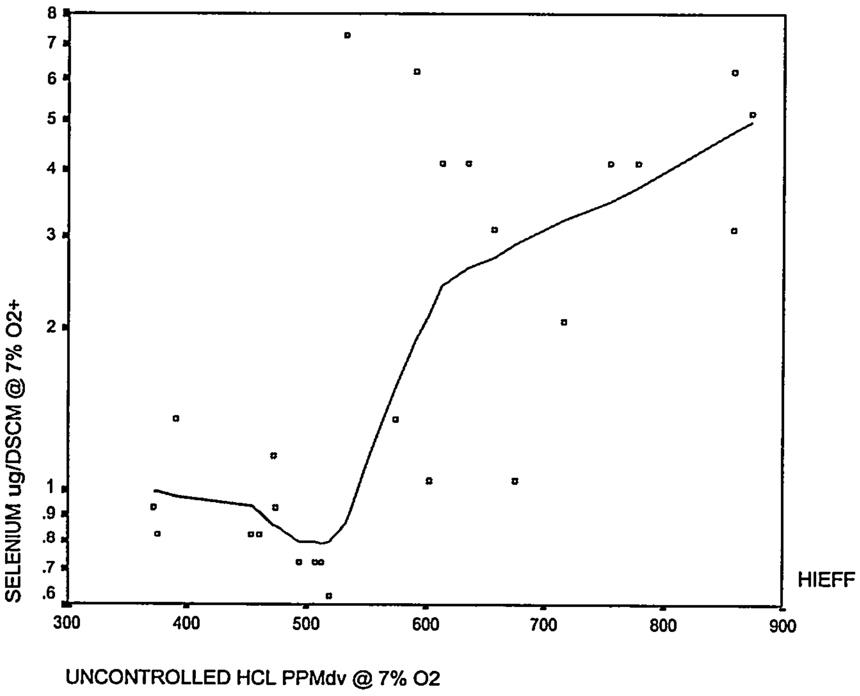


Figure 3. Relationship between chromium and uncontrolled HCl.

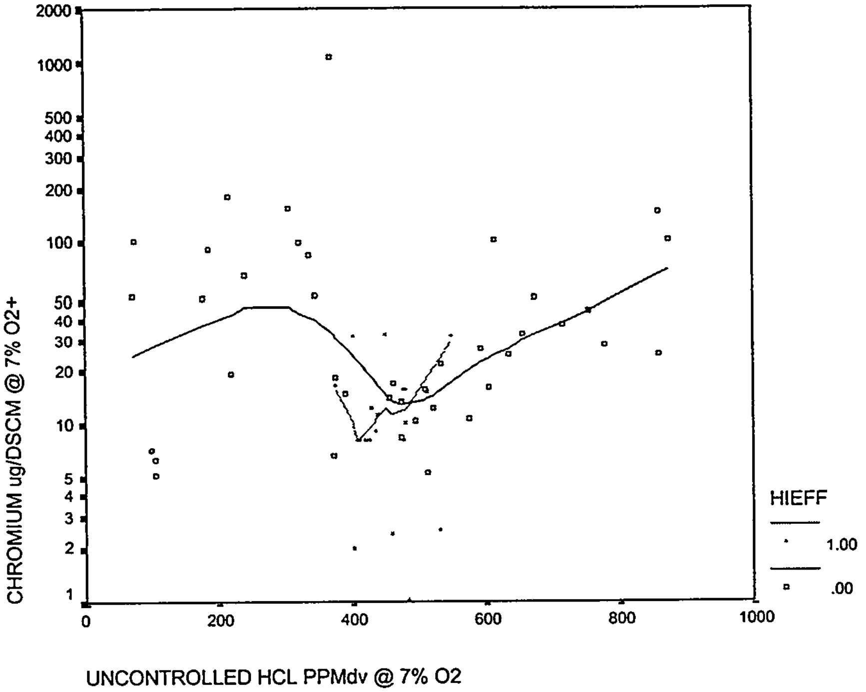


Figure 4. Relationship between arsenic and uncontrolled HCl.

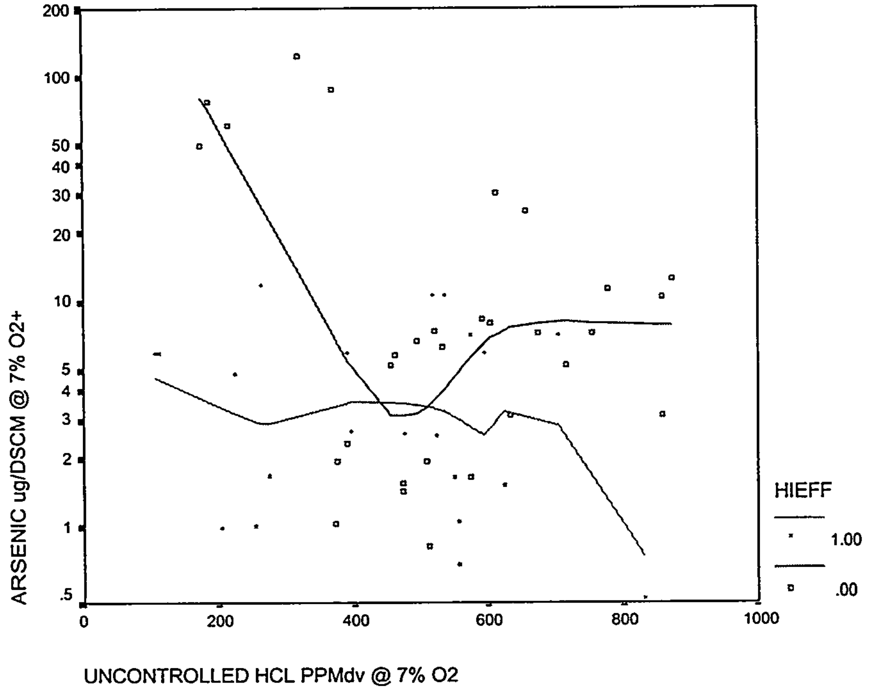


Figure 5. Relationship between nickel and uncontrolled HCl.

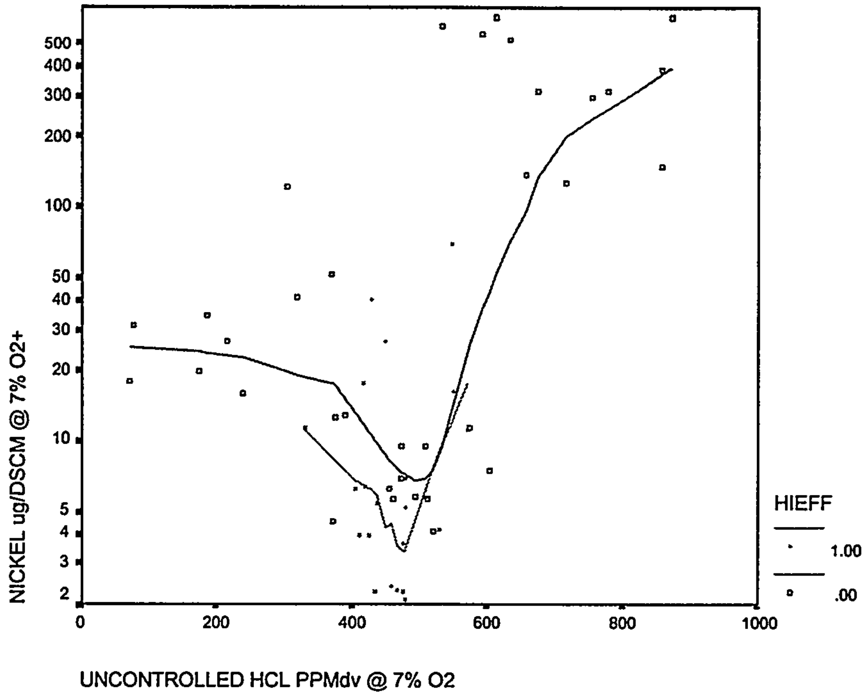


Figure 6. Relationship between cadmium and uncontrolled HCl.

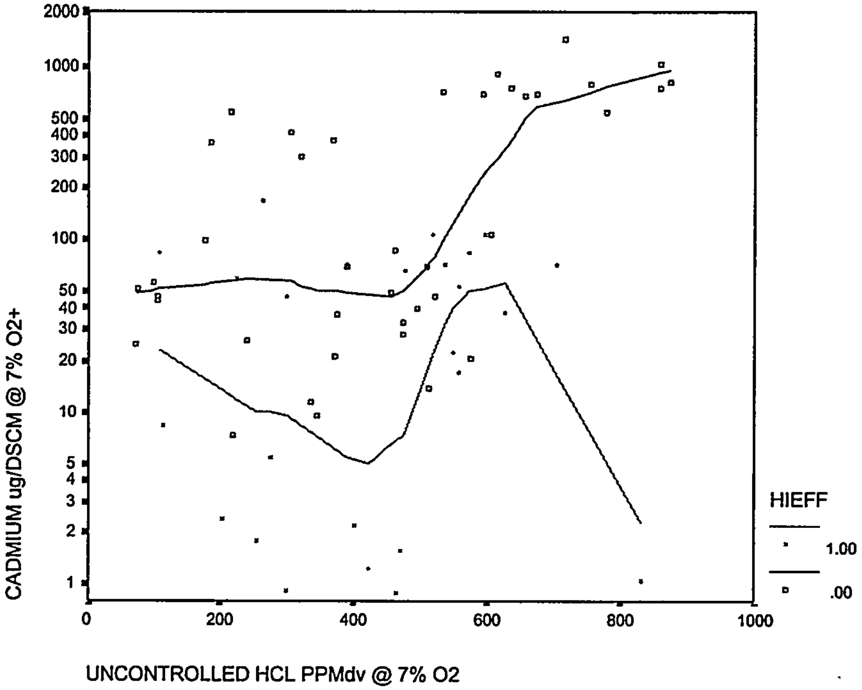


Figure 7. Relationship between lead and uncontrolled HCl.

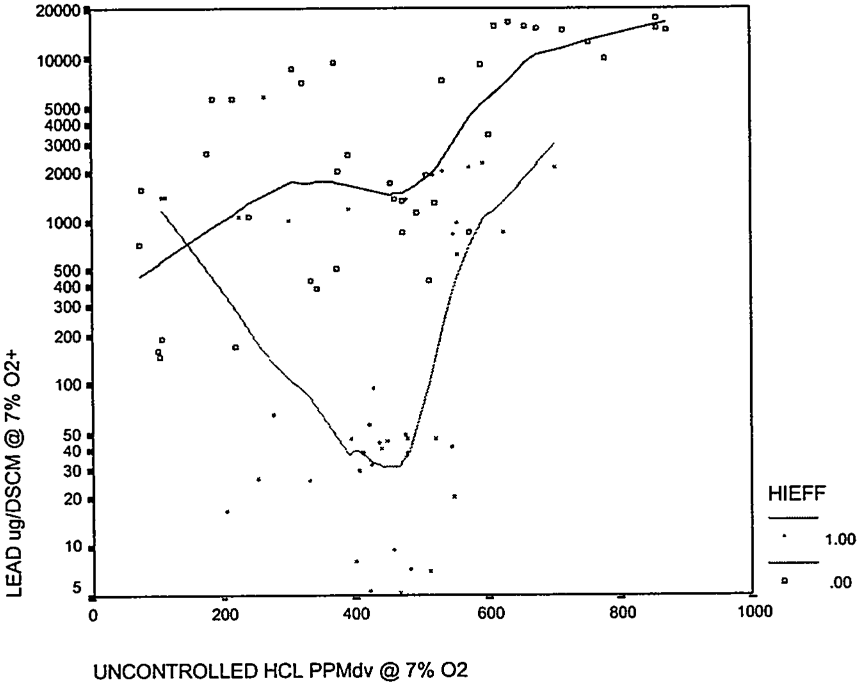


Figure 8. Relationship between total chlorobenzenes and uncontrolled HCl.

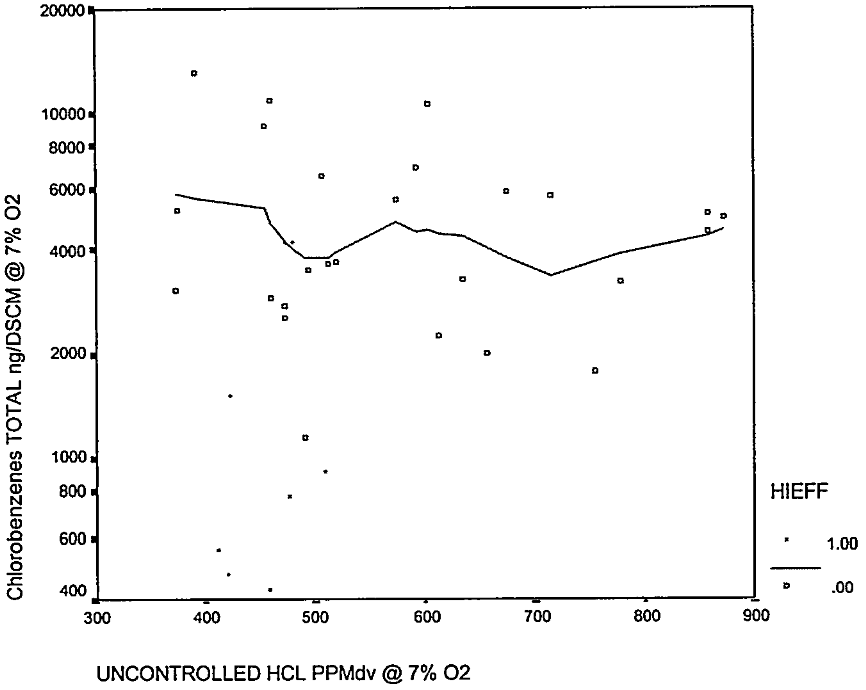
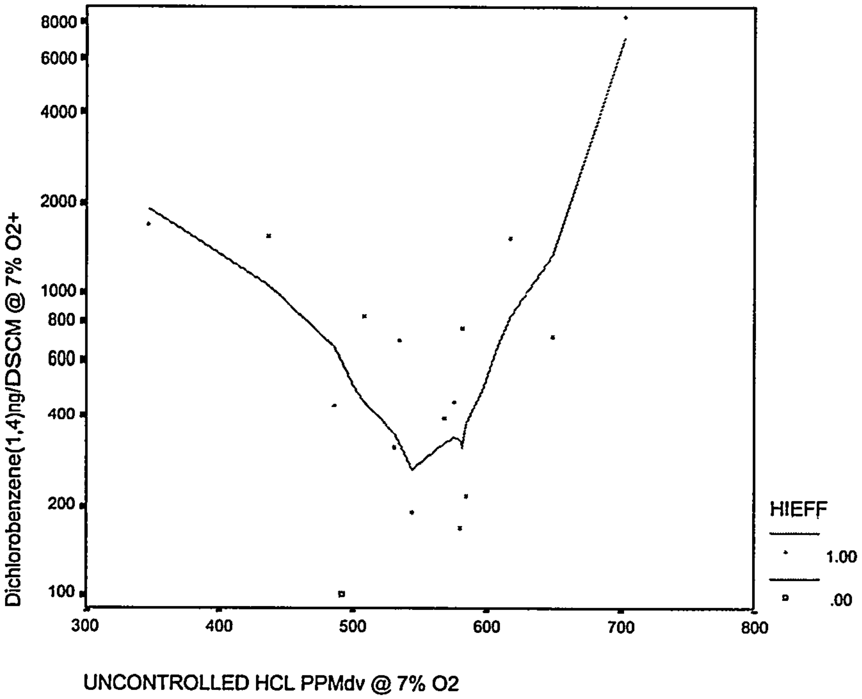


Figure 9. Relationship between 1,4 dichlorobenzene and uncontrolled HCl.



TECHNICAL SESSION III

Regulatory Issues

Acceptance of Waste-to-Energy as Part of an Integrated Approach to Waste Management is Better for the Environment and Could Reduce Community Waste Management Costs

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INTRODUCTION

Many countries have set targets for reducing the quantity of waste that ends up in landfill. Early waste management strategies were often based on assumptions of an impending landfill shortage or a desire to reduce the environmental impact of landfill itself, although this can be most economically achieved through landfill design and engineering. In recent years the emphasis has shifted to the recovery of resources that were perceived to be wasted by landfilled materials and this has resulted in the setting up of thousands of kerbside recycling programs aimed at recovering paper and packaging, increasingly complemented by green or yard waste programs.

Since a recycling based approach has limitations, the concept of 'integrated waste management' emerged. To many this means using a variety of treatment options including material recycling, composting and waste-to-energy (wte) to handle waste and landfilling the left-overs. Unfortunately wte tends to be dropped out of the mix for a variety of reasons and communities make do with the remaining options. Also waste policy makers, even if committed to integrated waste management, often fail to integrate waste policy with other policies which aim to reduce our overall impact on the environment, those relating to greenhouse reduction, renewable energy, resource optimisation and, ultimately, sustainability. The latter implies reducing our impact on the environment in a manner which meets social and economic objectives as well as environmental ones.

The reason wte is left out of the equation is in many cases based on the perception that it is more polluting than other means of managing waste and that, rather than recovering resources, it destroys them.

Complicating the development of appropriate waste strategies is the concept of a 'waste hierarchy' which assigns a higher place to methods of handling waste which recover materials than those which recover energy.

This paper examines the benefit of addressing these perceptions and how the use of wte in a fully integrated waste strategy can help communities to meet resource recovery and environmental impact reduction objectives cost-effectively.

PUBLIC PERCEPTION AS POLICY DRIVER

Many who live in a highly urbanised environment would regard a weekend away in a rural retreat with evenings in front of an open fire as the ideal break. They would be happy to burn timber in the fireplace but would object to the burning of organic material or wood derivatives such as paper in a wte plant. They would happily burn several tankfuls of fuel getting there and back but would be concerned about the burning of petroleum derivatives such as plastics to recover the energy content. They would object to the pollution potential of a wte plant without realising that both the open fire and the automobile were more polluting and whilst they would understand that in both cases the 'destruction' of the resource derived an energy benefit they would be less likely to see the same benefit being derived from a wte facility. Physical, material based, recycling is so much easier to visualise.

Community, state and national policies are based on similar perceptions. For example the city of Seattle chose to exclude wte from its waste strategy on the basis of public opinion.

We should also remember that politicians too are members of the public and are likely to share the same perceptions. This point was made by researchers at the Energy Systems Division of Argonne Laboratory conducting a study for the US Department of Energy into the impact of mandated recycling rates on energy consumption. The Argonne study suggests:

> "Congress specifically excluded combustion for energy recovery from counting towards the recovery goals, probably because combustion is viewed as a form of disposal and therefore is assumed to waste resources and have negative environmental impacts. However, cocombustion in coal fired plants or combustion in appropriately pollution controlled waste-to-energy plants is safe, avoids landfill costs. And can displace fossil fuels - in some cases more fossil fuels than by recycling. Therefore the objectives of the proposed legislation must be examined to see if they can most effectively be met by recycling at the mandated rates or by other methods of disposition."[1]

This approach is interesting as the US government had previously adopted policies which encouraged the development of wte facilities.

German policy on packaging waste provides another example of how wte is seen as a less than optimum means of recovering resources. Although the German Packaging Ordinance sets high recovery and recycling targets for packaging and insists that all types of packaging are recovered it prohibits the use of wte as a recovery option, insisting on recovery methods not based on combustion. The measure has resulted in real problems for the plastics industry because the volume of material recovered far exceeds the reprocessing capacity and, in some cases, the available technology. This has led to a number of creative solutions including the use of plastic waste as a reducing agent in steel blast furnaces. This is not categorised as combustion because the oxygen comes from the iron ore and not the atmosphere.

The legislation is about to be changed to allow some use to be made of energy recovery under defined conditions relating to the proportion of the total energy recovered.

Germany's insistence on material recovery in preference to energy recovery has resulted in increased community costs with the cost of recovering plastics calculated at thousands of dollars a tonne.

France on the other hand allows both the recovery of materials and energy from waste and this has resulted in reduced community costs. The Netherlands government negotiated a 'Packaging Covenant' with industry which agreed to eliminated packaging waste from landfill by the year 2000 using a combination of approaches including wte. Although this objective was reached ahead of schedule it now appears that the covenant will need to be renegotiated to include minimum rates of recycling for each material type so that the Dutch scheme meets the requirements of the European Packaging and Packaging Waste Directive which insists that at least 15% of each material group is recovered through physical recycling means, although the directive itself recognises energy recovery as an equivalent means of resource recovery.

The debate in Europe is now centred on whether wte should be demoted in accordance with the 'waste hierarchy' with the result that the Directive will state a distinct preference for material recycling. Again it is felt by some that wte does less than a complete job of resource recovery.

RECYCLING AND RESOURCE RECOVERY

When householders puts out an item for collection each week they see the whole item disappear and therefore it is easy to assume that in each case it is fully recovered. The high resource recovery assumption is further strengthened by pictures of bales and bales of recovered materials. So in the consumer's mind a glass bottle becomes a new glass bottle (never mind about the cap and the label) and an aluminium can becomes a new can - which needs a new lining as the old one wasn't recovered.

Recycling rates are reported on the basis of the volume of material collected rather than the amount recovered at the end of the process. It is not generally recognised that recycling is an industrial process which consumes further resources and generates wastes and impacts and that material losses occur during collection, sorting and processing. i.e. no material is 100% recyclable. Rarely is the reported waste saving discounted by the waste generated in the recycling process.

Several studies have looked at the comparative benefit of using secondary rather than virgin resources which is one way of judging the merit of recycling. A study for the US Department of Energy[2] into glass recycling concludes "the maximum energy saved is only about 13%" and recycling saves no energy if the glass has to travel more than 100 miles further than the distance to the landfill. The study concludes "Recycling of glass does not save much energy or valuable raw material and does not reduce air or water pollution significantly. The most important impacts are small reductions of waste sent to landfill...." (but of course glass is inert in landfill)

A similar conclusion was reached by the Tellus Packaging Study[3] which aimed to put packaging policy on a scientific base. It suggested a 23% saving in overall impact for glass, ignoring all transport impacts which in the case of glass are significant. The manufacture of steel containers had an impact similar to than of glass on a volume packed basis and this was not reduced by recycling it. Aluminium starts off with a higher per ounce packed impact but it is the only pack where impact is significantly reduced by recycling "cans made from recycled aluminium have impacts below 40% of the recycled glass level as do (unrecycled) aseptic packages (juice boxes) paperboard and HDPE juice containers"

The study also makes the point that the major portion of the environmental impact associated with packaging relates to its manufacture not its disposal with the environmental impact of disposal typically less than 1% of overall impact.

A similar theme is followed by T Kingsbury in a yet unpublished study[4] comparing the benefits of source reduction with those of recycling. In his paper he lists energy savings by material type gleaned from a number of sources. Savings range from 75,000 Btu/pound for aluminium against a virgin material production energy of 97.500 Btu/pound down to 1000Btu/pound for glass whose virgin material production energy is 8,500 Btu/pound (Given the different pack weights for these materials it would be interesting to compare per pack savings) Plastic bottles come in at 22.000 Btu/pound saving, paperboard at 13,500 and steel cans at 5,500. Again transport impacts are excluded. In percentage terms the savings incurred range from 75% for aluminium down to 12% for glass. Plastic, paperboard and steel come in at 57%, 44% and 20% respectively.

There is no suggestion here that recycling leads to full recovery of resources whereas there is a tendency to criticise wte because not all of the energy in a material is recovered in a wte plant.

Kingsbury goes on to suggest that higher energy gains result from an emphasis on source reduction, reducing pack weight, a conclusion shared by the Tellus study.

WTE AND RECYCLING COMPARED

Several studies have compared the resource recovery potential of wte with that of recycling and have concluded that they are comparable for most combustible materials. The Argonne study into mandated recycling rates referred to above concluded that for kraft paper wte was comparable to recycling whilst a Swedish study[5] suggests that for paper an optimised mix of recycling, where it is cost-efficient, and wte is the best solution since recycling can reduce the use of certain resources and wte can be used to conserve fossil fuel.

A collaborative study[6] conducted in Germany recently comparing the mechanical recycling of plastics with a range of energy recovery based technologies showed that in the case of a plastic detergent bottle mechanical recycling was superior to energy recovery only when recycled plastic could be substituted for virgin plastic on a 1:1 basis (i.e: there was no reduction in function or efficiency through the use of recycled materials) In energy recovery terms, greenhouse benefit terms and renewable energy terms the use of recovered plastic in, say, a blast furnace achieved 92-94% of the benefit of mechanical recycling. Given the high cost of recovery of plastic waste for recycling in Germany, a case could be made for sending it unsorted to a wte plant with other non-recyclable household waste.

LIMITS TO SUTAINABLE RECYCLING

It would be easy to conclude that if recycling is good for the environment, more recycling would be even better. There is a tendency amongst waste policy makers to set and increase recycling targets on just that assumption.

Given the task of reviewing the European approach to recycling recently, the Instsitute for Prospective Technological Studies based in Seville, Spain reported back to the European Parliament as follows:

> "Recycling is not always necessarily the preferable waste management solution since it is limited by the Second Law of Thermodynamics and obeys the law of diminishing returns. Other options such as prevention, reuse and recovery of energy can offer ecological or economic advantages over recycling according to the application area. In this light, the growth of the recycling industry is not a necessarily desirable policy target. The point is to perform recycling at its optimum rate both on an economic and environmental point of view. This optimum can vary widely according to material, location, available infrastructure, application, scientific and technological state of the art. etc.
>
> The desirability for increasing recycling depends on its relative merits compared to the other waste management options in a given geographic area."[7]

So what are the limits to sustainability for recycling? Obviously they vary by material and situation. Juha Kaila of Finland presented a paper on glass recycling[8] to the ISWA workshop held as part of the R'97 Conference in Geneva in February of this year in which he suggests that if the impact of the collection vehicle is taken into account, fossil fuel use considerations would dictate a glass collection rate of between 40 and 60% and if the truck's emissions were to be the deciding factor a collection rate of between 10 and 30% was sustainable.

FRAGMENTATION OF THE WASTE STREAM

One of the consequences of the 'Integrated Waste Management' approach to waste is that it results in a multiplicity of waste streams - a stream for each 'solution'. This can result in the duplication or multiplication of waste collection systems putting more resources behind collection and sorting at increased community cost. Whereas in the old days one truck used to come past to pick up all the trash, now there can be two, three or even four separate fractions requiring collection.

Again Germany supplies an example of a trend. On top of its controversial approach to the recovery of packaging waste the German government has passed legislation to control the recovery of other materials. Called the Closed Substance Cycle and Waste Management Act it seeks to make all industry waste materials part of 'substance loops' with the producer taking the responsibility for the establishment of loops for products produced. The recovery of waste therefore becomes the responsibility of every original owner or producer of wastes or products that eventually become waste. Wte is , however, not excluded as a recovery option but restricted to materials with an inherent calorific value of 11MJ per Kg going through a plant that recovers a minimum of 75% of this energy.

The legislation targets certain industry sectors, e.g. electronics, white goods, automobiles, and will lead to the development of a multiplicity of waste streams as recovery options tend to be based on what the material recovered is (and who is notionally responsible for it) rather than what it is made of and therefore what resource recovery option best suits.

Further complicating the material recovery task is the ever increasing range and complexity of products, ones which defy disassembly. Some say products should be designed for recycling, but that too is debatable.

Dealing with the waste fraction already commonly targeted for recovery we see three continuing trends. The first is towards lighter packaging, the second is a greater variety of pack types and the third is the increased use of multi-material or multi-layer which although more efficient make mechanical recycling difficult, if not impossible. The packaging industry is doing its bit for the dematerialisation of consumption - doing more with less. Each of these trends will make recycling more expensive as a resource recovery option. To get an appreciation of the impact of these trends have a look at the packaging currently on supermarket shelves that is not being recycled. It is mostly efficient, lightweight packaging that, whilst not being recyclable can easily and safely be used as a source of energy.

THE NEED FOR RE-INTEGRATION

The tendency in recent years has been to find different things to do with different parts of the waste stream. Much of waste policy has been based on the landfill diversion imperative rather than any genuine consideration of the relative environmental merits of available alternatives or the need to base strategies on the reduction of overall environmental impact rather than the reduction of solid waste. In many cases the recovery of material resources has been pursued at the expense of energy and other resource use and the generation of a range of other impacts.

The result is a multiplicity of approaches and programs each coming at significant community cost. Again taking kerbside recycling as an example there have been a number of studies which have sought to allocate the collection cost to each of the materials being collected. Whilst it is possible to get close to breaking even on some materials, especially in areas where landfill costs are high, plastic bottles, PET and HDPE are typically collected at a significant cost - studies show collection costs approaching $1000 in excess of their market value. The cost of collecting and reprocessing the variety of lightweight packaging collected by the German DSD system is substantially higher. As these materials are a good source of energy it would make sense to allow them to go with the residual waste to a wte plant rather than to persist with their collection.

The disproportionately high recovery cost for some materials is largely the result of persisting with policies and strategies on prevailing perceptions rather than on substantive fact based analysis of what can be achieved in the way of impact reduction at optimum cost. The starting point of such an analysis should be the realisation that in many ways energy is the common denominator to the question of resource optimisation and impact reduction. A re-examination of options that focus on energy rather than material optimisation would show that wte has a role to play in both resource recovery and environmental impact reduction.

There is also a need to re-examine waste policy to try to bring together the divergent waste streams and treatment options as reducing their number can increase overall efficiency and cost-effectiveness.

Including wte in the range of treatment options allows the waste manager to recover resources in the form of energy from those materials currently not recyclable, materials for which there are no markets and materials which present a risk to community or worker health and wte can do so with a relatively low overall environmental impact.

If we were to take the concept of policy integration further and consider the need to take into account greenhouse issues, renewable energy, air and water impacts, inter-generational equity and sustainabilty in the development of a responsible waste management strategy, again wte would be the centrepiece or unifying theme.

The role of wte is recognised by many governments. It forms the focus of waste strategies for the Danish and Swiss government who have a 'here and now' approach to waste - solve the waste problem where it is generated and in the current generation. Singapore burns 85% of its waste in three modern wte plants which supplement the local coal fired power stations. Yes, Singapore does recycle paper, and aluminium for which it can find markets and has an impressive record in building and construction waste recycling.

Japan has close to 2000 plants each servicing a local community but has recently caught the recycling bug, passing legislation to increase the recovery of household recyclables. Japan's latest facility, due to come on stream this year, is part of the Tokyo Harbour Sub Centre, a new development built on reclaimed land in Tokyo Bay (an old landfill site) designed to house 60,000 people and accommodate a further 150,000 office workers during the day. The waste generated by this community goes through underground pipes directly into the wte plant. This provides district heating, hot water and air conditioning to its host community and generates a portion of its electrical energy. Local use of the energy recovered optimises the environmental benefits.

We should continue to encourage the community to see waste as a resource but as a source of energy as well as secondary materials. A greater emphasis on energy recovery will result in opportunities to consolidate waste streams and reduce overall costs. The environment benefits from a more complete recovery of resources in a manner that has a relatively low impact and yield other benefits such as greenhouse gas reduction.

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[1] Mandated Recycling Rates: Impacts on Energy Consumption and Municipal Solid Waste Volume Energy Systems Division Argonne National Laboratory, December 1993

[2] L.L. Gaines et al Energy Implications of Glass Container Recycling Energy Systems Division Argonne National Laboratory and National Renewable Energy Laboratory, March 1994

[3] F. Ackerman et al CSG/Tellus Packaging Study for the Council of State Governments and the US EPA, Tellus Institute, May 1992

[4] T Kingsbury Source Reduction in Recycling Terms Unpublished draft, Jan 1997

[5] Environmental Impacts of Waste Paper Recycling International Institute for Applied Systems Analysis, Sweden

[6] Life Cycle Analysis of Recycling and Recovery of Households Plastics Waste Packaging Materials, Fraunhofer Institute, Munchen, Technical University of Berlin and University Kaiserlautern

[7] L Bontoux et al The Recycling Industry in the European Union: Impediments and Prospects Institute for Prospective Technological Studies, Seville, Spain, December 1996

[8] J. Kiala Limits to Sustainable Recycling - A Case Study on Glass Recycling ISWA Workshop on Sustainability R'97, Geneva, February 1997

Economic Factors Influencing the Development of Resource Recovery Facilities in the Continental U.S. and Overseas

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In the 1970's there was a confluence of economic and social influences which were responsible for creating the resource recovery industry: an industry which we are all here today, in some capacity, to discuss and hopefully to advance.

The waste-to-energy industry did not exist in the U.S. before 1975: so the industry just turned 20 years old. That is quite young for a major industry, making it still possible to have live industry veterans, who can also be historians and maybe even prophets of the future, at conferences such as this one.

It is my opinion that, as with most industries, the waste-to-energy/resource recovery industry is economically driven. It wasn't always so, but, with the ever-advancing global privatization of what were formerly municipal or public services, I believe we've seen the last of the publicly owned and/or subsidized projects. I also happen to think that the privatization movement is a very good thing. The free market brings with it accountability and responsibility, and minimizes political influence as a dominant factor in the determination and implementation of appropriate infrastructure solutions.

Before discussing economic influences, a bit of industry history is appropriate. A major environmental event, which many see as the starting point of our industry, thrust me into this delightfully and painfully complex business. It was Earth Day 1970. Though I am here today to discuss economic issues, I am an engineer, problem-solver and environmentalist first. If I were a pure capitalist, I would not be in this business and here today as an advocate of the resource recovery industry. The economics for success have not been good in this business for the past five years. I don't believe this industry is dead, but it has been in a deep coma for the past five years and economic indicators don't paint a bright picture for the next five years.

The first large-scale public participation in an environmentally focused activity occurred on Earth Day in April 1970 and it, among other things, spawned the environmental movement which has had such an influence on our industry (both positive and negative). It also created a public awareness of environmental issues including the manner in which society manages its wastes. This in turn was communicated to our Congress which, in its wisdom, produced the Resource Conservation and Recovery Act (RCRA) of 1976. This Act had a noble purpose stated as "to promote the protection of health and the environment and to conserve valuable material and energy resources". In other words, the conservation and recovery of resources became part of the law of the land.

In 1973, shortly after the first Earth Day, we experienced our first energy crisis brought on by what was then called the "Arab Oil Embargo". (See Figure 1) There were dramatic increases in oil and gas prices and the environmental community, with newly found power, sought to have renewable energy sources developed to replace our growing dependence on imported and limited supplies of fossil fuels. Congress again responded by passing the Public Utilities Regulatory Policy Act (PURPA) of 1978 which, among other things, would provide a reliable buyer for energy generated from independently produced power from renewable resources.

These two acts were intended to provide communities and private industry with both a ready and financeable market for energy generated from waste, and a national commitment to abandon landfilling as the primary method of waste disposal.

But, back to the history:

I choose 1975 as the date that the waste-to-energy industry began because that is the year that the Saugus, Massachusetts RESCO facility went on-line, accepting waste from Boston metropolitan area communities and supplying steam to General Electric. It was the first privately developed and financed facility to make money at generating energy from waste. It brought the Von Roll mass burn technology to the U.S., to work for the first time on U.S. waste materials. It did not have an easy start-up and did not initially generate electricity. However, after several significant modifications, the RESCO facility became a successful operation and is still operating, over 20 years later.

But, most importantly, RESCO was done privately, with no government subsidies, and included an air pollution control system which met or exceeded all standards in place at the time. The macro economics were good, but not great, and this facility should have been the beginning of elimination of the landfill approach in the U.S.

Certainly there were other energy-from-waste facilities constructed in North America prior to that time. (See Figure 2) They were, however, municipally sponsored projects which did not have to meet the test of the marketplace economics and thus must be considered subsidized or protected projects. The earliest of these is the Hamilton, Ontario Solid Waste Reduction Unit (SWARU) which went into service in 1969 and, after a number of retrofits, is still in service today. It was the first *prepared fuel* waste-to-energy system and the technological "grandfather" of the SEMASS facility. Despite its technological contribution, it was, and still is, publicly owned and that is why I use the free-market Saugus facility to mark the birth of the industry.

The Congress, obviously reacting to concern for the environment and intending to encourage the development of renewable energy sources, thought that the waste-to-energy/resource recovery approach was good national policy. (See Figure 3) But, the regulators apparently did not; and, as regulators can do, they slowed the process by regulating the waste-to-energy industry, if not to death, certainly into the comatose state where it now resides. I have previously stated that the resource recovery industry, along with other industries, is economically driven. Well, how then do regulators impact the industry? Simply by influencing the economics through regulation or de-regulation, as well as slowing any process they are involved in. Time is money when it comes to the development of these complex projects and, just as de-regulation drives the price of a product down, regulation or pending regulation drives the price up.

We cannot, however, lay the blame entirely at the door of the regulatory community.

If there is one thing that we overlooked as an industry that has hurt us more than anything, it is the lack of inclusion of landfills under the original Clean Air Act of 1970. Though we tend to blame the regulators and politically correct environmentalists for that, a large portion of the blame rests with our industry --- in particular, with the large parents of industry players who have a vested interest in protecting the economics of mega-landfills.

But, getting beyond blame, the regulatory community chose to impose incredibly tough air quality standards on waste-to-energy facilities while ignoring the severe environmental impacts (including air impacts) of landfills. They also ignored or postponed air quality upgrades to other energy generation facilities. So, what was intended by Congress as an economic incentive became a severe handicap to our industry. (See Figure 4) Waste-to-energy facilities are the most heavily regulated energy generation facilities in the U.S., while emissions are cleaner than coal, oil and even natural gas in some cases. The trucks bringing waste to the facilities are now a greater source of air pollution than the modern waste-to-energy facility stack gasses. In a feeble attempt to correct this obvious environmental error, the Clean Air Act Amendment of 1990 for the first time brings landfills under the Act but sets no firm standards. In addition, the MACT (Maximum Achievable Control Technology) standards were proposed (and adopted in December 1995) on an industry that represents a great solution, not part of the problem. At least in Europe where tight air quality standards are in place, they apply to all energy generating facilities, and landfills are recognized as the last resort in waste management and price controlled accordingly.

However, I am not advocating price controls or regulation; I am advocating de-regulation and open market solutions with a level playing field. The setting and enforcing of uniform environmental standards should be the only government function. Objective comparative environmental assessment is essential to that function. What are the environmental, social and economic impacts of the disposal alternative, the recycle/landfill alternative, and the resource recovery alternative? That is a legitimate question for government to ask and answer.

Let's look at two Energy Answers facilities for examples of the economics of private sector resource recovery systems. (See Figures 5 & 6) Both the SEMASS and Pittsfield facilities are located in Massachusetts and were built and operated privately, without public subsidy. SEMASS is a 3000 ton/day facility designed, developed, built and operated by EAC and now owned and operated by American Ref-Fuel. Pittsfield is a 240 ton/day modular system acquired and upgraded by EAC in 1993.

In both cases the private sector decision to invest and build was based on the projections that each facility could produce a return to investors of approximately 30%. The mix of expenses and revenues were, and remain, quite different: Pittsfield has a relatively low energy sales component, while SEMASS has somewhat lower tip fees and materials sales revenue. The project economics were a function of local economics, regional economics, technology choices and capital and O & M costs. (See Figure 7)

These projects have operated successfully for 8 and 15 years respectively and have provided a valuable community and environmental service in a tough regulatory environment (Massachusetts). So why can't these economics be duplicated now and what could we as an industry do to improve the project economics for future projects?

First, let's look at the factors influencing the economics and discuss them:

1. Energy prices

2. Waste disposal prices

3. Economics of the particular resource recovery system
    - size
    - local subsidies available
    - technology cost
    - local economics (tipping fees and energy prices)
    - interest rates

4. Regulatory community position and support/lack of support for resource recovery

5. Site selection

6. Public perception of resource recovery vs. landfill/recycle

7. Environmental issues and their appropriate management
    - air pollution control
    - ash management
    - community impacts; traffic, noise, odor

8. Politics

The first two factors are generally out of the direct control of our industry and are the two factors which most critically influence the economics of resource recovery systems. We will look at them a bit more closely since overly aggressive projections of these prices has led to the deteriorating economics of our industry which we have experienced.

First, let's look at energy projections. (See Figures 8 & 9) I chose gas as the fossil fuel to establish the base price for wholesale energy since a large number of gas-fired combustion turbine combined cycle power plants are being built by the non-utility generators both in the U.S. and abroad. Energy prices will in the near term, in effect, be set by the supply and price of natural gas. Supplies right now seem to be abundant but the projection of future pricing is left to each project developer to develop and defend. One warning: as the price of energy escalates, as it undoubtedly will someday, and waste-to-energy becomes more attractive, so may other energy sources such as photo voltaics, biomass and most importantly, coal. This should be factored in to moderate aggressive projections of escalating energy prices.

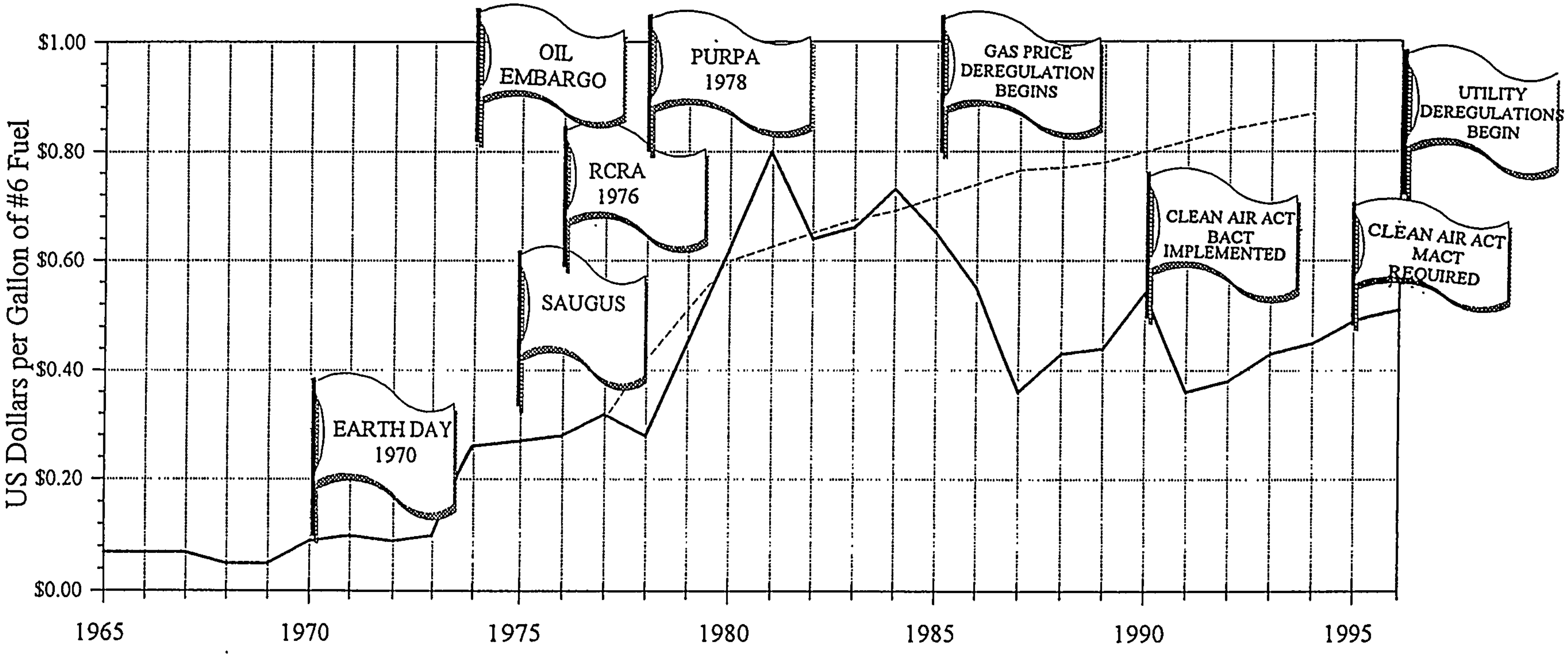
Then, we should discuss the past projections and future of tipping fees (See Figure 10) which in great part will be determined by the treatment of landfilling (and I think it would be appropriate to return to the old term "dump" when a landfill is not being used to productively restore a piece of scarred land). If the government in its wisdom chooses to impose uniform environmental standards and enforce them, then I think that tip fees will rise and therefore make resource recovery relatively more attractive economically. If not, I have seen compelling numbers which suggest that the U.S. has enough permitted landfill capacity to last through he next century, and the law of supply and demand being what it is, I would expect landfilling prices to remain quite low.

With these two factors essentially out of the control of our industry, it is then necessary to find the potential project locations where waste and energy prices are likely to be highest and to focus on the other factors in an attempt to bring facilities into a more competitive position compared with the disposal alternatives.

Therefore, the key to developing good resource recovery project economics in anticipation of competing with the dumping of resources in landfills (dumps) is to: select locations where energy and dumping costs are high; reduce capital and O & M costs through creative design and proper incentives; recover more materials and reduce residue disposal costs; increase energy efficiency; improve environmental performance; educate the public and regulators about the environmental benefits of a resource recovery approach; and don't attach your project to a political sponsor.

NO. 6 Heating Fuel Prices

1965-1996



Source: US Department of Energy 1977

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Figure #1

Resource Recovery Facility Startups

1970-1996

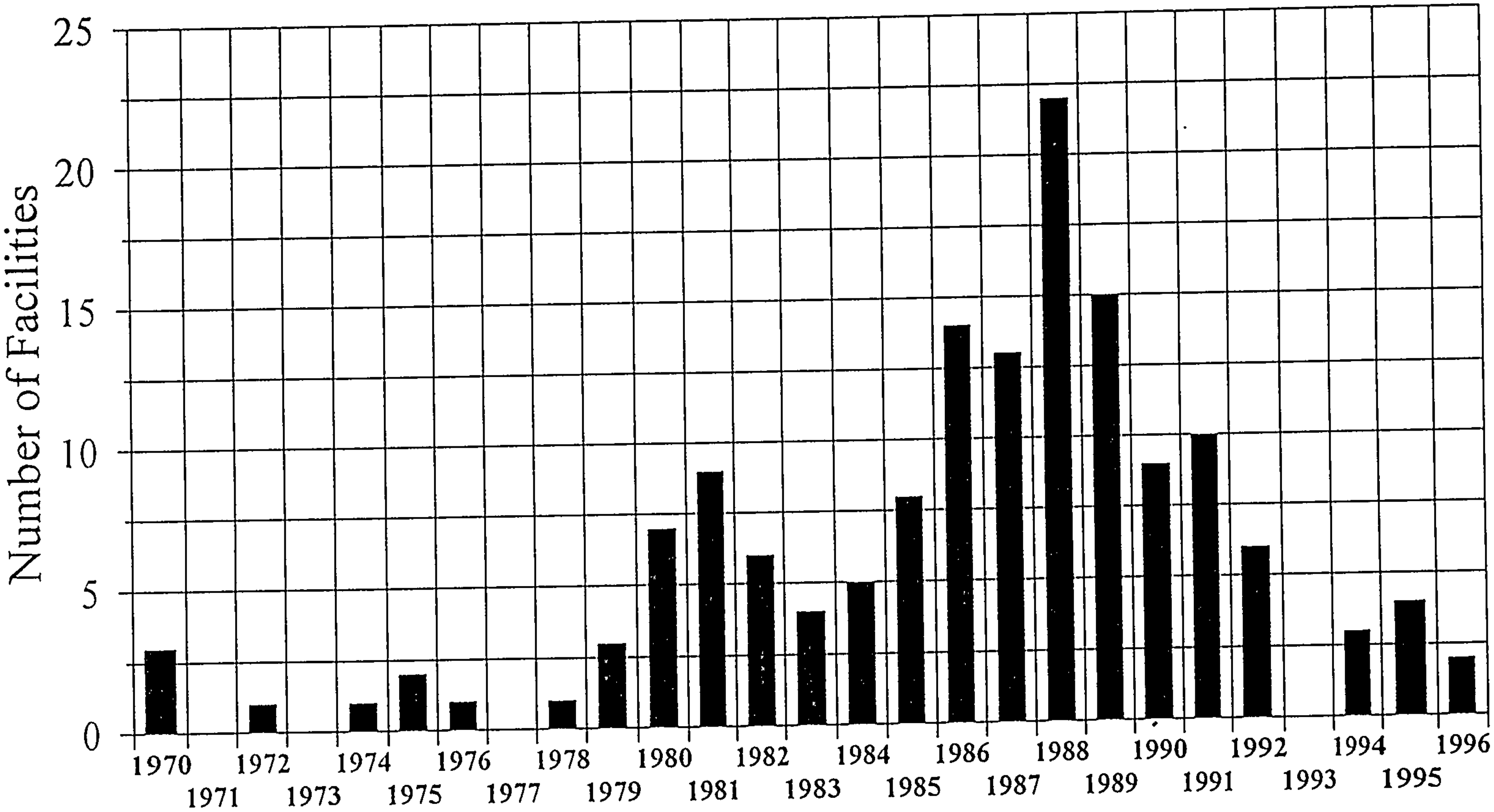

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Figure #2

RESOURCE CONSERVATION AND RECOVERY ACT (RCRA) 1976

Objectives:

Sec. 1003 The objectives of the Act are to promote the protection of health and the environment and to conserve valuable material and energy resources ...

National Policy:

Sec. 4001 ... developing and encouraging methods for the disposal of solid waste which are environmentally sound and which maximizes the utilization of valuable resources including energy and materials which are recoverable from solid waste and to encourage resource conservation.

Figure #3

Resource Recovery Facilities

Projected versus Actual

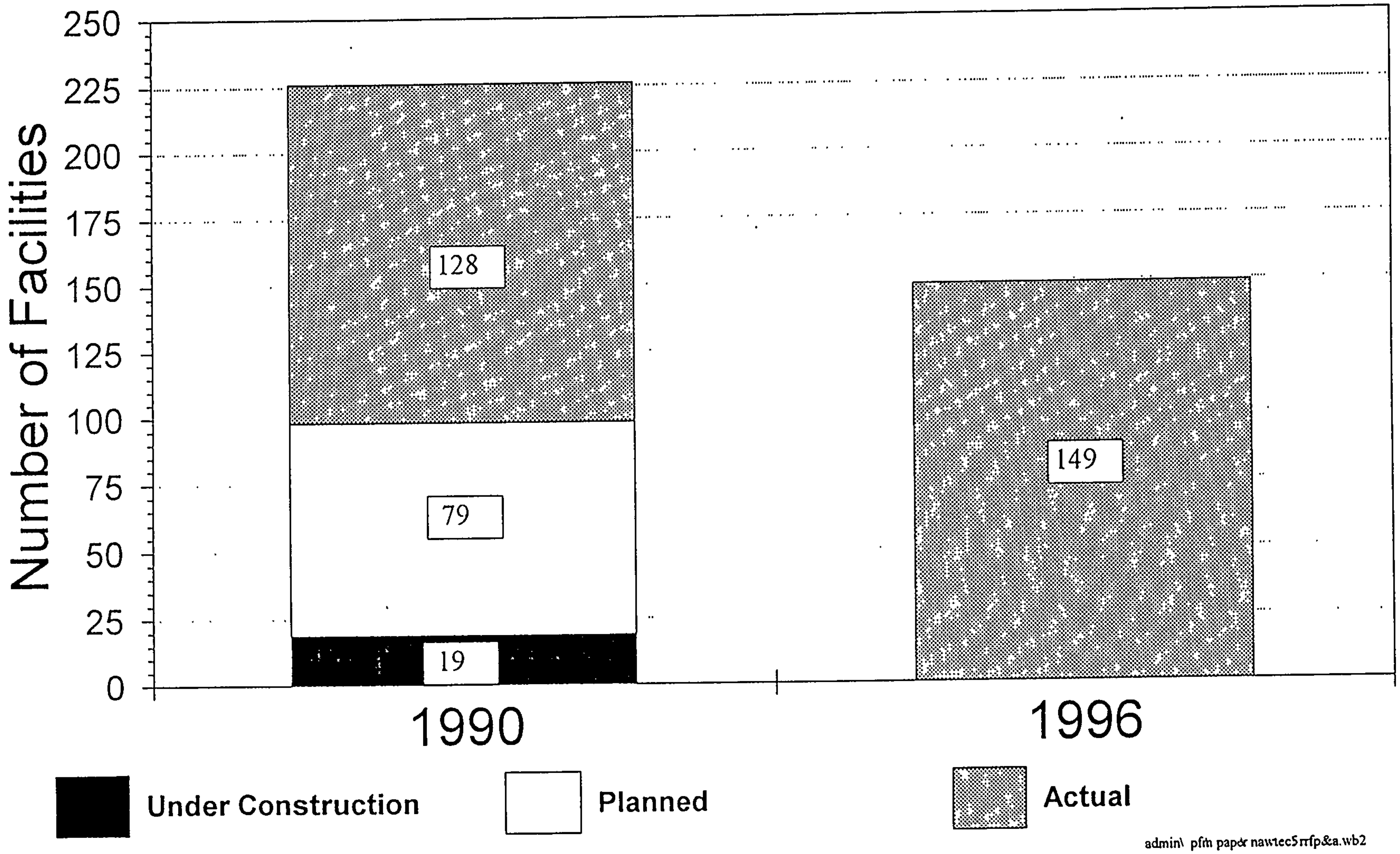

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Figure #4

SEMASS Resource Recovery Facility

COST and REVENUE PROJECTIONS

1800 Tons Per Day (average daily throughput)

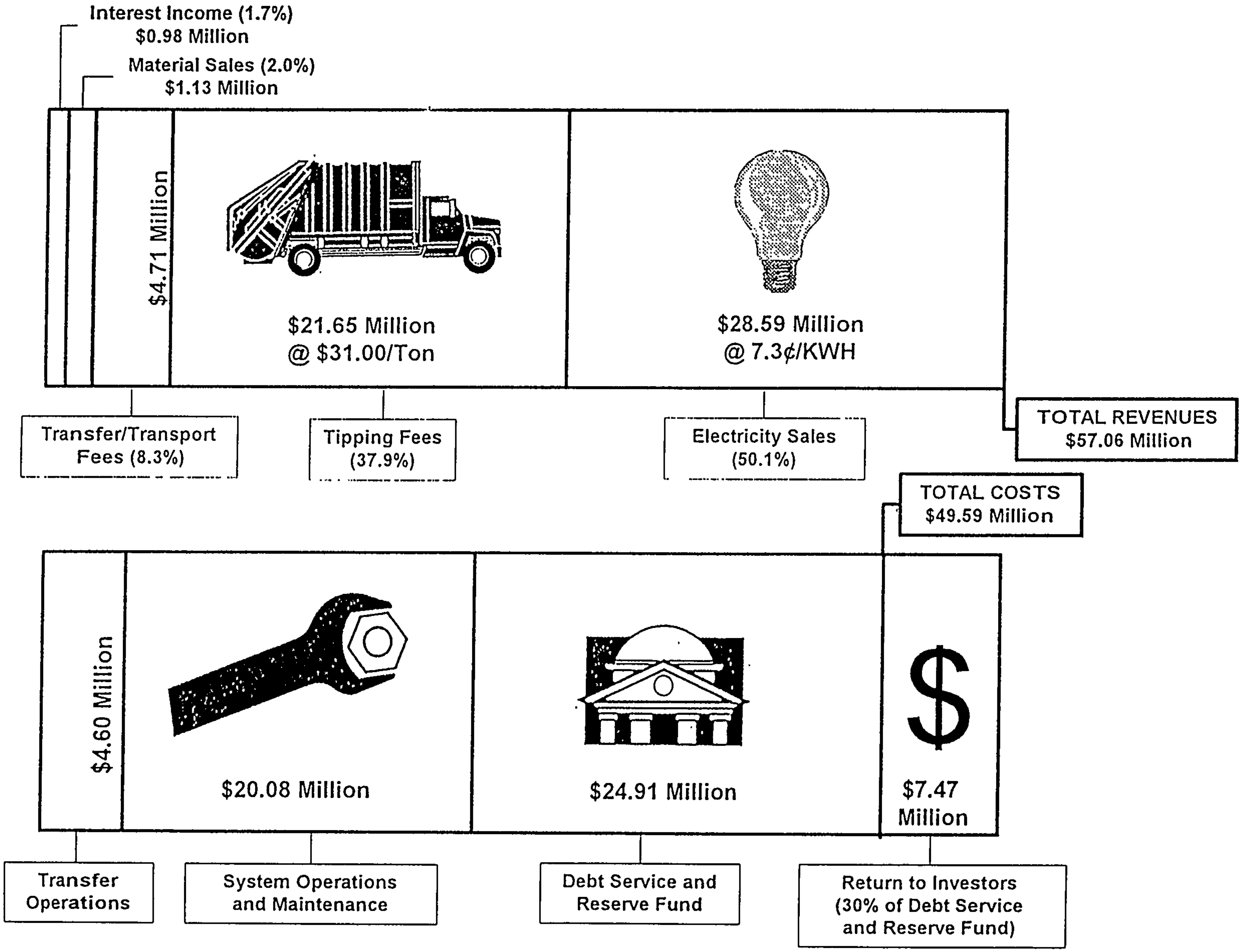


Figure #5

PITTSFIELD Resource Recovery Facility

COST and REVENUE PROJECTIONS

240 Tons Per Day (average daily throughput)

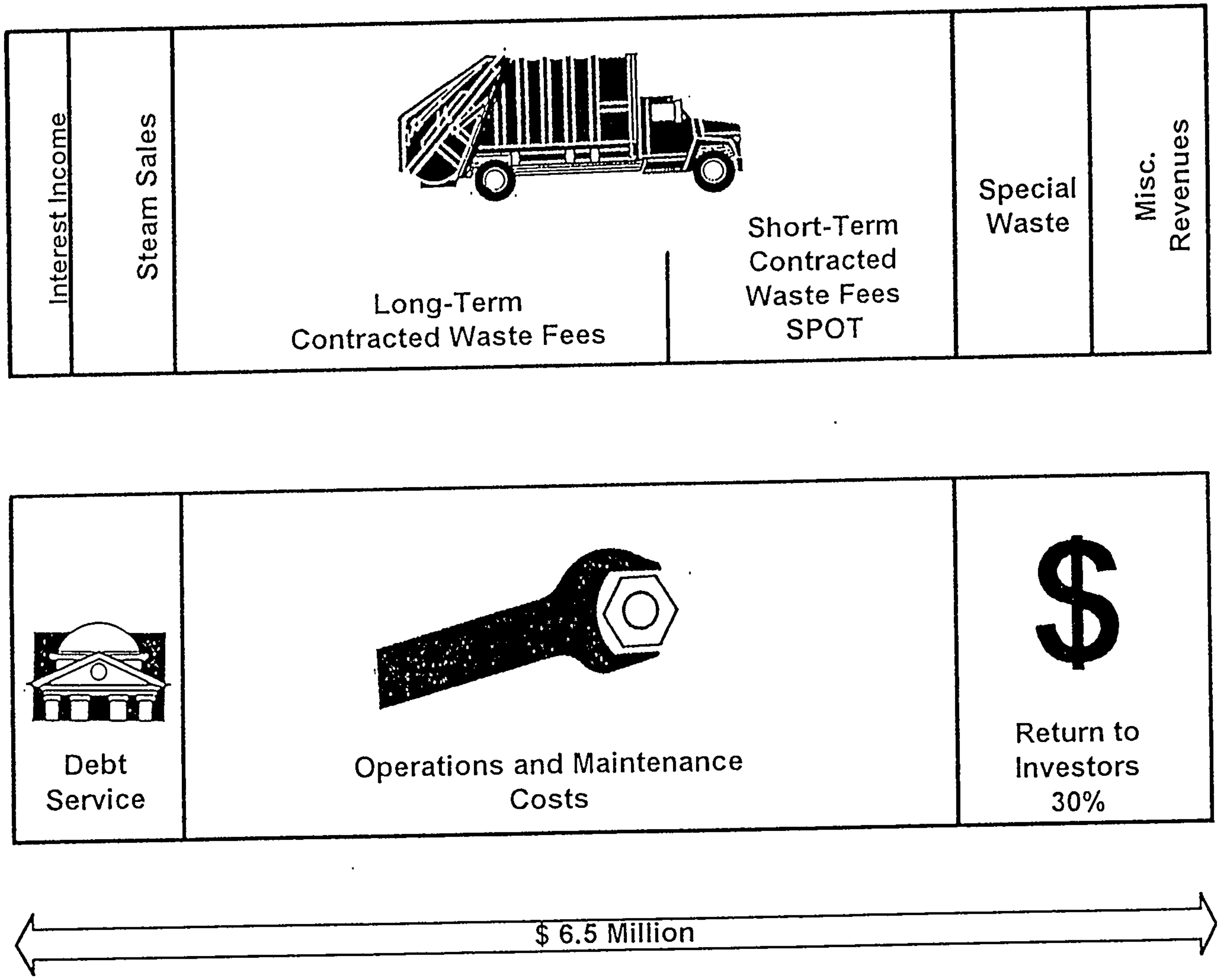


Figure #6

O & M Cost Components

- Operator's Fee
- Host Fees, Taxes, Rent
- Residue Disposal Costs
- Transfer and Transport Costs
- Maintenance
- Environmental Compliance
- Administration/Public Relations

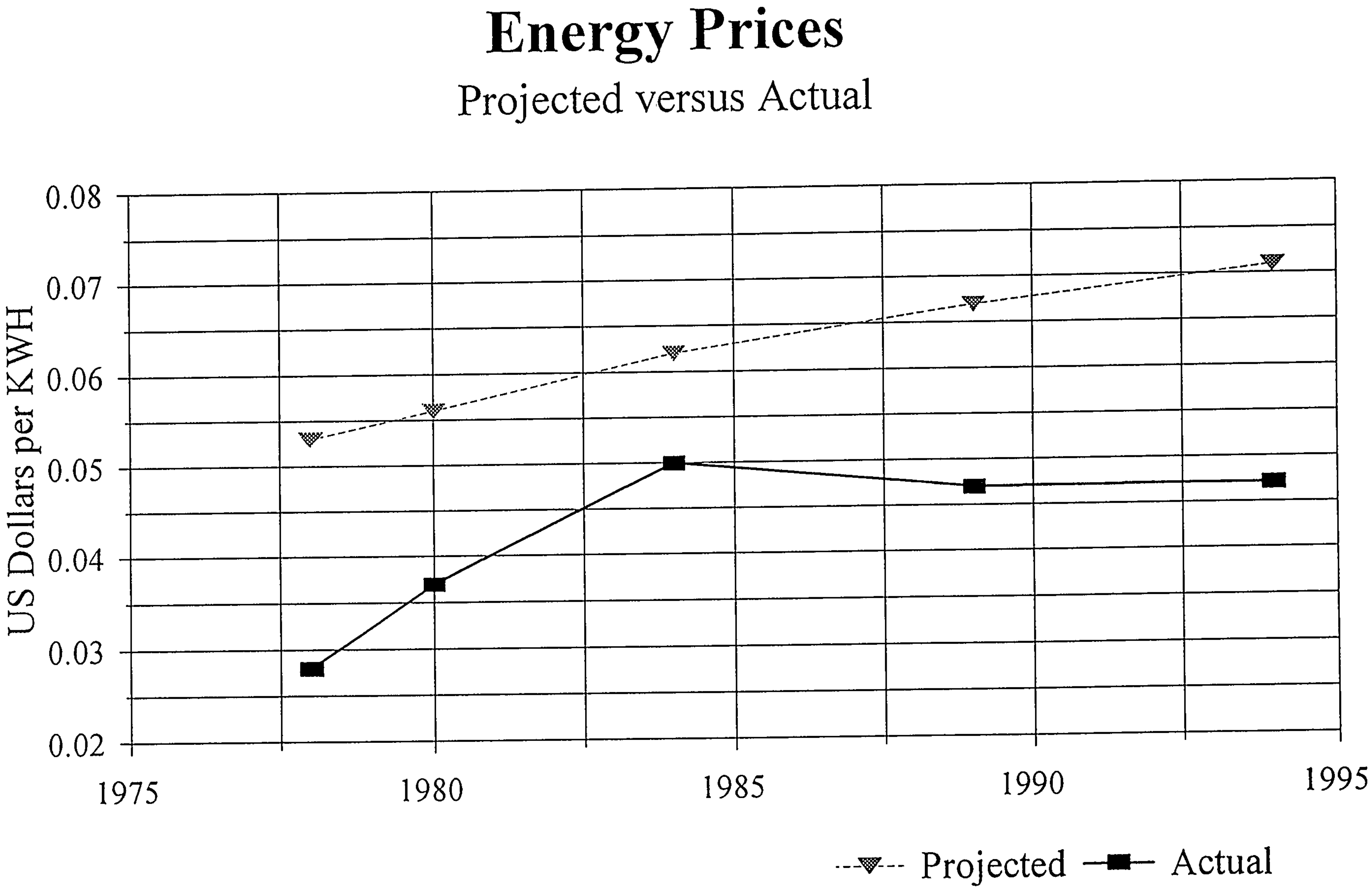
Revenue Components

- Energy Sales
  - Electricity
  - Steam
  - Permit limits

- Tipping Fees
  - Contract
  - Spot
  - Quantity
  - Special Wastes

- Interest on Reserves

Figure #7



Commercial Natural Gas Prices

1970-1996

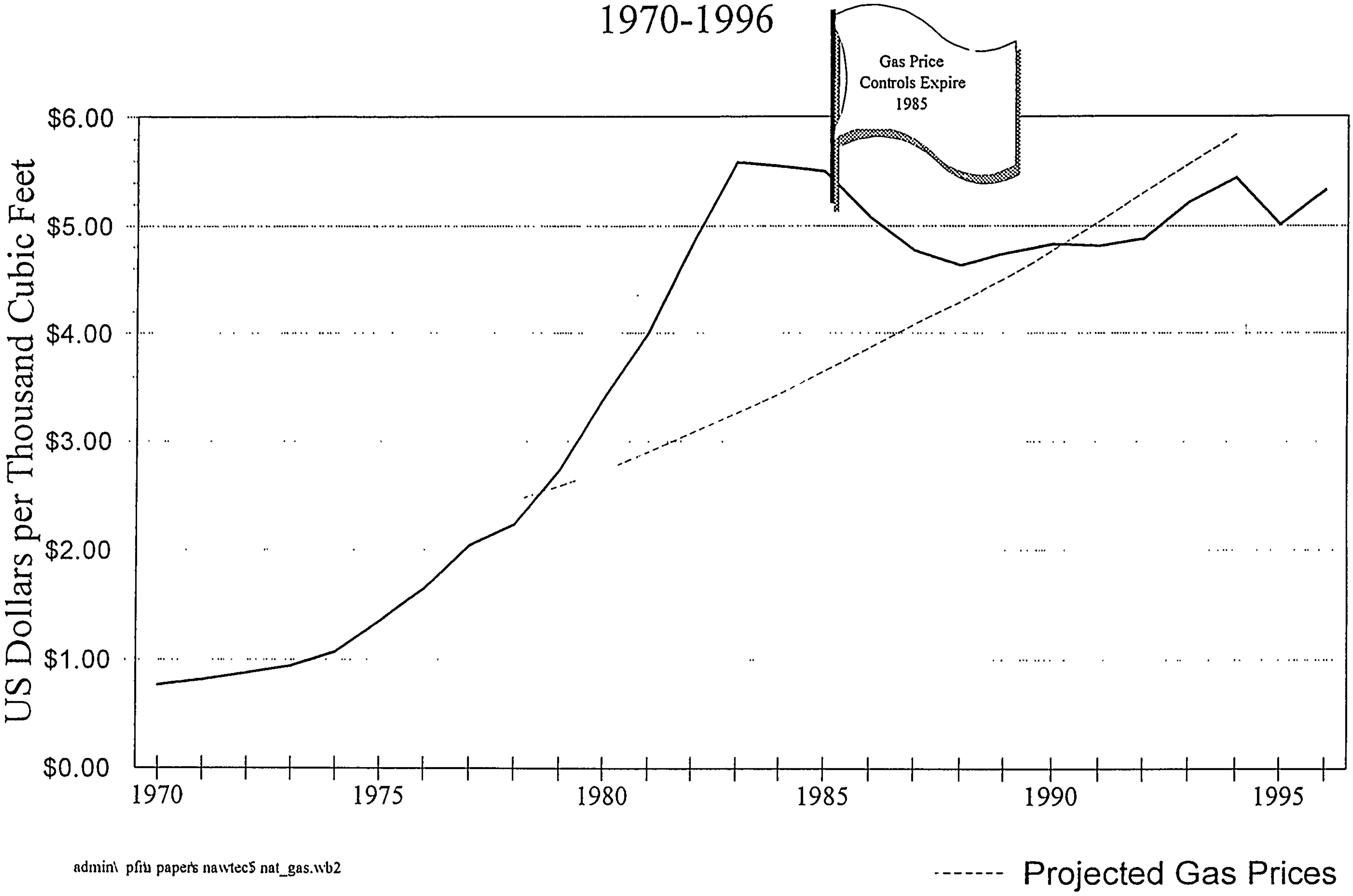


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Figure #9

Projected versus Actual Tip Fees

SEMASS Resource Recovery Facility

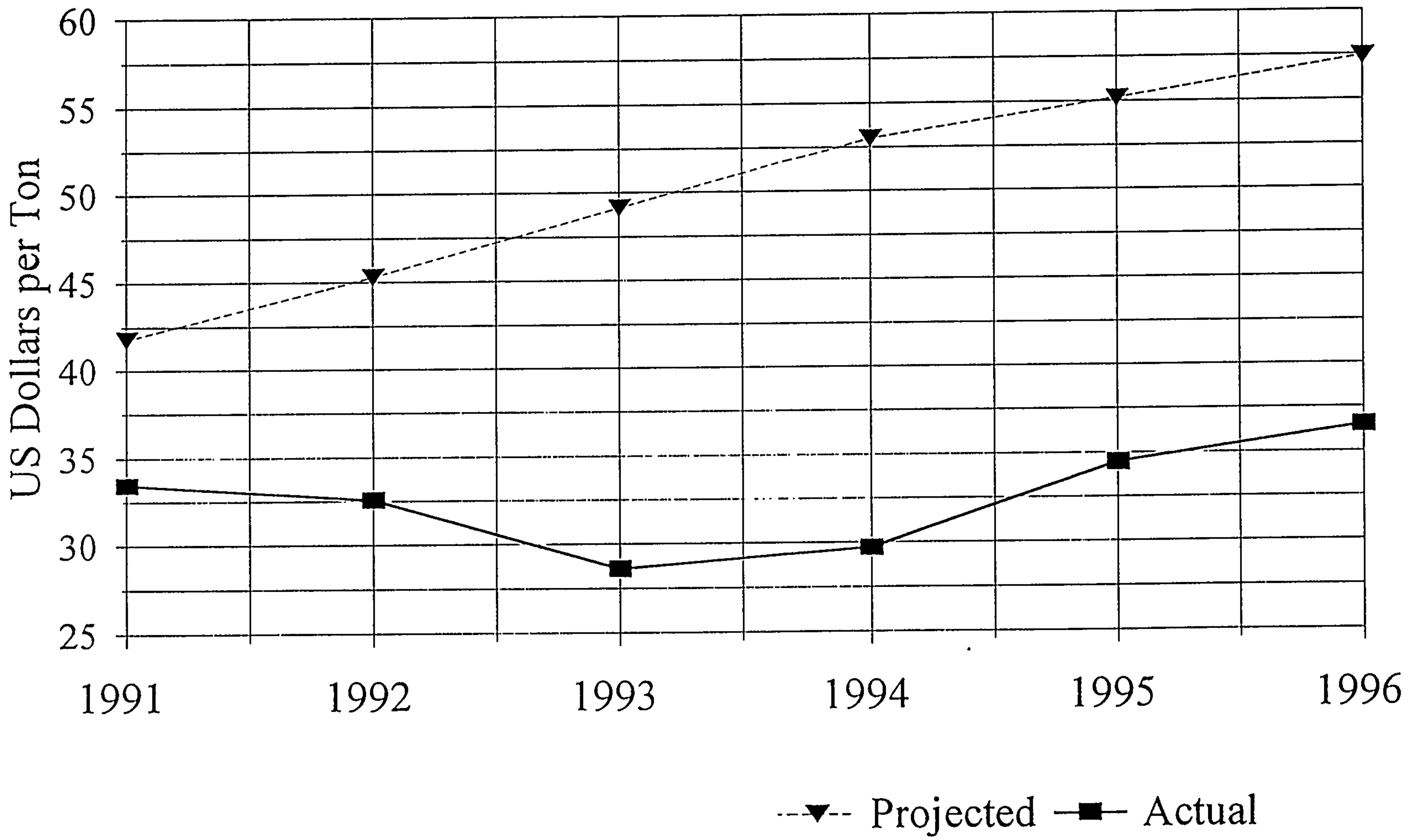

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Figure #10