TECHNICAL SESSION I

Recycling Issues

Recycling Steel Automatically–Through Resource Recovery

Walter J. Foley
General Manager, Federal Relations
Steel Recycling Institute
1667 K Street, NW Suite 460
Washington, DC 20006

ABSTRACT

Last year, more than 55 percent of all steel cans were recycled. But no matter how effective the local recycling programs may be, some steel cans and other steel products are overlooked and appear in MSW. This missed steel fraction is automatically recycled by resource recovery facilities through magnetic separation.

More than three-fourths of the operating resource recovery plants magnetically separate steel cans and other discarded steel items either pre- or post-combustion. Recovering ferrous scrap clearly reduces the post-combustion material that is landfilled and heightens the facilities' environmental performance.

Both the resource recovery and steel industries must heighten public awareness of the benefits of automatic steel recycling. Magnetic separation at resource recovery facilities is a simple method of diverting what would otherwise be relegated as solid waste to the landfill. It should be recognized as an increasingly important and valued part of the resource recovery and steel industries' overall recycling efforts.

This paper will discuss the status of steel can recycling in the United States, describe how recovered ferrous is beneficiated before recycling by the steel industry, and make recommendations for heightening awareness of the steel recycling contribution made by resource recovery facilities.

INTRODUCTION

Communities, businesses and institutions collect steel cans for recycling through curbside and dockside programs throughout the country. Last year, about 55.9 percent of all steel cans were recycled. Ferrous scrap dealers, the "original recyclers," collect and process enormous tonnages of scrap iron and steel for recycling. But no matter how effective local recycling efforts may be, some steel cans slip through recycling's nets and appear in the municipal solid waste stream. And the many other smaller iron and steel scrap items that do not routinely go to the scrap yard are also discarded. In areas served by resource recovery, however, this missed steel fraction is automatically recycled through magnetic separation.

More than three-fourths of the operating resource recovery plants magnetically separate steel cans and other discarded steel items either pre- or post-combustion. Automatic recycling of steel clearly reduces the post-combustion material that is landfilled and heightens the facilities' environmental performance through tangible recycling achievement. Magnetic separation at resource recovery facilities is a simple and desirable method of diverting what would otherwise be relegated as solid waste to the landfill. It should be recognized as an increasingly important and valued part of the resource recovery and steel industries' overall recycling efforts.

SOURCES OF STEEL SCRAP

It's important to understand how all forms of steel recycling take place and how it relates to resource recovery. The steel industry has a healthy appetite for steel scrap. The two types of steelmaking furnaces in use today, the basic oxygen furnace and the electric arc furnace, were designed to make fullest use of scrap resources. In fact, 70 million tons of steel scrap were recycled in 1995 alone.

This scrap is obtained from three sources: mill scrap generated during the steelmaking process itself; industrial scrap generated from the manufacturing process; and post-consumer scrap, or old steel products. Mill and industrial scrap resources never enter the municipal solid waste stream. They are routinely collected and shipped to ferrous scrap processors which prepare them for recycling.

However, more than half of the steel industry's supply of steel scrap comes from post-consumer scrap resources, some of which is derived from or never enter the municipal solid waste stream. These include the millions of tons of steel cans, cars, appliances and construction and demolition materials recycled each year. For the most part, each of these commodities have a collection system that captures a large portion of them for recycling. There are some instances, though, where they will show up at a waste-to-energy plant.

Automobile recycling is a success story of huge proportions–with a virtual 100 percent recycling rate. Cars are not buried but are stripped, flattened and shredded, enroute to steel mill consumption. Various automobile parts, however, including oil filters and body components, incidentally enter the municipal solid waste stream and can be captured through resource recovery.

Appliance recycling is now also growing through communities across America. The recycling rate for appliances in 1995 was 74.8 percent. Appliances should be collected, processed and recycled routinely without ever entering the waste stream. Various components, such as replaced parts, and small appliances like toasters and fans show up in the municipal solid waste stream and are gathered by resource recovery.

Construction and demolition projects affect resource recovery by adding ferrous tonnage to the scrap iron and steel automatically recycled through magnetic separation. New construction or demolition on smaller jobs generate incidental iron and steel scrap that go to the municipal solid waste stream and can only be efficiently recovered through resource recovery. Larger jobs create significant quantities of scrap, however, that goes directly to a scrap dealer for mill preparation.

Therefore, through magnetic separation, waste-to-energy plants play an important role in capturing for recycling those ferrous components of the municipal solid waste stream that evade traditional recycling programs. Clearly, automatic recycling by magnetic separation at resource recovery facilities is a simple and desirable method of diverting what might otherwise be relegated as solid waste to the landfill. It is an increasingly important part of the resource recovery and steel industries' overall recycling efforts.

THE STEEL INDUSTRY: RECYCLING STARTED HERE

Most resource recovery facilities, recognizing the inherent recyclability of steel, magnetically separate scrap iron and steel rather than landfill it. When properly prepared, this recovered ferrous scrap is readily marketed. In addition to melting steel cans and other ferrous derived through resource recovery, the steel industry is also a major consumer of source separated steel cans, appliances, automobiles and steel construction and demolition materials. Iron and steel foundries also consume source separated steel cans in significant quantities, therefore providing additional incentive for steel cans to be included in curbside and drop-off programs. We need to look at why steel cans as well as other municipal solid waste derived ferrous are desirable when this has not always been the case.

Steel Mills and Foundries Recycle Steel Cans and Other Ferrous Scrap

Recycling steel scrap has always been an integral part of the steelmaking process. In fact, for the past 50 years, more than 50 percent of the steel produced in the United States has been recycled into a multitude of new steel products. These new steel products will eventually be remelted again by mills to make new steel.

Due to technological advances in the art of steelmaking, the two types of furnaces used in today's steel mills require steel scrap to make new steel. The first, the basic oxygen furnace, combines molten iron with approximately 28 percent steel scrap. The other, the electric arc furnace, melts virtually 100 percent steel scrap.

Through advances in technology and increases in efficiency in the steelmaking and manufacturing processes, less mill and industrial scrap is being generated. This has created a demand for post-consumer scrap.

Increasingly since 1988, steel food, beverage, paint and aerosol cans, which are recyclable as scrap themselves for new steel production, have been filling this shortfall. Manufactured from the highest grade of steel, they are recognized as an excellent source of steel scrap and have gained great acceptance as a desired commodity. One of the reasons why is that steel cans no longer have the restrictive amounts of tin that melters once feared. They can now be directly charged into a steel mill furnace rather than be routed to a detinning facility first. As a result, the steel industry is prepared to consume all steel cans collected, recycling them into new steel.

In addition to new steel, steel cans are also being recycled into iron products. A study performed by the University of Wisconsin-Madison first confirmed how steel cans could serve as a scrap resource for foundries across the United States. Taking part in the study, Waupaca Foundry in Wisconsin recycled more than 15,000 tons of steel cans into iron products. Since then, several other foundries are recycling steel cans and are using or considering using municipal solid waste derived ferrous from resource recovery. There are more than 1,500 iron and steel foundries, which will potentially provide end markets for many communities across the United States.

METHODS OF COLLECTION FOR RECYCLING

In the last seven years, old steel products have become a more desirable scrap resource. Automobile and construction and demolition material collections have long supplied steel mills and foundries with enormous quantities of steel scrap, while steel can and appliance collection programs have more recently taken root and now share a greater portion of the steel industry's overall recycling efforts. Magnetic separation at resource recovery facilities supplement these collection programs and, often in the case of steel cans, may even serve as the only steel recycling program in the community.

Source Separation Recycling Programs

Most residents are serviced by curbside recycling, or a combination of curbside and drop-off programs, that accept steel cans. In a curbside program, residents are responsible for commingling recyclables together into a storage bin and placing the bin at the curbside for collection. Recyclables are collected by truck and delivered to a secondary processor for sorting, preparation and shipment to end markets.

Drop-off programs may operate as the sole recycling program in rural areas where curbside recycling is not feasible. To participate in this recycling program, residents bring their steel cans and other recyclable materials to a drop-off site. These sites may also supplement curbside collection, giving residents additional opportunities to recycle steel cans. Multi-commodity buyback centers operate somewhat similarly. In the United States, there are now more than 16,000 curbside, drop-off and buy back collection programs that accept steel cans for recycling.

Steel cans and other recyclables generated by schools, businesses, hotels, restaurants and other commercial/institutional establishments are collected through their own dockside recycling programs. Employees separate empty steel cans and store them in a large container or roll-off for recycling. Haulers collect and deliver recyclables to secondary processors for handling and shipment to end market.

Many communities have established temporary or permanent collection programs to ensure that appliances do not enter the municipal solid waste stream. By weight, the typical appliance consists of about 75 percent steel, which is largely why 1,600 ferrous scrap processors across the country process ship them to steel mills for recycling. Since 1990, the national recycling rate for major home appliances has risen from 32 percent to 74.8 percent due in part to increased private and public sector awareness and the continuing development of a strong infrastructure for recovery of ferrous scrap from appliances.

Despite their complex construction, automobiles are one of today's most recycled commodities. Whole automobiles are simply not landfilled. The reason why is that the steel and iron components, which make up about 70 percent of the weight of the average vehicle, are too valuable. Instead, automobiles are shredded at ferrous scrap processing yards. In 1995, approximately 13 million tons of steel from shredded automobiles was shipped to steel mills for recycling.

The sheer size and number of construction and demolition projects in the United States produce a considerable amount of steel scrap. Each year, the steel industry recycles approximately 30 million tons of steel recovered from construction and demolition projects.

Automatic Recycling of Steel Cans and other Ferrous from Resource Recovery Facilities

Whether source separation recycling is available or not, resource recovery facilities offer unique advantages. It takes steel mill temperatures in excess of 2800 degrees Fahrenheit to melt steel. The typical waste-to-energy facility's furnace temperature rises as high as 1800 degrees Fahrenheit, but far short of the temperature needed to melt steel. But, by magnetically separating steel scrap before or after combustion, resource recovery facilities avoid landfilling this recyclable steel scrap. The incremental costs of cleaning and processing of steel scrap for reuse by steel can end markets is largely offset by the incremental revenue and cost avoidance. The intangible value of recyclability itself is even higher and is suggested as a benefit for all concerned.

When seeking to maximize the diversion of recyclable material from the solid waste stream, curbside and drop-off collectors and processors are largely dependent upon the participation of area residents in a traditional recycling program. However, magnetic separation of steel cans at resource recovery facilities automatically recovers more than 90 percent of the steel can scrap generated from a community. Residents participate in recycling steel cans just by disposing of them normally. For instance, it was determined in Florida in 1994 that steel cans are being recycled at a rate exceeding 64.4 percent. This higher than national average recycling rate for steel cans is rightfully credited to magnetic separation by resource recovery facilities across the state.

Just as importantly, steel cans and other ferrous scrap are automatically recycled from the entire community serviced by resource recovery. This means that in addition to all households being covered, area businesses, schools, and other commercial and institutional establishments automatically recycle their used steel cans, old bicycles, tools and other used items. Therefore, magnetic separation of steel at resource recovery facilities achieves tremendous economies of scale by fulfilling the functions of both residential and commercial/institutional recycling programs for steel items.

Finally, resource recovery facilities magnetically separate all types of steel products, including steel food, beverage, paint and aerosol containers, appliance and automobile components, and construction and demolition debris from a community's solid waste stream. Steel paint and aerosol cans, in addition to steel food and beverage cans, are part of the steel industry's overall recycling efforts–even though they may not be included in a community's source separated recycling program. Minor or even major product contamination of these containers is handled in a very forgiving nature by the combustion process. In addition, ferrous scrap not normally recoverable–such as steel box springs from a mattress–are recovered for recycling from the 80 percent of the facilities that separate steel post-combustion.

According to the Steel Recycling Institute's most recent statistics, 98 resource recovery facilities across the country separate steel cans and other ferrous for recycling, accounting for more than 40 million residents serviced. Of these, more than 18 million residents are serviced exclusively by resource recovery, meaning their steel cans and other post-consumer steel products would not be recycled if it were not for the presence of these facilities.

PROCESSORS OF STEEL CANS AND MUNICIPAL SOLID WASTE-DERIVED FERROUS SCRAP

All steel products, whether collected from communities through source separation recycling programs or through magnetic separation with other ferrous scrap at resource recovery facilities, require processing for shipment to steel industry end markets.

Source Separation Recycling Programs

When collected through community recycling programs, steel food and beverage cans should initially be rinsed clean. Steel aerosol cans must be empty of their contents, and steel paint cans should only have a thin skin of dry paint left on the inside of the can. All steel cans may be processed and baled together, regardless of type.

Ferrous scrap dealers have long supplied the steel industry with processed scrap. More recently, many of these businesses have added steel cans to their collections of appliances, automobiles and construction materials as the demand for steel cans has risen. Scrap processors are effective processors of source separated steel can scrap because much of the necessary equipment to process steel cans is already in place, and the links to end markets for steel cans are well developed.

Material recovery facilities also process steel cans recovered from communities through community recycling programs. These facilities magnetically sort steel cans from commingled recyclables for baling and shipment to end market.

Appliances, automobiles and construction and demolition material are processed at ferrous scrap yards for recycling. Automobiles and appliances are shredded and the steel is magnetically separated from the remaining material. Depending are their size, construction and demolition materials may be sheared, baled or shredded before shipment to end market.

Cleaning Steel Cans and Other Ferrous at Resource Recovery Facilities

Before they are recycled, steel cans and other ferrous scrap generated from resource recovery facilities must first be upgraded through additional processing. This is necessary because ferrous recovered from the estimated 20 percent of facilities that separate it before combustion has residue from solid waste, while ferrous recovered after combustion is coated with ash.

Specialty vendors typically perform the necessary steps. Methods vary from vendor to vendor, but ordinary proven mechanical processes are used, such as shredding, air blowers, screening, trommeling and additional magnetic separation. Cleaning the ferrous scrap produces a marketable material with predictable chemical characteristics.

Most operators would agree that this process should be performed on the site of the resource recovery facility. When performed on-site, no additional arrangements or negotiations need to be made regarding leftover residue. It can just go back into the resource recovery plant–or, if ash–be appropriately managed. Off-site cleaning of the steel does occur, however, when there is limited space at the site of the facility, or when existing equipment for process already exists off-site. Residue is disposed of in accordance with local, state and federal laws.

CONCLUSION

Steel cans, automobiles, appliances and construction materials are already recycled in enormous quantity. Automatic steel recycling through resource recovery assists the steel industry in recovering the smaller ferrous components that would otherwise be landfilled. Performing magnetic separation decreases a resource recovery facility's costs associated with the disposal of post-combustion material and generates incremental scrap revenue. Whether recovered pre- or post-combustion, ferrous scrap is a marketable material. These facilities, through automatic recycling, recover virtually all steel cans from the community–independent of active participation by residents. The increased diversion of steel cans and other ferrous items from the solid waste stream accordingly improves the measured statistical rate of steel can recycling and provides a measurable recycling statistic for resource recovery.

Scrap Tire Derived Fuel: Markets and Issues

John Serumgard
Scrap Tire Management Council
Washington D.C. 20005

For Presentation at the
Fifth Annual North American Waste to Energy Conference
Research Triangle Park, NC
April 22 - 25, 1997

INTRODUCTION

More than 250 million scrap tires are generated annually in the United States and their proper management continues to be a solid waste management concern. Sound markets for scrap tires are growing and are consuming an ever increasing percentage of annual generation, with market capacity reaching more than 75 % of annual generation in 1996. Of the three major markets - fuel, civil engineering applications, and ground rubber markets - the use of tires as a fuel is by far the largest market. The major fuel users include cement kilns, pulp and paper mills, electrical generation facilities, and some industrial facilities. Current issues that may impact the tire fuel market include continued public concern over the use of tires as fuel, the new EPA PM 2.5 standard, possible additional Clean Air Act emissions standards, access to adequate supplies of scrap tires, quality of processed tire derived fuel, and the possibility of creating a commodity market through the development of ASTM TDF standards.

Scrap Tires are an ubiquitous by-product of contemporary social and economic society. Our personal mobility is almost entirely dependent on the pneumatic tire, whether in automobiles, buses or even airplanes. The transport and delivery of most goods is also dependent on the pneumatic tire. To recall an old slogan of the American Trucking Association, "If you got it, a truck brought it", and it goes without saying that the truck was riding on pneumatic tires.

Tremendous strides have been made over the last several years in both the durability and the longevity of tires. Auto tires routinely provide 40,000 mile or more of travel, almost four years of life for the average car, and many give 60,000, 80,000 or more miles of life. Medium truck tires, those used on the typical over the road semi-trailer, are heading toward a 500,000 life (with the advantage of one, two or more retreadings). Ultimately however, all tires reach the end of their useful lives as tires and then become a solid waste issue.

In the past there were many poor management practices routinely used for scrap tires, some of which resulted in adverse environmental impacts (and frankly we are still living with the some of those consequences). However, in the last few years much attention has been devoted both to imposing responsible restrictions on the handling of scrap tires and on the development of reuse, recycling and recovery markets for scrap tires. As with any other material being diverted from the solid waste stream, the development of alternative use markets is imperative to making diversion a success.

In 1990, as the Scrap Tire Management Council was being organized, the USEPA estimated the markets for scrap tires as being less than 11% of annual generation. After several years of growing scrap tire markets, the Scrap Tire Management Council estimates that as of the end of 1996, scrap tires markets had the capacity to consume over 75% of annual generation. This is a tremendous expansion of the sound markets for scrap tires and a real life success story for an industry that largely did not exist only seven years ago.

ABOUT THE SCRAP TIRE MANAGEMENT COUNCIL

The Scrap Tire Management Council (STMC) is a non-profit advocacy organization, organized and supported by the North American tire manufacturing industry to be the spear-head of efforts to identify and promote environmentally and economically sound markets for scrap tires. The primary goal of the Council is to assist in the creation of market demand for 100 percent of the annually generated scrap tires in the United States. Based on current market demand and projected market growth, it is envisioned that this goal should be met by the turn of the century.

NATIONAL GENERATION RATES

For the past two years, this country generated approximately 253 million scrap tires, or approximately one scrap tire per capita. This number should increase gradually to approximately 260 to 275 million by the turn of the century.

A question is often raised about the number of tires in stockpiles. As part of the 1994 market update, the Council undertook a survey of all state regulatory agencies to compile the most comprehensive listing of stockpile inventories. According to the data collected, the numbers suggest that there are approximately 700 to 850 million scrap tires in inventory. This is a far cry from the two to four billion number some sources including the United States Environmental Protection Agency have been using.

The significance of this finding is two fold. First, it places into perspective the actual dimensions of the stock pile situation. Second, those scrap tires in stock piles have only two market applications; as tire-derived fuel or in civil engineering applications. If the tires must be shredded, rough shred applications such as lightweight fill, would then become available for these tires.

MARKETS FOR SCRAP TIRES

There are three major markets for scrap tires:

- Tire-derived fuel (TDF), including both whole tires and processed tires;
- Products (including those made from size-reduced rubber and stamped, punched or cut rubber products); and
- Civil engineering applications.

In addition there are other markets for tires, including:

- Export of good used tires and retreadable casings; and
- Agricultural and miscellaneous applications

Over the past six years the number of annually generated scrap tires having markets has increased from 11 percent (25 million units) in 1990, to 38 percent (95 million) in 1992 to almost 56 percent (138 million) in 1994. At the end of 1995, 69 percent (174 million) scrap tires were being sent to markets. And as of the end of 1996, STMC preliminary projections indicate that sound scrap tire markets have the capacity to consume more than 75 % of annually generated scrap tires, or more than 190 million scrap tires (Table 1). While this has been a very dynamic growth rate, current events suggest that it will be unlikely for a continuation of this rate of market expansion.

Table 1: Estimated Scrap Tire Market Capacity at January 1, 1997 (preliminary)
(Millions of Tires)

Fuel	145.5
Products	
Cut, Punched, Stamped	8.0
Ground Rubber	10.0
Civil Engineering	10.0
Export	15.0
Agriculture & Miscellaneous	2.5
TOTAL:	191.0

Although the Scrap Tire Management Council (STMC) is predicting a slower rate of market growth, the STMC is confident that, ultimately, the market demand for 100 percent of the annually generated scrap tires will be developed.

At present, the markets for scrap tires include the following.

Tire Derived Fuel currently consumes 145.5 million scrap tires annually. Tire derived fuel includes both whole tires and processed, or cut up, tires. The principal market segments utilizing tire derived fuel include:

- cement kilns;
- pulp and paper mill boilers;
- utility boilers;
- industrial boilers; and
- dedicated scrap tire to energy facilities.

The newest market to develop is the use of tires in the metal industry, including foundry cupolas. The combined fuel market segment has the ultimate capacity to consume some 250 million scrap tires a year, or nearly all that are generated. The TDF requirements range from whole tires (i.e., as used in cement kilns or dedicated scrap tire to energy facilities), to rough shreds (i.e., as used in cement kilns & dedicated scrap tire to energy facilities) to 1" X 1" to 2" X 2" shreds (i.e., as used in pulp and paper mills, industrial and utility boilers). The type of TDF necessary for any end-user will be a function of the type of combustion facility, the type of primary fuel used and, the feeding system used.

Products include products cut, punched or stamped from tire carcasses (usually only from bias ply tires), and products manufactured using ground crumb rubber produced from scrap tires and other scrap rubber. Cut, punched and stamped products include dock bumpers, heavy duty flooring, muffler hangers and various other industrial and consumer products. Ground rubber is produced by grinding up scrap tires and removing the steel and fiber. Other sources for ground rubber include factory scrap from both tire and non-tire rubber products manufacturing and the rubber buffing dust produced as a by-product of the tire retreading process. Ground rubber is used in some new rubber products such as mats, in asphalt rubber, in friction products, in products produced using a binding agent such as polyurethane, and in sports surfaces.

Civil engineering applications include the use of shredded tire material as light weight fill material, as leachate field material in on site septic systems, as alternate daily cover and in leachate layers and gas collection layers in landfill operating and construction, and in such constructions as artificial reefs and floating breakwaters. In these applications the tire derived materials substitute for the materials normally used and bring new engineering value to the application.

CHARACTERISTICS OF TIRE-DERIVED FUEL

Eighty-eight (88) percent of the tire is composed of carbon and oxygen, which accounts for its rapid combustion and relatively high heating value. Tires contain approximately 14,500 - 15,000 BTU's per pound. This compares favorably to coal which, on the average, contain some 12,000 BTU's per pound. Subsequently, when substituting tire-derived fuel (TDF) for coal, a kiln operator can reduce coal by 1.25 pounds for every pound of TDF used.

Tire-derived fuel is also a consistent material. Tires, regardless of where they were manufactured, or by whom, typically contain 1.2 - 1.5 percent (by weight) sulfur, 1.5 percent (by weight) zinc, less than one percent moisture, two and one half pounds of high grade steel per passenger car tire and a short list of trace metals. Tires are also very low in nitrogen, relative to other fossil fuels.

The consistent composition, and the relatively low quantities of certain constituents (i.e., sulfur, nitrogen) and the relatively high heating value of TDF are the primary reasons TDF can be used successfully in a wide array of combustion facilitates. It is also the reason why TDF can have a positive impact on the emissions from these facilitates.

CURRENT ISSUES AFFECTING THE TIRE FUEL MARKET

Even as the use of tire derived fuel is expanding, there are issues that could complicate future expansion, or cause questioning of current uses. In addition, there are steps that can be taken to improve the climate and the market for tire derived fuel. Discussed below are several of these current issues.

Continued public concern over the use of tires as fuel

Whenever a facility proposes to begin using tires or TDF as a supplemental fuel, it may encounter various levels of public concern or opposition. For example, some people may be concerned about black smoke or adverse odors while others may be concerned about possible harmful emissions. Yet another group may oppose the use of tires as fuel because it is not recycling or a higher value reuse.

For many people, the only experience they may have with burning tires is a TV news story about a major tire fire with raging flames and lots of smoke. Or they may have encountered an actual burning tire somewhere in their experience, and it probably wasn't all that pleasant. What they have seen or experienced is the products of incomplete combustion of tires. In fact, when tires are used in a properly controlled combustion environment, such as a fuel boiler or a cement kiln, they make an excellent fuel with no adverse smoke or emissions. And this conclusion has been reached by a number of responsible organizations, including the US EPA and the California Integrated Waste management Board, in a variety of published studies. Usually, the presentation of this evidence to the concerned public will help dampen their concerns.

Likewise there has developed a considerable body of emissions data from facilities that have gone through the fuel permitting process and conducted emissions tests. This data universally demonstrates that tires are generally a better and a cleaner fuel than coal, the fuel it normally replaces. Most facilities seeking to use tires as fuel will have to undergo their own air emissions testing as part of the permit modification process. Again, when this data is presented, reasonable people normally accept that TDF can be used safely in the facility seeking to use it. For those people concerned that using tires as fuel is not the highest value use for tires, the fact that these higher value markets may not exist in the local market area, or may be developing so slowly that they can not begin to consume large volumes of tires in the reasonably foreseeable future. In the meantime, markets are needed for tires.

With the expansion of the TDF market to more than 100 using facilities across the country, and about an equal number in the considering or testing process, the possibility of public opposition seeming more wide spread is apparent. It is to be hoped that continued presentation of the facts, and of sound data derived from emissions testing, will dissuade all but the most irrational opposition. Or in other words, that good science will offset shrill voices.

The new EPA PM 2.5 standard.

The US Environmental Protection Agency has recently issued a new proposed standard to regulate particulate emissions down to the 2.5 micron level. Many industries are deeply concerned about this proposed standard both because in their view there is little evidence of real hazard from particulate of this small size and because of the perceived difficulty in meeting it. To date, facilities using tires as fuel has been able to meet existing particulate standards. In fact, in many applications, the use of TDF fuel results in **reduced** particulate emissions when compared with the baseline fuel. It is to be hoped that this past experience suggests that the PM 2.5 proposed standard will not adversely affect the use of TDF. However, until we have some actual testing results, this will be an area of concern.

Possible additional Clean Air Act emissions standards

The Clean Air Act of 1990 adds significantly to the range of substances that will eventually be subject to air emissions standards. Of course many of them will not be of any concern for tires. However, tires are composed largely of petrochemical based compounds and thus there may be compounds or substances that could possibly of concern. Until we know the standards which will have to be met, this issue will continue to be an area of concern for the use of TDF.

Access to adequate supplies of scrap tires

It probably sounds somewhat implausible to discuss the issue of access to supplies of scrap tires when there are around 800 million in stockpiles and probably 60 to 70 million that are not currently going to markets. However, the economics of scrap tire markets limits the distance that tires or even tire derived fuel can be transported. Typically whole tires are limited to around a 150 mile transportation distance before the cost of transportation outweighs the value of the tires. Processed TDF can be transported a longer distance, but that distance is also a function of the value being placed on the TDF as reflected by the amount being paid for it. TDF markets also tend to develop in states where there is an effort being made to develop scrap tire markets. As a result, fuel users could find themselves being in a locally competitive market for tires, even as other parts of the country are finding difficulties in creating scrap tire markets. Some states have developed such a high level of market demand that they are importing scrap tires from other states (i.e. Connecticut, Maine, Illinois and South Dakota).

As for those stock piles, unless there is some funding available to clean them up and process them, either from the stock pile owner or a state agency, they won't make it to any market. The amount a fuel user would be willing to pay for the TDF normally would not be enough to remove tires from a stock pile and process them to the proper size. The economics of scrap tires generally requires both a front end tip fee, usually collected from the original owner of the scrap tire, and the price received when the final scrap tire derived product is sold. Many stock piles have been effectively abandoned by their owners, or the owners have no financial capacity to remediate their piles.

Quality of processed Tire Derived Fuel

At present, there are more than 500 companies in the latest edition of the Scrap Tire Users Directory who claim to be producing tire derived fuel. It is likely that a significant number of those producers are not capable to producing a quality TDF product on a consistent basis. They can probably produce some good product when their shredder knives are new, and they are operating at a slow enough rate to allow reprocessing of out of spec product. But give them a few weeks or months on the knives, and a processing speed needed to keep up with their tire collections, and the product they are producing might be useful only for civil engineering uses. That would be fine, if that's where they were marketing their product. But some of them seek to market this product to fuel users that other producers may have developed, and the lure is of course price. If the fuel user changes suppliers and then finds that the quality of material being delivered is not up to specification, and is causing problems in the boiler, the user may just stop using TDF. In the long run, we believe that TDF suppliers able to consistently deliver quality product will be the ones who will survive in the market place. Unfortunately, in the meantime, the quality of TDF being supplied to the market will be an issue of concern.

This is not to imply that the fuel user is entirely without blame. It is the basic imperative of the tire fuel market that most fuel users' main motivation for using tires is economic—that is they are seeking reduced fuel costs by replacing a percentage of their basic fuel with TDF. Unfortunately some fuel users believe that they should receive all of the benefits of using TDF, that they should be entitled to squeeze the last cent out of their suppliers. This attitude can be initially productive for the fuel user, but if the TDF processor is not making enough to meet its costs, including maintenance and knife replacement needs, then the quality of the TDF will drop and the user will experience problems. The better scenario will be for the fuel user to be willing to pay a fair price for the TDF, one that will allow the TDF supplier to be competitive for tire supply and to operate in such a fashion as to be a consistent supplier of quality TDF.

The development of ASTM TDF standards

Most every fuel product has a series of size and quality standards accepted by the fuel market place that allow the fuel product to be bought and sold as a commodity. At present, we do not have such a set of standards, accepted by both TDF suppliers and TDF users, that would allow TDF to be traded as a commodity. The Scrap Tire Management Council is taking an active leadership role is one major effort to develop such a set of standards, just as it has done with the ground rubber market. In the case of the TDF standards, the venue for this activity is the American Society for Testing and Materials (ASTM) and its D34.08 subcommittee. The D34 committee deals with waste management and the D34.08 subcommittee deals with thermal treatment. The STMC is working to develop a draft standard for this committee to consider, and to involve the TDF producer and user communities in this effort. If a standard can be developed, it is hoped that it would become the basis for efforts to trade TDF as a commodity, such as on the Recyclables Exchange of the Chicago Board of Trade.

CONCLUSION

All scrap tire markets are expanding, including the use of tire derived fuel. There may come a time when the use of tire as fuel begins to decline as other markets place a higher value on tires and their consumption begins to cut into the supply of tires available. However, this situation is likely to be several years off. In the mean time, the tire derived fuel market must be encouraged and promoted. A significant part of this effort will be to deal with the issues raised in this discussion that could potentially harm the scarp tire fuel market. Everyone interested in the markets for scrap tires should take an active part in the efforts to develop sound scientific information about scrap tire use, and to implement and expand scrap tire fuel markets in a responsible manner.

Advanced Thermal Processing Alternatives for Solid Waste Management

Walter R. Niessen
Camp Dresser & McKee Inc.
10 Cambridge Center
Cambridge, MA 02142

ABSTRACT

The 1990's have seen a resurgence of interest in the development of new thermal processing alternatives for municipal solid waste (MSW). Sparked by increasingly stringent environmental regulations, much of this creative energy has been applied to technologies for the gasification of MSW: converting the solid, hard to handle material into a clean, medium- to high-Btu fuel gas. Other developers have focussed on full combustion technology but with a "twist" that lowers emissions or reduces cost.

A comprehensive study of these new technologies was recently completed under the sponsorship of the National Renewable Energy Laboratory of the U.S. Department of Energy[1]. The study characterized the state-of-the-art among emerging MSW thermal processing technologies that have reached the point of "incipient commercialization." More than 45 technologies now under development were screened to develop a short list of seven processes that have passed through the "idea" stage, laboratory and bench-scale testing, and have been prototyped at an MSW feed rate of at least several tons per hour. In-depth review of these seven included inspections of operating pilot or prototype units and a detailed analysis of technical, environmental and economic feasibility issues.

No attempt was made to select "the best" technology since "best" can only be defined in the context of the constraints, aspirations and circumstances of a specific, local situation. The basic flowsheet, heat and material balances and available environmental data were summarized to help the reader grasp the underlying technical concepts and their embodiment in hardware. Remaining development needs, as seen by the study team are presented. Economic analysis shows the general balance of capital and operating costs.

INTRODUCTION

Several new or enhanced technologies that thermally process MSW are now well established. They include those that burn waste in the same physical form in which it is generated (grate-fired, mass burn incinerators) and those that first process the waste to a refuse derived fuel (RDF) and then burn the RDF (alone or with fossil fuels) using a spreader stoker grate. Mass burn and RDF combustion facilities are supplemented with elaborate back-end flue gas and residue treatment. Beyond these well-proven combustion processes, a new technology class has emerged: refuse gasification. Here, the organic fraction of MSW is heated to drive off a combustible gas with a substantial fuel value. The gas can be cleaned and burned in a gas engine or gas turbine to generate electricity. Alternatively, the gas is very usable as a boiler fuel either in thermal power plants or in industrial boilers. Emission data for combustors burning this gas generally show very low emission rates of dioxins, acid gases and other problematic pollutants. The processes studied in detail; identified with the name of the developer, are:

- Energy Products of Idaho (EPI)
- Pedco Incorporated
- ThermoChem Inc.
- Battelle
- Proler International Corporation
- Thermoselect Inc.
- TPS Termiska Processer AB

Of the seven emerging technologies discussed here, two (Energy Products of Idaho and Pedco Incorporated) use full combustion but in novel contexts. The other five processes (TPS Termiska AB, Proler International, Thermoselect Inc., Battelle, and ThermoChem Inc.) use gasification methods followed by fuel gas clean up. In niche market sectors and in the broader market, the five gasification technologies studied here are emerging as "commercially ready" alternatives.

The rate of penetration of the thermal processing market by new technologies will be paced by their environmental acceptability, their economic acceptability and their performance acceptability. From an environmental viewpoint, the seven technologies appear as a sound response to the regulatory challenges of the revised New Source Performance Standards (NSPS) and the Maximum Achievable Control Technology (MACT) rules[2]. Table 1 summarizes the process features and environmental characteristics of the seven processes.

Economics has always been a critical and probably pacing factor that affects the penetration of thermal processing technology in U.S. MSW practice. Table 2 summarizes preliminary economic data characterizing the seven processes. One must use caution in using these estimates since most of the processes are still evolving. Most of the processes have capital costs that are comparable to the $121,000 per Mg/d ($110,000 per t/d) typical of contemporary mass burn systems. The net operating cost, which is equivalent to the break-even tipping fee, for the gasification technologies are comparable to those for *owner-operated* mass burn facilities. The revenue stream from selling energy continues to be critical to overall economic acceptability.

The results are less clear concerning "performance." Most of the processes studied (excepting Thermoselect) require an RDF feed. Landfills are still required for RDF residues and/or ash. Historically, most RDF facilities have incurred substantial post-construction rework, capital investment, down-rating of capacity etc. Most of the seven systems have significant development tasks ahead of them. Unfortunately, the catalyst of vigorous U.S. market activity is lacking to push this development and to foster risk-taking. Further, many systems are quite complex. This presents some problems in gaining acceptance by client communities, by regulatory authorities and from the financial and engineering entities involved in concept selection and project accomplishment.

APPROACH TO THE ANALYSIS

Initially, more than 45 firms were identified as possible candidates. A two-stage screening process selected seven firms to be evaluated in detail. Data received from the 45 were analyzed to produce the recommendation for the list of seven firms as limited by available study funds. The scope of the detailed evaluation effort for the seven selected technologies was broad. Data for the detailed evaluation were obtained from the developers based on a faxed request, a detailed questionnaire, and extensive technical discussions before and after site inspection visits.

The evaluation included exploration of *technical issues* affecting the basic process feasibility, reliability, workers' safety, operability, and maintainability. Very important was the remaining degree of scale-up from the present level of development to commercially useful equipment. Also, operating experience was seen as critical.

Environmental issues concerned the total emission profile of the operations. Environmental acceptability is a basic requirement for the viability of any process. Since almost any process can comply with regulations if sufficient resources are assigned to the task, this requirement is one of assuring that each process system includes the necessary features, equipment, and staff to achieve 1996 emission codes.

Business issues revolved about the financial and work force resources of the firms to achieve commercial viability. The capital and operating costs of the system are important factors in the award of disposal contracts. To keep the focus on the thermal processing core of the processes, standardized costs were developed for the processing of MSW to an RDF. Also, cost curves were developed for conversion of the energy product of the processes (high pressure steam or a fuel gas) into electricity. The resulting technology cost information is then an economic picture of a generic plant that may not be optimal with standardized feedstock and energy conversion components. A serious buyer should contact the developer organizations to give them the opportunity to propose their costs for any specific situation.

TECHNOLOGY SUMMARIES

1. Energy Products of Idaho (EPI)

EPI is a limited partnership headquartered in Coeur d'Alene, Idaho. EPI's basic business is the design and fabrication of fluid bed combustion systems. Their corporate experience favors full combustion mode for their systems, they have pilot plant and commercial plant experience (three commercial systems) in a "starved air," gasification mode. Their most proven product, however, is the full combustion system. The EPI incineration system uses a bubbling-type fluid bed concept accepting a prepared 10 cm (4 in.) top size RDF (Figure 1). Within the bed, RDF particles are exposed to a vigorously turbulent, hot, oxidizing environment that promotes rapid drying, gasification, and char burnout. EPI proprietary design features in the bed provide continuous removal of oversized non-burnable materials. Hot gases from the bed are passed through a boiler to generate high pressure, superheated steam used to generate electricity or for process applications. A conventional dry scrubber-baghouse with carbon injection can achieve current air emission standards[2].

EPI combustion technology is commercially available now. EPI has installed five furnaces in the U.S. with capacities of more than 55 Mg/d (60 t/d) burning an RDF fuel. They also designed and built three wood-fired, gasification-mode systems (1982-1985). They have acquired in-house operating experience with an RDF in their pilot plant gasifier, but by early 1997, they had no operating commercial-scale plants using RDF in the gasification mode.

Therefore, in matters of technical maturity and commercial verification, the full combustion mode EPI system is implementable with limited risk. The gasification mode requires additional testing, operating experience and design maturation and, thus, presents potential users with much greater risk.

2. TPS Termiska, AB

TPS Termiska Processer (Thermal Processes), or TPS, is a small, independent Swedish company of about 50 employees working in the specialized field of energy and environmental process research and technology development. Their technology involves starved-air gasification of an RDF in a combined bubbling and circulating type fluid bed (Figure 2). The lower, bubbling bed section provides the extended residence time for the burnout of massive or very wet feedstocks. As the particles shrink, they enter the circulating bed zone where gasification is completed and the ash is swept from the furnace. Following the gasification bed, TPS inserts a second circulating bed "cracker" unit. In the second bed, a ground magnesium-calcium carbonate (dolomite) is injected to catalyze the conversion of high molecular weight tarry gasification byproducts into low molecular weight, non-condensible compounds. Also, the alkalinity of the dolomite reduces acid gas concentrations. The TPS system produces medium heat content fuel gas.

The technology offered by TPS is presently close to commercial availability. In 1992, a commercial, two-bed unit was installed in Gréve-en-Chianti, Italy with a combined capability of 30 MW to gasify 100 percent pelletized RDF fuel or coarsely shredded wood or agricultural residues.

The manufacturing methods for the TPS-design gasifier systems, the long-term operability of their beds with acceptable management of bed solids, the projected emission control performance, the feeders, etc., have all been tested at Gréve in MSW-based RDF service. Therefore, it is believed that the TPS system should be implementable with only moderate technological risk.

3. Proler International Corporation

The Proler SynGas Process is a patented technology to reform hydrocarbon-containing wastes into a gaseous product. It is represented by a 1.8 Mg/h (2 t/h) demonstration plant in Houston, Texas. The process was originally developed to gasify automobile shredder waste (ASR but limited test results show its suitability to process MSW. Proler feeds preshredded material into a rotating, kiln-like reactor (Figure 3). In the proposed commercial process, the reactor is fired with the hot exhaust gases from a "Vitrifier" auxiliary unit that uses part of the product gas, carbon char and oxygen to melt the mineral residue. The overall process produces a medium heat content fuel gas that, after cleanup, is suitable for power generation or other fuel uses. The residue is discharged as what is stated to be a "commercially useful byproduct".

Proler states that preliminary design work has been completed for a full-scale 865 Mg/d (960 t/d) commercial facility using MSW as feed stock and consisting of two process lines at 18 Mg/h (20 t/h) each. However, some technical issues require resolution before successful commercialization for MSW can be assured:

- The demonstration plant is now processing an RDF at a top size of 5.8 cm (2 in.). Proler expects the commercial plant to accept shredded material with a top size of 15.24 cm (6 in.) as a process change to achieve cost reduction in waste processing. This substitution may have adverse process impacts and has not yet been sufficiently tested to accept the change as acceptable.

- The demonstration plant has operated only on a limited basis with shredded MSW. An extended campaign of operation is essential to evaluate potential problems.

- The reliability and performance of the Vitrifier and the integration of this equipment with the existing gasifier have not yet been accomplished.

- The planned commercial size at (40 t/h) of MSW represents a scale-up of 5.5:1 on a per line basis over the demonstration plant. Experience with other MSW combustion and thermal process development shows that such a substantial step implies a high risk factor.

Further testing with MSW to resolve these issues seems desirable. Proler has an intent to continue their development efforts and to offer a comprehensive performance guarantee.

4. Thermoselect Inc.

The Thermoselect system processes co-mingled MSW into what are stated to be environmentally-safe products (Figure 4) that include reactor gas, vitrified solid granulates, elemental sulfur and sodium salts. No liquid effluents are discharged into the environment. The process is intended to reduce formation and emission of particulates and other pollutants.

Gasification is achieved at a high temperature. The mixture of solid refuse and char reaches a temperature of 800°C (1470°F) as it reaches the discharge end of a preprocessing section described by Thermoselect as the Degasification Channel. The products of gasification are then held in a reactor at a temperature of 1200°C (2192°F) for more than four seconds. Ash and metals fall out and are fused and granulated in a chamber called the "Homogenizer". The reactor gas is quenched in a spray chamber to below 90°C (194°F). Data suggest that this combination of time and temperature destroys the complex organic compounds produced in the gasification process and yields a gaseous product (primarily CO, H_2, CO_2 and steam) that has nearly reached chemical equilibrium. The raw gas is cleaned in a gas purification system that removes acid gases, hydrogen sulfide, particulate and volatile heavy metals. Air emissions result from the combustion of the cleaned reactor gas in turbines, gas engines, boilers and other means for the generation of electric power or other useful energy forms.

The Thermoselect demonstration facility in Fondotoce, Italy consists of one process line with a nominal capacity of 4 Mg/h (4.4 t/h) or 100 Mg/d (106 t/d). The line at the pilot plant includes all of the process units (acid and alkaline scrubbers, a hydrogen sulfide removal scrubber, coke filters, etc.) that are envisioned for the full scale, commercial plant. Tests results show only minute traces of organic compounds in the cleaned reactor gas. No chlorinated aromatic hydrocarbons other than traces of polychlorinated dibenzo p-dioxin (PCDD) and polychlorinated dibenzo furan (PCDF) were detected.

This system should comply with U.S. environmental regulations. The demonstration plant is stated to have gone through 15,000 hours of operation and operates continuously for five days a week processing unshredded municipal and industrial wastes. The plant uses the product gas to drive an engine generator.

Major unresolved areas are:

- Optimization of energy use.

- Use of Thermoselect's reactor gas in gas turbines is untested as of early 1996, but is not expected to be a problem.

- Waste heat recovery to improve overall plant thermal efficiency to include finding uses for low grade heat.

- Continuity and reliability of operation needs to be confirmed. The demonstration plant has only been operated on a five day per week cycle. Continuous, seven-day per week, around the clock operation is yet to be shown.

- Scale-up. The current demonstration plant is reported to have a "nominal capacity of 4 Mg/h (4.4 t/h)" but, experience to date shows that the unit appears to operate at an actual throughput of only 3.8 Mg/h (4.2 t/h). The "Standard Design" two-line capacity is 10 Mg/h (11 t/h) or 240 Mg/d (264 t/d). Therefore, the scale-up factor based on actual operational experience is about 2.7:1. The success of the planned commercial size facility is yet to be proven.

5. Battelle

The Battelle High Throughput Gasification System (BHTGS) uses indirect heating in a twin circulating fluidized bed (CFB) gasifier and combustor (Figure 5). RDF is gasified in a CFB using steam as the fluidizing medium to generate a medium heating value gas 18.6 to 22.4 MJ/Nm^3 (500 to 600 Btu/sft^3) without oxygen. Residual char is consumed in an associated CFB combustor. A circulating sand phase exchanges heat between the separate reactors.

Battelle's process development began in 1977. Detailed process development activities were begun in 1980 with the construction of Battelle's process research units (PRUs). Experimental data have been generated in gasifiers of 15 cm (6 in.) diameter and 25 cm (10 in.) diameter with a throughput of 0.22 and 9.1 Mg/d (0.24 and 10 t/d) dry RDF, respectively. Data from these showed that extremely high throughput, more than 19.5 Mg/h-m^2 (4,000 lb/hr-ft^2) could be achieved.

Tests showed the technical feasibility of the gasification process and provided the basis for detailed process conceptual design and economic projections to be generated. Testing was conducted in 1989 in a 25 cm (10 in.) internal diameter gasifier with a height of 6.9 m (22.7 ft) and a 1.0 m (40-in.) internal diameter combustor with a height of 3.5 m (11.5 ft). The throughput was 0.65 Mg/d (0.72 t/d). The longest continuous operating run was approximately 100 hours at 9.1 Mg/d (10 t/d) dry RDF. A 200 kW gas turbine has been installed on the PRU and operated with recharges from wood for about 60 hours as an integrated gasifier-turbine system.

Battelle has licensed its BHTGS Process to Future Energy Resources Corporation (FERCO) of Atlanta, Georgia for the North American market. A commercial scale demonstration is underway at the Burlington Electric's McNeil Generating Station in Burlington, Vermont using wood chips.

The BHTG process is said to produce gaseous emissions from the reactor complying with the EPA's MACT standards and NSPS for municipal waste combustors (MWC)[1]. Wastewater from the process contains only trace quantities of organic materials. The outlet of a simple industrial treatment system at Battelle's test site showed wastewater to be within the EPA's drinking water standards.

Major unresolved development and demonstration needs include:

- Important process development issues relate to fuel preparation and reactor gas cleanup.

- The specific level of fuel preparation necessary for the process has yet to be determined. Data suggest that fine shredding of the feedstock will not be required. Feed size range will be dictated by the feed system requirements and the rate of gasification processes.

- Product gas cleanup developments include tar cracking and particulate removal.

- Much more operating time with refuse at PRU scale is necessary to confirm the preliminary results obtained during the 1989 study at Battelle.

- The overall design concept needs to be expanded from a development focused on gasifier technology to a full plant with all auxiliaries and subsystems.

6. Pedco Incorporated

Pedco Incorporated is headquartered in Cincinnati, Ohio. The firm was originally formed in 1967 and has gone through several stages of growth and spinoff since. The present firm was formed in 1984 to pursue, among other interests, the development and commercialization of an innovative solid fuel combustor.

The Pedco Rotary Cascading Bed Combustor (RCBC) is, in essence, a robust solid fuel burner and heat recovery system. It is not a gasifier. Beyond conventional solid fuels (such as coal or wood chips) it can burn prepared MSW. Pedco's basic business is involved with the design of industrial combustion systems for steam generation based on the RCBC concept.

The RCBC burner consists of a rotating, horizontal, cylindrical combustion chamber (Figure 6). A bundle of boiler tubes projects into one end of the chamber. The rotational speed of the chamber is high enough such that a substantial fraction of the bed material is continually airborne. This produces an environment similar to that of a fluid bed but, here, a mechanically fluidized bed. The hot falling solids cascade across the whole diameter so that the boiler tubes are submerged in hot fuel and bed material. The hot solids recycle preheats the combustion air and dries and ignites the incoming fuel.

Pedco has two furnaces now operating in the U.S., a development unit at North American Rayon Corporation and a specialized unit based on Pedco design principles used by a commercial hazardous waste management firm in the Houston, Texas area. The plants are reported to have shown acceptable reliability, environmental emissions, and basic operability and maintainability characteristics.

Pedco prefers to provide their RCBC system as a factory assembled RCBC burner with a waste heat boiler configuration that is of a size where shipping by truck or rail is feasible. The design heat release rate of the Pedco basic RCBC system is approximately 233,000 MJ/h (100 x 10^6 Btu/h) corresponding to daily RDF rates of 168 Mg/d (185 t/d). Air pollution trains (besides the addition of low cost, coarse limestone screenings to the bed for acid gas control) would normally involve a fabric filter unit. Pedco believes that its in-bed limestone addition and consequent acid gas absorption eliminates the necessity for the spray dryer absorber used in many mass burn plants. Additional data are needed to confirm this position.

Pedco has yet to develop and adopt a front-end waste system to produce a sized RDF feed for the RCBC system. Pedco has only limited experience with an RDF and has not yet established a firm basis on which to specify their optimum top size. Development of a generalized RDF flow sheet should not be proble-matic. One notes, however, that most RDF facilities have required extensive redesign and reconstruction effort to bring the RDF processing elements to an acceptable level of reliability and performance.

Major unresolved development and demonstration needs include:

- Pedco must select or develop a full system concept and associated detailed specifications starting with RDF receipt and processing and including electrical generation and residue handling.

- Continuity and reliability of operation of an RCBC system must be confirmed in RDF service. Problems associated with fouling and/or plugging of the ash handling chutes with wire and oversized non-combustible materials; fouling problems with boiler tubes; air emissions; and tube abrasion and corrosion problems must be assessed in continuous RDF service.

- Experience to date with the cluster of boiler tubes inserted into the RCBC device has been limited to low pressure, saturated steam. To maximize power production, higher pressures and superheated conditions are preferred. Higher skin temperatures on the tubes may affect erosion and corrosion sensitivity and should be evaluated before commitment to a full scale facility.

7. ThermoChem Incorporated

The Manufacturing and Technology Conversion International, Inc. (MCTI) Steam Reforming Process is an indirectly heated fluidized bed reactor using steam as the fluidizing medium (Figure 7). Under license from MCTI, ThermoChem, Inc. (TC) have the exclusive rights to apply its Pulse-Enhanced™ heater and steam-reforming technology to a variety of applications.

Pulse Enhanced™ indirect heating technology combined with fluid-bed and steam-reforming provides a process for converting the organic material in an RDF to fuel gas while separating the inorganic without oxidation or melting. The key to the process is the array of Pulsed Enhanced™ heater tubes immersed in the fluidized bed. Gaseous fuel is burned in the tubes such as to create an oscillating pressure. The effect of the pulsing flow is to significantly enhance heat transfer between the combustion products and the tube wall. This greatly increases the efficiency of energy exchange between the fuel and the bed material. The organic waste fed to the fluid-bed steam reformer reacts with steam to produce a medium heat content fuel gas.

MCTI's development efforts began in 1984. Experimental data have been generated in different scale reactors from 9.1 to 2,722 kg/h (20 to 6,000 lb/h) using various biomass and waste feedstocks. A 13.6 Mg/d (15 t/d) demonstration unit was operated on rejects from a cardboard recycle paper mill in Ontario, California in 1991-1992. Later, this unit, moved to TC's test facility in Baltimore, processed coal, woodchips and straw.

Based on 6.8 kg/h (15 lb/h) pilot plant tests, the TC Process appears to comply with the EPA NSPS for MWC's. Tests suggest the residue meets EPA TCLP leachability criteria set for landfill disposal as a nonhazardous waste. Wastewater contains only trace amounts of organic materials.

Major unresolved development and demonstration needs include:

- TC must select or develop a full system concept and associated detailed specifications starting with RDF receipt and processing and including electrical generation and residue handling.
- Continuity and reliability of operation of a TC system must be confirmed in RDF service. Of particular concern are problems with tube corrosion, erosion, and plugging.
- Problems with the cyclone capturing particulate in the bed off-gas must be evaluated in RDF service. The cyclones are subject to pluggage as they are in conventional atmospheric fluid beds.
- Solids removal from the bed must be evaluated and robust, reliable solids handling systems must be developed and tested.
- Considerable demonstration work is needed to address remaining uncertainties regarding air emissions, residue quality, plugging of the spaces between the tubes with wire, metals, rocks, etc. These uncertainties translate into persistent risks that should be carefully considered before use.

CONCLUSIONS

Intense developmental activity applicable to the thermal processing of MSW is underway in the U.S. and Europe. One can identify more than 45 distinct efforts at some stage of process development now. Most of the processes are based on MSW gasification (as opposed to full combustion). In part, the focus on gasification reflects the current stringent regulatory situation in both the U.S. and Europe regarding the control of air emissions. Thus, processes that allow clean-up of the reactor gases before its combustion offer potential economy since the volume flow treated is small. The cleaned fuel gases can then either be burned in gas engines or gas turbines to generate electricity or sold as a fuel in conventional boilers.

Although many of the 45 processes are still at the bench or laboratory scale, several have progressed to a pilot or semi-works level where the difficult problems of reliability, flexibility etc. appear. The seven processes selected for study are all very near to commercialization. One technology has been carried out in four, full-scale commercial facilities and another in a two-furnace commercial plant. That means that most processes still present some risk to a prospective owner. This risk could show itself as higher capital or operating costs, lower reliability or lower energy recovery efficiency than have been forecast at this time. The development record for new MSW processing technologies suggests that such problems are probable for some processes as they move into full scale commercialization.

Based on data from pilot facilities, each of these processes can probably achieve full compliance with the U.S. EPA Maximum Achievable Control Technology (MACT) standards and the New Source Performance Standards (NSPS) for Municipal Waste Combustors promulgated in final form in December 1995[2]. Only one process matches a technology group as used by the EPA in their standard setting. Many are gasifiers and not the full combustion systems referenced in the EPA standards. Therefore, knowing how the federal standards will be applied is uncertain. As with most permitting issues, the ultimate resolution of these questions must wait until actual permits have been submitted and final regulatory action is required.

The residues from the processes do not present problems in the Toxicity Characteristics Leaching Procedure (TCLP) leaching tests. The quantity of data in this area, however, is limited and experience in mass burn plants suggests that significant variation in TCLP results can be expected. Two of the processes (Thermoselect and Proler) include process steps where the residues are melted (vitrified). For these processes, the TCLP results are exceptionally low since the metals are bound in a glass structure and cannot be readily solubilized. Both firms believe that the vitrified residue granules may be marketable and, therefore, that their process will have a lower operating cost than is shown in Tables 2a,b. As yet, however, the value of the granules, if any, has not been established in the U.S. marketplace.

The overall conclusion that can be drawn is that competitive alternatives to conventional mass burn or refuse derived fuel (RDF) combustors exist. The alternatives may not offer exceptional economic advantages. Most of the processes studied present a much lower air emission profile than do conventional plants. This may merit investigation by communities or regional jurisdictions considering volume reduction technology where air emissions are of particular concern. One should note, however, that conventional mass burn technology can also meet the recently promulgated MACT and NSPS[2] emission requirements. The economic data in Table 2 is intended to provide perspective; not to be directly applicable to a specific situation. *To obtain fair, applicable economic data, cost issues should be addressed directly with the firms* (see Appendix A).

The preceding technical descriptions, many of the economic estimates and the prospective environmental performance would suggest that these new technologies define the future of WTE facilities. However, with the exception of EPI and, to a degree TPS, all of the processes have important development and/or demonstration steps between the present status and proven commercial availability. All except Thermoselect require processing of MSW to an RDF, possible but always problematical. Experience with Purox, Landgard, Torrax and many other processing technology developments in years past has shown that commercial and technical success does not come easily if at all. The unrelenting crucible of 24 hours a day, seven days a week operation in combination with the malevolent nature of refuse clearly presents a profound challenge to the process developer.

Also, most of the process developers suggest optimistic overall energy recovery levels. However, almost all lose energy in the RDF-making step. Some use a water quench to cool the synthesis gas, thus losing 400 to 600 Btu/lb MSW in sensible heat. Others achieve superior environmental characteristics at the price of greatly increased process complexity and higher capital and operating costs. Several firms are small and will suffer with the extended facility development schedules and under the draconian financing requirements of most U.S. system procurements.

Still, the adventure and excitement of technical innovation and the promise of successful commercial development spurs these firms forward. The professionalism, the high technical standards, and the business commitment in most of the seven development firms were impressive. Further, despite a weak U.S. market, most firms are aggressively seeking clients for that vital "first plant." I wish them well.

ACKNOWLEDGEMENTS

This paper is based on research funded by the National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy. The support of NREL and DOE is gratefully acknowledged as are the technical contributions of the members of the Steering Committee representing NREL, USEPA and Southern California Edison Company.

REFERENCES

1. Niessen, W., Marks, C., and Sommerlad, R., "Evaluation of Gasification and Novel Thermal Processes for the Treatment of Municipal Solid Waste," Contract YAR-5-15116-01 report to the National Renewable Energy Laboratory, July 1996.

2. Federal Register, *December 19, 1995* - 40 CFR Part 60.

Appendix A

Offices of Development Firms

1. Energy Products of Idaho (EPI) Ltd. Partnership
4006 Industrial Avenue
Coeur d'Alene ID 83814
Tel: (208) 765-1611
Fax: (208) 765-0503

2. TPS Termiska Processer AB
Studsvik, S-611 82
Nyköping, Sweden
Tel: 011-46-155-22-13-00
Fax: 011-46-155-26-30-52

3. Proler International
4265 San Felipe, Suite 900
Houston, Texas 77027
Tel: (713) 963-5940
Fax: (713) 627-2737

4. Thermoselect Inc.
201 West Big Beaver Road ,Suite 230
Troy, Michigan 48084
Tel: (810) 689-3060
Fax: (810) 689-2878

5. Battelle
505 King Avenue
Columbus, Ohio 43201
Tel: (614) 424-4958
Fax: (614) 424-3321

6. Pedco Incorporated
214 East 9th Street
Cincinnati, Ohio 45202
Tel: (513) 361-8643
Fax: (513) 351-8646

7. ThermoChem, Inc.
10220-H Old Columbia Road
Columbia, Maryland 21046
Tel: (410) 312-6300
Fax: (410) 312-6303

Table 1 Environmental Comparison of Developing Technologies

Process Name	Thermal Treatment Technology	Air Pollution Control	Water Pollution Control	Residue Treatment or Disposal
EPI, Inc.	Bubbling Fluid Bed Combustor	Lime Spray Dryer Absorber, Fabric Filter, Selective Noncatalytic Reduction, Activated Carbon Injection	None: Dry System.	Landfill
TPS Termiska AB	Circulating Fluid Bed Gasifier with Dolomite Cracker	Scrubbing of Fuel Gas to Remove Particulate Matter, Condensable Organics, and Acid Gasses, NO_X[1]	Cleanup of Scrubber Liquor. Not specified.[2]	Landfill
Proler International	Rotary Reactor Gasifier and Cyclonic Ash Vitrifier	Fabric Filter, Wet Scrubber, NO_x[1]	Cleanup of Scrubber Liquor. Not specified.[2]	Proposed Sale as Vitrified Aggregate; Otherwise landfill.
Thermoselect, Inc.	Raw Waste Gasifier	Acidic and Alkaline Scrubber, H_2S Removal, Activated Coke, NO_x.[1]	pH Adjustment, Metal Precipitation, Filtration, Distillation.	Proposed Sale as Vitrified Aggregate; Otherwise Landfill.
Battelle	Circulating Fluid Bed Gasifier and Combustor	Wet Scrubber, NO_x.[1]	Cleanup of Scrubber Liquor. Not Specified.[2]	Landfill
Pedco Incorporated	Rotary Cascading Bed Combustor	Lime Spray Dryer/Absorber, Fabric Filter, Selective Noncatalytic Reduction, Activated Carbon Injection.	None. Dry System.	Landfill
ThermoChem	Pulse-Heated Circulating Fluid Bed Gasifier		Cleanup of Scrubber Liquor. Not specified.[2]	Landfill

Notes:

1. NO_x control may be required for the gas engine or turbine combustor.
2. Details of treatment were no specified by the developer.

Table 2 Summary of Statistics for Developing Technologies (per ton quantities relate to raw MSW)

Process	Product Energy Form	Plant Size Evaluated (Mg/d$_{raw}$)	No. Burnaces	Capital Cost ($000)	Process Capital ($000)	Proprietary Capital (%)	Capital Cost ($/Mg/d)	Energy Product (MJ/Mg)$_{raw}$
EPI Inc.	Steam	780	2	79,415	28,015	35.3	101,800	12,918$_{net}$
TPS Termiska Processor AB	Gas	1600	2	170,675	58,875	33.3	106,700	7,602$_{net}$
Proler International Corp.	Gas	1247	2	153,625	57,625	37.5	123,200	11,385$_{net}$
Thermoselect Inc.	Gas	1440	6	236,790	192,790	81.4	164,400	7,404$_{net}$
Battelle	Gas	849	2	80,532	12,532	15.6	94,900	11,548$_{net}$
Pedco Incorporated	Steam	800	2	87,067	28,167	32.4	108,800	10,387$_{net}$
ThermoChem Inc.	Gas	849	1	91,733	20,983	22.9	108,800	7,857$_{net}$
Generic Mass Burn	Steam	1365	3	150,000	30,000	20.0	109,900	6,860$_{net}$

Process	Gross Operating Cost ($/Mg)*	Prime Mover#	Gross Power (kWh/Mg)	Net Power (kWh/Mg)	Net Operating Cost ($/Mg)†	Gross Heat Rate (MJ/kWh)§	Net Heat Rate (MJ/kWh)§
EPI Inc.	85.21	ST	1088	895	52.71	9.69	11.78
TPS Termiska Processor AB	71.84	GT/ST	1230	1024	38.91	8.57	10.29
Proler International Corp.	99.15	GT	1281	1091	59.47	8.23	9.67
Thermoselect Inc.	123.24	GT	1083	778	94.92	9.74	13.55
Battelle	79.37	GT	1001	871	47.63	10.53	12.11
Pedco Incorporated	78.87	ST	886	868	52.29	11.89	12.15
ThermoChem Inc.	81.17	GT	1149	1004	44.56	9.17	10.50
Generic Mass Burn	85.88	ST	633	578	63.11	18.35	20.10

*Gross operating cost/ton raw refuse—total of capital charges, insurance, labor, maintenance, and supplies before energy credits.

†Net operating cost/ton raw refuse—gross operating cost less energy credit.

§Heat rate—factor relating the fuel value in the raw refuse (assumed at 11.6 MJ/kg, 14 MJ/kg as RDF) to the gross or net generation.

Prime Mover---ST=Steam Turbine,GT=Gas Turbine, Gt/St=Gas Turbine with heat recovery and additional generation using a steam turbine

Conversion factors: MG times 1.1 yields tons; kwh/MG times 0.826 yields kwh/ton; MJ times 1147.9 yields Btu.

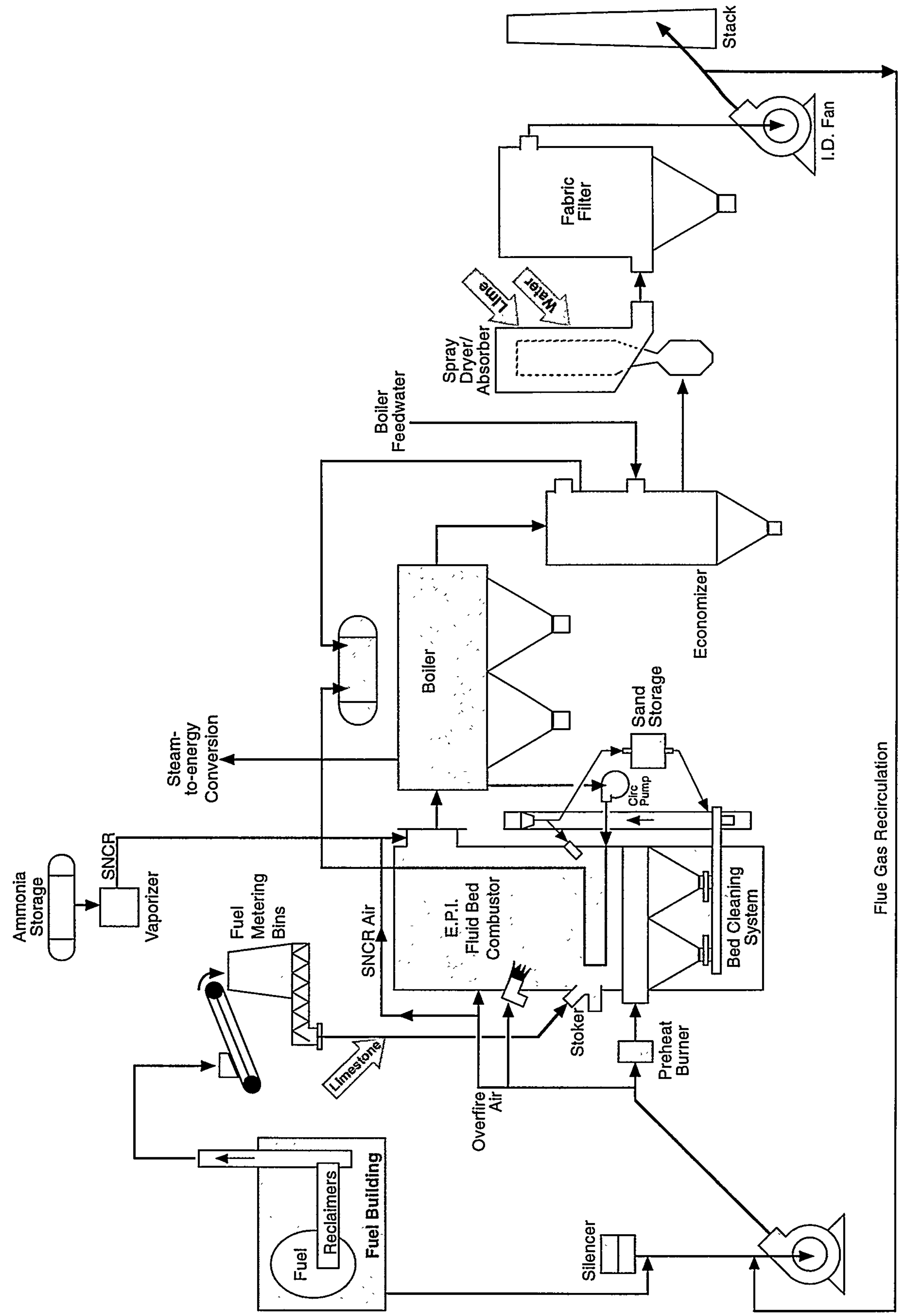


Figure 1. Energy Products of Idaho Process Flowsheet

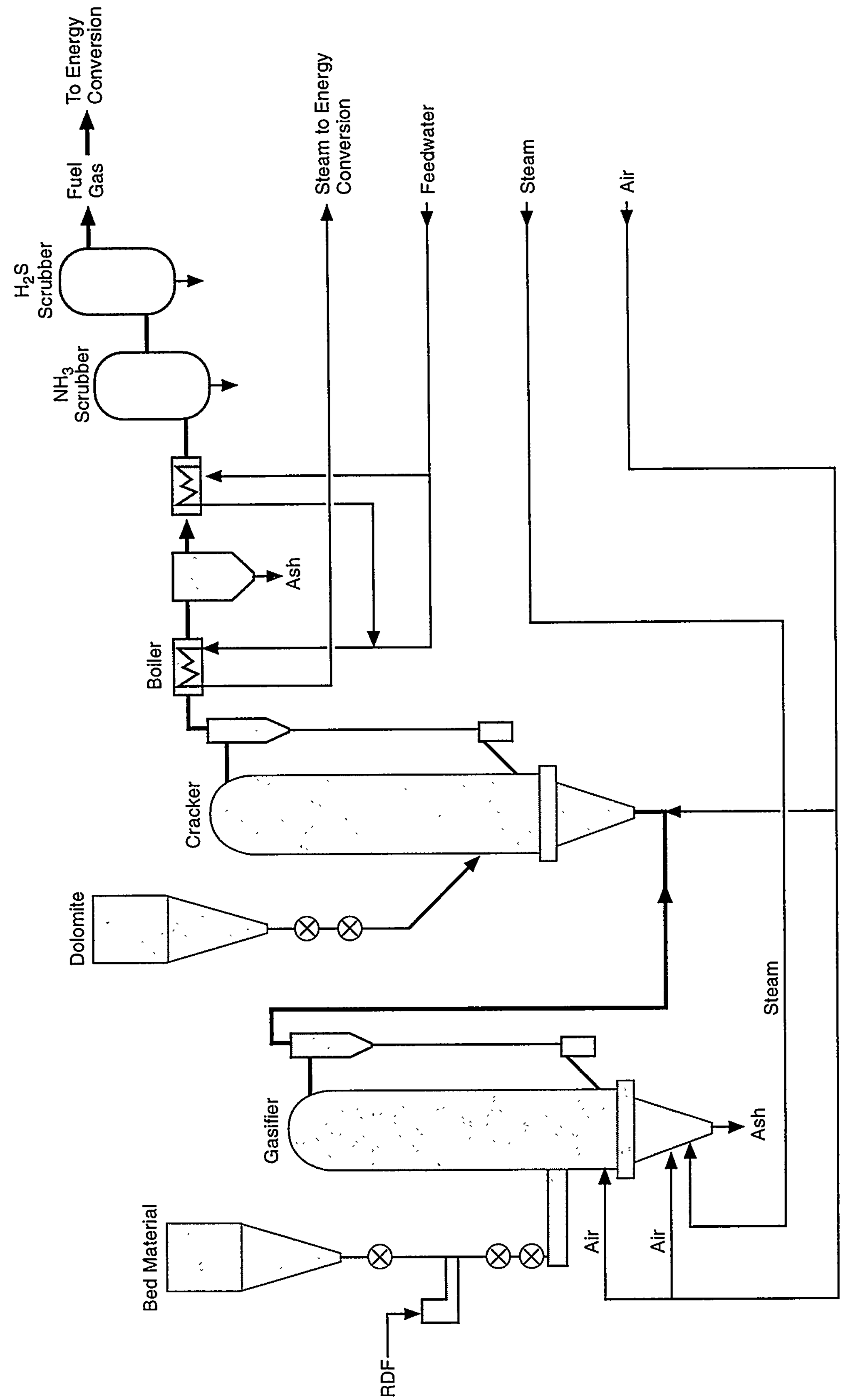


Figure 2. TPS Termiska Processer AB – Process Flowsheet

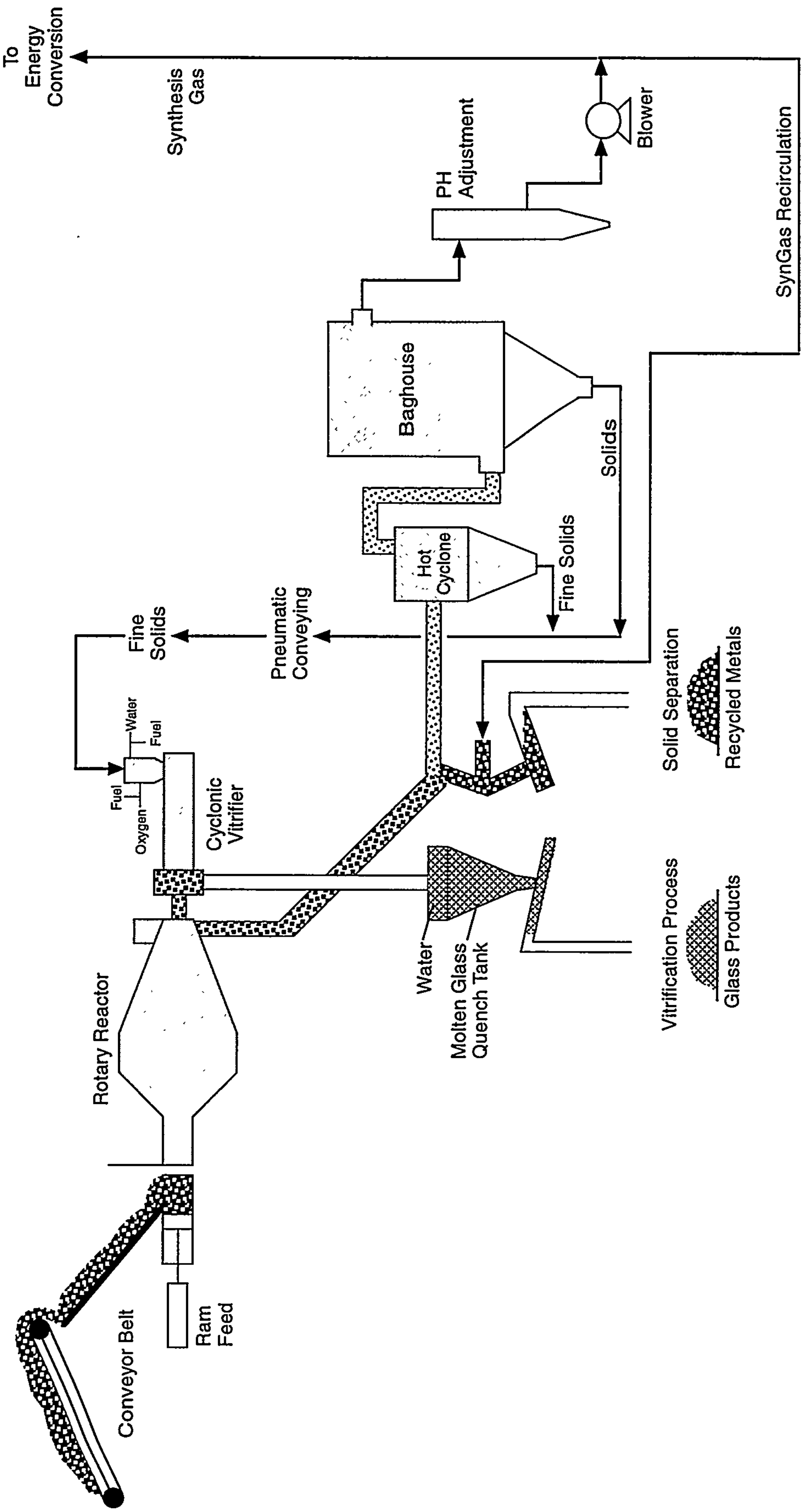


Figure 3. Proler Process Flowsheet

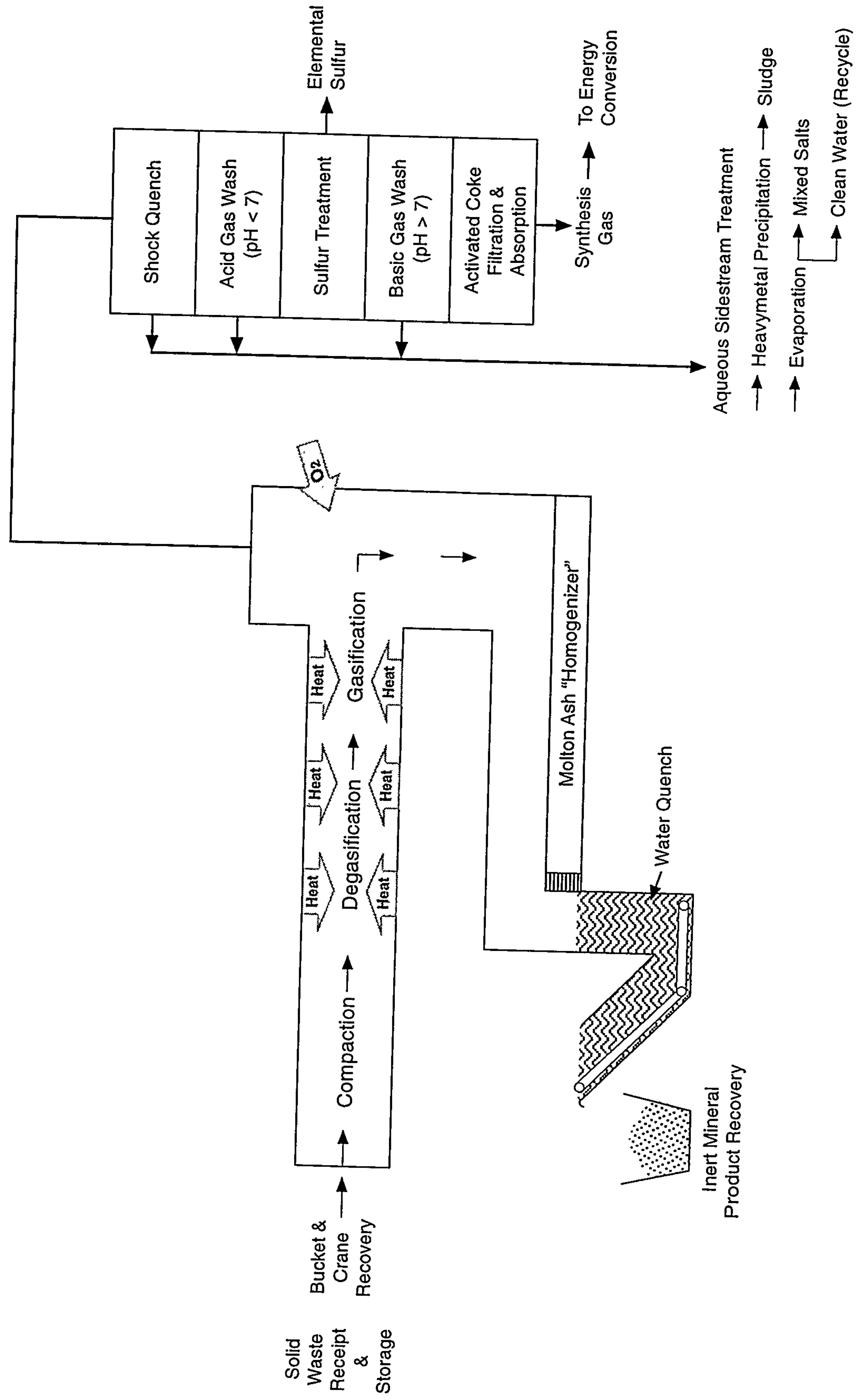


Figure 4. Thermoselect Process Flowsheet

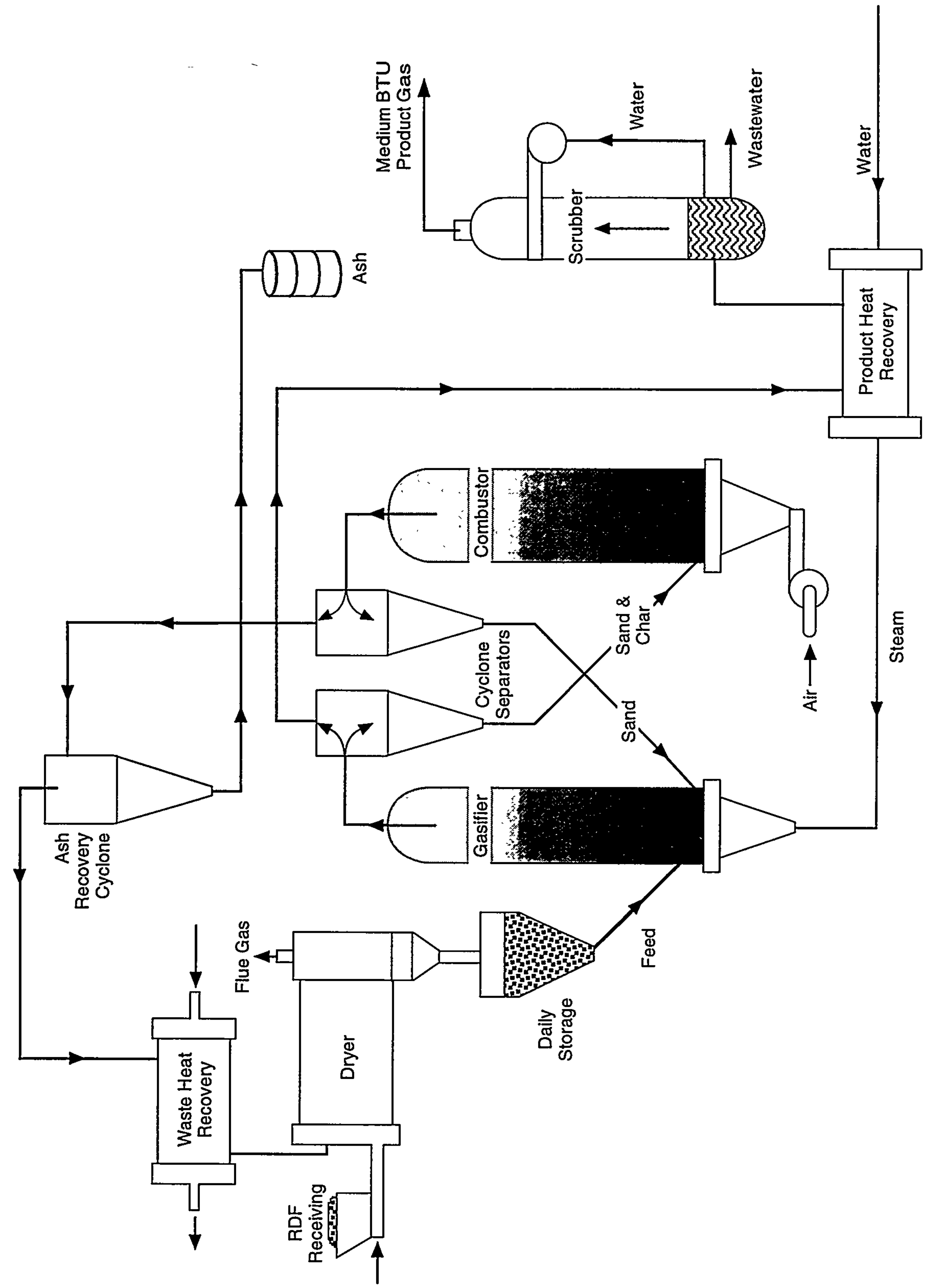


Figure 5. BHTGS Process Flowsheet

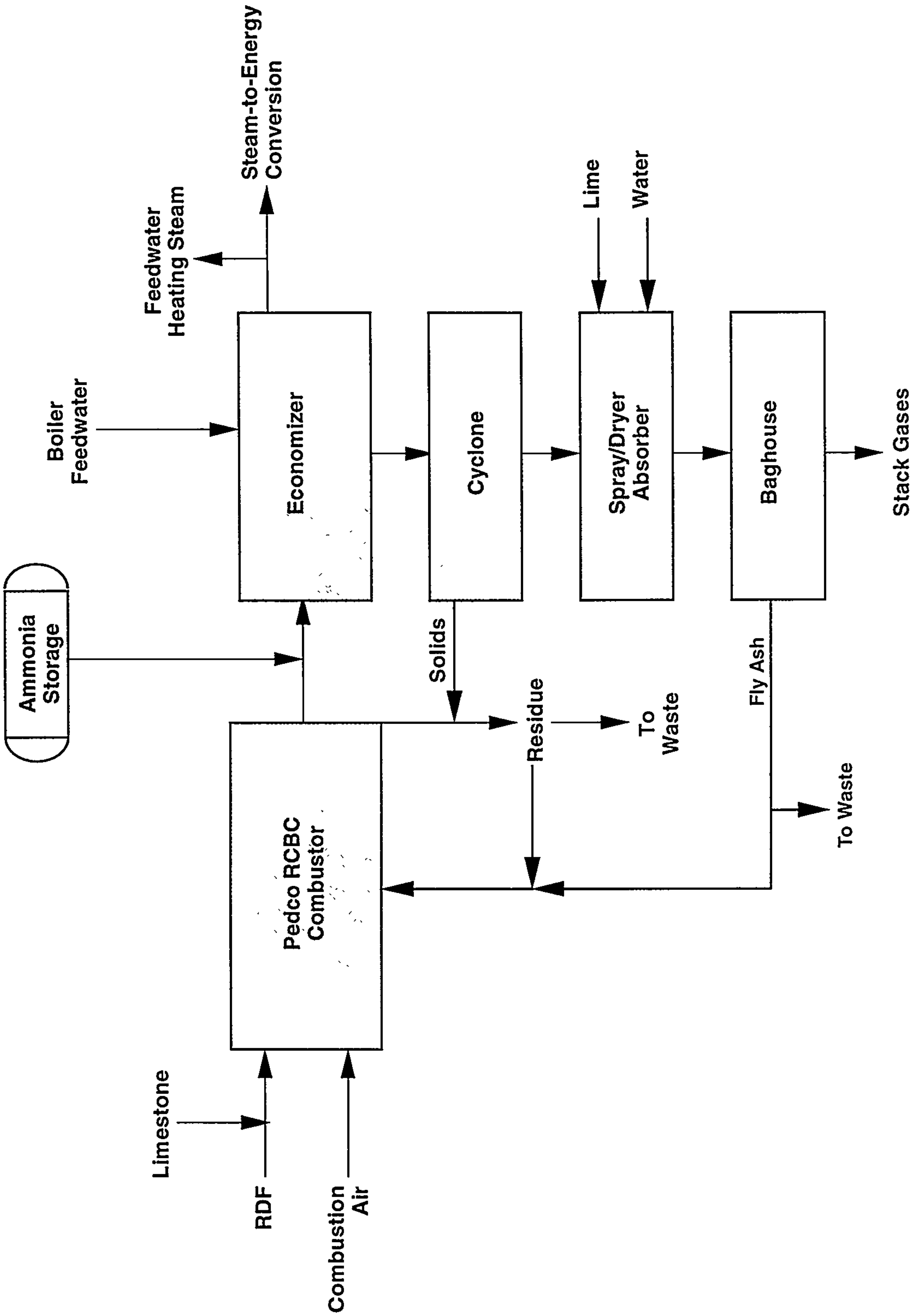


Figure 6. Pedco Process Flowsheet

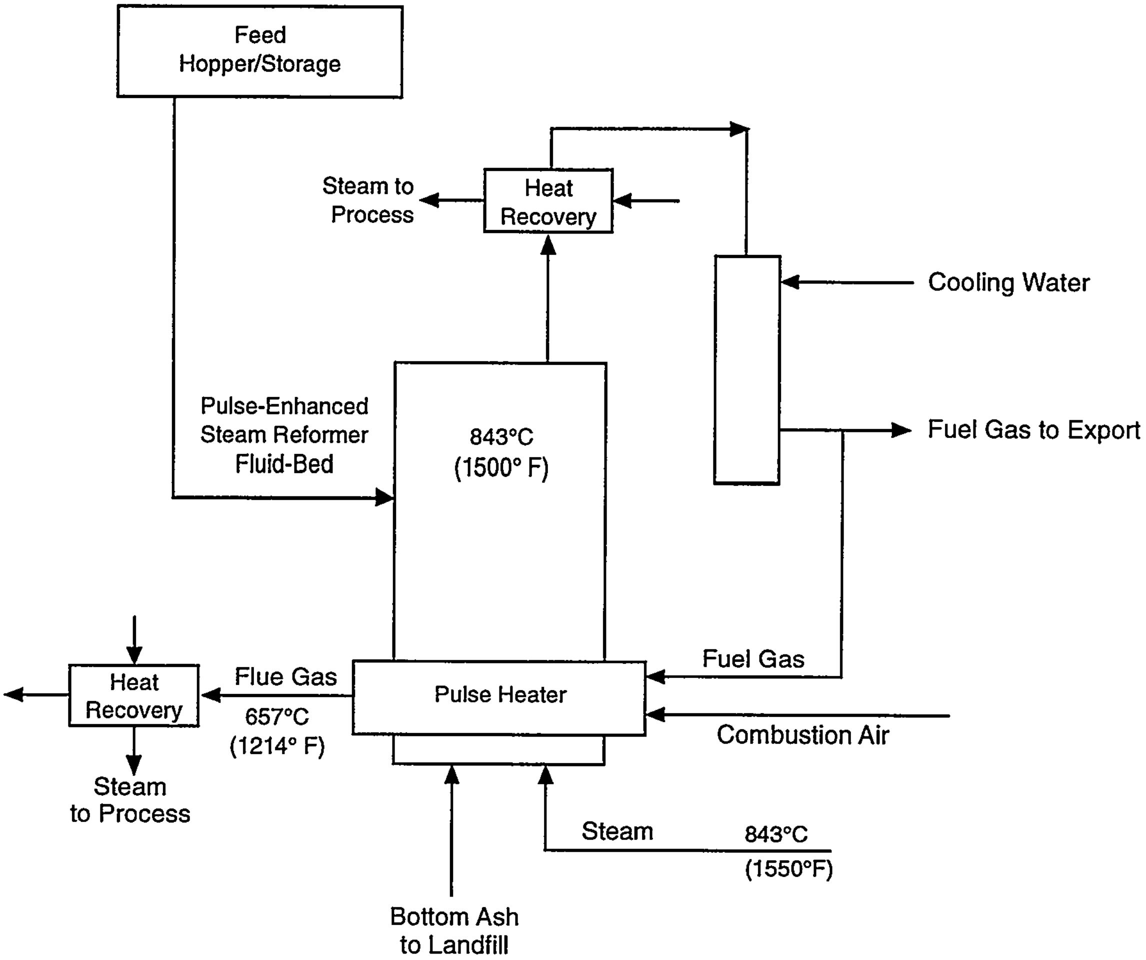


Figure 7. Thermochem's Process Flowsheet

Production of Biomass Fuel for Resource Recovery:
Trash Recycling in Dade County, Florida

Paul J. Mauriello, AICP and Kathie G. Brooks, AICP
Department of Solid Waste Management
8675 N.W. 53rd Street
Suite 201
Miami, Florida 33166

ABSTRACT

Dade County, Florida has been in the forefront of resources recovery from municipal solid waste since the early 1980's. The County completed its 3,000 tons per day (six days per week) refuse derived fuel waste-to-energy facility in 1982. The Resources Recovery facility is operated under a long-term agreement with Montenay-Dade, Ltd. The trash processing capability of this facility was upgraded in 1997 to process 860 tons per day (six days per week) of trash into a biomass fuel which is used off-site to produce electrical energy. Under current Florida law, facilities like trash-to-fuel that produce alternative clean-burning fuels for the production of energy may receive credit for up to one-half of the state's 30 percent waste reduction goal.

Introduction

Prior to waste diversion problems, and the U. S. Supreme Court decision invalidating waste flow control by local government, Dade County, Florida was preparing to expand its 3,000 tons per day refuse derived fuel waste-to-energy facility by 50 percent. Industrial revenue bonds in the amount of $190 million were sold in 1990 to finance the expansion, and to retrofit the facility with a new air quality control system to meet federal maximum available control technology standards.

Localized opposition to the expansion resulted in formation of a Citizens Task Force For Solid Waste Management in 1991. This group, appointed by the Board of County Commissioners, was charged with evaluating the need for additional waste disposal capacity and the appropriateness of the planned expansion to fulfill that need. The Task Force was staffed by a consultant team, hired by the County to prepare its master plan for solid waste management, and members of the County's solid waste management department. After two years, thirty meetings, and countless hours of staff time, the Task Force agreed that additional waste disposal capacity was needed and that the expansion of the Resources Recovery facility was the appropriate technology.

The Board of County Commissioners, however, was not convinced and asked the consultant to continue to evaluate other technologies. At approximately the same time, Montenay-Dade, Ltd. was approached by Okeelanta Corporation, a central Florida sugar producer, regarding Montenay's ability to provide biomass fuel for an electric power plant Okeelanta was planning. The Trash-to-Fuel (TTF) alternative was born. TTF had several advantages over expansion of waste-to-energy capacity at the Resources Recovery facility. The process was less costly than on-site combustion, off-site combustion was more attractive to residents in the vicinity of the facility, and in 1993 the County was successful in its effort to have the state legislature amend the state's Solid Waste Management Act to allow clean-burning fuels, used for the production of energy, to count toward achievement of the state's 30 percent waste reduction goal for counties.

Although waste diversion problems and associated financial impacts were threatening to derail the TTF project, the County and Montenay were able to mutually agree on modifications to their operations and management agreement that take into account unstable waste flows to the facility. The new agreement, dated September 1, 1996, requires the County to deliver all the garbage available in the County's solid waste management system, up to 936,000 tons, but no less than 572,000 tons. The County must also deliver a minimum of 400,000 tons of trash for TTF and on-site combustion, the on-site portion of which may be displaced by garbage (130,000 tons). The result is an overall annual minimum waste delivery requirement of 972,000 tons and a maximum of 1,206,000 tons depending on waste flow (refer to figure 1). Moreover, to assist with the financial impacts of the loss of revenue producing waste tonnage, the revised agreement provided for a reduced fee of approximately $5 per ton for 234,000 tons of the 936,000 tons to be combusted on-site, thereby reducing overall facility costs by more than $1 million per year.

The TTF Process

The TTF process was constructed at a cost of approximately $26 million and is currently in start-up mode. Under the County's operations and management agreement with Montenay, the operator guarantees that TTF will process 270,000 tons per year of trash (862 tons per day, six days per week). The TTF processing fee to the County is $22.41 per ton, plus an additional fee of $1.36 per ton for the resulting processed fuel that qualifies for recycling credit under state law. When debt service cost and transportation of rejects and residue for TTF are factored in, the total cost per ton is approximately $38.

The primary components of the process are a trash sorting floor where reject and non-processable materials are removed from the trash stream, a material storage pit (existing), hoppers, conveyors, shredders, ferrous metal separation, material sizing trommels, material storage bunkers, load-out area, and outbound scale. The biomass fuel material produced must contain no more than 3 percent oversize material (over 5 inches in diameter) in order to meet customer specifications.

TTF outputs include biomass fuel 50 percent, fines 30 percent (dirt, grit and stones), rejects 17.6 percent (non-biomass materials sorted from the incoming trash stream), and ferrous metals 2.4 percent (refer to figure 2). The fuel is hauled out by Okeelanta at its sole cost, and no payment is made to Okeelanta for taking the fuel. The fines are categorized as primary (loamy dirt material) and secondary (stones). The primary fines will be supplied to a third party for plant nursery use. The County is responsible to accept up to 10 percent of the total incoming TTF material as primary or secondary fines annually (27,000 tons). This material may be used as landfill cover by the County. Disposition of fines above the 10 percent fines guarantee is the responsibility of Montenay. A special unmanned scale was constructed to weigh-out the fuel and fines. The County is responsible for disposal of up to 17.6 percent of the total incoming TTF material as rejects annually (47,520 tons). Disposition of rejects above the 17.6 percent rejects guarantee is the responsibility of Montenay. Ferrous metals recovered from the TTF process are transferred to the Resources Recovery ferrous bunker for further processing by Namco International Corporation, an on-site third party metals processing company under contract with Montenay.

Conclusions

Dade County was successful in negotiating unique waste delivery guarantees and financial enhancements to ensure that this innovative expansion of its Resources Recovery facility would proceed without WFC. Without reinstatement of local government waste flow control (WFC) authority by the federal government, however, the formation of public/private partnerships to develop facilities similar to Dade's TTF process elsewhere in the State of Florida, or elsewhere in the nation is unlikely. In South Florida, the potential for development of such facilities is reduced further by the abundance of low cost waste disposal alternatives, primarily landfills.

References

1. Official Florida Statutes 1995. Published by the State of Florida, Tallahassee.

2. Third Amended and Restated Operations and Management Agreement by and between Metropolitan Dade County, Florida and Montenay-Dade, Ltd., September 1, 1996; Resolution number R917-96.

3. Non-Exclusive Agreement Between Metropolitan Dade County, Florida and Waste Management Inc. of Florida for Provision of Municipal Solid Waste Disposal Services, October 27, 1995.

DADE COUNTY, FLORIDA
RESOURCES RECOVERY FACILITY
GARBAGE AND TRASH COMMITMENTS
September 1, 1996

From:
September 1, 1996

AOSWGT*	Garbage Minimum	572,000
	Trash Maximum	364,000
Total		936,000

After:
RTIAPCD**

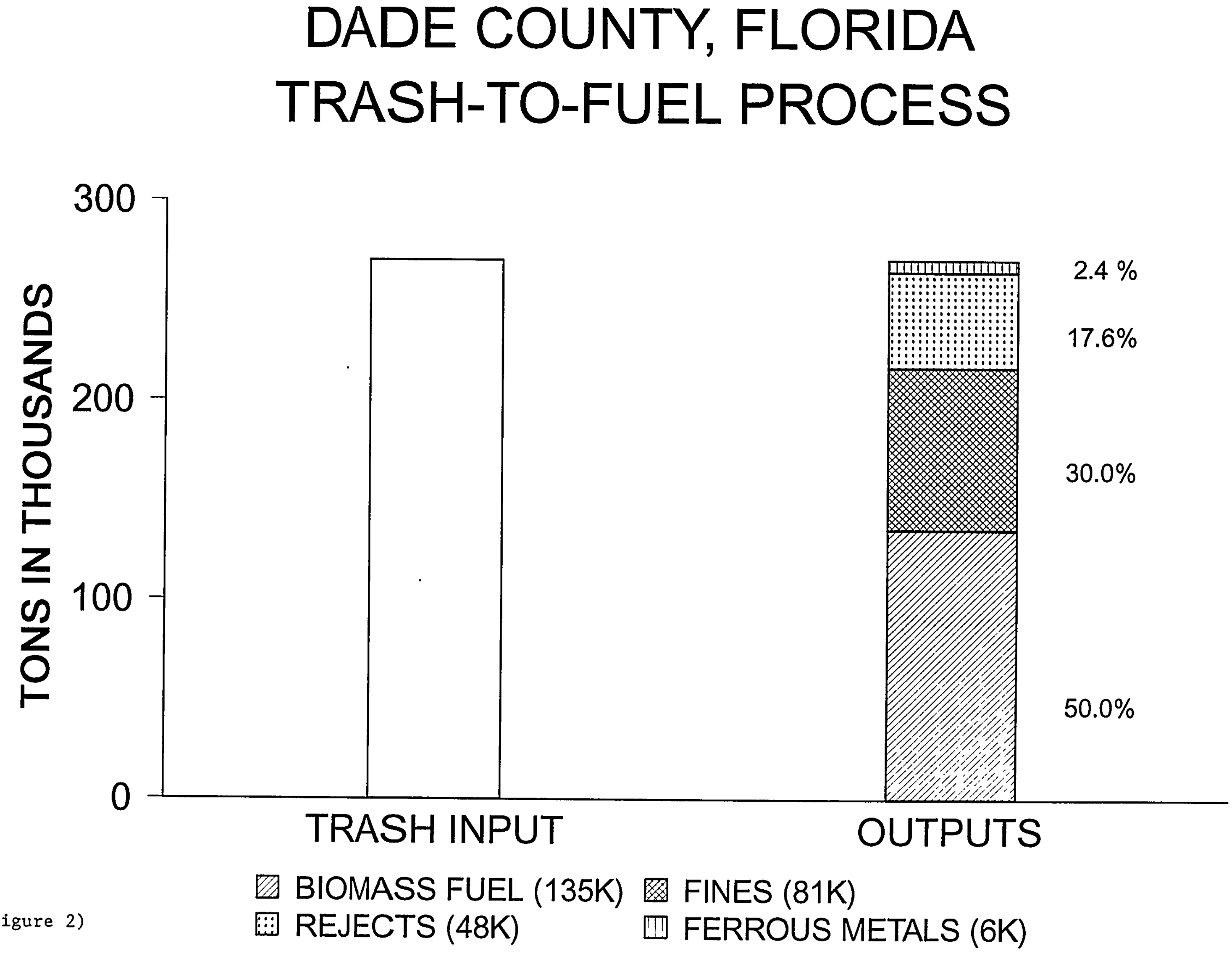
AOSWGT	Garbage Minimum	572,000
	Trash Maximum	130,000
	Subtotal	702,000
ARTGT***		270,000
Total		972,000

MAXIMUM WASTE DELIVERY AMOUNTS

If garbage is available for delivery, County must deliver up to -	936,000
ARTGT -	270,000
Maximum Waste Delivery Amount -	1,206,000

*AOSWGT - Annual On-site Waste Guaranteed Tonnage
**RTIAPCD - Recyclable Trash Improvements Actual Performance Completion Date
***ARTGT - Annual Recyclable Trash Guaranteed Tonnage

(Figure 1)


DADE COUNTY, FLORIDA
TRASH-TO-FUEL PROCESS
TONS IN THOUSANDS
300
200
100
0
TRASH INPUT
OUTPUTS
2.4 %
17.6%
30.0%
50.0%
▨ BIOMASS FUEL (135K)
▩ FINES (81K)
⊞ REJECTS (48K)
▥ FERROUS METALS (6K)

(Figure 2)

TECHNICAL SESSION I

Retrofits & Emissions Characteristics

Design, Operation, and Performance of a Modern Air Pollution Control System for a Refuse Derived Fuel Combustion Facility

Edwin H. Weaver
Belco Technologies Corporation
7 Entin Road
Parsippany, NJ 07054

Cosmo Azzinnari
Belco Technologies Corporation
7 Entin Road
Parsippany, NJ 07054

ABSTRACT

The Robbins, Illinois refuse derived fuel combustion facility was recently placed into service. Large and new, the facility is designed to process 1600 tons of waste per day. Twenty-five percent of the waste, or 400 tons per day, is separated out in the fuel preparation process. The remaining 1200 tons per day is burned in two circulating fluidized bed boilers.

The system is designed to meet new source performance standards for municipal waste combustion facilities, including total particulate, acid gases (HCl, SO_2, HF), heavy metals (including mercury), and dioxins. The system utilizes semi-dry scrubbers with lime and activated carbon injected through dual fluid atomizers for control of acid gases. Final polishing of acid gas emissions, particulate control, heavy metals removal, and control of dioxins is accomplished with pulse jet fabric filters. This paper discusses the design of the facility's air pollution control system, including all auxiliary systems required to make it function properly. Also discussed is the actual operation and emissions performance of the system.

INTRODUCTION

The air pollution control system for this facility consists of one semi-dry scrubber and pulse jet fabric filter for each of the two refuse combustion trains. Reagent preparation and delivery and compressed air for atomization of the reagent are provided in a system common to both air pollution control trains. A general system schematic is shown in Figure #1.

Each air pollution control system is designed to treat the flue gases from the combustion of 600 TPD of refuse derived fuel (RDF). This refuse firing rate translates to approximately 176,000 ACFM of flue gas at a temperature of 475°F. All of the system inlet design parameters are provided in Table #1.

To comply with new source performance standards for municipal waste combustion facilities, the system is designed to remove 95% of the HCl entering the system, or achieve an outlet emission rate of 25 ppm @ 7% O_2. SO_2 emissions are designed for 30 ppm @ 7% O_2 or an 85% reduction of the SO_2 entering the system. Particulate emissions are limited to 0.010 gr/DSCF @ 7% O_2. Mercury emissions are limited to 80 ug/Nm^3 @ 7% O_2 or an 85% reduction of the mercury entering the system. Dioxins are controlled to a maximum of 30 ng/Nm^3 @ 7% O_2. Certain heavy metals are also controlled. A summary of the mandated emission levels for the facility is provided in Table #2.

SEMI-DRY SCRUBBER

The flue gas from the incinerator enters the top of the semi-dry scrubber through flow tubes. In each flow tube, calcium hydroxide along with a small amount of activated carbon for dioxin and mercury control is introduced through a dual fluid nozzle in a finely atomized liquid form. The calcium hydroxide mixes with the flue gas and reacts with the acid gases to form solid particulate. As the flue gas and reaction products flow downward in the scrubber, the reaction products are completely dried. Although some of the particulate drops into the hopper under the semi-dry scrubber, most of the particulate is carried to the fabric filter where it is removed from the gas stream.

The design of the semi-dry scrubber for this process necessitates the satisfaction of two major criteria. First, the reagent slurry must be atomized to produce a droplet spectrum that provides for the optimum acid gas absorption and reaction. Second, the vessel must be configured to ensure that the droplets evaporate and the reaction products produced dry before reaching the wall of the vessel or exiting the vessel. This prevents buildups which would impede the operation of the system.

The semi-dry scrubber utilizes dual fluid nozzles to atomize the lime slurry. A total of 10 nozzles per scrubber vessel were provided. The flue gas entering the vessel is equally divided into three gas streams. Each gas stream passes through a "flow tube" where a dual fluid nozzle sprays the atomized slurry concurrently downward with the gas flow. A sketch of this arrangement is shown in Figure #2. The cool liquid contacting the hot flue gas induces turbulence and mixing. At the same time, a gas velocity reduction of approximately 90% occurs as the flue gas enters the main body of the scrubber vessel. The combination of these two processes induces a thorough mixing of the reagent and acid gases. During this mixing, the acid gases are absorbed by the reagent, creating solid particulate and removing the acid gases from the flue gas stream.

In order for this reaction to occur efficiently, the droplet spectrum from the dual fluid nozzles must be such that the droplets are not too small and therefore flash dry nor are they too large, which reduces the surface area available for reaction and causes a problem with particle drying. A useful measurement of the droplet spectrum is the sauter mean diameter (SMD). The SMD is defined as the droplet diameter which has the same surface to volume population as the entire droplet population. This number helps define the size distribution of the droplets. A wide size distribution, which is not desirable for semi-dry scrubbing, will have a higher SMD than a narrow size distribution of droplets. Field testing on this process has shown that an SMD of 60 to 70 microns produces a droplet spectrum which does not have an excessive amount of large droplets and also does not have too many fine droplets. The theoretical drying profile for the droplet spectrum for the BELCO nozzle used in this installation is shown in Figure #3.

Overall geometry of the scrubber vessel is also an important consideration. The vessel must be designed so that the flue gas expands and utilizes as much of the vessel as possible for drying of the particulate. The unit must also be designed such that, considering the trajectory of any large droplets, no large droplets reach any wall surface before drying. The flue gas exit from the vessel is arranged so that the gas is turned out of the vessel without disturbing the gas flow patterns in the vessel and without the use of any internal turning devices which would create a point of buildup for solids. The key physical dimensions for this vessel, which incorporate the above items, are shown in Table #3.

REAGENT PREPARATION AND DELIVERY

A critical part of the system design is the delivery slurry, dilution water, and compressed air for liquid atomization. The slurry must be prepared, stored, and delivered in a manner that avoids the typical operating and maintenance problems that are associated with slurry handling and delivery.

For system redundancy, two 100% capacity lime storage and slurry preparation systems were provided. Each lime storage silo has a capacity of 143 tons of pebble lime which represents 7 days of storage at maximum acid gas loadings. The pebble lime is slaked in a detention type slaker, each of which is rated at 7,000 lb/hr. The lime slurry produced is stored in a tank, each tank having a capacity of approximately 24,000 gallons of slurry.

Activated carbon for the system is stored in a silo. This silo has a capacity of approximately 15 tons, or one truckload of activated carbon. The activated carbon is added to the lime slurry in a batch type process. When the slaker operates and lime slurry is added to the storage tank, activated carbon is mixed with water and transported to the slurry storage tank. The amount of activated carbon added is adjustable and coordinated with the slaking operation so that the desired concentration of activated carbon in the slurry can be maintained. A schematic of the slurry and activated carbon preparation system is shown in Figure #4.

Slurry from the storage tanks is delivered to the scrubber vessel through a series of pumps. The first pumps deliver slurry to the atomization level of the scrubber. Most of the slurry pumped is recirculated back to the lime slurry storage tank. This allows for a slurry velocity of approximately 4 to 7 ft/sec in the piping which avoids erosion from high velocity or settling from low velocity. Redundant pumps and recirculation loops were provided to ensure the ability to continuously deliver slurry to the scrubbers. Slurry is delivered to the vessel by diaphragm type pumps. The speed of these pumps is variable and controlled by a signal from the acid gas monitor. This ensures that the proper and optimum amount of slurry is continuously delivered to the scrubber. Again, redundant pumps were provided to ensure continuous operation. A schematic of the slurry delivery is provided in Figure #5.

Dilution water is added for temperature control, assuming that the liquid in the slurry is insufficient to reduce the gas temperature to the desired level. A control valve regulates the amount of dilution water, which is mixed with the slurry in a small manifold just prior to entering the nozzles. The amount of compressed air delivered to the nozzles is controlled to ensure optimum atomization of the liquid. This entire system is shown in Figure #6.

PULSE JET FABRIC FILTER

A modular pulse jet fabric filter with roof access doors was selected for this facility. The use of full roof doors allows for easy accessibility and a large area for storage when maintenance or filter bag changeout is required. Flue gas enters each module in the hopper area where a manual damper is provided for insulation. A series of vanes turn the gases up toward the filter bags. Gas is drawn through the filter bags, removing particulate and provided a surface for secondary removal of acid gases. The clean gas exits the module through a poppet valve which is used for module isolation during off line cleaning or module maintenance. Compressed air for cleaning the filter bags is provided through pulse pipes located above the filter bags. Cleaning air is controlled by Goyen valves located on each pulse pipe. A general schematic of a filtering module is shown in Figure #7.

The pulse jet fabric filter for this facility has a total of eight modules. The eight modules allow for maintenance to be performed in one of the modules at the same time one module is off line for cleaning, with the remainder of the modules in service to filter the particulate from the flue gas. Each module has a total of 256 bags, with each bag 6 inches in diameter by 16.5 feet long. This results in a net-net air to cloth ratio of 4:1 at maximum design conditions. The filter bags are constructed of 16 oz/yd^2 fiberglass with 10% Teflon B coating. The cages are 20 wire cages constructed of mild steel with a light galvanized coating. A summary of the fabric filter specifics is provided in Table #4.

SYSTEM OPERATION AND PERFORMANCE

This facility was first placed into operation in October, 1996. Facility acceptance testing was performed in January, 1997. To date, operation of the air pollution control system has been excellent. The scrubber has operated without any problems, except for some minor issues with the strainers and slurry hoses. There is no evidence of buildups inside the vessel and there have been several internal inspections during outages for boiler related issues. The fabric filter has operated reliably, with pressure drops typically ranging from 5 inches to 5.5 inches.

The first formal emissions testing from the facility showed excellent performance, with emissions well below the permitted levels. A summary of this test is provided in Tables #5 and #6.

SUMMARY

Well designed refuse incineration facilities with state of the art air pollution control systems provide an efficient and effective method of reducing waste volume. Semi-dry scrubbers utilizing dual fluid atomizers have been developed to a state of the art technology whcih provides excellent performance and low emission levels. The emissions from this facility show that environmentally sound emission levels are readily achievable, allowing a facility such as this to be a "good neighbor" at the same time that it helps to solve the problem of waste disposal.

Table 1. System Design Parameters

Refuse Firing Rate	600 tons per day per train
Flue Gas Flow to APC Equipment	176,026 acfm
Flue Gas Temperature	475 °F
Maximum Inlet HCl	1,500 ppm @ 7% O_2
Maximum Inlet SO_2	600 ppm @ 7% O_2

Table 2. System Design Emissions

HCl Emissions	25 ppm @ 7% O_2 or 95% removal
SO_2 Emissions	30 ppm @ 7% O_2 or 85% removal
Particulate Emission	0.010 gr/dscf @ 7% O_2
Mercury Emissions	80 μg/Nm^3 @ 7% O_2 or 85% removal
Cadmium Emissions	10 μg/Nm^3 @ 7% O_2
Lead Emissions	100 μg/Nm3 @ 7% O_2
Dioxin Emissions	30 ng/Nm^3 @ 7% O_2

Table 3. Semi-Dry Scrubber Design

System Type	Downflow
Atomizers	Dual Fluid Nozzles
Number of Atomizers	10
Scrubber Diameter	30.0 feet
Scrubber Cylindrical Height	40.0 feet
Residence Time at Design Flow Rate	11.7 seconds

Table 4. Fabric Filter Design

Fabric Filter Type	Pulse Jet
Number of Modules	8
Number of Bags per Module	256
Total Number of Bags	2048
Bag Dimensions	6" diameter by 16.5 feet long
Total Cloth Area	51,343 ft^2
Net-Net Air to Cloth Ratio	4.00 : 1
Bag Material	16 oz/yd^2 Fiberglass with 10% Teflon B Coating

Table 5. Emission Test Results (100% RDF Firing)

Pollutant	Emissions Uunit A	Emissions Unit B	Permit Limit
HCl (ppm)	4.6	6.2	25
SO_2 (ppm)	1.0	0.5	30
Particulate (gr/dscf)	0.0015	0.0056	0.010
Arsenic (μg/dscm)	0.2	0.2	10
Cadmium (μg/dscm)	ND	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
Total Dioxin-Furans (ng/dscm)	2.1	4.9	30

Notes:

All concentrations are at 7% O_2.
ND-below detection limits.

Table 6. Emission Test Results (50% Residential Waste & 50% Wood)

Pollutant	Emissions Unit B	Permit Limit
HCL (ppm)	2.4	25
SO_2 (ppm)	0.6	30
Particulate (gr/dscf)	0.0047	0.010
Arsenic (μg/dscm)	0.3	10
Cadmium (μg/dscm)	0.1	40
Chromium (μg/dscm)	5.9	120
Lead (μg/dscm)	22.1	15.8
Mercury (μg/dscm)	0.5	80
Nickel (μg/dscm)	3.1	100
Total Dioxin-Furans (ng/dscm)	2.1	30

Note:

All concentrations are at 7% O_2.

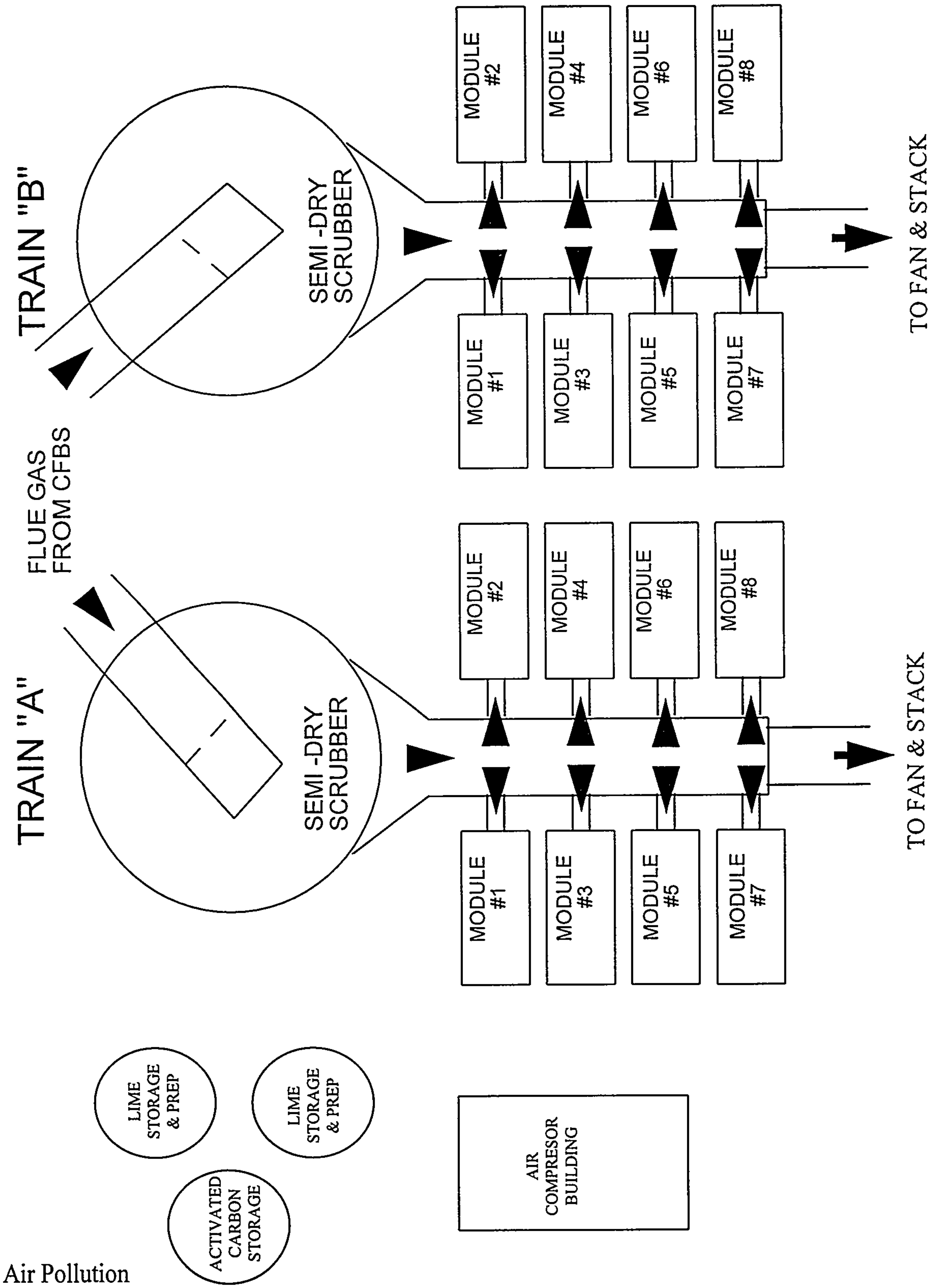


Figure #1- Air Pollution Control System

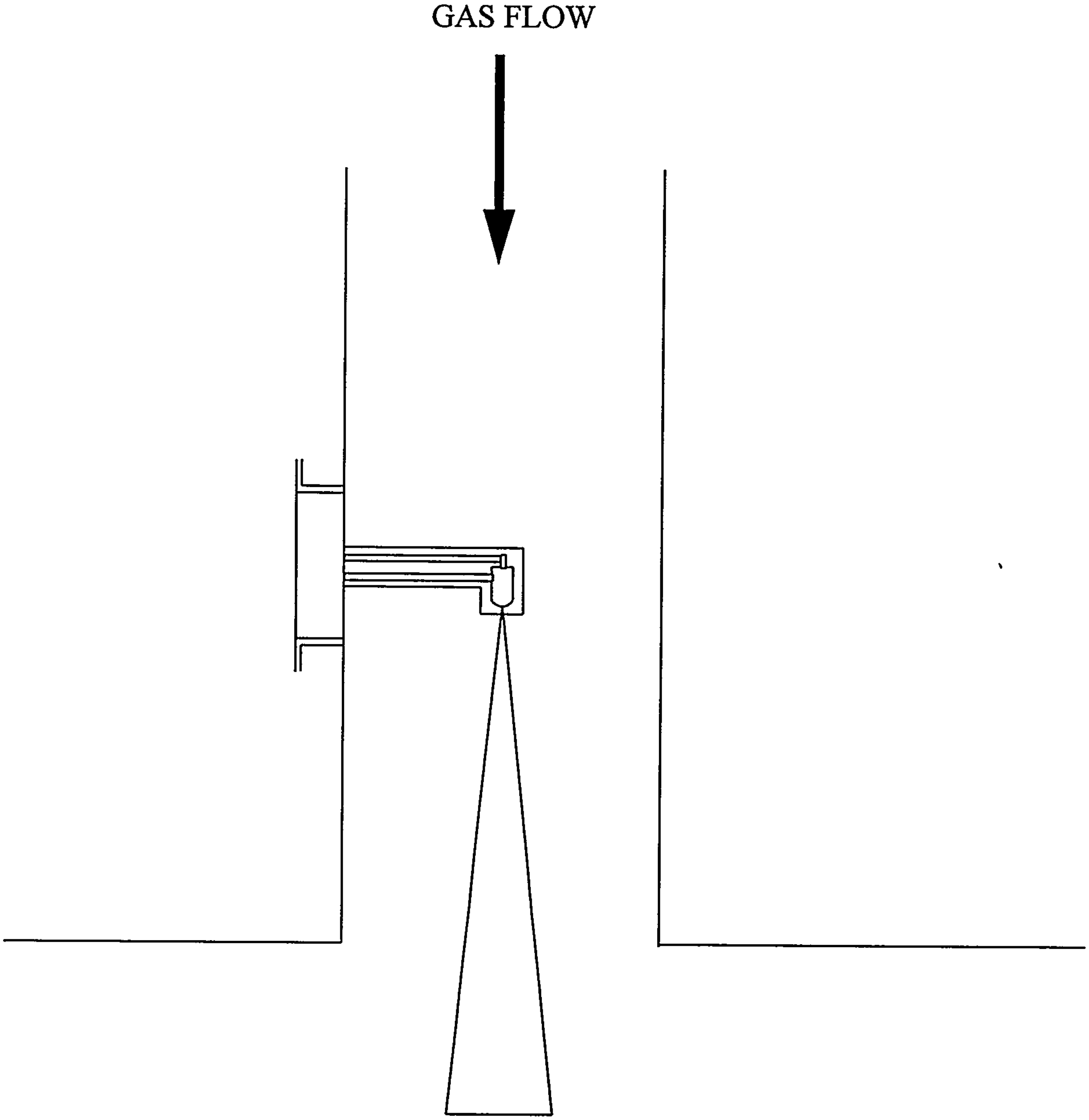


Figure #2
Atomization and Mixing

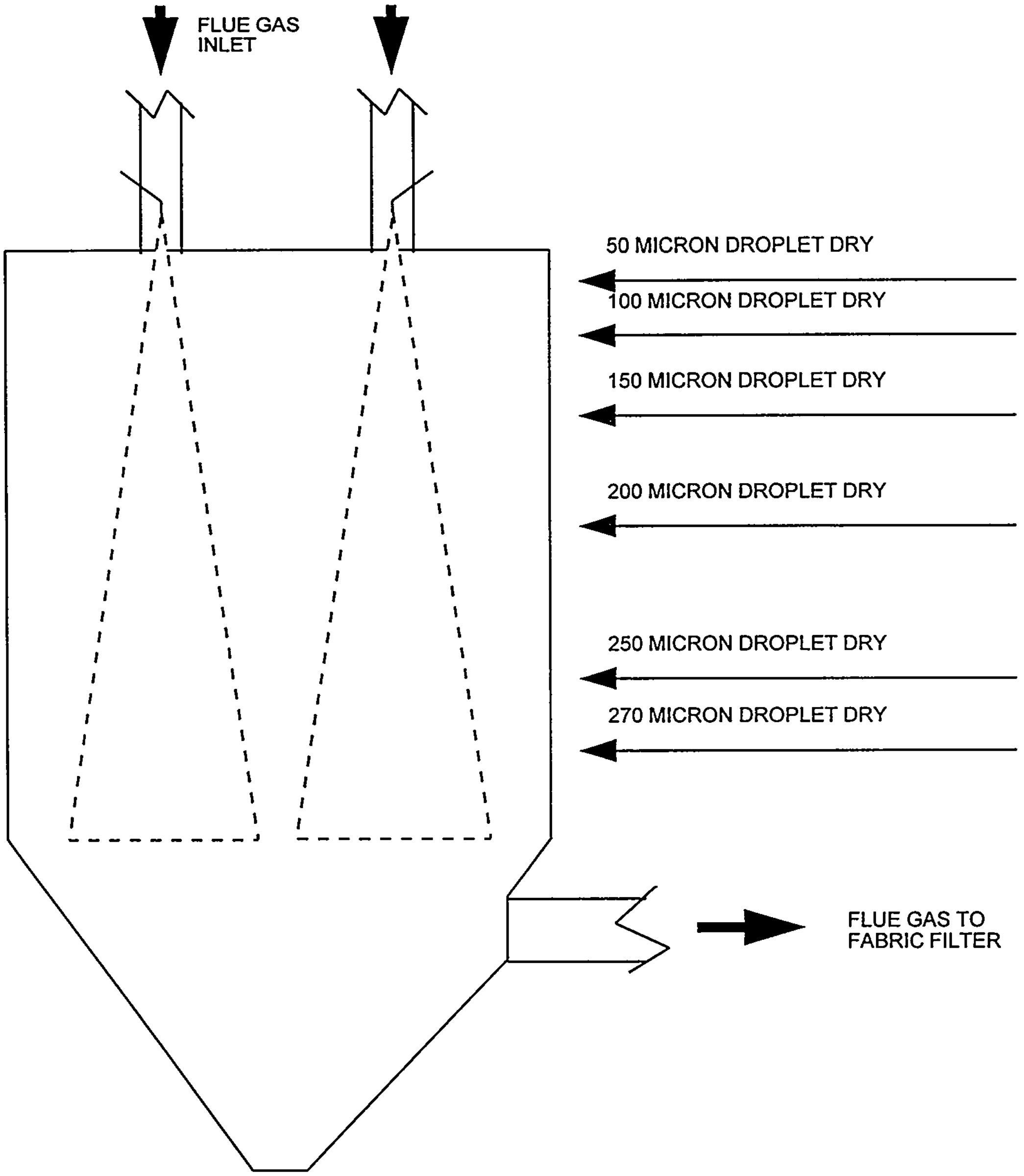


Figure #3
Typical Drying Profile

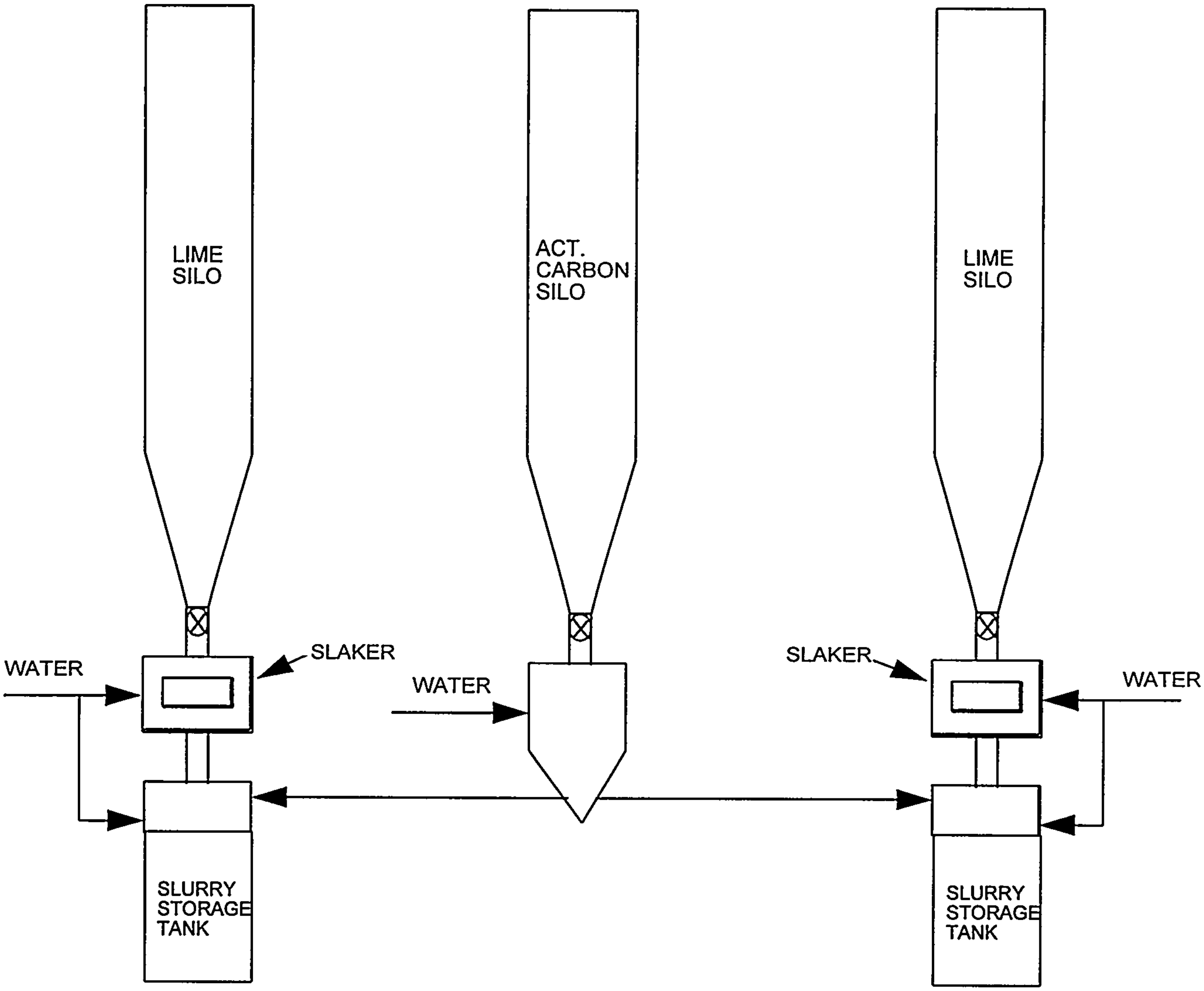


Figure #4
Slurry and Activated Carbon
Preparation

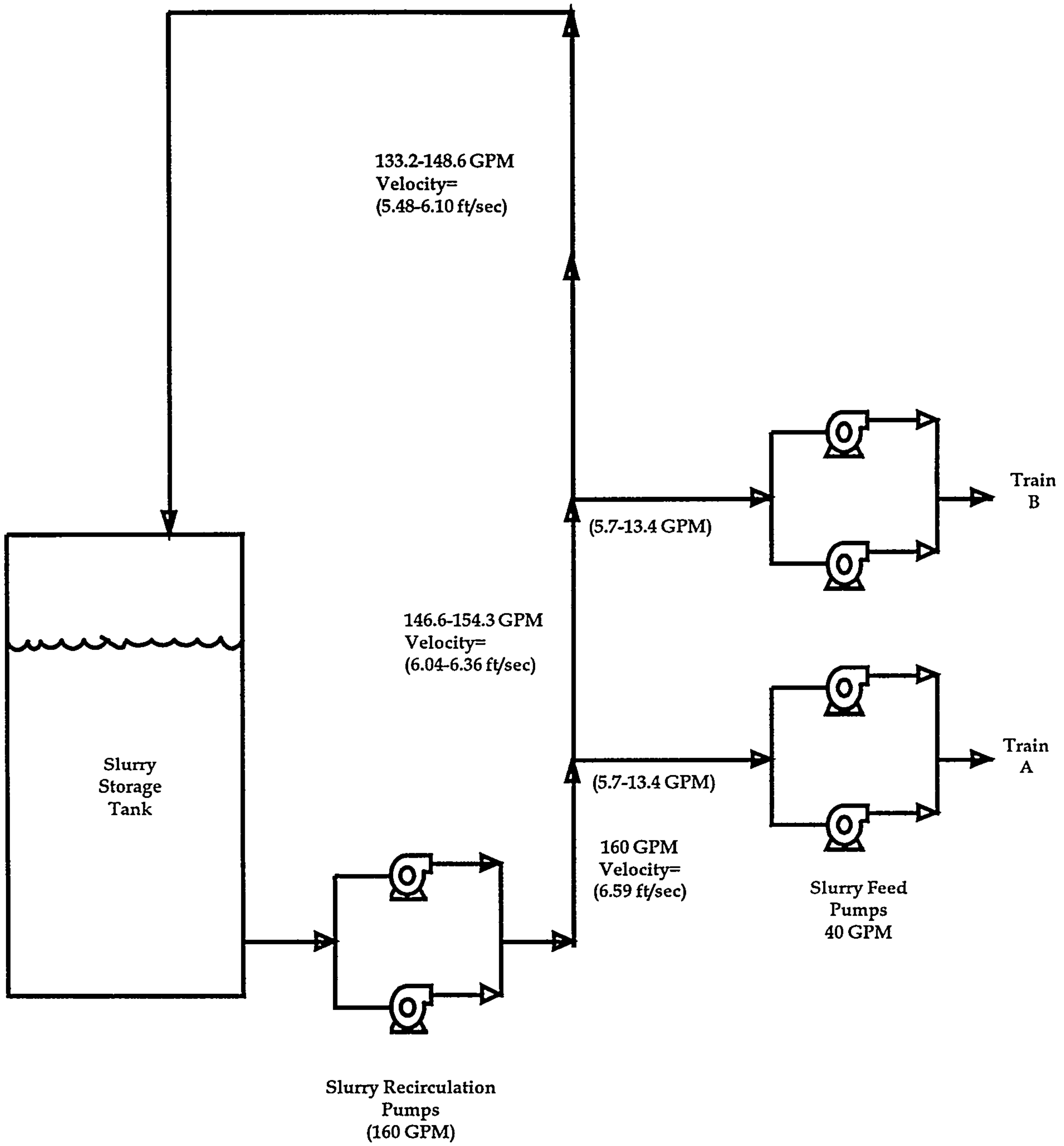


Figure #5
Slurry Recirculation

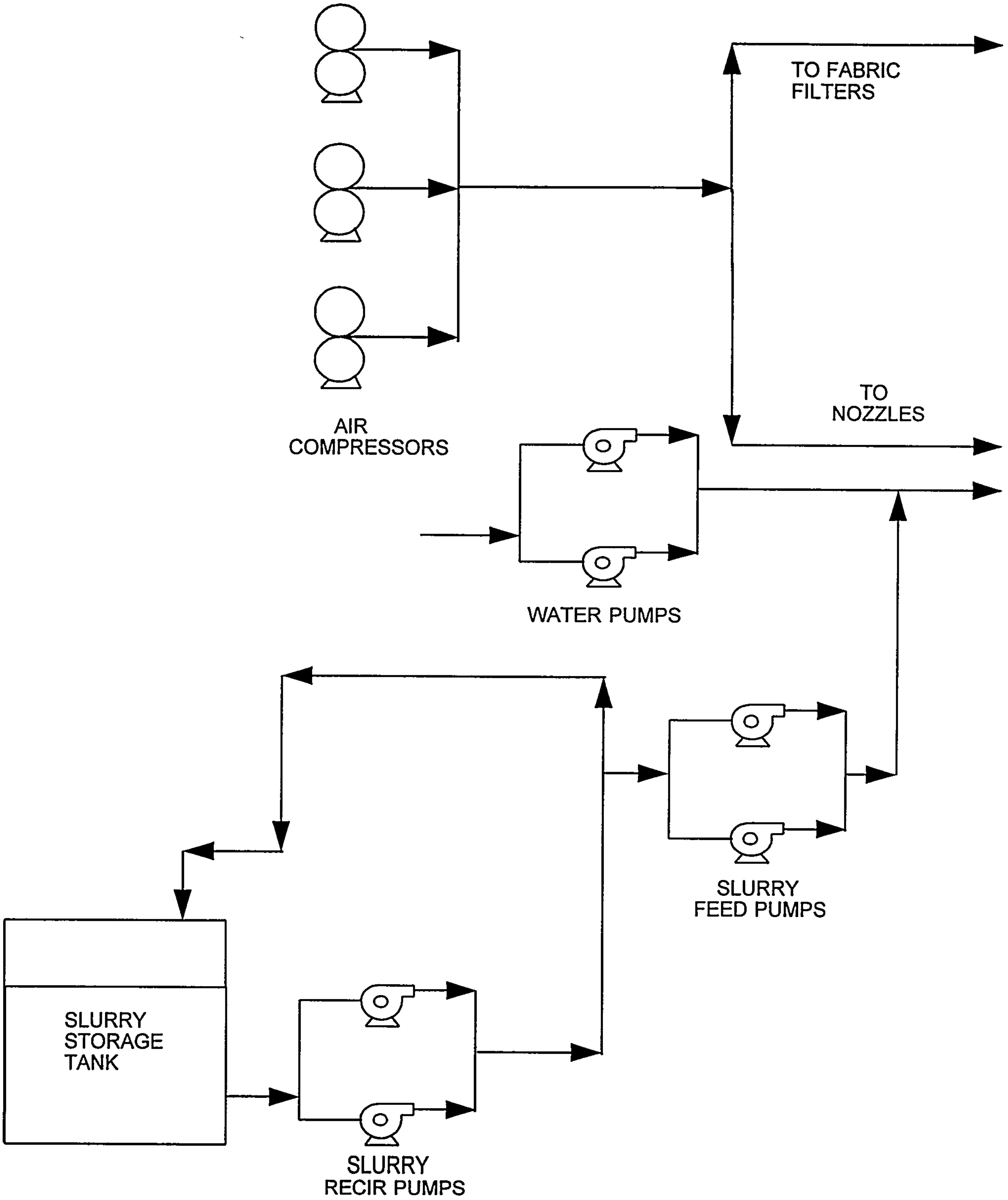


Figure #6
Slurry, Dilution Water & Compressed Air

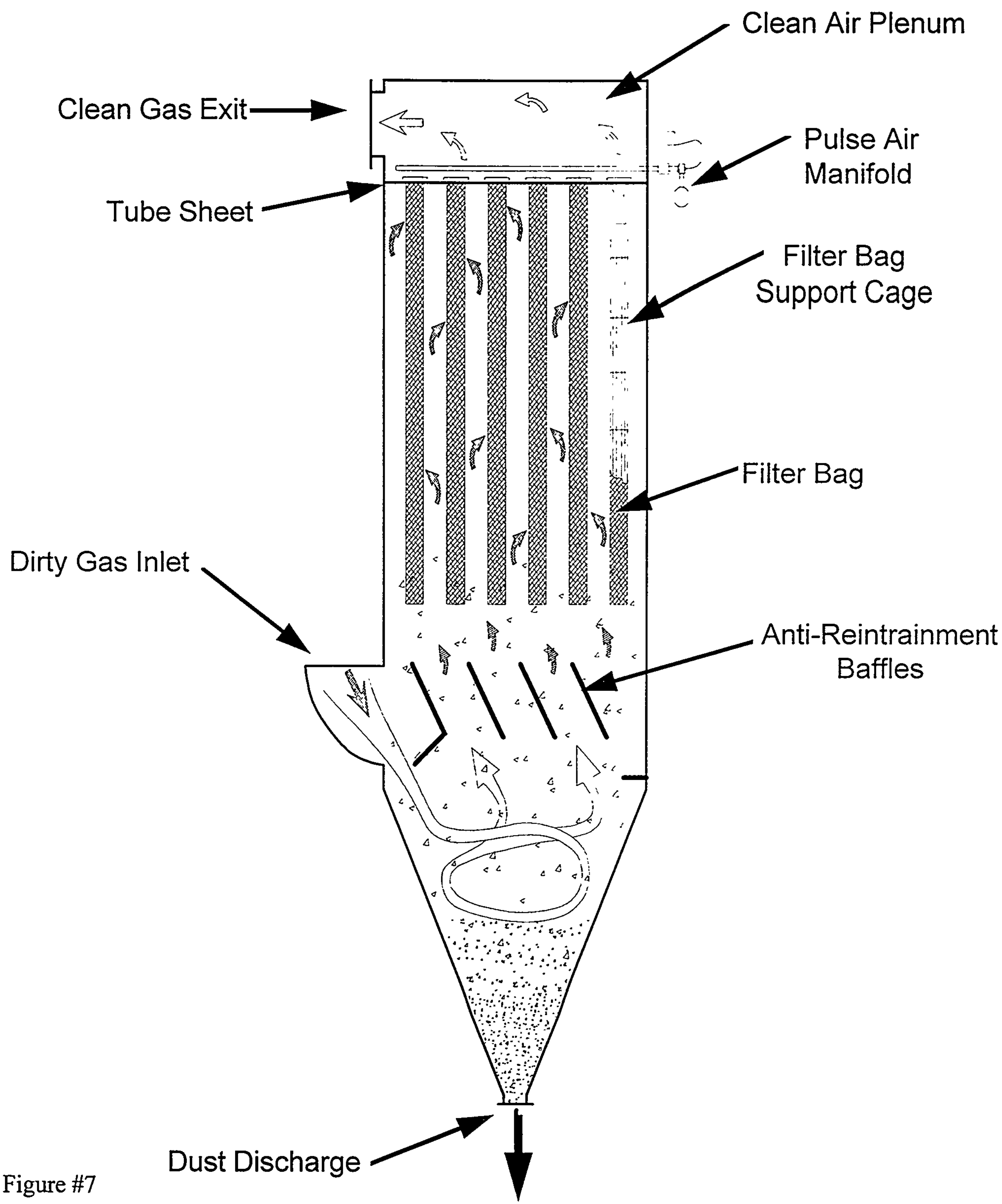


Figure #7
Typical Filtering Module

Air Pollution Control for Waste to Energy Plants - What Do We Do Now ?

Mark R. Sankey
Research-Cottrell
US Highway 22 West at Station Road
Branchburg, NJ 08876-3599

Anthony Licata
Licata Energy & Environmental Consultants, Inc.
345 Concord Road
Yonkers, NY 10710-1848

INTRODUCTION

Recent regulations require owners and operators of many waste-to-energy facilities to upgrade their existing air pollution control equipment. While it makes sense for some of these to install systems which meet BACT (Best Available Control Technology) standards, for others such a route could be less than the best choice. For the purpose of this discussion we will consider BACT standards to be at least 90% SO_2 reduction and 95% HCl reduction. For SO_2, this is higher than required by new source performance standards (NSPS) as defined in December, 1995 and summarized in Table 1. An air pollution control system to meet BACT standards generally includes a spray dryer injecting lime slurry, addition of other reagents for control of mercury, etc., and use of a fabric filter. For many units, a less expensive upgrade which seeks only to meet the latest regulatory requirements might be optimum. In some instances, this could be the difference between a plant continuing in operation, or closing. Political uncertainties and the current economic climate make these decisions very difficult.

OVERVIEW OF THE SITUATION

Review of Regulations

After significant discussion and review, the latest federal regulations for waste-to-energy plants were promulgated in December, 1995. On the federal level guidelines were issued for existing municipal waste combustors. States have the authority to define their own requirements, but these must satisfy the guidelines as a minimum. A summary of these guidelines is included as Table 2. For new plants, the requirements are more stringent than the previously promulgated regulations. Actually, they represent a codification of typical existing permits. Spray dryers and baghouses will be the most commonly installed equipment for these with lime stoichiometry high enough to ensure the required removal rates of acid gases. The requirements for dioxins, furans, and heavy metals are generally attainable with such an equipment installation. The mercury emission specified is the same for all cases. Its evident that the developers of the guidelines sought to mitigate the financial hardship on smaller plants and those with Electrostatic Precipitators (ESPs) instead of fabric filters. One could also surmise that they did not believe the benefits of more thorough changes would justify the costs.

The most significant differences between the NSPS and existing plant guidelines are in the area of acid gas and dioxin/furan emissions. Recent litigation has brought more uncertainty to the situation. The lines of demarcation based on plant rather than unit size were successfully challenged in U.S. District Court. On March 21, 1997 the District Court granted EPA's motion to remand NSPS and Emission Guidelines for MWC greater than 250 tpd and vacate the standards for units 250 tpd or less. This ruling by the Court means that emission standards for large units remain in effect and EPA will have to redraft and promulgate the standard for small plants. The larger existing Municipal Waste Combustors (MWCs) will have to be in full compliance by December 19, 2000. While the compliance strategy for the larger existing units is now clear, it still makes sense to review equipment capabilities and potential modifications on the basis of the emission limits as shown in Table 1 and plan for upgrades now.

Equipment Capabilities

We have made some mention of the equipment typically used to achieve the performance levels referenced. As further background, we can consider typical performance levels guaranteed with use of ESPs as compared with fabric filters. Early in the development of acid gas removal systems for waste to energy plants, there were trends to use ESPs following a spray dryer. This was especially strong in Japan. Generally, these were applied where required removal rates were relatively low. Operating results from this market and elsewhere show that this equipment arrangement can perform above the requirements for small and large existing plants. Where fabric filters inherently have the ability to perform better than ESPs for collection of acid gas, there is potential for existing ESPs to be retained while maintaining acceptable performance. This is predicated on ESPs being of sufficient size. If an ESP is too small it may be sensible to increase the size or make other modifications rather than replace the unit with a fabric filter. Of course, the ESP must be capable of meeting the particulate emission limit as well as the maximum opacity of 10%. We will address modifications and other performance enhancements for ESPs in detail later.

Dry injection of lime or sodium based sorbents is used in some facilities for acid gas control. Generally this is followed by a fabric filter. For such existing installations classified as small units, no change should be required. For large units, the only necessary addition should be cooling equipment to bring the temperature to the level needed to optimize acid gas neutralization. This will usually mean installation of a water spray or quench tower. In duct quenching is not a reliable means of cooling in our opinion.

Some installations which only have ESPs may be able to achieve required performance with dry injection. Certainly higher amounts of lime are needed than with a fabric filter. Also operation at an optimal temperature is more critical. Since in most cases a quench tower is required, we would expect additions of spray dryers to be more common. Such a step also allows future upgrade of the ESP.

REVIEW OF LIME TECHNOLOGY

Technical Issues

For MWC air pollution control systems, lime is the principal sorbent used to control acid gas emissions. The authors have observed that many otherwise astute managers and administrators in the MWC industry are often not entirely aware of the unique economics, properties and reactions associated with the use of lime. We have seen numerous applications where quicklime was selected over other sorbents, most notably hydrated lime without any up-front assessment performed to fully analyze the technical and economical impacts of the selection. We considered it appropriate to review the technical aspects of the use of lime.

Calcium oxide (CaO) is called "pebble lime" or "quicklime". CaO is not very reactive in absorbing acid gases at post combustion temperatures and conditions that exist in MWC facilities and has to be converted into the hydrate form to be reactive in scrubbing systems. The hydrated lime [$Ca(OH)_2$] has been demonstrated to remove acid gases in high temperature applications such as furnace injection. Hydrated lime is highly reactive and is made from CaO by adding controlled amounts of water in a hydrator to produce a powder. The resulting material has large reactive surface area with a mean particle size of 5 microns.

Pebble lime is slaked to form a slurry. CaO is converted to $Ca(OH)_2$ in the slaking process in which four parts of water are added to one part of CaO to form $Ca(OH)_2$ in a slurry that contains about 25% solids. The term slaking applies to the combining of varying proportions of excess water and quicklime, which yields a milk-of-lime, a lime slurry, or a viscous lime paste. This conversion requires two simultaneous steps that take place in the slaker. The first step converts the CaO into $Ca(OH)_2$ hydrate. The second step converts the hydrate to a slurry by mixing 3.96 lbs. of free water with one part hydrate (1.32 lbs) that results in a 25% solids slurry (5.28 lbs).

Hydrated lime can be introduced into the flue gas stream using several methods as follows:

- injection into the flue gas in a dry form;
- injection into the flue gas in a dry form after the gas has been conditioned by the addition of water which serves to increase the moisture content of the flue gas and to concurrently reduce the flue gas temperature; or
- injection into the flue gas as a wet slurry.

Quicklime is delivered to most sites as a "pebble" nominally 3/4" in diameter. In order to be reactive, quicklime has to be slaked and converted into a slurry form. Slaking is manpower intensive for most plants and is a high maintenance process. There are also capital costs associated with the purchase and replacement of equipment. Slaking is as much an art as it is a science.

Many factors affect slaking including:

- reactivity of the lime
- lime quality
- particle size
- water quality and temperature
- distribution of water, and
- level of agitation

In order to analyze the cost differential between use of pebble and hydrated lime, we need to determine the relative usage. Please see Table 3 for details of this calculation.

A typical MWC would require either 12.9 lbs of hydrated lime or 10.5 lbs of pebble lime per ton of MSW burned to react with all of the SO_2 and HCl emitted. By ratio of the above, we can see that 23% more hydrated lime than quicklime is required to achieve the stoichiometric reduction of MWC acid gases. Both hydrated lime and quicklime sell for about the same unit price. However, when you purchase hydrated lime you are buying 32% water which reduces the actual calcium content. As you can see for the above, it is the Ca to SO_2 or HCl ratio that is important.

In actual applications, this theoretical balance never occurs. Due to the inability to provide perfect contact between all of the lime and the acid gas molecules, excess reagent is required in the process to achieve SO_2 and HCl emissions of less than 25 ppm. In addition, several secondary chemical reactions take place that also use some undefined portion of the lime. For example, lime will react with carbon dioxide in the flue gas as follows:

$$Ca(OH)_2 + CO_2 \Rightarrow CaCO_3 + H_2O$$

There is also a positive reaction that occurs. The presence of HCl in the flue gas actually improves the lime's capture of SO_2. This reaction has been discussed in numerous papers.

The ratio of the actual amount of lime used to the theoretical amount required is called the stoichiometric ratio. A typical MWC equipped with a spray dryer and an ESP will require about 35 lbs of pebble lime per ton of MSW while a MWC with a spray dryer baghouse will require about 20 to 25 lbs per ton to meet the current NSPS standards of 25 ppm of HCl (a 95.3% reduction) and 30 ppm of SO_2 (an 85.8% reduction). These values may vary for particular plants, depending on temperature and moisture conditions in the system. Based on the typical values cited, the stoichiometric ratio for a plant with an ESP would be:

$$35 \div 10.5 = 3.33$$

Typical air pollution system requirements developed by Dravo Lime's testing program to control acid gas emission to the NSPS requirements are as follows:

Technology	Hydrated Lime		Quick Lime	
	Lbs of $Ca(OH)_2$ per ton of MSW	Stoichiometric Ratio	lbs of CaO per ton of MSW	Stoichiometric Ratio
Spray dryer/fabric filter	24	1.86	20	1.90
Spray dryer/ESP	35-40	2.71-3.10	30-35	2.85-3.33
Dry injection/ fabric filter	50	3.87	n/a	
Conditioned dry injection/fabric filter	24	1.86	n/a	

These results are shown to compare results of hydrated lime versus quicklime and do not necessarily reflect actual MWC plant operation.

Economics of Lime Technologies

As previously stated, in order to obtain equivalent levels of acid gas removal, it requires more hydrated lime than quicklime which results in an increased operating expense. Quicklime, however, requires more capital equipment, more operational and maintenance personnel, and a higher level of skill. As a rule of thumb, smaller plants or plants that require upgrading but have less than 20 years of expected life may find that a dry lime injection or conditioned dry injection of hydrated lime may be less expensive. The following analysis was made to compare operating cost for applying hydrated lime (conditioned dry injection) vs. Quicklime (lime slurry) (see Table 4).

The analysis in Table 4 was based on the following inputs:

- Three plant sizes were selected: 250 T/D, 500 T/D and 1,500 T/D. Each plant has an annual capacity factor of 85% and a 20 year life expectancy.

- The delivered price of both hydrated lime and quicklime is $80.00 per ton.

- The quicklime (slaker and slurry system) requires one person about half time for operations and maintenance which results in a personnel cost of $30.00 per hour inclusive of all overheads and benefits. Alternatively, the hydrated lime system requires about half as much personnel time resulting in a cost of $15.00 per hour on the same basis.

- 23% more hydrated lime is required than quicklime to meet the emission standards. For this analysis, we used a factor of 25 lbs of quicklime per ton of MSW burned and 30.7 lbs of hydrated lime per ton of MSW burned.

SPRAY DRYER / FABRIC FILTER SYSTEMS

A spray dryer followed by a fabric filter has become the standard approach to air pollution control at MSW plants in the United States. As we have mentioned, this has resulted from the regulatory requirements and determination of lowest fixed cost. We felt this presentation would be incomplete without addressing the scenario of a backfit of such a system. Based on a 3 train installation, with total plant capacity in the range of 750 to 1000 tons per day (TPD) and supply of one common lime storage, preparation, and pumping system we reviewed recent budgetary pricing. For a refractory type furnace with high excess air usage, the result is a cost of about $10,000/TPD of capacity. For a water walled furnace with lower excess air and thus lower gas flow rate, the cost is about 10% less or $9,000/TPD. These costs are also based on use of a dual fluid nozzle atomization system including compressors. While these cost ratios include installation, costs for demolition and other site work have not bee included.

Operating costs will vary somewhat depending on the acid concentrations in the flue gas resulting of course from the make up of the waste burned. Based on actual industry experience, pebble lime usage can vary from roughly 20 to 30 lbs./ton of waste burned. Actual usage can vary because the slurry feed rate can be varied based on actual flue gas concentrations. As well as SO_2 monitors which are commonly in use today, HCl monitors have proven reliable. Use of such a signal could add a measure to reagent savings. We estimate power usage for a complete spray dryer and fabric filter system to be about 10 kWh/ton of garbage burned. This includes power to run air compressors for slurry atomization.

In many cases there is not a need to replace the particulate collection device, but addition of a spray dryer is the best approach. With existing ESPs, this is an approach which can keep a plant in compliance, especially for units smaller than 250 TPD.

SPRAY DRYER BACKFITS

For a variety of circumstances including existing equipment, plant layout, desire for higher performance, and more stringent state regulations, plants may choose to add spray dryers to ESP or fabric filter systems. As we have mentioned, a quench tower can often do the job. Where some tower designs can only accommodate water spray, designs which could easily handle use of lime slurry in the future should be considered. Without getting sidetracked to detailed analysis and comparisons, rotary atomizer and dual fluid nozzle designs are available. Conversion of quench towers to spray dryers is favored with spray nozzles which have been used extensively for quenching. Upflow and downflow designs are also variations which owners will encounter when investigating spray dryers. These differences impact design, capital cost, and operating expenses and are worth understanding, but it is not our purpose to do that here.

As with any backfit, there are layout issues to be considered. Room for the basic tower diameter plus inlet and outlet ductwork must be available. A rule of thumb for layout requirements would start with calculation of the tower outlet gas flow at 285°F. Evaporated quench water must of course be included. Various tower designs and manufacturers use differing design velocities, but an upflow, dual fluid nozzle design would have velocity in the range of 5.5 to 6.5 feet per second. Inlet and outlet duct velocities of 60 feet per second are typical. For a unit capacity of 250 TPD, an upflow tower would be about 15 foot diameter.

Costs for backfits will vary with size and layout difficulties. There are situations where existing silos or other equipment can be reused and reduce costs. Availability of compressed air for dual fluid atomization is also an important factor. For a two unit plant with total capacity of 500 TPD, costs for a spray dryer backfit will range from $5000 to $6000/TPD of capacity. This covers installation, a complete pebble lime storage, slaking, and pumping system and compressors.

DRY INJECTION

Dry injection has many potential uses for upgrading pollution control systems. Related to acid gas removal, injection of dry lime has been demonstrated to provide acid gas removal at the levels now required for small plants. Sufficient moisture must be present, but this should not be any problem for MSW applications since proper temperatures for reaction are usually achieved with water spray cooling. For installations where this is not available, a quench chamber must be added. For future performance upgrade by addition of lime slurry, a tower design which would permit future use of slurry could be considered. This technology works best when followed by a fabric filter but, with proper gas conditioning it can also be effective with ESP's.

While past practice has followed a trend of using spray dryers with lime slurry produced by on-site slaking, our discussion of lime technology shows potential advantages of using dry lime injection. This is a current trend in Japan. The problems and costs associated with slaking and handling of slurry are avoided. It is well established that when operating at the same conditions of temperature and moisture upstream of a particulate collection device, acid gas removal levels are about the same whether using lime as slaked slurry from pebble lime, or lime as dry hydrated reagent injected into the gas stream. Experience indicates a slightly higher lime usage for dry injection than for spray drying with slurry. This increase is about 10 to 15%. We attribute this to the more favorable reaction environment when slurry is "drying" and the acid gas is exposed to the lime in a "wet" environment.

There are a variety of means available for injection. Some manufacturers use specially designed vessels to promote good mixing of reagent with the acid gas. In other cases, lime has simply been introduced through a pipe into the ductwork. The desired effects are rapid, intimate contact of acid and lime. Turbulent gas flow zones can be developed to produce this. Another important aspect is treatment time. The longer the contact period, the better the reaction. We expect that some reaction occurs in the baghouse inlet section as the gas is dispersed to the filter bag surface.

The filter cake is the final area where the reaction can occur. The longer the lime is available here for reaction, the better the utilization, and the lower the stoichiometric ratio and the operating cost. Her the term utilization refers to the extent the lime is used in reaction. Minimizing pressure drop through the cake and maintaining long cycles between cleaning help this process. Various types of cake modifiers have been used to facilitate this. Tesisorb is the name of one family of such materials. These can be fed to the system along with hydrated lime if convenient. The resulting thicker, yet more porous filter cake also provides a better bed for acid gas neutralization. Sizing fabric filters with appropriate air to cloth ratios is important. Generally, we use 2.5 net (including reverse air) for reverse air systems and 4.0 net for high pressure pulse jet systems. Net is defined as the condition with one fabric filter section off line.

Other additives can also be delivered to the system in this area. This can include activated carbon for mercury emission control or, as discussed below, Sorbalit. Some systems call for use of recycled ash which is also introduced dry.

RELATED CAPITAL COST SAVING TECHNOLOGIES

Key components of EPA's regulatory efforts for MWC's have been directed at controlling emissions of mercury and dioxins. There are a number of technologies that can reduce emissions of these pollutants, however, the predominant technology presently used employs activated carbon as the adsorbent medium. Carbon-based adsorption technologies include moving carbon bed filters; dry carbon injection, carbon slurry injection; and Sorbalit and Sorbalime.

Sorbalit/Sorbalime is a system for controlling emissions of acid gases, mercury, and organics in a single application. The sorbent component of the technology is produced by mixing lime, either calcium hydroxide (Sorbalit) or calcium-oxide (Sorbalime) with surface-activated substances such as activated carbon or lignite coke and sulfur-based components in a proprietary process. Sorbalit can be produced with carbon contents ranging from .5 to 65% depending on the technical and economic requirements of each facility.

Sorbalit/Sorbalime replaces the normal lime used at a plant either dry injection or milk-of-lime slurry. The key economic feature of Sorbalit/Sorbalime is that in most applications, no additional capital equipment is required while additional equipment is required for the injection of carbon in both a dry or slurry injection system. Field testing to date indicates that the amount of total carbon required by the Sorbalit process to meet regulatory standards is about half that needed by traditional carbon injection methods.

Conditioned Dry Inject and Fabric Filter Test Results

There are a number of MWC plants that were built in North America which employ a dry injection followed by a fabric filter. One such plant is the 440 T/D plant in Peel, Ontario, Canada which went online in 1992. This plant uses a quench tower to lower the boiler exit temperature from 260°C (500°F) to 160°C (320°F). The quench tower is followed by a dry lime system and a fabric filter. The Peel facility was meeting all of their existing permit conditions, however, they wanted to comply with Ontario's Guideline A-7 which is applicable to new facilities. In order to meet the A-7 Guideline, they would have to reduce their mercury emissions. The facility was also meeting the dioxin limits but was looking for additional margin and control.

A test program was conducted at the Peel facility where Sorbalit with a 4% carbon-based formulation replaced their normal hydrated lime. It was not possible to test the boiler outlet gases, so the test program was set up to measure the stack emissions comparing hydrated lime and Sorbalit. The test clearly indicates that Sorbalit reduced the Dioxin emissions by an order of magnitude and brought the mercury emissions into compliance with the proposed Ontario Guideline A-7. The summary of the test results will be found in Table 5.

Spray Dryer and ESP Test Results

The quicklime-based product, Sorbalime, was tested at a U.S. based MWC that was equipped with a spray dryer and an ESP. In this program, Sorbalime replaced the regular quicklime that the plant slaked for acid gas control. For this operation, no capital equipment was required and no changes were made to the plant operations. Prior tests at the facility had indicated that the spray dryer/ESP removed approximately 40% of the Hg emissions and 80% of the dioxin emissions. The Sorbalime test showed that existing spray dryer/ESPs can be upgraded to meet the EPA proposed standards without a major retrofit. The summary of the test results will be found in Table 6.

PRECIPITATOR UPGRADE APPROACHES

Rebuilds

If an ESP Owner intends to keep that unit in service, he needs to be sure it is in peak operating condition. A thorough structural and operational inspection should be made to determine any deficiencies. Some rebuilding or parts replacement may be needed.

Corrosion can be a serious problem for ESPs in MWC applications. Material and structural degradation is a significant cause leading to replacement of ESP internals. However, operational problems and need to enhance performance have also led Owners to consider some measure of rebuild. A fairly common practice in other industries is replacement of internals and casing repairs to deal with these sort of problems. Avoidance of corrosion requires elimination of inleakage, proper insulation systems and control of operating conditions. Where a quench chamber is upstream of an ESP, or fabric filter, it is imperative that complete evaporation be maintained.

Installation of rigid discharge electrodes can avoid shutdown of ESP sections due to breakage of wire electrodes or other similar high voltage system components. Such a replacement may require alteration of collecting electrode spacing, or use of different collecting surfaces. Interelectrode spacing, configuration of electrodes, and orientation of discharge electrodes with collecting surface profiles all affect electrical operation and orientation of discharge electrodes with collecting surface profiles all affect electrical operation and performance.

Rebuilds are a potential step in upgrade of an existing air pollution control system. If needed, effective collecting surface area can be increased depending on equipment arrangements. Rebuilds can also incorporate some of the technical advances.

Technology Advances

As with all pollution control equipment, precipitation has seen significant advancements in recent years. One area of changes is with controls. Again, as with other equipment, microprocessors have been applied to transformer-rectifier sets (high voltage power supply) controls. These regulate operation to ensure the maximum amount of usable power is available to the ESP. Electrical parameters are continuously monitored and the control automatically adjusts power to avoid wasteful sparks and arcs. Rapper controls have been similarly redesigned to incorporate state-of-the-art microprocessor components.

Changes to internal components have been focused on discharge electrode design and gas passage spacing, i.e. spacing between collecting surfaces. In certain applications, spacing has been increased to as much as 16 inches, thereby saving cost. The number of internal elements saved is proportional to the ratio of the spacing. Weight savings decreases load on supports and permits use of taller collecting surfaces increasing ESP capacity if necessary. For a given ESP casing on an MWC application, performance at wider spacings is as good or better than for ESPs at narrower spacing. Treatment time is the same in either case. This effect occurs due to greater electrical field strength in the wider spacing units which operate at proportionally higher voltage.

COHPAC

Based on use of a polishing collector downstream from an electrostatic precipitator, this technology named COHPAC (COmpact Hybrid PArticulate Collector) provides enhanced particulate collection. In MSW installations with existing ESPs it provides the benefit of a fabric filter step in the pollution control train without the need to completely abandon the ESP. The result will be increased collection of acid gas. The technology was developed by and is licensed from the Electric Power Research Institute (EPRI).

The first application of COHPAC technology added an entire baghouse with a length of ductwork downstream from an existing ESP. A more recent development uses the outlet field of an ESP as space for fabric filter bags. This approach is known as COHPAC II. The ESP internals in the outlet field are removed and gas flow modifications made for a very compact arrangement. The particular fabric filter technology used by Research-Cottrell is based on low pressure high volume cleaning. The cleaning system is the pulse jet type with cleaning air produced by positive displacement blowers. Bags are oval in cross section with a unique rotating air manifold.

The nature of this upgrade makes it suitable without regard to the original ESP manufacturer's design. However, dimensional requirements could hinder its viability in some otherwise promising situations. Certainly, where it does fit, arrangement and space requirements become immaterial.

Performance wise, we can expect acid gas removal rates for this technology range between those expected with ESPs versus those with fabric filters. With high air-to-cloth ratios that usually accompany COHPAC designs, its unreasonable to expect results as good as can be achieved with conventional fabric filter. Again, as with all of the techniques and modifications possible, this should be considered carefully based on the specific plant circumstances. The cost for a COHPAC II conversion of one outlet field of an existing ESP is about $2,000 per ton per day of unit capacity.

Complete Conversion to Fabric Filter

There may be cases where Owners choose to replace an ESP with a fabric filter. This is often approached by using a long duct run to a location beyond ID fans or stack, to build a new unit. Another approach, again used by some power plants, is to use the ESP casing as the housing for the new fabric filters. When some ESP configurations may not be well suited for this, it warrants some consideration. An advantage here is real estate savings. Ash handling systems may also be reusable. A disadvantage is that the MWC must be offline while the conversion work is done. Overtime, shift work, and/or extended outage costs will result.

CONCLUSION

While the legislative and economic atmosphere leaves many uncertainties, waste to energy plants must plan to upgrade. Full blown additions of spray dryers and fabric filters are not always necessary to comply with current regulations. Consideration of various alternatives should be made before committing to a strategy. Awareness of these alternatives could keep an otherwise viable plant from closing.

Table 1. 1995 NSPS for new MWC's

Pollutant	Plant Capacity > 250 tpd	Plant Capacity > 39 tpd but < 250 tpd
Dioxins/furans	13 ng/dscm	13 ng/dscm
PM	24 mg/dscm	24 mg/dscm
Opacity	10%	10%
SO_2	30 ppmv or 80% reduction	30 ppmv or 80% reduction
HCl	25 ppmv or 95% reduction	25 ppmv or 95% reduction
NOx	150 ppmv (180 ppmv first year of operation)	No control limit
Cd	0.020 mg/dscm	0.020 mg/dscm
Pb	0.20 mg/dscm	0.20 mg/dscm
Hg	0.080 mg/dscm or 85% reduction	0.080 mg/dscm or 85% reduction
Flyash/bottom ash fugitives	No visible emissions (exception for up to 5% of the time and for maintenance/repair)	No visible emissions (exception for up to 5% of the time and for maintenance/repair)

Table 2. 1995 Emissions Guidelines for Existing MWC's

Pollutant	Unit Capacity > 250 tpd [1]	Plant Capacity > 39 tpd but < 250 tpd [2]
Dioxins/furans	30 ng/dscm (non-ESP) 60 ng/dscm (ESP)	125 ng/dscm
PM	27 mg/dscm	70 mg/dscm
Opacity	10%	10%
SO_2	31 ppmv or 75% reduction	80 ppmv or 50% reduction
HCl	31 ppmv or 95% reduction	250 ppmv or 50% reduction
NOx	200-250 ppmv (Varies by MWC type, except none for mass burn refractory)	No control limit
Cd	0.040 mg/dscm	0.10 mg/dscm
Pb	0.49 mg/dscm	1.6 mg/dscm
Hg	0.080 mg/dscm or 85% reduction	0.080 mg/dscm or 85% reduction
Flyash/bottom ash fugitives	No visible emissions (exception for up to 5% of the time and for maintenance/repair)	No visible emissions (exception for up to 5% of the time and for maintenance/repair)

[1] U.S. EPA proposal - U.S. District Court - February 4, 1997

[2] U.S. EPA rule - December, 1996 Vacated by U.S. District Court

Table 3. Calculation of Comparative Usage Rates for Quicklime Versus Hydrated Lime

The theoretical reaction of the lime products (with their molecular weights) are as follows:

A. Hydrated lime and its production

$$\underset{56}{CaO} + \underset{18}{H_2O} \Rightarrow \underset{74}{Ca(OH)_2} + \text{Heat}$$

$$\underset{74}{Ca(OH)_2} + \underset{64}{SO_2} \Rightarrow \underset{120}{CaSO_3} + \underset{18}{H_2O} \qquad \text{Capture Ratio} = \quad 74 \div 64 = 1.156$$

$$\underset{74}{Ca(OH)_2} + \underset{73}{2HCl} \Rightarrow \underset{111}{CaCl_2} + \underset{36}{2H_2O} \qquad \text{Capture Ratio} = \quad 74 \div 73 = 1.014$$

1 lb of CaO yields 1.32 lbs of $Ca(OH)_2$

To clarify, capture ratio represents the theoretical amount of lime required to remove or capture acid gas on a weight (Lbs.) basis.

Thus, the stoichiometric, theoretically perfect, reaction of $Ca(OH)_2$ with acid gases requires:

1. 1.156 lbs of $Ca(OH)_2$ to capture 1.0 lbs of SO_2
2. 1.014 lbs of $Ca(OH)_2$ to capture 1.0 lbs of HCl

Without pollution controls, the average MWC facility has the potential to emit the following amounts of acid gases: [lbs/ton of municipal solid waste (MSW) burned]

SO_2 = 5.03 lbs/ton (Equivalent to 212 ppmdv @ 7% O_2)
HCl = 7.03 lbs/ton (Equivalent to 532 ppmdv @ 7% O_2)

Other acid gases such as HF and H_2SO_4 are also emitted in small amounts and are collected in the system but are not federally regulated in the U.S.

Table 3. Calculation of Comparative Usage Rates for Quicklime Versus Hydrated Lime. (Continued)

The characteristic stoichiometric requirement for $Ca(OH)_2$ per ton of MSW is:

SO_2 = 5.03 lbs SO_2/ton MSW x 1.156 lbs $Ca(OH)_2$/lb SO_2 = 5.815
HCl = 7.03 lbs HCl/ton MSW x 1.014 lbs $Ca(OH)_2$/lb HCl = 7.128

TOTAL 12.943 (12.9) lb $Ca(OH)_2$/ton MSW

B. Pebble lime (hydration process not included)

$CaO + SO_2 \Rightarrow CaSO_3$ Capture Ratio = 56÷64 = 0.875
56 64 120

$CaO + SO_2 \Rightarrow CaSO_3$ Capture Ratio = 56÷73 = 0.767
56 73 111

The stoichiometry of CaO with acid gases requires:

3. 0.875 lbs of CaO to capture 1.0 lbs of SO_2
4. 0.767 lbs of CaO to capture 1.0 lbs of HCl

The following is the stoichiometric reaction of CaO for typical MSW:

SO_2 = 5.03 lbs SO_2/ton MSW x 0.875 lbs CaO/lb SO_2 = 4.401
HCl = 7.03 lbs HCl/ton MSW x 0.767 lbs CaO/lb HCl = 5.392

TOTAL 9.793 lb CaO/ton MSW

Since CaO contains about 7% unreactive material and inerts that are lost in the slaking process, the usage is adjusted to compensate for impurities. Accordingly, the adjustment is made by the following computation:

1.07 x 9.793 = 10.5 LB CaO/ton MSW

Table 4. Cost Analysis

Plant design capacity - T/D		250	500	1,500
Plant operating capacity - T/Y		77,562	155,125	465,325
QUICKLIME ANALYSIS				
Annual Capital Cost(1)		$8,000	$10,000	$15,000
Annual Replacement Cost		$4,000	$6,000	$8,000
Labor (O & M) - $/hr	$30.00	$134,400	$134,000	$134,400
Lime Cost - $/Ton Lime	$80.00	$77,562	$155,125	$465,325
Quicklime Usage - lbs per ton MSW	25	970	1939	5817
Total Annual Cost		$223,962	$305,125	$622,725
Unit Operating Cost - per ton MSW		$2.89	$1.97	$1.34
DRY INJECTION ANALYSIS				
Annual Capital Cost		-	-	-
Capital Replacement Cost		$4,000	$6,000	$8,000
Labor (O & M) - $/hr	$30.00	$65,700	$65,700	$65,700
Lime Cost - $/Ton Lime	$80.00	$95,246	$190,494	$571,419
Quicklime Usage - lbs per ton MSW	30.7	1191	2381	7143
Total Annual Cost		$164,946	$262,194	$645,119
Unit Operating Cost - per ton MSW		$2.13	$1.69	$1.39

Incremental capital costs above those required for the dry injection process.

Table 5. Peel Facility Test Results

Test (1)	Hg Stack Concentration $\mu g/Rm^3$ @ 11% O_2 [2] (@ 7% O_2)	PCDD/PCDF - I-TEQ Stack Concentration ng/Rm^3 @ 11% O_2 (@ 7% O_2)
Hydrated Lime Only		
#1	127	0.1200
#2	172	0.0860
#3	217	0.1100
Average	172 (241.5)	0.1053 (0.1478)
Sorbalit		
#4	31	0.0180
#5	26	0.0087
#6	20	0.0027
#7	12	0.0023
#8	5	0.0010
Average	19 (26.6)	0.0065 (0.0091)
A-7 Guideline	57 (80)	0.14 (0.196)

Conditioned Dry Injection and Fabric Filter

[2] R = reference condition, 25°C

Table 6. Spray Dryer and ESP Test Results

Flue gas temperature - 295°F
% C in Sorbalime 4%
Average SO_2 emission during test - 22 ppmdv
All data corrected to 7% O_2

	Hg Emissions	Dioxin Emissions	
	µg/dscm	Total ng/dscm	I-TEQ ng/dscm
Inlet			
#1	219.3	692.3	17.2
#2	252.3	1172.4	21.4
#3	209.9	3242.4	22.2
Average	227.1	1702.3	20.3
Outlet			
#1	34.0	31.4	0.54
#2	36.8	64.1	1.14
#3	22.7	32.9	0.6
Average	31.1	42.8	0.76
EPA Guideline	80 µg/dscm	60 ng/dscm	
Average % removal	86.2%	95.51%	96.35%

References:

A. Licata, M. Babu, W. Carlson "The Application of Activated Carbon Enhanced Lime for Controlling Acid Gases, Mercury, and Dioxins form MWCs," American Chemical Society, Spring Meeting, New Orleans, 1996

J. Kilgroe, A. Licata, "Control of Air Pollution Emissions from Municipal Waste Combustors," National Waste Processing Conference ASME, Atlantic City, 1996

Heavy Metal Partitioning in a Municipal Solid Waste Incinerator

Lars Sørum
SINTEF Energy
Department of Thermal Energy and Hydropower
7034 Trondheim
Norway

Morten Fossum
SINTEF Energy
Department of Thermal Energy and Hydropower
7034 Trondheim
Norway

Egil Evensen
Trondheim Energy Company
Sluppenveien 6
7005 Trondheim
Norway

Johan E. Hustad
SINTEF Energy
Department of Thermal Energy and Hydropower
7034 Trondheim
Norway

PEER-REVIEW

INTRODUCTION

Waste Management in Norway

Norway has the following priorities for management of municipal solid waste (MSW)[1]:

1) Reduce waste generation and toxic components in waste
2) Encourage re-use, recycling and energy recovery
3) Secure an environmentally safe management of residues

MSW consists of household waste and waste from the service and trade industry delivered to municipal waste treatment plants or recycling schemes. In 1995, a total of 2.7 million tons of MSW (1.26 million tons of household waste and 1.44 million tons of waste from service and trade industry) was handled as follows[2]: 68% was deposited on landfills, 18% was combusted, 13% recycled and 1% composted. Combustion of MSW is handled in five larger plants with energy recovery located in different cities in Norway. In addition, a new incinerator for MSW is planned. This incinerator will have to meet the new emission regulations given by the European Union which are more stringent than the present regulations. Hence, Norway is moving towards more stringent regulations, leading to an increased interest in the environmental aspects of MSW incinerators.

Heimdal Heating Central (HHC)

One of the largest MSW incinerators in Norway is situated in Trondheim and is owned and operated by Trondheim Energy Company (TEV). HHC consists of two lines each with a maximum capacity of 6.5 tonne/hour. The furnaces are moving grate units delivered by VonRoll, Switzerland. The flue gas cleaning system consists of an electrostatic precipitator (ESP) and a wet scrubber. The MSW incinerator is a base load energy production unit in a district heating system. In 1996, a total of 85600 tonne of MSW was incinerated in this plant with a heat production equivalent to 222 GWh. Figure 1 show a sketch of the incinerator. The MSW is delivered by trucks to a bunker for storage and mixing. The waste is collected from the bunker and into the feeding hopper by a waste crane. The waste is fed to the furnace by a dosing pusher. While the waste is transported through the furnace by a moving grate, primary air is supplied for combustion from below the grates and from the side walls. The side walls are cooled and insulated with refractory. Recirculated flue gas is injected into the flame above the grate before the flue gas enters the secondary combustion chamber. The flue gas first flows through a hot water generator and the ESP, which removes dust particles, before it enters the wet scrubber. In the wet scrubber, the flue gas pass through a quencher which reduces the temperature before it enters the wet scrubber where most of the pollutants in gas phase are removed. The water from the scrubber is first treated in a neutralization tank and then in a flocculation tank where particles are separated from the scrubber water. Then the scrubber water passes a sediment reactor where the solid phase is collected in the bottom. The solid phase is transported to a filter press where filter cakes are made. The water from the cleaning process is filtered in a sand filter and a ion exchanger system, before it goes to the drain. The clean flue gas is emitted through the 70 meter high stack. The bottom ash is deposited on a landfill, while the ESP dust and filter cakes are deposited in a landfill as hazardous waste.

Objective of the project

During 1995, TEV carried out an investigation program to examine the residues from the incinerator. Primary attention was on the heavy metals in the bottom ash, fly ash and the landfill leachate. The program was conducted in order to establish more information about characteristics of the residues and thus be able to undertake a sounder evaluation of the environmental aspects of the final treatment of these products. This program was supplementary to the emission analysis done periodically for the flue gas and drain water. The objective of this work has been to establish knowledge about the partitioning of heavy metals through the incinerator and calculate the concentrations of heavy metal in the input MSW. A comparison of the results obtained from this study with other studies such as the WASTE Program (Burnaby)[3] and Brunner/Mönch[4] is of interest to see equalities and differences in the heavy metal partitioning through the incinerator and also the estimated heavy metal concentrations of the input MSW. All of the three different MSW incinerators (HHC, Burnaby, Brunner/ Mönch) have similar furnaces (moving grate), but different cleaning systems.

Heavy metal characteristics

Heavy metals are environmental toxics which accumulates in the environment. Heavy metals do not break down, but will remain in the environment forever. Cadmium, lead, mercury, vanadium, chromium, nickel, copper, zinc and arsenic are the most important heavy metals found in emissions from combustion of MSW. Cadmium, lead and mercury got most attention due to their relative toxicity[5,6]. Some of the heavy metals, especially cadmium, can deposit in the soil and be absorbed by plants. Mercury can be transformed into methyl mercury in sediments and be accumulated in the food chain, especially through fresh water. Excessive levels of heavy metals can provoke a number of health effects. Excessive amounts of lead and mercury are especially dangerous with regards to damage to the nervous system and fetal life. Lead can also give cardiovascular diseases and anaemia. Excessive amounts of cadmium can damage the kidney after long term exposure and accumulating in the body[6,7]. In order to reduce emissions of heavy metals and other pollutant emissions, the Norwegian government has signed several agreements, both national and international, which have the aim of reducing emissions in the future. For example: the Parliament report on national reduction of 70% of 13 selected environmental toxics, the North Sea Declaration states that the emission of 40 selected substances to both air and water shall be reduced and the Montreal Protocol include reduction of ozone destructive.

EXPERIMENTAL METHODS AND PROCEDURES

The experiments performed during this investigation were mainly conducted in 1995 and 1996. The input MSW has the average composition given in table1[9]. The waste originates from the urban and rural areas in and around Trondheim municipality. The degree of material recovery of different components is estimated to[9]: paper 35%, food waste 22%, plastic/textiles/rubber 11%, glass 25%, metals 63% and other non-combustibles 50%. The total material recovery rate from MSW is estimated to 30%. In the sections below, a description of the sampling and experimental methods and procedures are explained.

Mass Balance

In this study the mass balance has been established for bottom ash, filter ash and filter cake. All of the values are mean values taken over a whole year and are on a dry basis.

All of the MSW delivered to the incinerator is weighed before dumped into the waste bunker. The weight of the waste is continuously recorded every year. The bottom ash, filter ash (ESP dust) and filter cakes are always weighed (on a wet basis) before sent to the landfill. However, the average moisture content has been determined for each of the different residues. All residues were expressed on a dry basis for the mass balance. The amount of flue gas has been calculated by measuring the flow through the stack with a pitot tube and micromanometer according to the Norwegian standard method (NS 4862). All of the moisture from the input waste was considered leaving with the flue gas.

Chemical Analysis

Chemical analysis of the different waste streams have been done according to different standard tests methods. The heavy metals presented in this investigation is mercury (Hg), zinc (Zn), chromium (Cr), cadmium (Cd), lead (Pb) and iron (Fe). Some of the residues and the flue gas has also been analysed for other heavy metals such as arsenic (As), nickel (Ni) and copper (Cu).

Bottom ash. For ten weeks samples were taken every Monday, Wednesday and Friday. The samples were taken from the bottom ash conveyor belt with a spade. Particles larger than 50 mm were sieved out and magnetic metals were removed with a magnet. Other easy visible pieces of metal was also picked out. The samples were air dried for 70 hours at 20°C before shipment to the laboratory, in order to enable crushing of the ash before analysis. Every sampling day six samples, each of approximately 2 kg, were taken with 1-1.5 hours intervals. The samples from one day were mixed and split into two parts and a sample of approximately 4 kg was sent to the laboratory for chemical analysis and another sample was analyzed for grain size distribution. The samples were sent to a certified laboratory in The Netherlands, Tauw Milieu bv, and the chemical analysis was done according to the standard test method ICP NPR 6425 for cadmium, chromium, lead and zinc; mercury was determined by the Cold Vapour-method NEN 5779. Full details of the chemical analysis of bottom ash is given in the report from Kummeneje[10].

The amount of iron in the bottom ash was determined by sieving and magnet separation test in a pilot plant with a capacity of 36 tons/hour[11]. Approximately six tons of bottom ash was handled in the sieving/magnet separation test. The bottom ash was first sieved on 50 mm sieve and this fraction was put through the magnet separator to determine the magnetic fraction. The rest fraction after sieving (<50 mm) was also separated for magnetic materials in the same system. The total amount of magnetic materials from the magnetic separation test was considered as iron.

Filter Ash. Samples of approximately 2 kg were taken once a week for three weeks. The samples were taken in the intermediate container below the conveyor belt from the filter ash bin. The samples were stored in plastic bags just above room temperature in order to prevent interaction with the surroundings before shipment to the laboratory. The laboratory, Tauw Milieu bv in The Netherlands, is certified for these chemical analysis. ICP-method NPR 6425 was used to determine the content of cadmium, chromium, iron, lead and zinc. The Cold Vapour-method NEN 5779 was used to determine the content of mercury. Full description of these chemical analysis of the filter ash is given in the report by Kummeneje[12].

Filter Cakes. Some samples of the filter cakes from the washing process were analyzed with Atom Absorption Spectrophotometry (AAS) to determine the content of lead, zinc and chromium [13]. Iron was estimated from values found in the literature. The content of mercury and cadmium was determined by measuring the difference in concentration in the water before and after the water cleaning process. For a whole year one sample was taken every day and all of the samples from one week were put together and analysed. The NS4768 and NS4781 methods were used to determine the content of mercury and cadmium in the samples.

Drain Water. The drain water has been analyzed for mercury, cadmium and lead according to Norwegian standard methods NS4768, NS4781 and NS4781. The amount of iron, zinc and chromium was estimated on the basis of values found in the literature.

Flue Gas. The Norwegian standard method NS 4863 was used to determine the content of lead, cadmium, mercury and chromium in the flue gas. The procedure is described in a SINTEF report[14]. The content of iron and zinc was estimated on basis of values found in the literature. Four samples of the flue gas were taken for chemical analysis.

Sources of error in mass balances

In addition to the usual measurement inaccuracy's connected to every measurement done in this investigation, the closure of the mass balance also represent a source of error. Since the measurement inaccuracy's are given by the standarized measurement methods, those will not be commented on further. However, the mass balance closure need further explanation. The examination of the bottom ash, filter ash, filter cakes, drain water and flue gas has served different purposes. In addition to the determination of heavy metal balances and concentrations in input MSW, determination of heavy metal concentrations in residues and flue gas with regards to soil, water and air pollution has been one of TEV's objectives with these investigations. All of the measurements used in the mass balances has, therefore not been performed within the same period of time and with different sampling rates. However, this investigation has tried to give relatively long term mass balances and determined the concentrations of heavy metals in input MSW on basis of these findings. Short term investigations within the same time period has both the advantages and disadvantages of stable conditions with regards to operational parameters and composition of input MSW. The closure of the mass balances is therefore more likely to happen in investigations with parallel sampling of the residues and flue gas rather than sampling in series. However, the heavy metal balances and concentrations in input MSW is also a function of the variations in operational conditions and composition of input MSW. More extensive investigations with sampling in parallel would be very interesting and would provide a more complete picture of the mass balances and concentrations of heavy metals in input MSW. The cost of such comprehensive measurements is one of the major problems.

HEAVY METAL PARTITIONING THROUGH THE INCINERATOR

The results of the mass balance, heavy metal partitioning through the incinerator, heavy metal content in the residues and flue gas are presented in the sections below. Further, calculated heavy metal concentrations in the input MSW on the basis of the heavy metal content of the residues and flue gas are presented.

Mass Balance

The result of the mass balance is given in figure 2. The figure show that 83 % of the input MSW is converted to CO_2 and H_2O and is emitted as moist flue gas. The mass flux of bottom ash was found to be 16.5 % and the mass flux of filter ash was 0.37 %. The dust found in the filter cakes was almost negligible (0.02%). Brunner and Mönch[4] found in their investigation a bottom ash portion of 20.5% and a flue gas portion of 77%. The flux of filter ash was the same as this study.

Heavy Metal Balance

Figure 3 and table 2 show the heavy metal balance between the different residues and flue gas for the incinerator.

Cadmium (Cd). Cadmium is a quite volatile metal in a combustion context with a boiling point of 767°C. Figure 3 show that 63% of the cadmium remain in the bottom ash, 24% is captured in the filter ash, 8% is emitted with the flue gas, 6% is captured in the scrubber (filter cakes) and virtually nothing is emitted via the drain water. In this study 37% of the cadmium was evaporated from the combustion process and entered the flue gas cleaning system. Several other studies on the evaporation of cadmium from MSW incinerators have been done and they have shown quite different results. The Brunner and Mönch[4] investigation stated that only 12% of the cadmium remained in the bottom ash, while the Burnaby project[3] could report an even lower content of cadmium in the bottom ash (3.7%). A Swedish investigation[15] of four different MSW incinerators found large variations in cadmium remaining in the bottom ash, varying from 13 to 83%. These large variations can originate from two different important parameters, namely combustion temperature and chlorine content in the waste. Cadmium has a boiling point which is close to the combustion temperature and the content of cadmium in the bottom ash will be dependent on the operating furnace temperature. The operating furnace temperature is a parameter which is strongly dependent on furnace construction, MSW composition and fuel/air ratio. Of these parameters the fuel/air ratio is the easiest to control. Two important factors in the evaporation of cadmium are: chlorine available to form cadmium-chloride and the chemical form of cadmium. With chlorine present, cadmium can form relatively volatile chlorides that will follow the hot flue gases[16]. When the temperature drops, volatile cadmium adsorbs on the relatively small particles which have the largest surface area. The emission of cadmium will therefore be highly dependent on the efficiency of the flue gas cleaning system and it's ability to capture particle emissions.

Table 2 shows the heavy metal balance, the estimated heavy metal content in input MSW and concentrations of heavy metals for the different residues and the flue gas. The total yearly input of cadmium for the incinerator is 434 kg and 33 kg is leaving with the flue gas. The total efficiency of the flue gas cleaning system regarding cadmium is 80% (63% in ESP and 17% in scrubber) in this study. The Burnaby study[3] which had a flue gas cleaning system consisting of a conditioning tower, reactor with lime injection and fabric filter showed an efficiency of 99.8% for cadmium. The Brunner and Mönch[4] study which only had a electrostatic precipitator as flue gas cleaning system had an efficiency factor of 86% for cadmium.

Of the heavy metals in this investigation, cadmium is the one with the highest portion emitted through the stack. The calculated cadmium concentration in MSW was 5 mg/kg. The calculated cadmium concentration in MSW in the Burnaby project[3] was 13.5 mg/kg while Brunner and Mönch[4] reported 8.7 mg/kg. The city of Trondheim is currently implementing a source separation system where environmentally harmful waste such as electrical and electronic waste is separated and sent to a special landfill site for hazardous waste. A study has shown that electrical and electronic waste contributes with a large fraction of cadmium in MSW[17]. The effect of separating this fraction from the input MSW will be followed with great interest.

Chromium (Cr). Chromium with a boiling point of 2672°C can be regarded as a non-volatile heavy metal from a MSW combustion point of view. This is also shown by the results of the heavy metal balance for the combustion plant (table 2). Of the total input of 1829 kg/year to the incinerator, nothing is emitted through the stack. Approximately 2% is captured in the flue gas cleaning system the rest is left in the bottom ash. The Burnaby study reported that 93% of the chromium was left in the bottom ash. Only 0.06% was emitted with the flue gas, the rest was captured in the flue gas cleaning system. Calculated concentration of chromium in MSW is 21.1 mg/kg. The Burnaby project[3] calculated the chromium concentration in MSW to 92.5 mg/kg.

Iron (Fe). Like chromium iron can be regarded as a non-volatile heavy metal in MSW combustion, with a boiling point of 2750°C. From the input of 764954 kg/year virtually nothing is emitted through stack or drain water, 0.4% is captured in the flue gas cleaning system while the rest is found in the bottom ash.

Brunner and Mönch[4] found in their study 99% of the iron in the bottom ash and 1% in the filter ash, while 0.02% were stack emissions. Calculated iron concentration in MSW in this study was 8823 mg/kg.

Mercury (Hg). Mercury is the most volatile of the heavy metals with a boiling point of 357°C. The volatile behaviour of mercury was confirmed in this study with only 6% remaining in the bottom ash. Mercury content in the bottom ash between 0.2-19% has been found in other studies[3,4,15]. Mercury differs from the other heavy metals by the fact that it is in gas-phase in a combustion plant[16]. Mercury is converted to a gaseous metal and gaseous chloride salt in the combustion process. The flue gas cleaning system had an efficiency of 95% for mercury. The wet scrubber captured 92% of the volatile mercury. Brunner/ Mönch[4] had a mercury removal efficiency of 25% with electrostatic precipitator, while the Burnaby study[3] had an efficiency of 40% where practically all captured mercury was found in the fabric filter. The calculated concentration of mercury in MSW in this study was 1.6 mg/kg, which is exactly the same concentration as a similar mercury balance study gave in 1994[18]. Other studies have indicated mercury concentrations in the range of 0.7 - 1.5 mg/kg[3,4,19]. Given the volatile nature of mercury, emphasis should be put into removing mercury containing waste from the input MSW in order to reduce mercury emission to the environment. A study has shown that electrical and electronic waste contributes with a large fraction of mercury in MSW[17]. The potential for reduction of mercury entering the incinerator by removing the electrical and electronic waste fraction should therefore be considerable.

Lead (Pb). Lead, with a boiling point of 1750°C, should in combustion of MSW normally be considered as a non-volatile metal. However, studies have shown that small portions of chlorine in the waste will decrease the volatility temperature with several hundred degrees[20]. From the total of 38061 kg/year input of lead to the incinerator, 94% is captured in the bottom ash, 5% is captured in the flue gas cleaning system and 0.2% is stack emission. Other studies have shown a large variation of lead in the bottom ash ranging from 58 to 89%[3,4,15]. This and other studies have shown that most of the volatile part of lead is captured on ash particles and cleaned in the filter units. The calculated concentration of lead in MSW was 439 mg/kg. Other studies have reported values in the range of 160 to 430 mg/kg[3,4,19]. As for cadmium and mercury, lead is also strongly represented in the older electronic and electrical waste fraction although not relatively as much as mercury and cadmium. The combination lead and PVC (resin PVC contains over 50% of chlorine[21]) is highly possible for the electronic and electrical waste fraction, giving an increase in the volatile release of lead in the combustion process.

Zinc (Zn). Zinc, with a boiling point of 907°C, is one of the more volatile metals in this investigation. Zinc is also the heavy metal with largest yearly stack emissions (76 kg/year). Most of the zinc was found in the bottom ash (86%), while most of the residual 14% is captured in the flue gas cleaning system. Only 0.1% is emitted through the stack. This study differ from other studies with a large portion of the zinc remaining in the bottom ash. Other studies[3,4] have reported 42 and 51% of zinc in the bottom ash, but like this study most of the volatile fraction of zinc is captured in the ESP. The large variation in volatility can be ascribed to differences in combustion temperature due to the relatively low boiling point which is in the area of the combustion temperature. The calculated concentration of zinc in MSW was 1044 mg/kg while others have reported 1873 and 2000 mg/kg[3,4].

CONCLUSIONS

In this study most of the cadmium (63%), zinc (86%), lead (94%), chromium (98%) and iron (100%) was found in the bottom ash. The filter ash captured most of the volatile cadmium (24%), zinc (13%), lead (5%) and chromium (2%). The wet scrubber captured most of the mercury (87%). From these results it is evident that a large portion of the heavy metals are captured in the bottom ash compared to other studies, indicating a relatively low combustion temperature. The calculated concentrations of heavy metal in the input MSW was 1.6 mg/kg for mercury, 5 mg/kg for cadmium, 1044 mg/kg for zinc, 439 mg/kg for lead, 21.1 mg/kg for chromium and 8823 mg/kg of iron. Long term monitoring of the flue gas and residues seem to be a better and easier way to measure the content of heavy metals in MSW rather than sampling the input waste. Reduction in heavy metal emissions is expected after implementation of source separation of environmental harmful waste including electronic and electrical waste in 1997. The potential for reduction of mercury is confirmed by the relatively high concentration in MSW compared to other studies. The continuing work on identifying and separation of MSW fractions with large concentrations of heavy metals seem to be an important method to reduce heavy metal emissions further. Improved flue gas cleaning systems, furnace constructions and combustion control will also contribute to reduced emissions. This work has contributed to a better understanding of the behaviour of heavy metals in MSW combustion and given complementary understanding of the efficiency of various flue gas cleaning systems for different heavy metals.

REFERENCES

1. Department of the Environment, Norwegian Parliament Statement No. 44 (1991-1992), Initiative for reduced waste amounts, increased recycling and a secure waste management, Department of the Environment, Oslo, 1992, p. 65 (in Norwegian).

2. Official Statistics of Norway, We are still producing more waste, Weekly Statistics No. 39, Official Statistics of Norway, Kongsvinger, 1996, p. 4 (in Norwegian).

3. The WASTE Program, Waste Analysis, Sampling, Testing and Evaluation (WASTE Program): Effect of Waste Stream Characteristics on MSW Incineration: The Fate and Behaviour of Metals, Final report of the Mass Burn MSW Incineration Study (Burnaby, B.C.), Vol. 1, summary report, 1993, p. 76.

4. Brunner, P. H., Mönch, H., "The Flux of Metals Through Municipal Solid Waste Incinerators", Waste Management & Research, 4(1):105-119 (1986).

5. Scholdager, J., Air Pollution - Emission, Diffusion, Settling and Effects, Lecture Presentation in The Course Energy Technology at Norwegian University of Science and Technology (NTNU), Trondheim, 1990.

6. World Health Organization, Heavy Metal and PAH Compounds from Municipal Incinerators, Report from WHO Meeting Florence 12-16 oct. 1987, Copenhagen, 1988, p. 67.

7. Øverli, J.M., Energy and Environment - Global and International Challenges, Statoil, Environment Project Publication No. 2, Trondheim, 1990, p. 31 (in Norwegian).

8. Berntsen, T., Environmental Political Statement - 1995, Department of the Environment, Oslo, 1995, p. 126 (in Norwegian).

9. Trondheim Municipality, Waste Management Plan for Trondheim Municipality 1996-1999, Trondheim, 1996, p. 107 (in Norwegian).

10. Gilde, T., Heimdal Varmesentral - Chemical Analysis of Slag - Results of Chemical Analysis of Slag and Leachate.Kummeneje a.s., Trondheim, 1995, p. 11 (in Norwegian).

11. Skjæveland, R., HVS-Waste Combustion - Characterization of slag with regards to separation of iron, preliminary experiments, Norwegian University of Science and Technology (NTNU) - Department of Geology and Rock and Mineral Engineering, Trondheim, 1996, p. 28 (in Norwegian).

12. Gilde, T., Heimdal Varmesentral - Chemical Analysis of Electrostatic Precipitator Dust - Results of Chemical Analysis of Filterdust and Leachate, Kummeneje a/s, Trondheim, 1995, p. 6 (in Norwegian).

13. Mathillas, F. R., Analysis and Characterization of filtercakes from the flue gas cleaning system of the waste combustion plant, Project work, Norwegian University of Science and Technology (NTNU) - Department of Geology and Rock and mineral Engineering, Trondheim, 1995, p. 36 (in Norwegian).

14. Horrigmo, W., Vassbotn, T., Flatberg, H., Emission Measurements at Heimdal Waste Incinerator 1995, STF84 F96402, SINTEF Energy, Department of Thermal Energy and Hydropower, Trondheim, 1995, p. 34 (in Norwegian).

15. Soma, M. H., What Kind of Emissions Do We Get from Waste Combustion, Technical Winterweek 1986, EG61b, The Association of Norwegian Chartered Engineers, Oslo, 1986, p. 31 (in Norwegian).

16. Benestad, C., Braastad, G., Normann, H. H., et. al., Combustion Plants - Instructions for Officials in Charge, 95:13, The Norwegian Environmental Protection Agency, Oslo, 1995, p. 86 (in Norwegian).

17. Department of the Environment, Collection and Treatment of Waste from Electrical and Electronic Products, T-1135 ISBN 82-457-0100-9, Department of the Environment, Oslo, 1996, p. 64 (in Norwegian).

18. Evensen, E., Assessment of the Mercury-Balance of the Combustion Plant, EE/EB/450, Trondheim Energy Board, Trondheim, 1995, p. 3 (in Norwegian).

19. Halmø, T., Solid Waste, Tapir, Trondheim, 1984, p. 316 (in Norwegian).

20. Federal Register, US EPA, Guidance on Metals and Hydrogen Chloride Controls for Hazardous Waste Incinerators, 1989.

21. C-H. Wu, C-Y. Chang, J-L. Hor, S-M. Shih, L-W. Chen, F-W. Chang, "On the Thermal Treatment of Plastic Mixtures of MSW: Pyrolysis Kinetics", Waste Management, 13:15 (1993).

Table 1. Average composition of MSW delivered to HHC[9].

COMPONENT	FRACTION [wt%]
Paper	30
Food wastes	17
Plastic, textiles,rubber, leather	6
Wood	8
Glass	7
Metal	12
Other combustibles	6
Other non-combustibles	14
Total	**100**

Table 2. Concentrations in residues, flue gas and waste and heavy metal balance.

	Cd	Cr	Fe	Hg	Pb	Zn
Concentration in residues, flue gas and waste						
Flue gas [mg/Nm^3 dry]@11%O_2	0.057	0.00075	0	0.013	0.162	0.159
Bottom ash [mg/kg dry]	19	125	53250	0.62	2513	5464
Filter ash [mg/kg dry]	323	127	9833	8	5833	37667
Filtercake [mg/kg dry]	1331	10	2600	5805	7027	8567
Drain water [Tg/m^3]	1.3	0.9	0	3.6	48.1	100
Input MSW [mg/kg]	5	21.1	8823	1.6	439	1044
Heavy metal balance for the combustion plant						
Flue gas [kg/year]	32.7	0.44	0	7.2	91.8	76.3
Bottom ash [kg/year]	272	1788	761768	9	35950	78165
Filter ash [kg/year]	104	41	3154	3	1871	12083
Filtercakes [kg/year]	27.7	0.2	54.1	120.8	146.2	178.3
Drain water [kg/year]	0.02	0.02	0	0.06	0.83	1.7
Input MSW [kg/year]	434	1829	764954	139	38061	90515

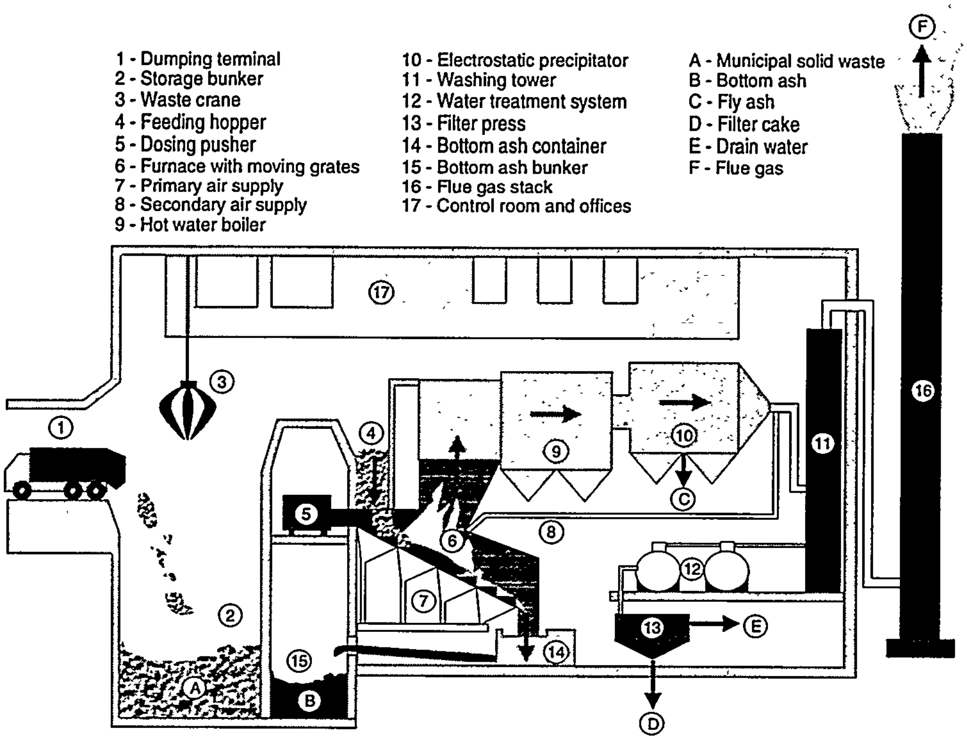


Figure 1. Sketch of the waste incinerator with major parts and mass fluxes indicated.

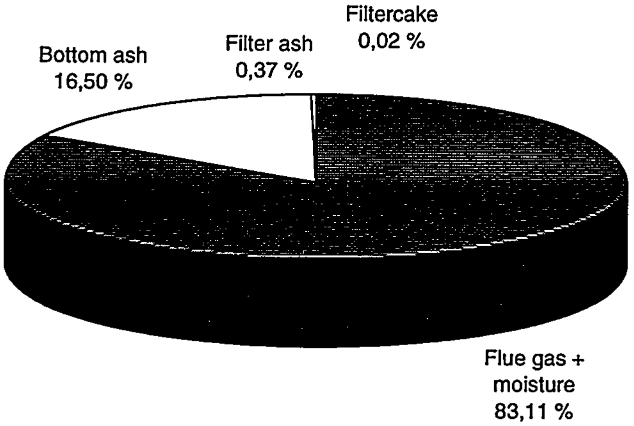


Figure 2. Overall mass balance for the MSW incinerator (dry basis).

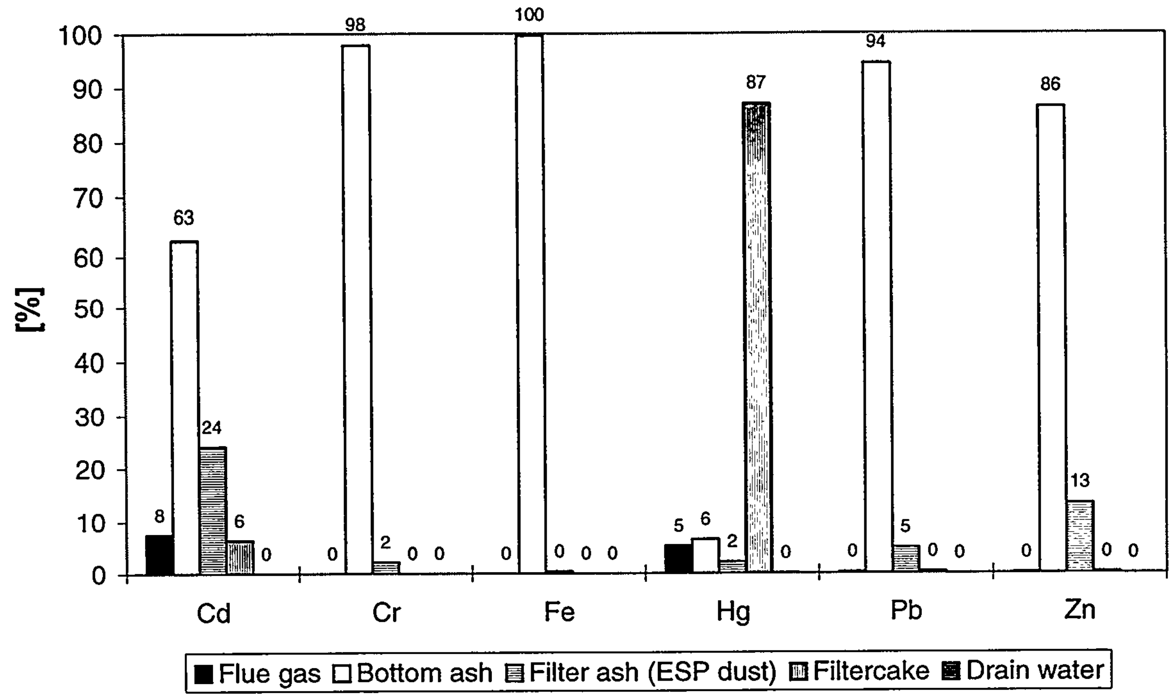


Figure 3. Heavy metal balances for the MSW incinerator.

TECHNICAL SESSION I

Implementation Issues

Using Life-Cycle Management to Evaluate Integrated Municipal Solid Waste Management Strategies

Keith A. Weitz and Subba R. Nishtala

Center for Environmental Analysis, Research Triangle Institute, 3040 Cornwallis Road, Research Triangle Park, NC, 27709, Ph: 919-541-6973, email: kaw@rti.org.

Morton A. Barlaz and Ranji Ranjithan

Department of Civil Engineering, North Carolina State University, Raleigh, NC, 27695, Ph: 919-515-7676, email: barlaz@unity.ncsu.edu.

Susan A. Thorneloe

Air Pollution Prevention and Control Division, National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Mail Drop 63, Research Triangle Park, NC, 27711, Ph: 919-541-2709, email: thorneloe.susan@epamail.epa.gov.

Introduction

Communities throughout the United States are struggling to develop efficient and cost-effective plans for managing their MSW. In the past, these plans primarily consisted of waste collection and disposal at a local landfill. Today's MSW management plans often include integrated systems that address all types of solid waste materials, solid waste sources, and waste management options [1].

Developing more efficient integrated MSW management plans necessarily involves complex decisions where tradeoffs between environment performance and cost and must be carefully analyzed. For instance, how does the cost and environmental performance of a MSW management system change if we include or exclude a specific material (e.g., glass, paper, plastic, metal) from our recycling program? And should we recycle newsprint if we are interested in waste-to-energy combustion? To better evaluate the tradeoffs involved with these types of questions, the entire life cycle of MSW must be considered. As shown in Figure 1, the life cycle of MSW starts with the production of products from virgin and/or recycled materials. Eventually, these products are discarded to the MSW stream and may be managed through a variety of options such as recycling, combustion, composting, and landfilling. Materials that are recovered and recycled are incorporated into new products and will eventually reenter the MSW stream. By taking a life-cycle perspective, it is possible to capture tradeoffs and transfers of environmental burdens from one waste management operation to another, or from one life-cycle stage to another, and analyze multiple system design issues concurrently [2,3,4].

The Research Triangle Institute (RTI) is continuing work under a multi-year cooperative agreement with the U.S. Environmental Protection Agency (EPA), through funding from EPA and the U.S. Department of Energy (DOE), to conduct a life-cycle study of integrated MSW management. The final outputs of this research include a database containing life-cycle inventory (LCI) and cost data and a computer-based decision support tool to help solid waste planners evaluate the environmental burdens and costs associated with integrated MSW management systems. RTI's research team currently includes life-cycle assessment and MSW experts from North Carolina State University, University of Wisconsin-Madison, and Franklin Associates, Ltd. Groups of internal EPA and DOE advisors and external stakeholders are also active participants in this unique forum which brings together experts from industry, federal government agencies, local governments, academia, and environmental advocacy organizations.

Overview of Key System Considerations

Figure 1 highlights the major components of our defined system. The system definition also includes specifications for the types of waste components, waste management upstream processing units, and waste generating sources. Because the waste management stage is the primary focus of this research, it is defined in greatest detail.

In general, all unit operations that have a bearing on the LCI are being evaluated. In cases where some portion of the MSW is recycled, the energy and resources expended and emissions generated in separating, transporting, and converting the recyclables to a new product are considered. These are then compared and netted out from the energy, resources, and emissions for manufacturing the same product from virgin materials. For example, the total amount of energy required to recover the recyclable from the waste stream and convert it to a new product is included in the LCI and termed Er. Similarly, the amount of energy required to produce a corresponding amount of the same product from virgin material is calculated and termed Ev. The net amount of energy (En) saved (or expended) to recycle a material is then calculated as the difference between Er and Ev (En = Er - Ev). Similar calculations are performed for all LCI parameters involved in the recycling and remanufacturing processes.

In operations where energy is recovered (e.g., combustion of MSW or Refuse-Derived Fuel (RDF), combustion of landfill gas), an energy offset is calculated. The methodology used for energy recovery is the same as that described above for remanufacturing. However, an assumption is made that any net energy "saved" offsets electricity generated from fossil fuel (coal, oil, or natural gas) and not from alternative sources (e.g., hydro, nuclear, and geothermal). The rationale for this assumption is that, because the alternative sources are "cleaner," they will be operating at capacity and any energy "saved" will reduce the reliance on electricity generation from "dirtier" sources.

Numerous pieces of capital equipment from refuse collection vehicles, through balers, to major equipment at paper mills are also important parts of the system. In theory, resources associated with the fabrication of capital equipment, as well as the construction of a new facility, should be considered as part of the LCI [2, 4]. This may be particularly relevant in evaluation of MSW management strategies which suggest the construction of a new facility, such as a material recovery facility (MRF), or the purchase of new refuse collection vehicles. Although theoretically correct, the inclusion of these resources introduces additional complexity which may not be necessary. Thus, the amortized purchase price of a facility or a piece of equipment is being used as a screen to evaluate the importance of its inclusion in the LCI. Where the amortized capital cost of a piece of equipment is low relative to the non-labor cost to operate it, an assumption is made that the resources involved in fabrication of the equipment are insignificant.

In the waste treatment and disposal end of the system, the energy associated with the treatment of liquid and solid wastes is also considered. For example, if biological oxygen demand (BOD) is treated in an aerobic biological wastewater treatment facility, then energy is consumed to supply adequate oxygen for waste treatment. Similarly, if a solid waste is produced which requires burial, energy will be consumed in the transport of that waste to a landfill and its burial in the landfill. These and similar parameters are included in the study.

It is important to recognize that the system boundary for cost analysis differs from that used for the LCI. The cost analysis focuses only on the cost of MSW management as experienced by the public sector. Thus, the cost analysis includes the cost of waste collection, transfer stations, MRFs, composting facilities, combustion, RDF plants, and landfills. In addition, where a waste is produced as part of a waste management facility, the cost of waste treatment is included in the cost analysis of that facility. For example, we include the cost of leachate treatment in our cost analysis of landfills. Costs associated with remanufacturing are not included because they are assumed to be reflected in the price paid to a community for recyclables or electricity (as generated through combustion of MSW or landfill gas).

Overview of Allocation Procedures

A major challenge in this research is allocating LCI data to the individual components of MSW. Existing allocation schemes are based on simplistic mass- or volume-based schemes. For this research, we are investigating and developing more accurate allocation procedures. A summary of the key assumptions, allocation procedures, key issues, and improvement needs related to the allocation of LCI data for each major unit operation are presented in Table 1.

Conclusions

The issues presented in this paper convey a sense of the complex relationships of environmental burdens and costs between different waste management operations. As data for upstream raw materials acquisition and manufacturing for MSW components are obtained and added, this complexity will be extended throughout the entire life cycle. However, such a life-cycle perspective is critical for making accurate and efficient decisions about the environmental burdens and costs of integrated MSW management systems.

The value of life-cycle thinking and more formal life-cycle assessment for evaluating integrated MSW management systems has also been recognized by many other countries, including Canada, France, Germany, the Netherlands, Sweden, and the United Kingdom, all of whom have studies underway in this area. We are continuing research in the context of this international initiative to advance the application of life-cycle concepts to integrated MSW management in the United States.

Finally, it should recognized that environmental LCI and cost data only present two components of a very complex system design problem and they must be combined with additional decision making factors to formulate a solution. Additional factors facing solid waste planners might include political pressures, social pressures, aesthetics, and level of available technology. Striking a balance between environmental, cost, and these additional decision making factors is crucial to the development of successful integrated MSW management strategies.

Acknowledgments

The information contained in this paper has been developed as part of ongoing research funded through an interagency agreement between the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy (DOE) under EPA Cooperative Agreement No. CR823052 with the Research Triangle Institute (RTI). Use of the methods or results presented in this paper does not imply EPA or DOE policy and are not intended to be used to make judgments about which material, product, or waste management practice is environmentally preferable.

References

1. White, et al. 1995. *Integrated Solid Waste Management: A Life-cycle Inventory.* Glasgow, UK: Blackie Academic & Professional.
2. Society of Environmental Toxicology and Chemistry. 1991. *A Technical Framework for Life-Cycle Assessment.* SETAC and the SETAC Foundation for Environmental Education, Inc., Washington, DC.
3. G. A. Keoleian and D. Menerey. 1993. *Life Cycle Design Guidance Manual: Environmental Requirements and The Product System.* EPA/600/R-92/226 (NTIS PB93-164507). Risk Reduction Engineering Laboratory, Cincinnati, OH.
4. U.S. Environmental Protection Agency. 1993. *Life-Cycle Assessment: Inventory Guidelines and Principles* . EPA/600/R-92/245 (NTIS PB93-139681). Risk Reduction Engineering Laboratory, Cincinnati, OH.
5. A. Kaneko and M. A. Barlaz. 1994. *Solid Waste Collection: A design and cost analysis tool,* North Carolina State University, Raleigh, NC (unpublished work).

Table 1. Summary of Existing and Proposed LCI Allocation Procedures

Major Operations	Key Assumptions	Key Design Characteristics	Existing Allocation	Proposed Allocation
Upstream	Closed-loop recycling, and products made from virgin versus recycled material are identical.	Energy grid structure can be specified by user. A typical process design will be used to estimate LCI data.	Mass	None. Primarily dependent on the allocation method used by developer of data.
Collection	Data on population, generation and, capture rate, etc. are input by the user.	Given data for a site, fuel used, and associated emissions are calculated.	Mass	Allocation procedures for collected materials are being evaluated on a volume basis.
MRF	Data on facility cost, labor cost, and productivity are input by the user.	MRF design depends on the collection type and the recyclables mix.	Mass	Allocation procedures are based on the specific equipment (e.g., baler) that is used to process recyclables.
Composting	Data on site conditions are input by the user to derive retention time, cost, and emissions.	Aerated windrow composting design is assumed.	Mass	Allocation procedures are currently being developed through laboratory testing and factorial analysis.
Combustion	Combustion with generation of electricity is assumed from a new facility that meets recent regulations.	Generic cost and design data are used, no detailed design is available.	Mass	Allocation of metal emissions is based on specific components of waste, allocation of other air emissions is based on ultimate analysis of waste components.
Landfill	Data specified by the user are used in designing the landfill.	Landfill designs with or without gas control and leachate collection can be considered.	Mass (organics only)	Allocation procedures are being developed based on analyses of waste components and leachate quality.

Figure 1. Life Cycle of Integrated Solid Waste Management