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Bioenergy Systems Report

Prospects in Developing Countries for

Energy From Urban Solid Wastes

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for

INTRODUCTION

In the 1970s and 1980s several types of plants and facilities have been built in the U.S. and Europe to produce energy from urban solid wastes. These include various types of combustion systems which produce steam, and systems to recover methane gas generated during the decomposition of urban solid wastes in sanitary (sealed) landfills.

Energy recovery is not the exclusive or even primary motivation for the construction and operation of these plants, although income from the sale of steam, power, or gas is crucial to the economic viability of each of the facilities. The primary goal of waste combustion plants is to dispose of most of the waste, leaving only a small fraction to be landfilled. The life of most U.S. and European landfills is quite short, and few appropriate sites for new landfills are available near urban centers. The initial landfill gas recovery systems were built to limit the hazards associated with the uncontrolled seepage of methane from large landfills.

During the same period many cities in developing countries have grown very rapidly. Despite inadequate waste collection systems, the total volume of collected wastes is very large. Present disposal methods create severe health and environmental hazards. Efforts are being made in many cities to develop more satisfactory systems for waste management and disposal. The urgency of the waste disposal problem has stimulated interest in waste-to-energy options.

Information on waste management practices and problems in developing countries has been published by the Urban Development Department of the World Bank, the United Nations Environment Program, other organizations, and commercial publishers. (A selected bibliography is on p. 24.) None of these publications has included a substantial analysis of the technical and economic feasibility of adapting U.S. and European waste-to-energy technologies for use in developing countries.

This Report has been designed to provide (a) a comparative analysis of the characteristics of urban solid wastes in the U.S., Europe, and developing countries; (b) basic information on the characteristics and operation of the principal types of waste-to-energy systems in use in the U.S. and Europe at present; and (c) a preliminary assessment of the feasibility of using each type of system with wastes available in developing countries.

The feasibility of a waste-to-energy option in a given city in a developing country is greatly influenced by the waste collection, scavenging, and waste disposal practices in that city and by the composition of the residual wastes. Although the details vary considerably from city to city, the following generalizations apply to the great majority of cities in developing countries:

1. Per capita waste generation rates are much lower than in the U.S. and Europe. Published data ranges from .25 to .60 kg/cap/day in lower income developing countries and from .50 to .85 kg/cap/day in the middle-income countries. In contrast, the European rates are from .70 to .85 kg/cap/day, while the rates in the U.S. range from 1.25 to 1.8 kg/cap/day.

2. In most cities the waste collection system depends heavily on human-powered collection equipment (pushcarts, wheelbarrows, two-wheel dollies with baskets, pedal tricycles) and carts drawn by animals. Narrow, unpaved streets prevent the use of trucks for house-to-house collection in many areas. In most cities a significant percentage of households are not served by the waste collection system.

3. The costs of present systems are very high. Some cities in developing countries spend a third or more of their municipal budgets on waste collection and disposal.

4. Householders, waste collectors, and scavengers at dumps remove most of the reusable or recyclable items from the wastes.

5. Incineration of the residual wastes has been precluded in most areas by both the high cost of modern incinerators and the low caloric values and high moisture content of the wastes. The use of sanitary (covered) landfills has been very limited due to the high cost of the heavy equipment needed to cover the wastes with soil.

6. Most of the wastes are simply dumped on open land. This practice generates a number of environmental and health hazards including odors, smoke from the spontaneous combustion

of some of the wastes, groundwater pollution, and the spread of diseases by the flies, rats, animals and human scavengers that occupy the dumps. The seriousness of these problems clearly justifies the careful consideration of any waste-to-energy option which could cover the cost of a better method of waste disposal and reduce medical costs resulting from the unsanitary dumps.

7. Despite low per capita waste generation rates, inadequate collection systems, and removal of recyclables by scavengers, the total volume of dumped wastes is very large in the major cities in developing countries. Many cities collect more waste than is used in medium-sized waste-to-energy plants in the U.S. (i.e., 1,000 to 1,500 tons per day).

8. The composition of the residual wastes contrasts sharply with typical wastes in the U.S. shown in the chart below. These differences are reviewed in Part One of this Report (pp 3-6).

The recovery and use of landfill gas and other systems for the anaerobic digestion of urban solid wastes are described in Part Two (pp.7 - 13). Presently available waste combustion systems with energy recovery are reviewed in Part Three of the Report (pp. 14 - 23).

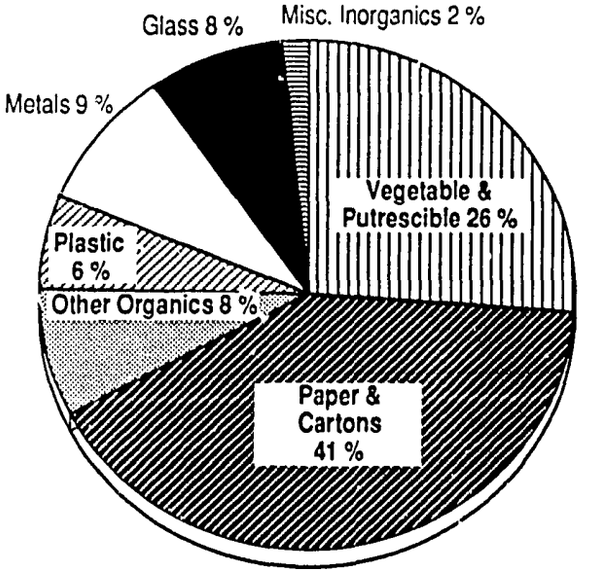
Efforts to use U.S. and European technology for the combustion of urban solid wastes in developing countries are only beginning at present, while the use of landfill gas technology has not yet begun in those countries. Waste-to-energy firms have been preoccupied with opportunities in their own countries and regions and have not yet seriously examined possible opportunities in developing countries.

Research for this Report has led to two preliminary conclusions concerning the technical feasibility of the use of U.S. and European systems in developing countries: (1) Present technology for the recovery and utilization of landfill gas appears to be suitable for use in developing countries, although the design of landfill gas projects would have to be modified to accommodate higher initial gas production rates and the shorter productive life of each landfill sector. (2) Several types of waste combustion systems with rotary combustors appear to have the capability of utilizing the types of wastes which are available in most cities in developing countries.

This series of Bioenergy Systems Reports has been sponsored since 1982 by the Bioenergy Systems and Technology (BST) Project of the Office of Energy, U.S. Agency for International development. The BST project provides information and assistance to USAID Missions, agencies of developing countries, and private sector firms on biomass energy options and opportunities. A Cane Energy Assessment program has explored options for diversification of the sugarcane industry, with special emphasis on energy by-products. A Rice Residue Utilization Program has examined options for the expanded use of rice husks and rice straw to produce electric power and/or industrial energy. These programs have been carried out under the supervision of Dr. James Sullivan, Director, Office of Energy, U.S. Agency for International Development, Room 508, SA-18, Washington DC 20523. Inquiries concerning this Report should be sent to Ms. Betsy Amin-Arsala at the above address, telephone (703) 235-3470, telex 550-130.

This Report has been compiled and written by Dean B. Mahin, International Energy Projects, P.O. Box 591, Front Royal, Virginia 22630, telephone (703) 636-2126, under an AID contract with TEM Associates Inc., Suite 840, 1900 Powell Street, Emeryville, California 94608, telephone (415) 655-6576.

Average Waste Composition
U.S. Cities, 1986



Source: U.S. Environmental Protection Agency, 1986

PART ONE:

CHARACTERISTICS OF URBAN WASTES IN DEVELOPED AND DEVELOPING COUNTRIES

A number of factors influence the composition and characteristics of the urban solid wastes (USW) available in a given city for use in a waste-to-energy system. These includes climate, income levels, types of available foods, packaging of foods and other items, extent of livestock in the city, sanitary facilities, type of waste collection system, and other factors.

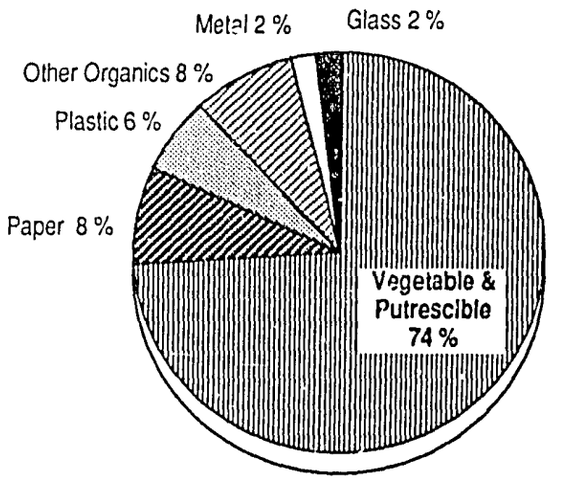
Although there are important variations from city to city, wastes from cities in AID-assisted developing countries usually have a much higher percentage of wet organic material and a lower percentage of dry combustible material than the USW collected in U.S. and European cities. The differences in the characteristics of the available wastes must be carefully considered in assessing the applicability of present waste-to-energy technologies to conditions in developing countries.

1. Vegetable & Putrescible Wastes

In the U.S. only about 8% of the USW is food wastes. The volume of garbage is low due to the wide use of processed and package foods (from which inedible portions have already been removed) and to the numerous homes with disposal units which shred the garbage and flush it into the sewerage system. On the other hand, many American families live in single-family homes surrounded by lawns, gardens, and trees; about 18% of the USW in the U.S. is "yard wastes" including leaves, grass clippings, and other biomass. The total vegetable/putrescible fraction of USW in the U.S. (including food wastes and yard wastes) is about 25%. This fraction is about the same in Europe, although it contains more food waste and less yard waste.

In AID-assisted developing countries the collected USW consists of a very high percentage of garbage and other vegetable and putrescible material. In those cities in which the organic material is not heavily diluted with street sweepings and other inert material, the vegetable/putrescible fraction of the waste usually exceeds 50% and is often 75% or more of the waste.

Average Waste Composition
Jakarta, Indonesia, 1985-6



Source: Chp. 4, Reference 4 (see p. 24)

This fraction is highest in areas or seasons in which locally grown fruits and vegetables are available in markets. In some climates the vegetative fraction increases sharply during the warmer and/or wetter season. For example, refuse collectors in Nigeria complain in the wet season of the very bulky refuse which contains a high proportion of the remnants of green vegetables and maize cobs and husks. Data from several countries shows that the vegetative fraction is higher in the USW from higher income districts than from lower income districts in the same city.

The vegetative fraction of the USW is lower in cities in which climatic or cultural factors limit the production of fruits and vegetables. In some cities (i.e., Kathmandu) the diet of lower income people consists of mainly of rice and other cereals; rice husks usually remain at the rice mill, and are rarely collected with urban wastes. The vegetative fraction is also lower in cities (i.e., Cairo) in which lower-income residents feed wastes to domestic animals (goats, chickens, and rabbits). In some cities, notably in South Asia, the vegetative/putrescible fraction includes a significant percentage of dried manure from unconfined cattle; a survey in Lahore, Pakistan, found that 12% of the USW was animal manure.

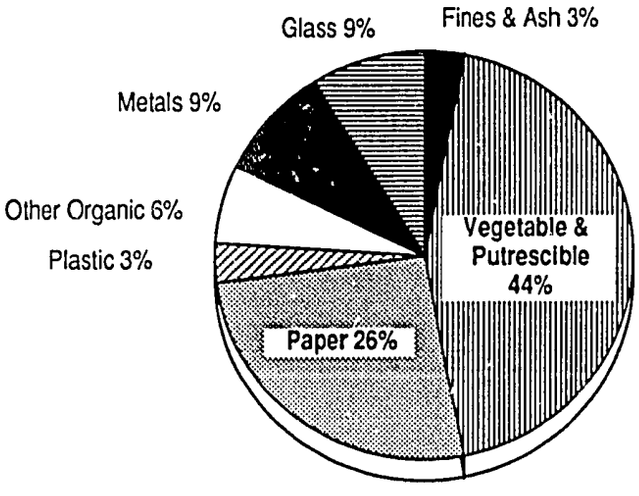
2. Paper and Paperboard

About 40% of the USW in the U.S. is paper and paperboard. About half of this category of waste is corrugated boxes; other components include newsprint (18% of the category), magazines (13%), mail advertising material (5%), paper food cartons (5%), wrapping and tissue (7%), and wax cartons (3%). The caloric content of these highly combustible wastes is very high (7,000 to 8,000 BTU/lb, 3600 to 4400 kcal/kg). The presence of this large percentage of paper and paperboard is the principal reason for the quite high caloric content of USW in the U.S.

The percentage of paper and paperboard is also high in the USW of most European cities; the average for the European Communities is about 29%. In several Latin American and Caribbean cities (including Port of Spain, Trinidad and Tobago, shown below) the USW contains 20 to 25% paper.

In most cities in AID-assisted countries in Asia and Africa for which data are available, paper and paperboard constitute less than 10% of the collected USW. Paperboard and higher-quality paper are usually removed by the homeowner or by refuse collectors for resale; most of the paper in the collected waste is low quality and/or soiled paper with a low energy content.

Average Waste Composition
Port of Spain (Trinidad & Tobago) 1980



Source: Solid Waste Master Plan, 1980 per Meridian Corp. *Study on Waste Disposal Options*, 1986.

3. Plastics

Various types of plastics, which have a high caloric content per kilogram, account for 6 to 7% of the USW in the U.S. and in Europe. Although a few higher-income cities in other regions have 5 or 6% plastics, such materials constitute less than 3% of the collected wastes in most of the cities in AID-assisted countries for which data are available.

4. Other Combustibles

Other combustible materials including textiles, rubber, leather, and wood account for about 8% of the USW in the U.S. and a smaller fraction of the wastes from European cities. Textile residues and rags amount to 3 or 4% of the USW in a number of cities in developing countries, but other types of combustible materials are not very significant in most cities. Due to the acute firewood shortages in many of the developing countries, there is very little wood or other woody biomass in the collected USW.

5. Non-Combustible Materials

Due to the less frequent discarding of glass and metal items and the recovery of most of the discarded glass and metal by scavengers, the percentages of these non-combustible items in the residual USW is very low in most AID-assisted countries.

About 9% of the USW in the U.S. is metals. This fraction is smaller in Europe (3 to 5%) and still smaller (1 to 3%) in the majority of cities in AID-assisted countries.

The small percentages of these recyclable materials in the USW in most developing countries limits the economic feasibility of those waste-to-energy systems which have been designed for the separation and recovery of these recyclable resources.

In some Indian cities and other South Asian cities, half or more of the USW consists of materials collected during the daily sweeping of unpaved streets. These sweepings include dirt, silt, dust, ashes, and other inert materials as well as animal manure, human fecal matter, and other fine organic material. The ash fraction is greatest in (a) cities in higher latitudes (i.e. Seoul, Istanbul) or higher altitudes (Addis Ababa, Lima) in

which stoves are needed for heating and (b) areas in which lower-income city dwellers use wood, other biomass, charcoal, or coal for cooking. In cities near the Sahara (i.e. Dakar), the USW contains a high percentage of sand blown in from the desert.

6. Density & Moisture Content

Due to the high percentage of paper and empty containers, the density of USW is rather low in the U.S. and Europe. The average is about 100 kg/m³ in the U.S. and about 150 kg/m³ in Britain. Due to the lower fraction of paper and higher fraction of wet garbage, the USW in most developing countries has a density of 250 to 350 kg/m³. In some south Asian cities in which the USW contains a high percentage of street sweepings, the density may be as high as 500 kg/m³.

Typical wastes in the U.S. contain only about 25% moisture; most of the moisture originates in the food waste and yard waste fractions. Since household waste is kept in covered containers or bags prior to pickup, the moisture content of the waste is not greatly affected by the amount of rainfall.

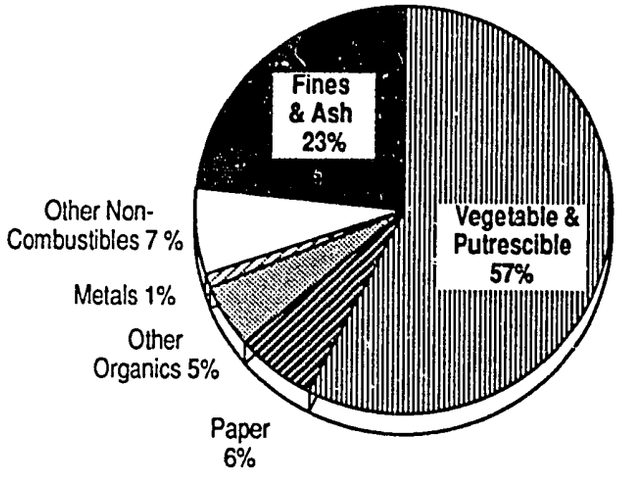
The much higher moisture levels in USW in developing countries are due primarily to higher percentages of food wastes and to greater exposure of the USW to rainfall. Bandung's waste contains about 80% moisture. In Manila, Bangkok, Taipei, Sao Paulo, and other cities the moisture content of the USW is about 60%.

In some cities the moisture in the USW varies substantially between the wet and dry seasons. The increased moisture in the wet season is due in part to the increased availability of fruits and vegetables as well as to rainfall reaching the wastes. In a survey of ten Indian cities at various seasons, moisture levels ranged from 5% to 50%. The cities with the lowest range of moisture levels were those in which the USW contains a high percentage of street sweepings and ashes. Due to the high fractions of garbage, the moisture content of the USW can be quite high even in cities with very dry climates; in Cairo, where rainfall is rare, the USW contains 40% to 60% moisture.

7. Caloric Content

Waste-to-energy systems have been developed in the U.S. and Europe to burn urban solid wastes with a high caloric content resulting from large fractions of paper and other dry combustibles.

Average Waste Composition
Delhi (India)



Source: Chp. 4, Reference 3 (see p. 24)

The most frequently used figure for the caloric content of USW in the U.S. is 4500 BTU/lb (2500 kcal/kg or 10,465 kJ/kg), but some estimates are higher. The design for a large new waste-to-energy plant in the New York City suburbs assumed an average USW caloric value of 5200 BTU/lb (2889 kcal/kg or 12,096 kJ/kg). European caloric values are lower; the average for the European Community countries is 3239 BTU/lb (1800 kcal/kg or 7534 kJ/kg).

Due to the lower percentages of dry combustibles, high moisture content, and (in some cities) high fractions of inert materials, the caloric content of the USW in most AID-assisted countries is only half to two-thirds that of U.S. wastes. Specific data on caloric values is available for only a few cities in developing countries.

The most extensive data is on Indian cities, in which the USW tends to contain high percentages of inert material. The lowest values (800 to 1100 kcal/kg, 1439 to 1979 BTU/lb, 3348 to 4604 kJ/kg) were for a group of 33 medium-sized Indian cities. Wastes from several larger Indian cities ranged from 1100 to 1500 kcal/kg (1979 to 2699 BTU/lb, 4604 to 6279 kJ/kg).

In several non-Indian cities on which data is available, the percentage of inerts is lower and caloric values are somewhat higher. Average values in kcal/kg were 1540 for Ismalia (Egypt), 1600 for Ibadan (Nigeria), 1782 for Taipei county (Taiwan), and 1842 for Manila.

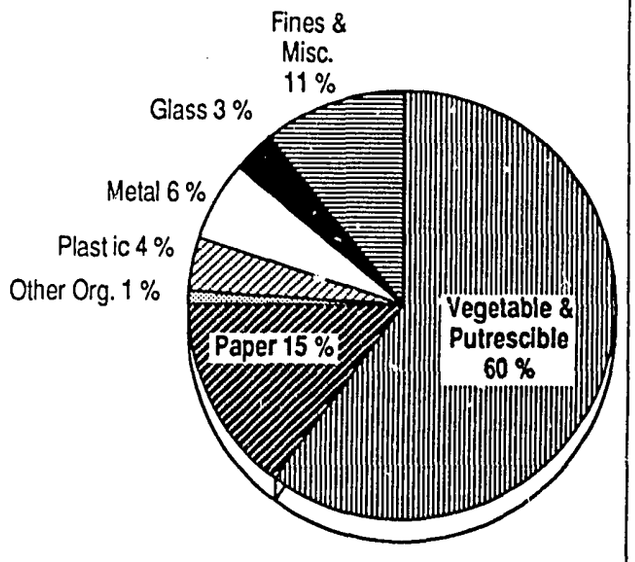
Due to the low caloric content of the average wastes, virtually all of the consultants who have examined solid waste problems in AID-assisted developing counties have assumed that incineration was not a viable option for waste disposal and that waste-to-energy systems involving combustion of the USW were also not feasible. Nonetheless, there would be several ways of increasing the average caloric content of the wastes to be utilized in a waste-to-energy system:

a. Waste Selection: Most published data on USW composition provides city-wide averages. Several studies show higher fractions of combustible materials and higher total caloric values for USW from higher income residential districts, as well as from commercial areas and some industrial areas. Residents of higher income districts discard more paper and paperboard, especially packaging material and reading matter. Their better and more varied diet is reflected in higher fractions of vegetative material. Their wastes contain smaller fractions of ash, dirt, and other inert materials than wastes from poorer districts. USW from some higher income districts in Cairo has 1700 to 1800 kcal per kilogram which is comparable to average wastes in Europe, while USW from low income districts in Cairo has only about 1500 kcal/kg. Since few cities will be able to afford a waste-to-energy plant large enough to process the city's entire daily collection of USW, the plant could be designed to utilize only those wastes with higher caloric values.

b. Waste Separation: In some areas it may be feasible to provide for the separate collection and disposal of the inert fraction of the remaining USW. This type of waste separation will be necessary to reduce the inert material in the USW to be used in a plant in India described on p. 19. In other cities with high inert fractions in the USW, these could be removed with a rotating cylindrical screen (trommel) as shown on p. 20. Manual removal of metals, glass, and other large non-combustibles from the waste conveyors would also increase the caloric content of the remaining wastes.

c. Co-firing with Other Biomass: There are several intriguing but untested possibilities for increasing the caloric content by co-firing USW with residues generated by biomass-processing industries located in or near metropolitan areas. In rice-growing countries the most abundant biomass residue is rice husk. Its caloric value (6200 to 6400 BTU/lb, 3445 to 3556 kcal/kg) is two to three times that of typical USW in those countries. Due to the high ash content of the husk (around 20%), the combustion system would need good temperature controls to avoid ash melting and slagging as well as good ash handling capabilities. Another option is sawdust, which has more calories and less ash than rice husk. A waste-to-energy plant close to a sugar mill might burn surplus bagasse with the USW, although sugar mills have usually been designed to consume all their output of bagasse in their own boilers. In some areas it might be feasible to co-fire coconut shell and/or husks from local coconut processing plants.

Average Waste Composition
Freetown (Sierra Leone) 1983



Source: Reference 2 (see p. 24)

PART TWO:

ENERGY FROM URBAN SOLID WASTES VIA ANAEROBIC DIGESTION

In recent years a number of developing countries have carried out projects and programs for the production of biogas through the anaerobic digestion of biomass, principally animal manures. During the same period many projects have been established in developed countries to recover and use the biogas - usually known as landfill gas - which is generated in sanitary (sealed) landfills through the anaerobic digestion of urban solid wastes.

There are more similarities than differences between the two types of projects. In both the carbon, hydrogen, and oxygen in the biomass are converted to a mixture of gases through the action of microbes. In both types slightly more than half of the mixture is methane (CH_4), the principal constituent of natural gas; most of the rest is carbon dioxide (CO_2). Both processes must take place in the absence of oxygen other than that in the biomass. Both types of biogas are excellent fuels for use in boilers, burners, engines, and gas turbines.

During the past decade facilities to recover and use landfill gas have been established at over 50 landfills in the U.S., at more than 75 landfills in Europe, and at several landfills in other countries including Canada and Brazil. Sanitary landfills are not widely used for waste disposal in developing countries, and there is no substantial reported experience with landfill gas in the AID-assisted developing countries.

This part of the Report will review recent experience with landfill gas (LFG) systems in developed countries and evaluate the potential for the production and use of LFG in developing countries. A final section will review biogas production from USW in above-ground digesters.

1. Landfill Gas Recovery

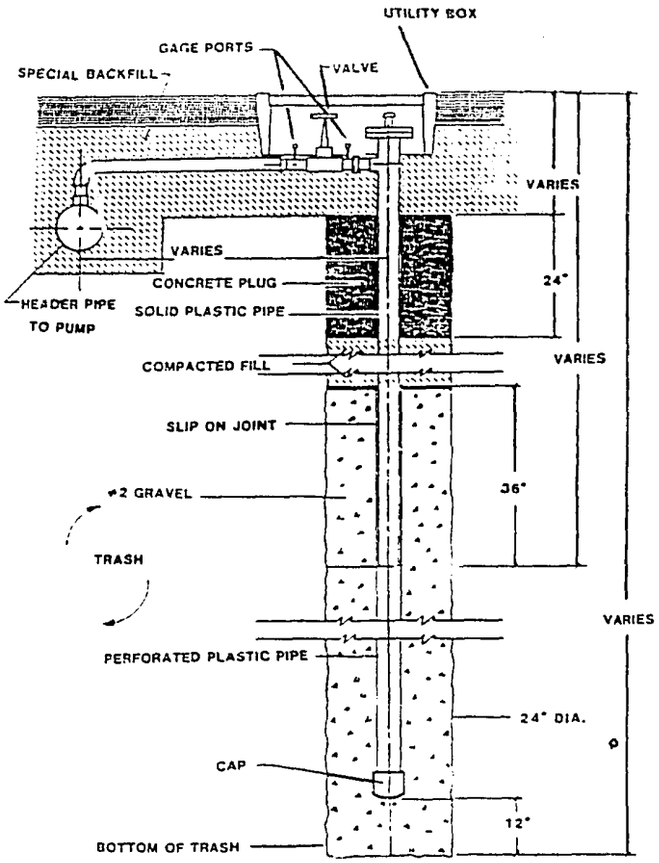
The first prerequisite for a landfill gas recovery system is a well-sealed landfill. The landfilled wastes must be covered with a sufficiently thick layer of soil to prevent the escape of the gas and infiltration of significant quantities of oxygen into the landfill. The depth of the cover depends on the soil and climate. Gas containment was inadequate at a landfill in Canada which was covered with dredged river sand. Dry soil usually allows more gas seepage than wet soil. As the landfill sector is filled, the sides must also be covered with soil. If drainage from the landfill (leachate) must be controlled to avoid groundwater contamination and/or to permit recirculation of the leachate through the landfill, a clay or plastic liner may be necessary at the bottom of the landfill.

Due to the capital investment required for gas recovery and utilization, a sizeable landfill is required for an economically viable LFG project. In the early 1980s experts agreed that LFG projects should be considered only at U.S. landfills exceeding the following minimums: 40 acres (16 ha) of surface area, two million tons of waste already landfilled, current intake of 150 tons per day, two more years of landfill life, and average refuse depth of 40 feet (12 m). Most of the larger U.S. projects are in landfills with a total area of 75 to 200 acres (30 to 80 ha), although the LFG system usually does not cover the entire landfill area.

The number of wells, which is usually from 1 to 6 per hectare, depends on the landfill depth and soil condition; the distance between wells can be greater if the landfill is deep and well sealed with a compact layer of soil. In most larger projects gas is drawn from 30 to 45 wells, although two large projects have about 80 wells each and a New York City system has 122 wells.

A shaft 12" to 36" (30 to 90 cm) in diameter is drilled into the landfill. The depth of the well depends on the depth of the refuse. Most wells are between 30' and 100' (9 to 30 m) deep, but some are deeper. A 3" to 8" (7 to 20 cm) diameter perforated plastic pipe is inserted into the well; the space around the pipe is filled with gravel, and the well is sealed at the top with concrete, clay, or asphalt. The wells are connected by a horizontal network of unperforated plastic pipes, on or just below the surface, which transmit the gas to the processing plant. A typical well is shown on p. 8.

Gas is sucked from the wells by one or more compressors. A small 18-well system uses a 60 HP compressor. In the large system at Penrose, California, shown in the sketch on p.10, gas is sucked from 83 wells by six 150 HP compressors. More powerful compressors may be needed in developing countries due to the higher density of the landfilled wastes. Most plants include a filter



to remove particulates and a drain for condensed moisture; some plants have a chemical filter to remove hydrogen sulphide. Other components of the central plant depend on the use of the gas.

Most landfill gas projects in the U.S. and Europe produce between 5.0 and 10.0 m^3 of gas per tonne of waste per year. Since it is difficult to estimate the original tonnage of wastes actually tapped by a given gas recovery network, data on output per tonne of waste is only approximate. Output figures tend to be lower in arid southern California and in colder areas in northern Europe, but are substantially higher in the moist warm climate of southern Florida.

In well-designed LFG projects in the U.S. and Europe the gas normally contains about 55% methane, although percentages as low as 30% and as high as 65% have been recorded. The caloric content of the landfill gas depends on the percentage of methane. It usually ranges from about 500 to 550 BTU/ft^3 (4456 to 4902 kcal/m^3, 18,656 to 20,522 kJ/m^3), but higher and lower caloric values have been recorded.

Lower percentages of methane (and thus lower caloric values) are usually the result of oxygen infiltration into the landfill; the oxygen combines with some of the methane to form additional carbon dioxide plus water. Oxygen infiltration can result from inadequate landfill cover, wells that are too shallow or too close to the edge of the landfill, or an excessive pumping rate.

2. Landfill Gas Utilization

Landfill gas is used as a fuel in several types of burners, furnaces, and prime movers; the energy produced from the gas is used for a wide range of industrial, institutional, and residential purposes. In each of the categories of landfill gas utilization described below except the last (paragraph "g"), the gas is used without the removal of carbon dioxide.

a. Space Heating and Cooling

LFG is widely used in Europe to produce steam or hot water to heat office or apartment buildings which are interconnected in district heating systems. Although waste combustion systems provide steam for district heating and cooling systems in the central business districts in a number of U.S. cities, most U.S. landfills are too far from downtown areas for this use of LFG. However, gas from a GSF Energy Inc. landfill in Los Angeles is transported through a 5.5 mile (8.8 km) pipeline to the boilers of the University of California at Los Angeles (UCLA). The use of about 4 million ft^3 (113,000 m^3) of LFG per day saves the University about $250,000 per year in fuel costs.

b. Industrial Process Heat

At London Brick Landfill Ltd.'s brick-making plant at Stewartby (Bedford), England, landfill gas is burned in five brick kilns. About 250 m^3 of LFG per hour is produced in twelve 25 m deep wells in a 72 ha landfill; the gas is used to fire 500,000 bricks per week. In a brick plant in the Netherlands most of the heat for a tunnel kiln is provided by landfill gas, but natural gas is automatically injected when pressure drops in the LFG line.

Fifty-six wells in a landfill at Richmond, British Columbia, Canada, provide 1200 m^3 of LFG per hour to the Canada Cement Lafarge plant. The gas is burned as a pilot fuel with coal slurry and waste carbon from an oil refinery, and supplies up to 15% of the energy needs of the cement plant.

c. Fuel for Industrial Boilers

LFG is used as a boiler fuel in a wide variety of industries in both the U.S. and Europe. In the U.S., industries using LFG include three oil refineries, a chemical plant, textile mill, a steel processing plant, a gypsum plant, and a sewage treatment facility. Steam produced with LFG is used in a kiln to dry concrete pipe in a plant in Canada. LFG facilities operated by a German firm provide steam to a meat packing plant, an auto parts firm, a rendering plant, and a plant producing sand, lime, and brick.

d. Electricity Generation
In Utility Steam Plants

LFG from the Aveley landfill in England is piped 2.5 miles (4 km) to a Thames Power Board steam plant and used as a base fuel in a 200,000 lb/hour boiler. After initial operation with one burner showed a payback period of less than two years on the initial investment, an additional burner was converted. Since 1981 an LFG facility operated by Gas Recovery Systems (San Mateo, California) has supplied gas to a Los Angeles power plant. Current output exceeds 4 million ft^3 (113,000 m^3) per day.

e. Electricity Generation With
Internal Combustion Engines

In the United States the development of power plants using LFG in internal combustion engines or gas turbines has been stimulated by the "PURPA" legislation described on p. 14. As a result of this law, which requires utility companies to purchase power generated by other companies and thus creates an assured market for power, landfill gas is used for power generation at over 75 LFG sites in the U.S.

A spark-ignition engine can be operated on 100% landfill gas. At more than 60 landfills in the United States, electric power is generated by using LFG in engine/generator sets originally designed for natural gas. These gensets range in output from 150 kW to 1900 kW; larger LFG power plants use multiple engines and generators.

The extent of the gas cleaning which is necessary before the gas is used in an engine varies from site to site and depends on the composition of the landfilled wastes. A refrigeration unit or other device to condense and remove moisture from the gas is included in all systems. Some plants have a scrubber to remove hydrogen sulphide. At the large Olinda facility described on p. 10, tests indicated up to 100 ppm of total chlorinated hydrocarbons which are highly corrosive to engines; these and other contaminants are removed with a proprietary solvent and are burned in an incinerator.

Perennial Energy Inc. (West Plains, Missouri) provides a transportable LFG power plant known as a "Meter-Beater" mounted on a trailer for easy shipment by truck. The compact plant includes engine, induction generator, switchgear, controls, and gas handling equipment. The plant can be ready to produce power a day after delivery. PEI has provided 100 to 150 kW Meter-Beaters and/or gas handling equipment for 11 LFG facilities. The firm installed two 675 kW Meter-beaters at a facility at Marina, California.

Pacific Lighting Energy Systems (Commerce, California) operates 11 LFG power plants in California and one in Maryland. At the smallest PLES plant in Lompoc in central California, the gas is used in a 825 HP engine which drives a 600 kW induction generator. Larger PLES systems have two or more 2,650 HP engines, each driving a 1875 kW synchronous generator. The largest PLES system, located on a 72 acre (29 ha) landfill near Los Angeles, has five engines and five generators and produces 9.37 MW. The components of the latter system are shown in the diagram on p. 10.

The total capital cost (including gas recovery system and power plant) of LFG systems in the U.S. with internal combustion engines has usually ranged between $1.0 and $1.6 million per Megawatt ($1000 to $1600 per kw). Revenue from the sale of electricity depends on the "avoided cost" rate paid by the electric utility pursuant to the PURPA law. Although one LFG firm will consider a project only if power can be sold for over $.06/kWh, some industry officials are reported to believe that $.04/kWh is the minimum price necessary to make a project profitable. A percentage of the income from power sales is paid to the local government agency or private firm which owns and operates the landfill.

Due to the more limited market for electric power, the use of LFG for power generation is less extensive in Europe than in the U.S. Those facilities which generate power usually have gensets in the

150 to 250 kW range. In each of four LFG projects operated by Biogas Systeme (Giessen, Germany), power is generated in two 250 or 450 kW gensets; each facility also provides gas for the boilers of an institution or factory.

At most LFG facilities in the U.S., the gas is used for only a single purpose. The Olinda facility of GSF Energy Inc. (Signal Hill, California) is an exception. Each day three million ft^3 (85,000 m^3) of LFG is used for power generation. The $11 million facility has three 2,650 HP engines, each driving a 1,900 kW generator; total output is 5.7 MW. GSF sells 120,000 kWh/day to Southern California Edison and 1 million ft^3 of gas per day to a Shell oil refinery.

f. Electricity Generation With Gas Turbines

Caterpillar Capital Company (San Diego, California) has supplied 22 gas turbines for installation at 13 landfills in 10 U.S. states. Twenty of these turbines produce 2.8 to 3.3 MW each. Seventeen of the turbines have been installed at landfill gas recovery facilities operated by Waste Management Inc. (Oak Brook, Illinois). WMI's LFG facility at the 83 acre (33 ha) Omega Hills landfill in Germantown, Wisconsin, has two Caterpillar Centaur gas turbines and produces up to 6.6 MW. The facility cost $4.5 million or $.68 million per MW. Caterpillar asserts that LFG systems with gas turbines, although somewhat less efficient and somewhat more expensive than those with engines, nonetheless involve lower life cycle costs due to greater reliability and reduced corrosion and maintenance problems.

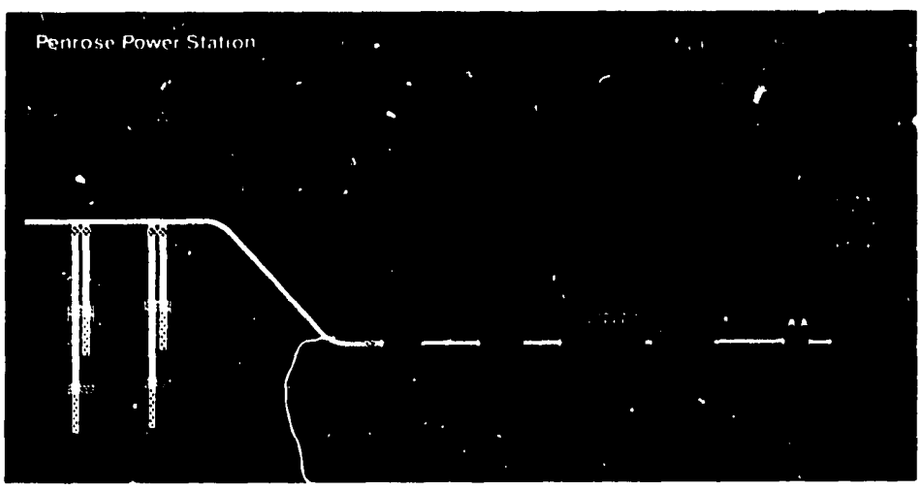
g. Use of LFG as Pipeline Gas After Carbon Dioxide Removal

At several LFG facilities in the United States, landfill gas is processed to remove carbon dioxide and the remaining gas, which is usually 95% to 98% methane, is sold to natural gas utility or pipeline companies.

Pipeline quality gas is produced at LFG facilities operated by GSF Energy near Chicago, Cincinnati, Houston, and New York. The carbon dioxide is removed in a computer-controlled "pressure-swing" process. Pressurized gas is passed through water; the methane bubbles through, but the CO_2 dissolves and is released in a subsequent depressurization stage. CO_2 can also be removed with membrane separation, molecular sieves, or chemical or distillation processes. A system operated by Waste Management Inc. at Pompano Beach, Florida, uses a chemical process with methyl diethanolamine.

The gas produced by these scrubbing systems has a caloric content of about 1,000 BTU/ft^3 (8900 kcal/m^3, 37,255 kJ/m^3) which is equivalent to that of natural gas. It is fed into the gas pipeline system and used by residential and industrial customers.

Landfill gas with a rather high caloric content (21,683 kJ/m^3, 582 BTU/ft^3) was used in the mid-1980s without carbon dioxide removal in the gas distribution system of Rio de Janeiro, Brazil. The LFG was mixed with manufactured town gas which had a caloric value of only 18,000 kJ/m^3 (483 BTU/ft^3).



3. Environmental Impacts of LFG Systems

The major environmental impacts of LFG systems are positive, while those of waste combustion systems are mainly negative.

Most cities in developing countries presently dispose of USW in open dumps. Covering the dumped wastes with a layer of soil would improve air quality by eliminating odors and smoke from the spontaneous or deliberate burning of dumped wastes. Sanitary landfilling would prevent the dissemination of disease germs from the open dumps by wind, insects, rats, animals , and scavengers in the dumps.

A gas recovery system at a landfill eliminates the escape to the atmosphere of the hydrocarbon gases which are inevitably formed during the decomposition of wastes in the landfill. Studies by GSF Energy indicated that the recovery of each million cubic feet (28,320 m^3) of landfill gas reduces hydrocarbon emissions to the atmosphere by 32 tons per day.

While leachate from sanitary landfills can contribute to groundwater pollution, this problem is no more severe than in open dumps. Landfills established for LFG systems could be designed to minimize leachate problems by sealing the bottom of the landfill and providing for the collection, disposal, or recirculation of the leachate.

4. Technical Feasibility of LFG Systems in Developing Countries

In most developing countries the waste composition, moisture level, and temperature are favorable for the rapid generation of landfill gas in properly designed landfills.

In the U.S. and Europe, only 45% to 75% of the landfilled waste is biodegradable; the USW contains substantial fractions of glass, metals, plastics, and other inert materials. Moreover, the large paper and paperboard fraction contains a significant amount of lignin, which is not biodegradable. Although the USW in some cities in developing countries contains substantial fractions of inert materials, in most cities the percentage of biodegradable materials is substantially higher than in the U.S. and Europe. In quite a few cities in developing countries 75% to 90% of the dumped waste is biodegradable.

Although the high moisture content of the USW in most developing countries restricts its use in combustion systems, high moisture is an asset in wastes to be used in LFG systems. Since the typical waste in the U.S. contains only 25% moisture, the moisture content of the landfilled wastes is often below the level required for maximum gas production. If the landfill receives limited moisture from rainfall, as is the case in semi-arid southern California, the speed of the anaerobic digestion process is rather slow. The average gas output of southern California landfills is only 2.0 to 3.0 m^3 per tonne of wastes per year, which is well below the 5.0 to 10.0 m^3/tonne/year output of most other U.S. and European LFG systems.

Laboratory tests and field observations have shown that increasing the moisture content of the landfilled wastes significantly increases the rate of gas production. Several LFG systems in the very moist climate of southern Florida produce from 20 to 30 m^3/tonne/year. Since there are no significant differences in waste composition or temperatures between southern California and southern Florida, the much higher gas production rates in Florida appear to be due to the difference in moisture content of the wastes in the landfill.

The other major factor affecting the rate of anaerobic digestion is temperature. There are two types of anaerobic bacteria. The mesophilic group are most active at temperatures around 35° C, while the thermophilic group thrive at temperatures around 50° C. The higher gas production rates from thermophilic digestion have been frequently demonstrated.

Due to the exothermic (heat-releasing) effect of anaerobic digestion, the temperature of decomposing wastes is much higher that the temperature of the surrounding soil. Recent research by EMCON Associates in northern California and by Waste Management Inc. in southern Florida indicated that the waste in landfills in those areas had reached temperatures from 45° to 60° C, the optimum range for thermophilic digestion. Most landfills in colder climates have internal temperatures from 35° to 45° C, which may exceed the optimum for mesophilic bacteria but are too cool for thermophilic digestion.

Although the USW in the interior of a large landfill is well insulated from the direct influence of

ambient air or solar radiation, the higher temperature in tropical areas of rainwater percolating into the landfill may tend to raise the internal temperature.

Southern Florida, located on a peninsula at about 25° North latitude, has a very moist climate similar to that of many lowland areas in developing countries. It seems probable that gas production rates from LFG projects in such areas would be closer to those in southern Florida than to the output from LFG projects in the northern U.S. and central Europe.

If the initial gas production rate per ton is high, the productive life of a given landfill sector will be relatively short. Although the expected life of LFG projects in southern California is usually stated as 15 to 20 years, the useful life of a project in Palm Beach County, Florida, with a very high gas production rate (30 m^3/tonne/year) is expected to be only six years. A World Bank consultant calculated that a landfill in Sao Paolo, Brazil, would produce 56% of its total gas output during the first year and that significant gas production would end after about six years.

The life of a total LFG system can be extended to many times the productive life of an individual landfill sector. Since there are few covered landfills at present in developing countries, most future landfill gas systems in those countries will undoubtedly be in landfills which have been designed for gas recovery. The layout and use of such a landfill would reflect the short period of gas production expected from each sector of the landfill. Each sector would be separated from other sectors by barriers of soil to prevent gas leakage. During a given year the centrally-located LFG plant would draw gas from several recently-filled sectors which were producing gas at high rates. New wells would be opened each year in new horizontal or vertical sectors.

Waning gas production from an older sector would be increased by temporarily removing aboveground horizontal pipes to the wells, extending the vertical collector pipes upward, adding a thick new layer of USW, covering with soil, and reinstalling the connecting pipes. Similar upward extensions of gas wells are routine practice at some landfills in the U.S. at present. If horizontal extension of the LFG system is preferable at a given site, equipment for the gas processing and utilization plant would be mounted on trailers and skiddable frames to facilitate moving the plant to a new location in another part of the landfill.

These conclusions must be considered tentative until there is adequate actual experience with the recovery of landfill gas from properly designed landfills in developing countries. The design of a LFG system at a specific site should be based on data from test wells which indicates the quality and quantity of LFG which can be recovered at that site. The data should be sufficient to demonstrate the effects of predictable variations in waste composition, moisture content, and temperature.

Landfill gas was recovered from several sanitary landfills in Brazil in the early 1980s. LFG projects in Sao Paolo, which has 80% of Brazil's sanitary landfill capacity, were suspended in 1983.

An experimental landfill gas project is being carried out at present in Sierra Leone by the German Agency for Technical Cooperation (GTZ). Although GTZ reports that the initial results are positive as regards gas quality and quantity, a technical and economic evaluation of the project will not be available until Spring 1989.

5. Economic Analysis of LFG Systems in Developing Countries

At present, analysis of the economic feasibility or attractiveness of LFG systems in developing countries is inhibited by the inability to predict the volume and quality of the gas which could be produced from landfills in those countries. In general, a cost/benefit analysis of a proposed system would evaluate capital and operating costs, and the income, savings and social benefits which would be derived from the system.

Capital costs depend on the size and characteristics of the gas recovery system, the type of gas processing and utilization, and the cost of necessary equipment and labor in the specific country. Many aspects of LFG systems, especially those related to gas utilization, are very site specific. The costs of a LFG project can only be estimated after the development of a detailed plan for the recovery and use of LFG at a specific site.

In the U.S. the costs of landfilling the USW are normally borne by the local government agency or firm which owns and operates the landfill. A

landfill gas firm usually negotiates a contract with the landfill owner which allows the firm to install a LFG system; the firm typically pays to the landfill owner a percentage of the income derived from the sale of gas or electric power.

Landfill gas could be used in developing countries for all of the purposes for which it is used in the U.S. and Europe, although some uses may be more attractive than others. The use of the gas as a boiler fuel would be feasible if there is a large potential customer for the gas near the landfill.

The use of LFG in an engine or gas turbine to produce electric power could be an attractive option in many areas in which the supply and/or reliability of grid power is inadequate. The economic attractiveness of this option would be influenced by the total cost per kWh (including capital costs) of power from the LFG system, the cost to consumers of grid power, the availability of an appropriate customer for the power (either the electric utility or a large industrial or institutional customer near the site), and the estimated income from the sale of the power.

6. Other Digestion of Organics From USW

Since the mid-1970s, several institutions and firms have conducted experiments with the anaerobic digestion of urban solid wastes in above-ground digesters. In early laboratory and pilot scale experiments, the typical substrate was a slurry mixture of the organic fraction of USW and sewage sludge with a low percentage of total solids; it was fermented in a continuous, completely-mixed digester.

In 1975 the U.S. Department of Energy awarded a contract to Waste Management Inc. to design and build a demonstration plant at Pompano Beach, Florida, to produce biogas from up to 36 tons of USW per day plus sewage sludge. The Pompano Beach plant also used completely-mixed digesters with a low percentage of total solids. A number of problems were encountered with the elaborate waste separation system and with the operation of the two 350,000 gallon (1324 m^3) digesters. Between 1982 and 1984 the waste separation facility was rebuilt, and the plant operated continuously for several months in 1985 until funds for the project were exhausted. The digesters operated at the thermophilic temperatures (50 to 60° C) for retention periods which were usually between 6 and 13 days. Biogas output was from 3 to 7 cubic feet of gas per pound of volatile solids (136 to 317 m^3 per tonne of total solids).

A pilot plant for the low solids mesophilic digestion of USW and sewage was tested recently in Sweden. A study indicated that a full-scale plant would produce 5.7 million m^3 of gas per year at a cost considered quite competitive in Sweden.

Recently, new systems for the "dry" digestion of USW have been developed in several European countries. A 284 ton/day system developed by Valorga S. A. (Vendargues, France) will begin operation in late 1988 in Amiens, France. It will include a crusher, a trommel screen, a density separator, and a magnetic separator to remove ferrous metals. The USW will be divided into three fractions. The inert fraction (10 to 20%) will be landfilled. The combustible fraction (15% to 30%) will be burned to produce steam for an adjacent industry and heat for greenhouses. The biodegradable fraction (50% to 80%) will be converted to biogas and compost in a 2,400 m^3 vertical steel digester at around 60° C and about 30% solids. During a nine-day retention period gas production is expected to be 130 m^3 per tonne of organic material. After scrubbing, the gas will be fed into the French gas pipeline network. The initial investment in the plant was about 120 million French francs or about $19 million.

A "DRANCO" (Dry Anaerobic Composting) process has been developed at the State University of Ghent in Belgium. The organic fraction of USW is digested for two to three weeks in a continuous digester at a solids concentration of 30 to 35%. Some of the biogas is burned to maintain an optimum temperature for thermophilic digestion (55° C). A plant processing 100 tons per day of the organic fraction of household refuse in a 3500 m^3 digester would produce about 160 m^3 of biogas per ton (about 16,000 m^3/day).

A "BIOCEL" process, developed at the Wageningen Agricultural University in The Netherlands, uses a batch digester operating with 35% solids at 30° C for a period of four months.

None of these above-ground digestion systems has reached full commercialization, and none has been tested in a developing country. The high cost of large steel and concrete digesters will undoubtedly preclude the wide use of these systems in developing countries.

PART THREE:

ENERGY FROM URBAN SOLID WASTES VIA COMBUSTION SYSTEMS

Several types of waste combustion systems with energy recovery have been built in the U.S. and Europe during the past decade. The principal types are (1) large plants producing high pressure steam through the mass burning of unsorted wastes, usually on sloping, moving grates; (2) smaller and/or modular plants producing lower pressure steam through the incineration of wastes, typically in starved-air and/or rotary kiln combustors; and (3) large plants using several types of waste separation devices to produce a refuse-derived fuel (RDF) for use in boilers.

Each type of system converts the energy in the USW to steam. Steam from each type of plant has been used for electric power generation, for heating and cooling, and for industrial process heat. However, the high pressure steam from mass-burn and RDF plants tends to be used for electric power generation, while the low pressure steam from smaller plants is most often used for space heating and industrial heat.

1. Large Mass Burn Power Plants

The construction of power plants using non-conventional sources of energy has been stimulated in the U.S. by "PURPA" legislation enacted in 1978. It requires electric utility companies to purchase power generated by other companies at a price equal to the costs which the utility avoids through the purchase. Most of the waste-fired plants are owned by non-utility companies and/or local governments. Power is sold to the utility at an "avoided cost" rate established pursuant to the PURPA legislation.

Research for this Report identified 41 mass burn power plants which are in operation or under construction in the U.S. at present. Each plant has a specific daily waste capacity and gross power output. The plants fall into three roughly equal groups: (1) Plants in the first group have capacities between 500 and 800 tons/day, outputs between 11 and 18 MW, and capital costs from $60 to $80 million. (2) Capacities of the second group range from 1,000 to 1,500 tons per day. These plants produce from 20 to 40 MW and cost between $70 and $160 million. (3) The largest plants process 2,250 or 3,000 tons per day and produce 60 to 80 MW; the capital costs of these plants range from $160 to $300 million.

Most of the mass burn plants are located in rather densely-developed urban or suburban areas. In most plants all of the processes occur within a single building which (except for the tall stack) resembles the modern buildings housing high-technology industries.

Refuse collection trucks enter an enclosed tipping hall and dump the USW directly or through a chute into a large refuse bunker. Since the plant operates continuously, the bunker must hold a reserve supply of USW for use at night and on weekends, when refuse trucks are not operating. The escape of odors from the tipping area and bunker area is minimized by drawing the combustion air for the furnace from the bunker and creating an inward draft through the truck entrance and tipping hall.

The waste is conveyed to the fuel hopper by a large overhead crane controlled by an operator in an air-conditioned cabin high above the bunker. Large objects which are unsuitable for burning can be set aside with the crane's grappling mechanism. In most plants the movement of the waste from the hopper to the grate is aided by hydraulic ram feeder.

Most of the mass burn plants have sloping, moving grates, but there are more variations in grates than in any other major component of these plants. Various plants use grate systems built in the U.S., Europe, or Japan. In the typical grate, underfire primary air is supplied in several individually controlled zones, supplemented by secondary air entering above the grates.

The mass burn plants in the U.S. have been designed to burn wastes with high caloric values and to produce high pressure, superheated steam. The designs for most plants assume that the wastes will have an average caloric value of 4500 BTU/lb (2500 kcal/kg, 10,465 kJ/kg).

All mass burn plants in the U.S. use waterwall boilers. In this type of boiler the hot gases pass through a chamber whose walls are lined with water-filled tubes for steam generation. The steam pressures in most of the plants are from 600 to 650 pounds per square inch (psi) or 41 to 45 bars. Some of the largest plants produce

steam at 850 to 900 psi (59 to 62 bars). After leaving the steam drum, the steam is superheated by passing it through tubes surrounded by hot flue gases. Steam temperatures range from 700 to 840° F (371 to 449° C).

The gross power output of most of the mass burn plants in the U.S. is between 450 and 750 kWh per ton of raw wastes. Ten to fifteen percent of the gross power is used internally in the plant.

Electricity generation with refuse is less significant in Europe than in the U.S. In the absence of legislation requiring utilities to buy power from other companies, sales of power to utilities are rare. Although about 70 waste-to-energy plants in Europe generate some electricity, the majority of these are smaller plants producing both steam and power for an adjacent industry or institution.

Due to the lower caloric value of the USW in Europe, the power output per ton is lower than in the U.S. A German agency indicated in 1983 that USW with an assumed caloric value of 8,400 kJ/kg (2,000 kcal/kg, 3600 BTU/lb) could produce up to 400 kWh of electric power per ton.

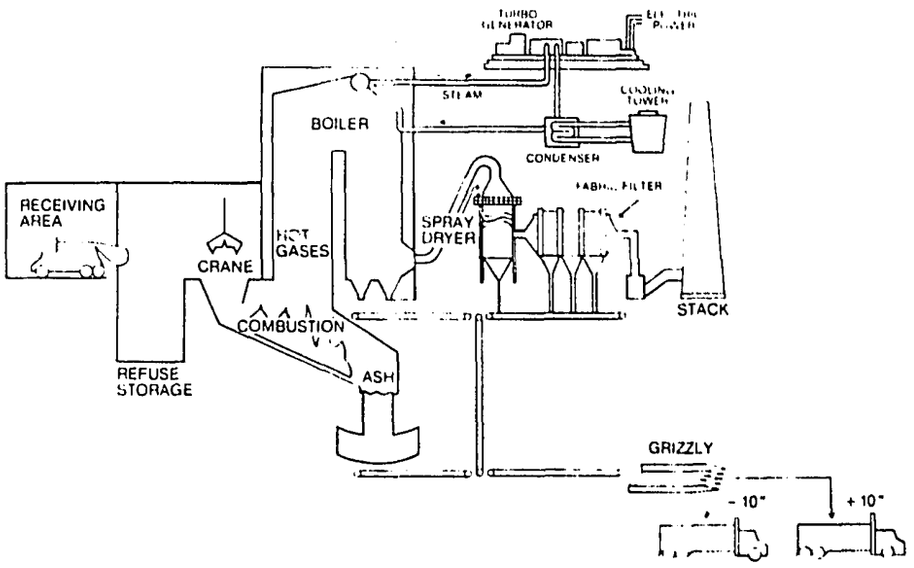
The layout of a typical moss burn plant is indicated in the sketch below of a new 2,250 ton/day plant at Bridgeport, Connecticut, built by Wheelabrator Environmental Systems Inc. (Danvers, Massachusetts).

There is no reported use of typical mass burn systems in any AID-assisted developing country nor any reported use of such systems with high moisture USW similar to that in many developing countries. Only one builder of typical mass-burn systems with grates suggested system modifications which would permit the use of high moisture USW. Babcock and Wilcox (Barberton, Ohio) proposed the use of preheated combustion air and a lower stoker grate release rate. For wastes with 25% to 35% moisture, air could be heated to 300° F (148° C) using extraction steam from the turbine with a minimal addition to capital costs. For wastes with 35% to 55% moisture, substantial modifications would be necessary to produce combustion air at 600° F (315° C); these changes would increase the capital cost of a 1,000 ton/day plant by about 45%.

2. <u>Mass Burn Plants Producing Steam for Heating and Cooling</u>

The steam produced by a majority of the mass burn plants in Europe and a smaller percentage of the mass burn plants in the U.S. is used in district heating systems. In such systems steam from a central plant is piped to a number of buildings within an urban district; the steam is used for space heating, water heating, and (in some cases) air conditioning.

Typical systems in Europe provide steam at pressures of 15 to 20 bars (217 to 290 psi) and



temperatures between 200 and 250° C. Some mass burn plants in the U.S. also produce low pressure steam, but most of the newer plants distribute high pressure superheated steam. A new plant built by Ogden Martin Services (Fairfield, New Jersey) will provide 500,000 lbs/hour (226,000 kg/hr) of steam at 510 psig (35 bars) and 710° F (376° C) through a one-mile pipeline to a downtown heating loop in Indianapolis, Indiana.

Steam from USW is used in district heating systems in at least ten U.S. cities. In most cases the USW plant meets a part of the demand for steam in systems fueled primarily with fossil fuels. Wheelabrator's new 3,000 ton/day plant in Brooklyn, New York, will provide 700,000 lbs/hr of steam to Consolidated Edison's loops which feed steam to 2,000 buildings and eight hospitals in New York City. At present 72% of the steam for these loops is generated with oil, 28% with natural gas.

Mass burn plants provide steam for space and water heating at several large U.S. military installations including a naval shipyard at Norfolk, Virginia, a navy base in Charleston, South Carolina, and an army arsenal in Huntsville, Alabama.

In Japan a number of city-owned waste combustion systems produce steam which is used in an adjacent community complex with indoor recreation areas, swimming pool, greenhouses, and/or other community facilities.

In some systems the steam is used primarily or exclusively for heating during colder months, but is used for electric power generation in warmer months. In others the steam is fed to absorption chillers to produce chilled water for air conditioning. Steam from a system at Harrisonburg, Virginia, heats university buildings in winter; in summer it is used in a 670 ton absorption chiller to air condition an indoor sports complex.

A large mass-burn plant producing steam from USW has been built in Shen Zhen, China, by Martin Gmbh (Munich, Germany) and Mitsubishi Heavy Industries Ltd. (Tokyo, Japan). The plant, which is in the startup phase, is very similar to the plants built by Martin in Europe and by Ogden Martin in the U.S. The system will apparently depend on separation by householders of the coal ash which accounts for 55% to 65% of the collected wastes in most large Chinese cities.

3. Mass-burn Systems With Rotary Combustors

Several types of smaller mass-burn systems include rotary combustors which can burn high moisture wastes. One of these is the system developed by O'Connor Combustor Corporation (Fullerton, California), now a Westinghouse subsidiary.

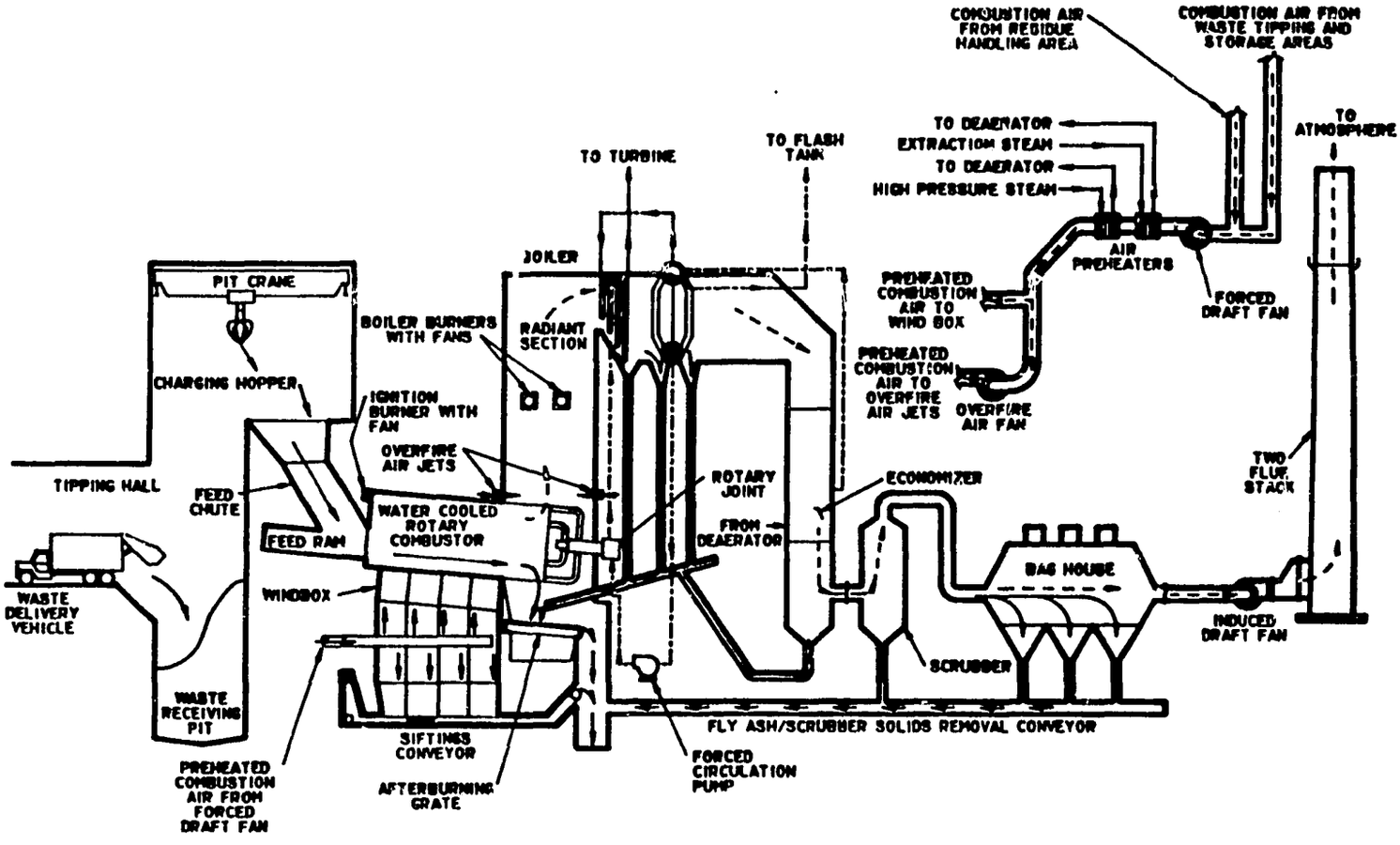
The O'Connor combustor is a hollow, water-cooled steel cylinder made of alternating water tubes and fins welded between the tubes. The fins are perforated to admit preheated combustion air. It is drawn from the tipping area and heated to 450° F (232° C) in a heat exchanger using high pressure steam and extraction steam from the turbine. Since the combustor is water-cooled, it is not necessary to use combustion air for cooling as in grate systems.

A 510 ton/day plant at Panama City, Florida, has two 120" (3 m) diameter O'Connor combustors. They burn USW supplemented with wood waste. The boiler produces 68,000 lbs/hr (30,844 kg/hr) of steam at 620 psig (42 bars) and 750° F (398° C). Gross power output is 12 MW; 13% of the power is used in the plant. The net output of 10.5 MW is sold to the Florida Power Corporation. The plant, which has been operational since 1987, cost $38 million or about $3.1 million per MW.

The use of preheated combustion air permits the O'Connor combustors to utilize wastes with up to 65% moisture; the first part of the slightly tilted combustor acts as a fuel dryer. Data from Westinghouse indicates the performance of the combustors with fuel with a higher heating value of 3,000 BTU/lb (1667 kcal/kg, 6965 kJ/kg) and 56% moisture; boiler efficiency would be 52% and power output would be about 210 kWh per ton or less than half the output with typical U.S. wastes. O'Connor rotary combustors were installed in four plants in Japan beginning in 1978 when the caloric values of the average USW in Japan were around 1600 kcal/kg (2800 BTU/lb).

Five plants using O'Connor combustors are in operation in the U.S. and three more are planned. A plant in Chester, Pennsylvania, will burn about 2600 tons/day in six units and generate 67 MW.

The layout of a plant producing steam from USW with Westinghouse/O'Connor rotary combustors is shown in the sketch on top of p. 17.



Another rotary combustor system developed in the United States is being used in a 100 ton/day waste-to-energy plant in western Malaysia. The rotary kiln technology was developed by Universal Energy International (UEI) of Little Rock, Arkansas. The plant in Kuala Terengganu, Malaysia, was built by Enercon Sd. Bhd., a firm in Klang, Selangor, West Malaysia, under a licensing agreement with UEI. The plant was built by Enercon under a contract with the Malaysian state of Terengganu. The total cost of the system was about $2.5 million.

Kuala Terengganu is located in the oil-producing area on Malaysia's west coast and is one of the highest income communities in Malaysia. Although no detailed analysis of the composition of the community's waste has been made, it may be similar to that in the Malaysian capital of Kuala Lumpur which contains the highest percentage of paper and paperboard of any Asian city (28%). Aside from paper, the rest of Kuala Terengganu's USW is mostly wet garbage. The energy content of the USW is estimated at 2500 to 3000 BTU/lb (1389 to 1667 kcal/kg or 5814 to 6965 kJ/kg.)

The USW is dumped on a flat floor and pushed by a front-end loader into a slow apron chain conveyor. A coarse shredder reduces the size of the waste and also reduces the moisture content by about 5%. A moving magnet removes virtually all of the ferrous metals, which are recycled. The shredded, metal-free waste is fed by a hydraulic ram feeder through a port in one of the stationary ends of the horizontal cylindrical kiln.

The rotary kiln is refractory-lined. It has a diameter of 8' (2.34 m) and is 30' (9.14 m) long. Primary combustion air is distributed through an air tube with a proprietary UEI design. The

shredded USW tumbles through the air stream as indicated by the arrows in the sketch below. The waste is first dried, then pyrolyzed and burned.

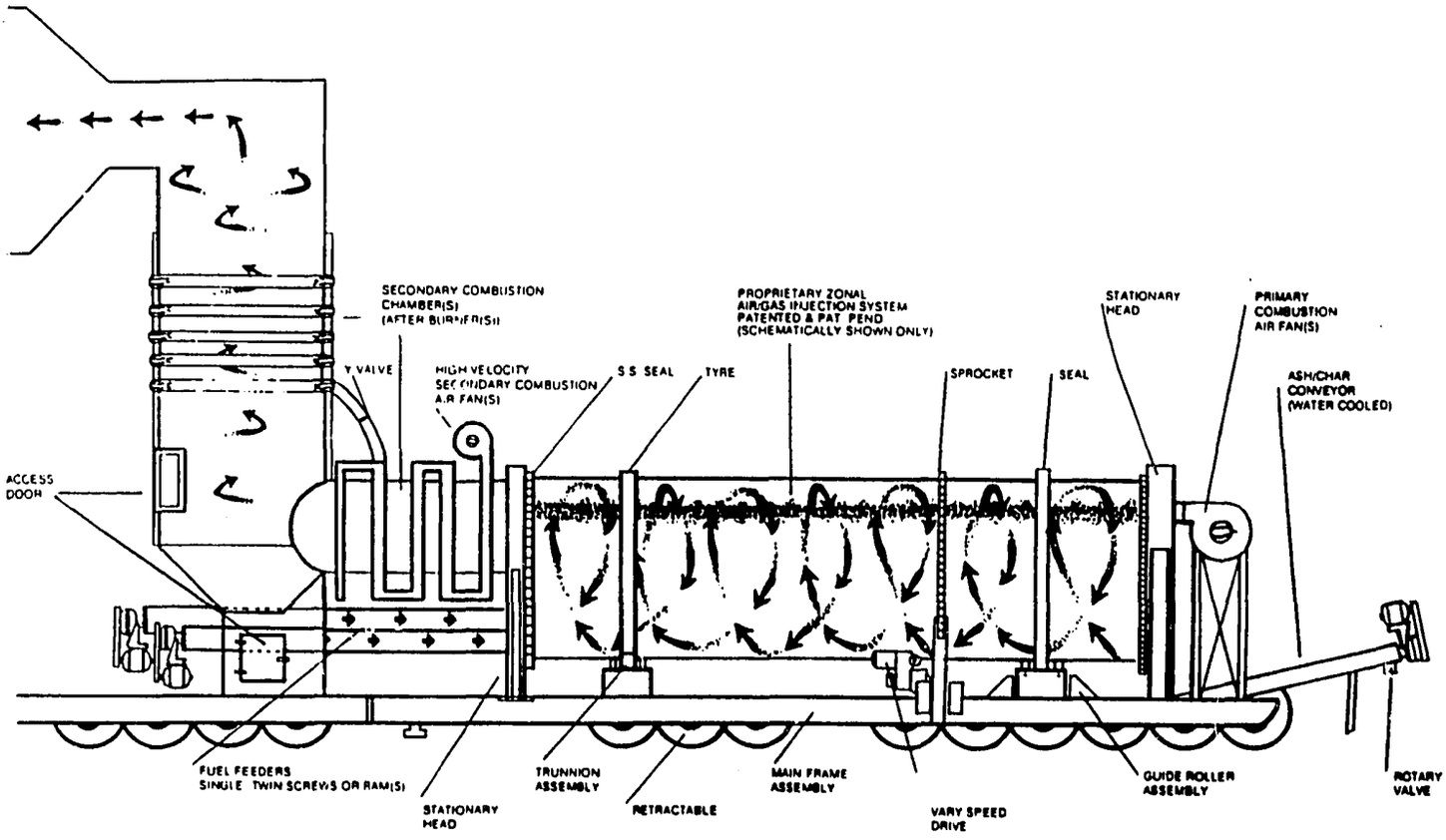
The gases produced in the starved-air kiln are only partially combusted. They flow into a secondary combustion chamber just below the tubes of the watertube boiler. Combustion of the gases is completed by mixing the excess air admitted through a pinhole grate. The secondary chamber is a vertical cylinder with a conical bottom and is designed to act as a cyclone. Fly ash drops to the bottom of the cone and is continuously removed by a screw conveyor through a rotary airlock.

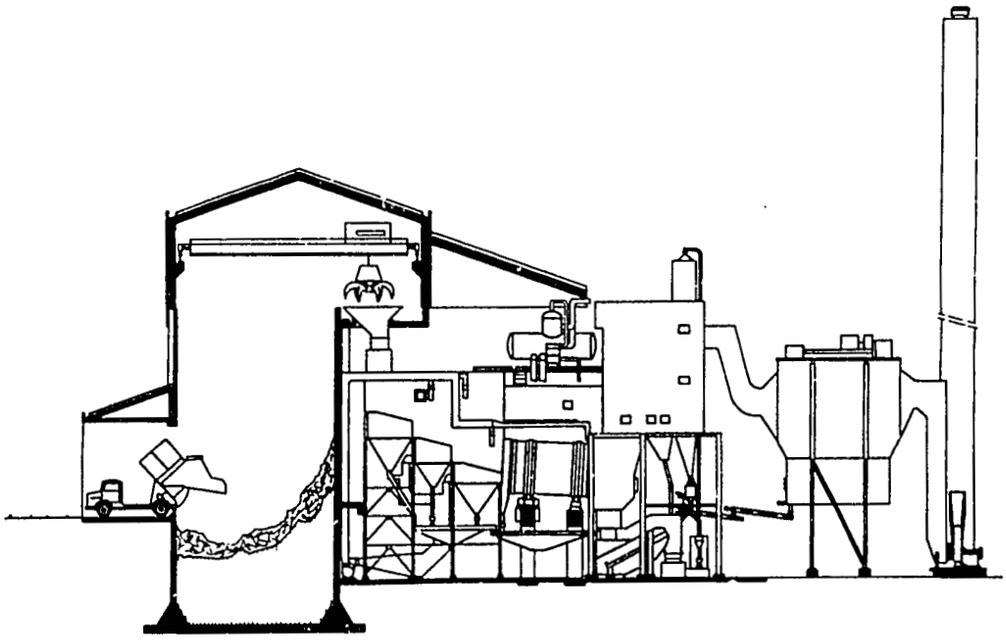
The boiler produces steam at 600 psig (41 bars) and 650° (340° C). It is used in a condensing turbine generator with a rated capacity of 1.5 MW; current output of the system is about 1 MW. The system uses about 20,000 gallons (75 m^3) of water per day.

Another system which can burn high moisture wastes has been developed by Volund A.S. (Brøndby, Denmark). The Volund system combines essential elements of both mass burn and rotary kiln systems. It has been used in the 1,000 ton/day plant built by Tampa Waste Management Energy Systems (Tampa, Florida) at McKay Bay near Tampa. Due to heavy rainfall and the substantial fraction of yard wastes, the moisture content of the Tampa USW can reach 50%.

The McKay Bay plant consists of four units, each with a daily capacity of 250 tons. After the wastes pass through a refractory-lined furnace with reciprocating step grates, they enter a refractory-lined rotary kiln. Use of the rotary kiln assures thorough burnout of all combustible materials during a total combustion period of about two hours. The McKay Bay plant produces 204,000 lbs/hr (92,534 kg/hr) of steam at 650 psig (45 bars) and 700° F (371° C); it is used to generate 22.5 MW of gross power, about 10% of which is used in the plant.

A 300 ton/day Volund system has been built at Timarpur near New Delhi in India with funding provided by the Danish International Development Agency. The plant consists of two 150 ton/





day units, one of which is shown in the sketch above. The waste is dried, ignited, and partly combusted on the grates and combustion is completed in the rotary kiln. Flue gas passes to a corner tube boiler which produces steam at 42 bars (609 psi) and 385° C (725° F). The steam is used in a condensing turbine with a rated output of 3.745 MW.

The design for the Timarpur plant assumed that the New Delhi wastes would have net caloric values ranging from 800 to 1462 kcal/kg (1439 to 2630 BTU/lb), with an average value of 1200 kcal/kg (2159 BTU/lb). Prior to plant startup in March 1987, the administration of Old Delhi was separated from that of New Delhi and only waste collected in Old Delhi was available for use in the plant. It contained a large percentage of sand and silt and had a density of 500 to 1,000 kg/m^3 and a net caloric value of only 600 to 900 kcal/kg (1079 to 1619 BTU/lb). The successful continuous operation of the plant with these wastes was not feasible.

Volund proposed (a) that a screening device be installed to remove the sand or (b) that only household wastes be used in the plant, with separate collection and disposal of street sweepings. A German consulting team was sent to New Delhi to investigate options for the operation of the plant; its report has not yet been published. At present the plant remains idle. Volund officials believe the Timarpur plant can be operated successfully if the necessary staff is hired and trained and if a continuous supply of suitable wastes is assured through the use of appropriate waste collection and/or screening techniques.

The electric power generated at Timarpur will be used for water pumping at a Delhi water works. The plant will be operated by the Delhi Electric Supply Undertaking. Capital cost of the plant was Rs. 180 million (approximately $11.5 million).

Some of the "modular" waste incineration systems described in the next section use rotary combustors. Research for this report did not reveal the use of any of those systems in an AID-assisted developing country.

In summary, systems using rotary combustors appear to offer the best prospects for combustion of USW with energy recovery in developing countries. A somewhat clearer picture of these prospects may emerge in the future as experience with the UEI system in Malaysia and Volund system in India is expanded and documented.

The typical future waste-to-energy plant in a developing country will use a fuel mixture with an average caloric content which is substantially higher than that of the average wastes collected in most cities in developing countries. Some plants will be located in higher income cities which generate wastes with relatively high average caloric values. In other cities the necessary fuel mixture will be achieved (as suggested on p. 6) by

selecting wastes from higher income districts, the separate collection of inert materials, the screening out of inerts at the plant, and/or the co-firing of USW with other biomass.

4. Smaller Waste Incineration Systems With Energy Recovery

Several U.S. firms provide factory-built modular waste incineration systems which include energy recovery. Typical modules have capacities below 100 tons per day but multiple units provide larger capacities. Some of these modular systems have rotary kiln combustors; others use a form of pile burning with various devices to move the wastes through the combustor. Some of the systems are "starved air" units in which combustion begins in a primary chamber with limited air and is completed in a secondary chamber with excess air. Other systems have a single chamber with excess air.

Most of the modular systems produce low pressure steam which is used for space heating or industrial process heat. A few multiple-module plants produce steam at relatively low pressures which is used for electric power generation. A survey in 1986 indicated that steam was the only energy product of 31 modular plants, while 5 produced electricity. As with the larger mass burn plants, these modular systems have been designed to burn the types of urban wastes available in the U.S. and Europe. Research for this Report has not revealed any use of these incineration systems with wastes with low caloric values and high moisture content. One firm indicated that its systems were capable of burning USW with a high percentage of food wastes but that a supplementary fossil fuel (coal, oil, or gas) might be needed.

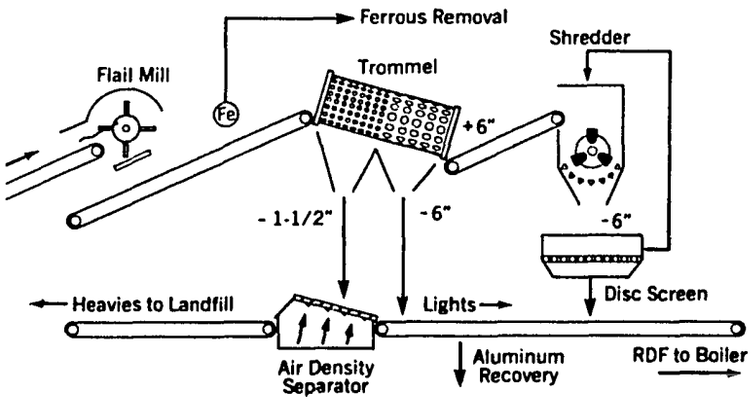
Several of the U.S. firms which provide modular waste incineration systems are currently bidding for some of the 44 incineration plants to be built under a new waste management program of the government of Taiwan. Some of the incinerators will include energy recovery. Average wastes in Taipei County are reported to have a caloric value of 1728 kcal/kg (3111 BTU/lb); moisture content is 56%. An analysis prepared by Hayden-Wegman Engineers indicated that 272 kWh of electric power could be produced from each ton of Taipei County's wastes but that the burning of fossil fuels in supplementary fuel burners would be necessary.

5. Resource Recovery Plants Producing Refuse-Derived Fuel

In another major category of waste-to-energy plants in the U.S. and Europe, several types of devices are used to remove metals, glass, and other non-combustible materials from the USW. The remaining "refuse-derived fuel" (RDF) is burned in boilers.

By 1986 about 23 of these plants had been built in the United States. Three quarters of the plants had capacities over 800 tons/day. The operation of some of these plants was limited by serious problems with the waste separation equipment and/or inadequate utilization of the RDF. A survey in early 1986 indicated that 10 of the RDF plants were closed down, six plants were operating again after suspending operations to permit modifications, and 7 plants had continued to operate. Despite these problems, a new generation of RDF plants is being built in the U.S. Another survey in 1986 indicated that 13 additional RDF plants were planned or under construction.

The waste separation system of a 2,000 ton/day plant in Palm Beach County, Florida, shown in the sketch below, includes the types of waste separation devices which are most widely used in RDF plants. The Florida plant is being built by Babcock and Wilcox (Barberton, Ohio). Each of three processing lines will contain the following components: (1) A flail mill will open plastic bags, break glass, and coarsely shred the USW. (2) Ferrous metals will be removed by a magnetic separator. (3) A rotary trommel screen will separate the wastes by size. (4) Larger items will be sent to a shredder. (5) Small but heavy particles will be removed by an air density separator and landfilled. (6) Aluminum cans will be removed



manually as the RDF is conveyed to the boiler of the 61 MW electric power plant.

The RDF produced by such a waste separation process in the U.S. consists mainly of shredded paper, paperboard, and plastics plus some sizeable pieces of organic material (garbage and yard wastes). In several European RDF plants which depend on air classification to separate out the lighter fraction, 60% to 80% of the RDF is paper and paperboard. The caloric content of the RDF from these plants ranges from 6,000 to 7,500 BTU/lb (3334 to 4167 kcal/kg, 13,956 to 17,443 kJ/kg).

Due to the extensive mechanical processing of the waste, RDF plants consume substantial quantities of electric power. A World Bank report on RDF plants in Europe indicated that from 70 to 90 kWh was needed for each ton of waste, exclusive of fuel drying which requires 100 to 120 additional kWh per ton. At an RDF plant in Florida with an especially elaborate waste separation system, 30% of the gross power output is used internally.

Some RDF systems produce boiler fuel for district heating systems. One of the earliest plants provides steam and chilled water for 20 buildings in downtown Nashville, Tennessee. A larger system produces steam for office buildings, two hospitals, a university, and a tire plant in Akron, Ohio. Steam from RDF helps heat New York state government buildings in Albany.

Several of the early RDF systems were designed to produce a light fuel which could be burned in suspension in existing boilers of utility power plants. However, several types of problems were encountered. Non-combustibles in the RDF often melted, forming slag that fouled boiler tubes. Plastics gave off chlorine and hydrogen chloride gases, which increased corrosion of boiler parts. A survey by the Electric Power Research Institute concluded that the use of RDF was "jeopardizing the efficiency, reliability, and availability" of the power plants.

These experiments led to the conclusion that the best use of RDF for power generation is in "dedicated" plants which have been specifically designed for power generation with RDF. Research for this Report has identified 13 such plants which are in operation or under construction in the United States at present. Most of these plants are quite new and quite large. Seven plants have capacities between 2,000 and 3,000 tons/day and outputs between 55 and 77 MW. The gross power outputs of these larger plants range from 472 to 735 kWh per ton of raw wastes.

In Europe, present trends emphasize maximum recycling of reuseable materials (including the paper and plastics which are the primary constituents of RDF), with less emphasis on the production and use of RDF. Some recycling plants in Germany accept only dry recyclables (paper, plastic, metals, and glass) which are dumped by householders in green bins; garbage goes in black bins and is composted, while other refuse (grey bins) is landfilled. Such recycling plants produce no energy product. A plant in Neuss has been described as the only plant in West Germany which is successfully sorting mixed USW; 65% is recycled, 40% is composted, and 25% is sold as RDF.

One of the options proposed by a team of British and other consultants for the disposal of USW in Bangkok involves the production of a refuse-derived fuel as well as compost and biogas. The "RDF" would consist of less than 20% (by weight) of the raw wastes. Published information does not specify waste separation techniques, characteristics of the RDF, or prospective uses of the RDF. No other analysis of the use of RDF technology in AID-assisted developing countries has been discovered during the research for this Report.

Two factors seem to preclude the use of RDF technology in most or all AID-assisted developing countries: (1) Waste separation systems are capital and energy intensive. Due to the lower fractions of recyclable materials (metals, glass, and paper) in the original household wastes and in the dumped residual wastes, income from the sale of recycled materials would not be sufficient to cover the capital and operating costs of the mechanical waste separation equipment. (2) The material remaining after the recyclables are removed would not resemble the refuse-derived fuel consisting mainly of paper and plastics which is produced by RDF plants in the U.S. and Europe. If the average wastes in most cities in developing countries were processed in the type of waste separation system shown on p. 20, the residual product would consist primarily of shredded garbage.

Although it seems unlikely that complete RDF systems would be feasible in developing coun-

tries, some devices used in RDF plants may be appropriate for waste combustion plants in developing countries. A magnetic separator removes ferrous metals from the USW burned in the plant in Malaysia described on p. 18. A shredder may be necessary to prepare the wastes for some types of combustors, as is the case in the plant in Malaysia. A trommel screen may be the best way to screen out inert materials in those cities in which the percentage of inerts is quite high. The typical future waste-to-energy system in developing countries may be a hybrid system with some characteristics of mass burn systems and some of RDF systems.

6. Economics of Waste Combustion Systems

An economic analysis of a waste combustion system must consider the capital and operating costs of a specific type of system at a specific site and the income and/or savings which would be generated by the operation of the system.

Capital costs are influenced by numerous variables including the type and capacity of the system, the extent of waste separation (if any), the pressure of the steam generated, the type of emission controls, and the use of the steam. A plant which produces steam for sale is less expensive than a complete electric power plant including turbine, generator, and condenser. The cost of any plant in a developing country depends in part on the extent to which appropriate components, services, and subcontractors are available within the country.

The typical U.S. waste-to-energy plant produces two types on income: (1) A "tipping fee" is paid by the waste collectors (local government or private firms) for each load of waste which is brought to the plant. The local government thus avoids the larger cost of disposal in distant landfills, which is over $50 per ton in some areas of the U.S. (2) The plant receives income from the sale of electric power or steam. Power is sold to a utility at the "avoided cost" rate established under the PURPA law. Rates for the sale of steam and for the sale of power to non-utility customers are highly influenced by the price in the area of boiler fuels, especially natural gas and fuel oil. In a developing country the cost/benefit analysis of a waste combustion system should include the social benefits (i.e., savings in medical costs) resulting from the use of a sanitary method of waste disposal.

7. Environmental Impacts of Waste Combustion Systems

The operation of a waste-to-energy plant can have serious negative effects on air quality, water quality, and water supply in the adjacent areas. In the U.S., such plants can be operated only after they demonstrate compliance with strict regulations for the protection of the environment which have been imposed by federal and state governments. Environmental protection organizations have continued to advocate tighter controls on emissions and ash disposal, and several proposals for such controls are under consideration by the federal government at present.

a. Emission Controls

In the 1980s designers of waste combustion systems (with and without energy recovery) have been required to use several types of techniques and equipment to control emissions from the plants. In the typical waste-to-energy plant in the U.S., the flue gas passes through two or more of the following devices to trap particulates:

Cyclone: In a cyclonic separator heavy particulates are driven to the outer wall by centrifugal force and fall to a bin at the narrower bottom, while the gas escapes through a narrow pipe.

Dry Gas Scrubber: The gas flows through a slow-moving bed of gravel: particulates stick to the gravel and fall to the bottom.

Fabric Filter: In the "baghouse" the gas passes through a number of fabric bags which trap fine particulates. Shaking or scraping devices remove the particulates from the bags.

Electrostatic Precipitator: Particles are negatively charged from a suspended electrode as they enter the precipitator. The gas then passes a positively charged plate which attracts the particles; they are removed by shakers or scrapers.

On another level, there is widespread public concern that emissions from waste combustion plants contain dioxins and furans which are thought to be carcinogens (i.e., substances which can caused cancer). These chemicals are formed when benzenes and phenols in the wastes unite with chlorine during the burning of polyvinyl chloride (PVC) plastic which is quite common in U.S. wastes. There seems to be a consensus in

the U.S. that dioxins and furans can be controlled by careful design and monitoring of the waste combustion system. The dioxins and furans break up into non-toxic compounds at temperatures between 1,500 to 1,800° F (815 to 982° C). Furnaces are designed to maintain high combustion temperatures and to provide long residence times. Ten plants built by Wheelabrator Environmental Systems operate at temperatures above 2500° F (1287° C).

Several U.S. plants use additional techniques to control acid gases. In one Ogden Martin plant slaked pebble lime is added to the dry scrubber to capture and neutralize acid gases; the lime is removed in the electrostatic precipitator which follows the scrubber. In some of Wheelabrator's systems, dry lime is injected into the gas stream for acid gas control and then removed in a baghouse filter. Nitrogen oxide emissions will be controlled by injecting ammonia into the furnace of a new Ogden Martin plant in California.

Foster Wheeler Energy Resources Inc. (Livingston, New Jersey) utilized a combination of combustion controls and emission controls to meet the especially strict regulations in the smog-plagued Los Angeles County air basin. The firm's 318 ton/day plant at Commerce, California, met emission requirements through carefully controlled flame intensity, furnace air distribution, furnace temperature profile, and residence time plus use of the latest dry scrubber and baghouse technology.

b. Ash Disposal

The volume of ash remaining after combustion of the wastes varies considerably from system to system. Wheelabrator and Westinghouse indicate ash volumes from their mass burn systems as low as 6 to 10%. Babcock and Wilcox gives 16% as a typical ash residue figure in mass burn systems, but indicates ash/fuel ratios as high as .24 and .27 in two large plants. Due to the removal of inert materials from the USW during the waste separation process, two plants reported only about 6% ash from the burning of refuse-derived fuel (RDF).

In some plants ash is cooled with water and then dewatered as it is conveyed to the ash container or removal system. If dry ash is dumped into containers or trucks, cooling with a water spray is necessary. In some mass burn plants metals are extracted from the ash with a magnetic separator or screening device.

There is growing concern in the U.S. that metals leaching from landfilled ash will pollute water supplies. In some areas the ash is dumped in a "monofill" dedicated to ash disposal in order to permit measures to prevent groundwater contamination by leachate. At a plant in Dade County, Florida, leachate and run-off water flow to a sealed pond and are reinjected into the landfill to avoid contamination of the aquifer which supplies most of the drinking water for the city of Miami. The U.S. Congress and the Environmental Protection Agency are considering new federal requirements for the disposal of ash from waste combustion systems.

The ash produced at some waste combustion facilities in Japan is treated prior to landfilling to prevent leaching. At some plants the ash is mixed with cement and water and hardened into pellets. At eight Japanese plants the ash is melted and transformed into granulated glass slag which occupies only one third of the original ash volume. Although it is expensive, this process controls leaching and conserves valuable space in landfills.

Uses for the ash have been found at a few plants. From 200 to 250 tons of ash and fly ash per day from the RDF plant in Dade County, Florida, are sold to a cement plant. Metal-free ash from the Wheelabrator mass burn plant at St. Petersburg, Florida, is used for roadbeds. Some of the ash from both of these plants is used to cover urban wastes at adjacent landfills.

c. Water Consumption.

Most power plants burning USW or RDF have condensing turbines with watercooled condensers. Most of the plants draw water for condenser cooling from rivers, reservoirs, wells, or the city water supply system. Limitations on the availability of water in some areas have required new methods of condenser cooling. Ogden Martin's new 750 ton/day plant in Babylon, New York, will discharge no water from the site; wastewater will be recycled and reused and leachate from an adjacent landfill will be purified and used as makeup water for the steam plant. Two of the firm's plants in Connecticut and Florida will use effluent from sewage treatment plants for cooling water, while another Ogden Martin plant in Massachusetts will have air-cooled condensers.

SUMMARY AND CONCLUSIONS

1. The total volume of urban solid wastes which is currently being collected in many cities in developing countries equals or exceeds the capacities of most waste-to-energy systems in the U.S. and Europe.

2. There is an urgent need to reduce the health and environmental problems arising from the open dumping of most of these wastes. These include odors, smoke, water pollution, and the spread of disease by insects, animals, and human scavengers. These problems could be minimized by the use of covered landfills and/or by the incineration of at least some of the wastes.

3. Due to the high percentage of biodegradable material and high moisture content of typical wastes as well as high ambient temperatures, properly landfilled wastes should produce large quantities of landfill gas in relatively short periods in most developing countries.

4. Landfills designed for gas recovery in developing countries would draw gas successively from horizontal and vertical layers of recently-deposited wastes.

5. Although the average caloric content of the collected wastes in most cities is too low for combustion in typical mass burn systems, the caloric content of the fuel for a waste combustion system could be increased by selecting wastes from higher income districts, screening out inert materials, and/or co-firing with other biomass.

6. Several presently available systems using rotary combustors are apparently able to operate effectively with wastes with relatively low caloric content and high moisture levels.

7. Due to the small fractions of plastics and paper in the collected wastes, systems designed to produce a refuse-derived fuel (RDF) consisting primarily of paper and plastics do not appear attractive in most cities in developing countries.

8. Options for the use in developing countries of steam from waste combustion systems and of gas from landfills are as wide as in the U.S. and Europe. Power generation options may be attractive in areas where the supply or reliability of grid power is inadequate. The economic feasibility of a proposed project depends on estimates of capital and operating costs and of income from tipping fees and energy sales.

9. Landfill gas and waste combustion systems with energy recovery in developing countries should be planned and managed as multi-purpose projects in which the primary objective is the reduction of health and environmental hazards arising from the open dumping of urban solid wastes. While they may not be highly attractive if viewed only as energy-producing facilities, the income produced by such facilities may at least provide the means of financing the solution to serious health and environmental problems.

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