WASTE-TO-ENERGY POWER PLANTS

Nature itself produces wastes such as dead branches, leaves, and sun-dried grasses. Primitive societies, once they had learned to master fire, used the energy in these wastes for cooking and heating. These wastes can be considered the baseline level above which modern civilization produces vastly increased flows of waste. A large proportion of these "modern-civilization" wastes is paper and cardboard, also derived from trees and grasses and also a principal source of energy. It is called *biomass* along with industrial wastes such as wood chips and sawdust, agricultural wastes such as sugarcane residues, and animal-husbandry wastes such as feedlot and chicken-house bedding. Industrial wastes with substantial energy content come from petroleum and chemicals and from their products, such as plastics, vehicle tires, and used oil.

The quantities are large and still increasing. In the hundred years from the early eighteenth century to the same period in the nineteenth century, the refuse yards to which all the solid wastes of the city of Edinburgh, Scotland were brought remained the same size (1). The thrifty people in charge sorted and sold or gave away everything that was brought in. The industrial revolution changed that situation radically. Municipal waste collections in Manchester, England increased 50 times from the 1930s to the 1990s (2). Domestic wastes collected from U.S. homes doubled in the 1960 to 1995 period to about 1.5 kg per person per day (kg/p/d) (3). These *post-consumer* wastes are those that are usually considered when the solid-waste situation is discussed. However, animal feedlot and manure wastes approach 20 kg/p/d (that is, 20 kg for every man, woman, and child in the United States, not just for those connected with animal raising) (4). Crop wastes are about 8 kg/p/d. Mining wastes in the United States have been estimated at 13 kg/p/d, but these have little energy content, in general. A list giving broad estimates (depending greatly on definitions of waste categories and subject to large uncertainties) is given in Table 1 (5). These estimates are sufficient, however, to indicate the problems and the opportunities.

Not included in this list are oil-refinery wastes, estimated to be capable of producing a steady output of 135 GW of electricity worldwide in 2010 (6), and the used oil (about 4.5 billion liters in the United States in 1990) and old tires from motor vehicles (around 125 million per year in the United States).

In this compendium, the predominant liquid wastes from which energy may be produced differ little in character from one country to another around the world, although the quantities produced, both absolutely and per person, obviously differ widely. The constituents of solid wastes vary considerably,

Table 1. Organic Wastes Produced in the United States in 1971[a]

	Mass (10^6 tonnes)[b]	
Source	Total	Readily Collectable
Agricultural crops and food wastes	390	23
Manure	200	26
Urban refuse	130	71
Logging and wood manufacturing residues	55	5
Miscellaneous	50	5
Industrial organic wastes	44	5
Manicipal sewage solids	12	1.5

[a] The total has a potential energy equivalent to 175 billion liters of oil per year.
[b] Dry ash-free basis.

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however, both within large countries and from one country to another. In the United States and elsewhere, the climate has a large influence, with the municipal collections in the south and west of the country being dominated by palm fronds at certain seasons of the year, for instance. In poorer countries such as Lebanon, urban wastes have less paper and more food wastes (generally disposed of in sink grinders in richer countries), so that the moisture content is higher and the overall quantity per person is lower (7).

THE PROBLEMS OF SOLID-WASTE PRODUCTION AND TREATMENT

It is generally conceded that as countries move to what is generally regarded as the western model, the production of consumer goods, packaged food and drink, newspapers and magazines, and everything associated with automobile transportation increases very greatly; that the resulting solid-waste flow increases enormously in quantity and variety, including a large number of noxious and toxic materials; that a large proportion of citizens are careless in disposing of these wastes; and that the authorities responsible for collection and disposal of wastes do not always use the highest standards that could protect future generations from harm. The following aspects are less-publicized aspects of the solid-waste problem.

Are We in Danger of Burying Ourselves in Trash?

We are not, in the overall sense, burying ourselves in trash. A large proportion of the materials we use comes from quarries, mines, and the like, and we leave most of these sites unfilled. A "satellite's eye's view" of the material-transportation network of any country would show trains, barges, and road vehicles taking materials from mines and quarries principally into towns to be used in buildings and roads and industry. A large proportion of these vehicles would be empty on the return trip. [Cities in the past did, however, frequently get buried in their wastes. Some medieval German cities avoided this danger by requiring that wagons that had brought in produce take out wastes to be deposited in the countryside (1)]. A project investigated in the early 1970s by the New York Central Railroad to transport compacted wastes from New York City to a large quarry near a small town in Ohio failed because the town residents, who had anticipated enduring about five years of noise and dust in return for a golf course and other recreation areas created as part of the agreement, discovered that it would take 175 years at then-current rates of production of New York solid wastes to fill the quarry. Even the prospect of residing tax-free from the fees paid on the disposed refuse was insufficient inducement for the townspeople to agree to the scheme.

Concerns about Transporting Wastes to Landfills

There are two primary concerns over transporting wastes to landfill them in distant sites. One is of little importance: the cost of doing so. We as a society have been parsimonious in allocating resources to reduce the impact of our wastes, and the costs of transportation and of responsible treatment are considerable only in relation to the almost negligible costs of the past. [In 1970 the landfill costs for the author's then-home city of Cambridge, Massachusetts were officially given as 50 cents per tonne. In the 1990s the disposal costs (additional to collection costs) for this urban region of the country were in the region of $100 per tonne.] We can afford to do much better. The second concern has more validity: the as-yet unsolved problem of groundwater pollution. Modern solid wastes, even those collected from homes, are extremely heterogeneous, incorporating used batteries, containers with paints, varnishes, cleaning solutions, pesticides, fungicides, unused medical drugs, and many other potentially toxic materials. Industrial wastes can include all types of noxious solids and liquids. Rain percolates through refuse dumps, dissolving some solids and combining with some of the liquids to produce what is known as *leachate*. If this passes directly into an aquifer, drinking-water wells in the vicinity can be rendered hazardous within a short period of time. If there is no nearby aquifer, a leachate "plume" spreads out underground and moves slowly, perhaps only a few meters per year. Soil scientists estimate that in some cases these noxious plumes may not pollute an aquifer for thousands of years. However, in most cases the pollutants will begin to appear in regional water within tens or perhaps hundreds of years. Many efforts are being made to devise methods by which such plumes can be contained or diverted, but none has yet proven effective.

Rules have therefore been established for the safe landfilling of solid wastes (so that a landfill differs from a dump in that such rules are nominally followed). The pits are lined with waterproof clay or a membrane of urethane or other long-lasting and supposedly impenetrable material. The leachate is collected at the lowest point of the liner and taken to a treatment facility. However, public concern over alleged (and often confirmed) serious health effects from polluted drinking water and perhaps from gaseous emissions from old dumps, as well as public confidence that landfill safeguards will operate perfectly for hundreds of years, is so low that it is very difficult to get acceptance for the establishment of new landfills.

Concerns Over the Incineration of Solid Wastes

The open burning of refuse was, in the distant past, acceptable in rural areas but prohibited in towns. Controlled burning in an enclosed furnace with a high stack to disperse the smoke seemed to be an advanced solution for towns when the first so-called incinerator was built in England in 1874. Incineration was not practiced in the United States in the period up to the 1970s to the extent that it was followed in Europe and elsewhere. However, in the late 1960s a "solid-waste crisis" was declared in the United States, and a period of intense research and of the adoption of improved treatment measures followed. (These beneficial activities were unfortunately cut short by the "oil crises" of 1973 to 1978). Partly as a response to the concerns over putting solid wastes in the ground, the burning of wastes, often with no attempt at energy recovery, became popular. However, suspicions that the smokestack emissions from incinerators were also responsible for serious health effects grew. Consequently, it has been difficult to get public acceptance of new incinerators, even those equipped with sophisticated air-pollution-control equipment such as electrostatic precipitators. Gases such as dioxins and hydrogen chloride can pass through these units. If exhaust-gas water-spray scrubbers (an expensive solution often requiring the use of additional fuel oil to reheat the gases before discharge) are used, a potentially noxious sludge must be disposed of.

THE OPPORTUNITIES

Problems lead to opportunities. The opportunities are particularly attractive in the waste-to-energy area, although not in the relatively unsophisticated incineration plants of the past. These involved, in general, so-called "mass burning" of untreated or minimally separated wastes and had low thermal efficiencies (expressed as the output of useful heat or useful power divided by the calorific value of the wastes). Low efficiencies imply high-temperature high-volume discharge of exhaust gases, difficult and expensive to treat. The attainment of high efficiency in itself results, therefore, in a reduction of pollution, in that the exhaust flow and temperature are reduced. It is easier to incorporate exhaust-cleaning systems. Nitrogen oxide emissions will probably be greatly reduced. Dioxin emissions are also likely to be reduced.

To reduce emissions from incinerators, better control systems are needed. Even the most highly sophisticated control system cannot greatly improve the combustion process in mass-burning in which, for example, a piece of dry tissue paper may be close to a stack of water-soaked telephone books. One is consumed in a fraction of a second, while the other dries and smolders for hours. Therefore there is also a need for better fuels.

This is an area in which we have retrogressed to some extent. The incinerator near where the author grew up in Great Britain in the 1930s and 1940s had a so-called "picking belt" on which all incoming refuse was loaded. The belt lifted the refuse through two or three meters to a horizontal section over an elevated floor and hoppers. Four to eight people (called *pickers*) would be stationed beside the belt, each with a responsibility to remove useful or noxious or difficult-to-burn items in a restricted category and to deposit them into a hopper. Thus an income was generated from the sale of ferrous and nonferrous metals, newspapers, and so forth, and a more uniform feed went to the incinerator. The exhaust emissions were also less liable to be contaminated with the products of combustion of paint and pesticide cans and the like. In the late 1980s and 1990s there has been a revival of the picking belt, along with research and development work to automate it, to produce a more homogeneous combustible product. This operation is called *full-stream processing* (3).

A further improvement in the fuel is to use hammer mill or other types of shredders to produce a more uniform fuel from a stream out of which undesirable components have been separated. (Serious explosions have occurred in solid-waste hammer mills into which partly full cans of gasoline and live ammunition, for instance, have been fed, so that sorting of the input is necessary.) The shredded waste, mostly paper and plastic, can then be fed (normally after warming and moisturizing) to a briquetting or pelletizing unit. The product is called refuse-derived fuel (RDF) or sometimes densified RDG (d-RDF) (8); it can be stored, transported, fed and burned in the same way as coal. If the presorting is done effectively, it has much lower emissions than coal. It has been frequently co-fired with coal in utility steam generators with the purpose not only of reducing the emissions to below some regulatory limit but of reducing the cost of the fuel. (Power companies can indeed charge a "tipping fee" for the acceptance of wastes; the greater the degree of pretreatment, the lower the fee.)

The final degree of pretreatment is to convert the wastes into a liquid or gaseous fuel of desirable characteristics. Doing this has two beneficial side effects. One is that the treatment process is in effect a chemical plant, out of which there is tight control of all effluxes. The other is that the clean fuel so produced can be burned in processes that have much higher potential thermal efficiencies, and possibly much lower capital costs, than incinerators. These improved processes will be discussed below, after a review of the baseline mass-burning waste-to-energy plant.

ALTERNATIVE METHODS OF RECOVERING ENERGY FROM WASTES

Mass-Burning Incinerators Raising Steam

Incineration may be carried out without any attempt to recover energy from the combustion heat. Energy recovery in association with incineration should be welcomed, although the power generated from the wastes must perhaps be looked upon only as a byproduct. Perhaps surprisingly, the costs of incineration with and without energy recovery are similar in many cases examined (see below) because cooling of the gases reduces the cost of the gas-cleaning equipment required and thus compensates for the added costs of heat-recovery equipment.

In cooler climates there is sometimes a market for the low-quality steam produced from incineration plants for district heating. Electrical energy production from incineration normally uses systems based on steam turbines. Scores of such plants have been operating regularly all over the world. A steam-cycle waste-to-energy plant would seem to be an improvement over mass-burn facilities with no energy recovery. On the other hand, steam-cycle plants have rather low efficiencies (15–25%) and thus produce a low power output for a given flow of wastes. Therefore the additional costs associated with power production may not be justified. Figure 1 (7) gives

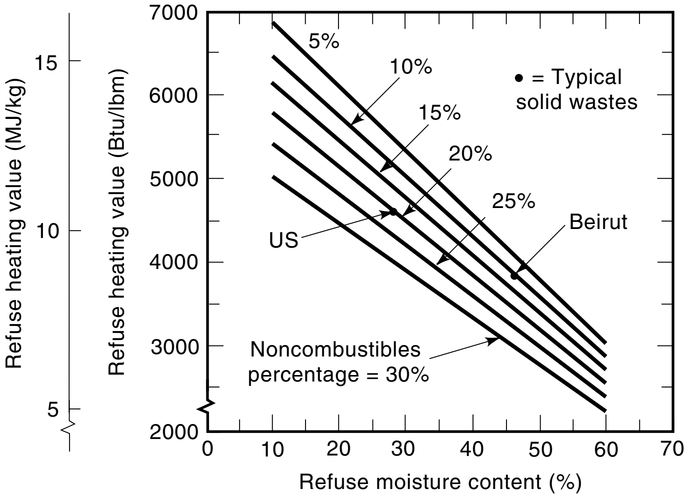

Figure 1. Refuse heat values versus moisture content and percentage of noncombustibles. (From Ref. 7.) Moisture content depends on presence of food wastes, on climate, and on collection practices, and has a large influence on heating value.

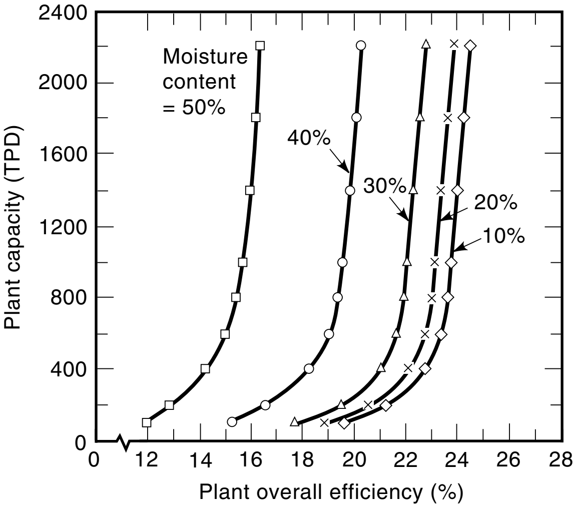

Figure 2. Overall plant efficiency of steam-cycle plants versus refuse capacity and moisture content (steam conditions 41 bar, 400°C). (From Ref. 7.) This chart emphasizes the effect of the data shown in Fig. 1: moisture content beyond 20% has a strongly negative effect on the efficiency of traditional steam plants, especially at lower capacities.

refuse heating values versus moisture content and noncombustibles content, with typical refuse compositions for Beirut and for the United States shown on the plot. Beirut is chosen as an example of an urban area not totally overtaken by consumerism. The overall efficiency depends on the moisture content and the capacity of the plant as shown in Fig. 2.

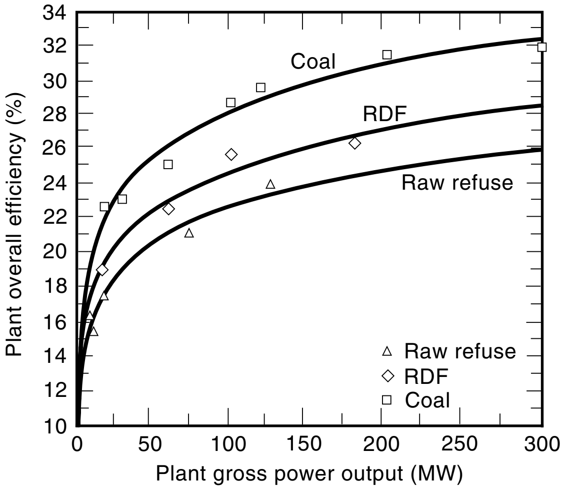

Figure 3. Steam-plant overall efficiency versus output power for different fuel types. (From Ref. 7.) The different fuels result in different plant overall efficiencies, principally as a result of their moisture content (see Fig. 2).

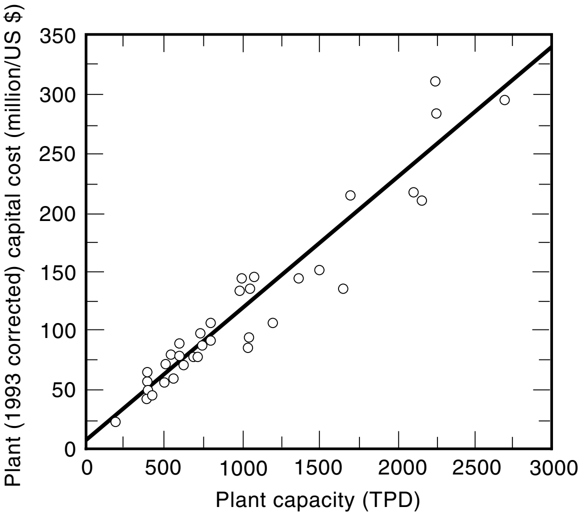

Figure 4. Capital cost of waste-to-energy plants versus capacity. (From Ref. 7.) There is remarkably little variation in capital cost per tonne-per-day capacity with size.

Data on coal-, RDF-, and raw-refuse-burning facilities allow the generation of a graph such as shown in Fig. 3. Plant efficiency is shown to be directly proportional to the kind of fuel used: The better fuel strongly affects the boiler efficiency through better combustion, as well as through permitting higher steam pressures and temperatures without excessive boiler-type corrosion. [Useful information on RDF combustion and emissions is given by Lockwood (9).]

Modern mass-burn facilities provide an efficient, environmentally tolerable, but expensive way to help dispose of the ever-increasing amount of solid waste. Figure 4 gives the capital cost in the United States versus capacity for a number of incineration facilities; the cost per tonne-per-day (TPD) capacity is found to be fairly uniform. The capital cost of the latest U.S. steam-cycle plants appears to be about $130,000 per daily tonne capacity [Engdahl (10)]. Furthermore, data indicate that the prices of RDF and mass-burning water-wall installations are indistinguishable. This similarity results from the extra cost of RDF front-end preparation being offset by the comparatively smaller furnace and emission-control system that is required, according to Rigo and Conley (11).

To make the steam-turbine waste-to-energy system economical, the capacity should be at least 500 TPD. Figure 5

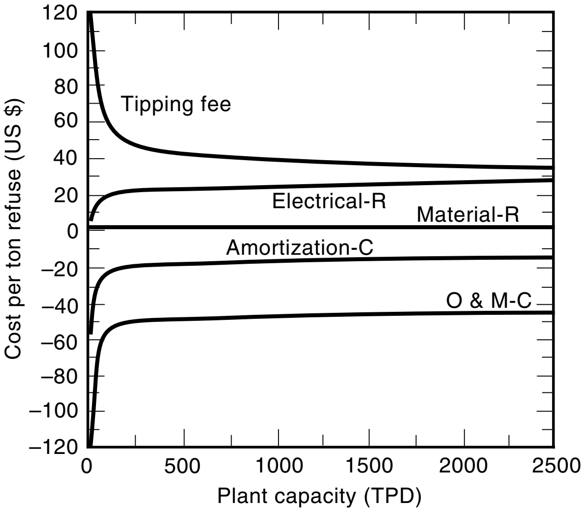

Figure 5. Component costs versus steam-plant capacity. (From Ref. 7.) The *tipping fee* is the charge per tonne needed in US conditions to operate the facility without a net loss.

shows the component costs and revenues in the United States versus plant capacity. The figure also shows the minimum disposal or “tipping” fee needed in the United States to balance the operation, with electrical sales and material recovery considered the principal income earners. A tipping fee is seen to be necessary and decreases very slowly with capacity above 500 TPD: It is nearly equal to the electrical revenues at a very large capacity (over 2500 TPD).

Co-firing of Wastes in Utility Boilers

Municipal wastes converted to RDF are being successfully fired along with conventional fuels in utility boilers. The conventional fuel is generally coal, because RDF as pellets or briquettes can be handled by similar equipment and has similar residence times in the furnace. A typical proportion is to have 25% of the heat input from RDF. A Swiss enhancement of RDF, described by Haneda (12) as “epoch-making,” mixes calcium compounds, presumably lime, with the RDF. This stabilizes the RDF pellets mechanically, prevents the degradation that has been a problem with RDF, and produces “exhaust concentrations of hydrogen chloride and dioxins [that] were virtually zero.” Because these two pollutants are the primary concern of people living near refuse-burning plants, this development could indeed be significant.

The US Department of Energy, in connection with its program to encourage biomass conversion to electricity, gives the efficiency of the co-firing option at 1.81 MWh/t, versus current steam-raising incinerators averaging 1.03 MWh/t. Another way of expressing efficiency is that the highest thermal efficiency of electrical generation from mass-burn incinerators is under 25%, whereas when RDF is co-fired with coal in utility plants the thermal efficiencies range from 35% to 43%, the levels for the steam plants themselves.

Another waste stream that has been co-fired with coal is that of used automobile tires. A pulverized-coal boiler (which required considerable modification in the feeding mechanism) in Toronto, Ohio burned up to 20% whole tires, one tire every 10 seconds (13), in a test of the process. There was a 36% reduction in emissions of nitrogen oxides, a 28% reduction in particulates, and a 14% reduction in sulfur dioxide. The heat rate (efficiency) also improved. Another successful test used fluidized-bed combustors to burn a mixture of coal and shredded tires (with the wire bead removed). This is a combustor in which the combustion air is fed through a grate at the bottom with sufficient velocity to maintain the coal particles, limestone, and pieces of tire in an airborne (fluidized) state. There are several types of fluidized-bed combustor; they are particularly effective in burning “dirty” fuels like coal, partly because intimate contact is given with limestone and other absorbents to remove sulfur and other pollutants. Shredded tires have also been burned in 560 MW cyclone boilers at Illinois Power’s Baldwin plant. The company estimated fuel savings of two-thirds of a million dollars annually while reducing coal consumption by 80,000 tonnes and reducing sulfur dioxide emissions by over 3000 tonnes (13).

Three plants in the United States are totally fueled by scrap tires, taking about 10 million tires annually (13). (About 120 million automotive tires are discarded annually in the United States).

Another fuel that has been co-fired with solid wastes is oil shale, in the proportion of 75% RDF to 25% oil shale on an experimental basis (14). The shale contributes energy and acts as an additive or absorbent to remove sulfur dioxide, hydrogen chloride, and other pollutants.

Fueling Gas Turbines with Wastes

Almost all modern utility-plant construction entails gas turbines, alone or, more usually, in combination with steam turbines. The firing temperatures (at entry to the turbine rotors) reached 1700 K by the late 1990s, when steam cooling was adopted for the high-temperature rotor blades. These high temperatures produced high turbine-exhaust temperatures, sufficient to produce high-pressure superheated steam without supplementary firing when the exhaust gases were fed to a steam generator. This in turn supplies a steam turbine. The combination is called a *combined-cycle gas turbine* (CCGT). A gas turbine requires considerably cleaner fuel than does a steam plant, and all high-efficiency plants burn natural gas or a refined fuel oil related to kerosine. It seems, therefore, that if a gas turbine, a CCGT, or a stand-alone unit is to be fueled by wastes, these have (with two exceptions discussed below) to be converted to a gas or liquid fuel. A review of some alternative processes and of the plants that have been proposed to use them is given later. First we make mention of some approaches to direct burning of wastes.

There have been some unsuccessful attempts in the past at producing a gas turbine that could burn solid wastes directly, for instance the CPU-400 process of Combustion Power Corporation (15). A larger effort has been devoted to burning coal in gas turbines, either indirectly in the successful closed-cycle turbines developed by Escher-Wyss, discussed by Keller (16), or directly in various open-cycle experiments funded by the US Department of Energy and reviewed by Webb (17). None of the experimental units had reached commercial viability by the mid-1990s.

The present author has been working on a modification of a gas-turbine cycle adopted for the US Navy: the intercooled-regenerative cycle (18). The compressor is split into two units separated by a water-cooled intercooler. The compressor-delivery air then passes through a heat exchanger heated by the turbine exhaust augmented by a second combustor, the addition of which is the principal modification to the cycle (Fig. 6). The fuel needed in the first, high-pressure (so-called “topping”) combustor is thereby greatly reduced. In the unmodified intercooled-regenerative cycle there is only one, high-pressure combustor). The purpose of the modification to this cycle is to avoid contact of the solid-fuel constituents with the highly stressed turbine blading while allowing a high turbine-inlet temperature to be used to produce high efficiencies (50% to 60%). About one-half the thermal input is through the low-pressure combustor, and about one-half is through the high-pressure combustor. This design is named the supplementary-fired exhaust-heated gas turbine (SFEHGT). The refuse combustor burns RDF in a fluidized bed together with sorbents such as lime. It is unlikely that hot-gas cleanup will be needed. However, it has been tentatively specified. Various hot-gas-cleanup systems for coal combustion are being developed for the US Department of Energy; they are reviewed by Webb (17). The process uses a moving-module regenerator patented by M.I.T. To withstand the high temperatures transferred from the RDF combustor the heat-exchanging surfaces are of ceramic honeycomb. The ceramic modules are assem-

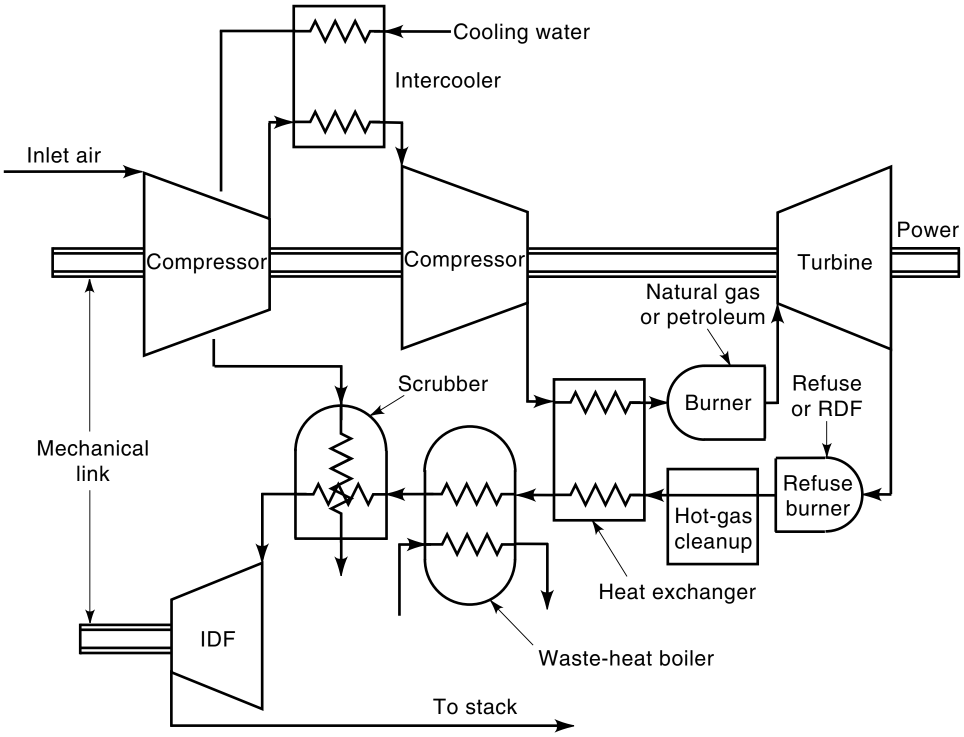

Figure 6. Supplementary-fired exhaust-heated gas turbine (SFEHGT) cycle diagram. (From Ref. 7.) This is, loosely, an intercooled-regenerative gas turbine with the addition of a refuse burner in the turbine exhaust, and an induced-draft fan after a scrubber.

bled into two heat-exchanging “faces” as they are shuttled around a closed loop (Fig. 7). Modules can be individually replaced for servicing without shutting down the plant. The regenerator is described by Wilson (19). The gas leaving the regenerator at just under atmospheric pressure passes to a waste-heat boiler to produce low-quality steam or hot water; doing so further cools the gases, thereby aiding in exhaust-gas cleanup. No credit for the energy content of this byproduct has been assessed in calculating the overall thermal efficiency. The gases leave the waste-heat boiler and pass to a water-spray scrubber that (a) removes chlorides and other soluble and condensable pollutants from the exhaust flow and (b) cools the gases to close to atmospheric temperature. A motor-driven induced-draft fan takes the cool moist gas up to atmospheric pressure. It could therefore be of fiberglass or similar low-cost construction. Its use has two advantages. It increases the incineration-plant thermal efficiency by reducing the turbine back pressure. It thus allows hot gas to be expanded further, while cold gas is compressed at a lower cost in power than the increment delivered by the turbine. It also aids in simplifying the feed process for the RDF through reducing the pressure in the solid-waste combustor to slightly below atmospheric pressure. The use of two combustors thus allows very high efficiencies to be obtained in a gas-turbine plant that has direct combustion of RDF and that does not require an associated steam-turbine plant. This process is in the laboratory stage.

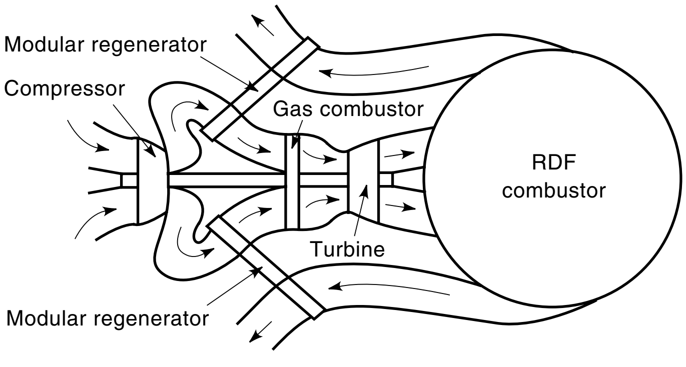

Figure 7. Conceptual sketch of a gas turbine plant. (From Ref. 7.) An attempt has been made to show the size of the RDF combustor (which could be an incinerator) in relation to those of other components.

Alternative Technologies for the Conversion of Wastes to Clean Fuel

One gasification process should be mentioned first: natural decomposition. Gas turbines have run on sewage gas at least since the 1950s, and from at least the early 1980s large landfills have been capped and drilled to supply fuel gas, largely methane, to gas turbines.

Three methods of improving on the slow natural processes have been strongly advocated, but have not been successfully put into practice to the end of the 1990s. Pyrolysis or starved-air combustion involves heating solid wastes in the absence of sufficient air to achieve full combustion, an established process (carbonization) for converting coal into coke and coal gas. The products of the pyrolysis of solid wastes are a char and a gas. The carbonization process, as recommended by Beer (20), is particularly suitable to the SFEHGT cycle discussed above.

The two other processes are acid and enzymatic hydrolysis of organic wastes to produce ethanol. Lynd et al. (21) point out that the technology for ethanol production from cellulosic materials is fundamentally different from that for production for food crops. (Fuel ethanol is successfully produced by fermentation, in Brazil from sugar cane and in the United States from corn and other starch-rich grains.) Lynd et al. state that 1990 production cost of ethanol is similar for the two forms of hydrolysis. However, the enzymatic process was at an earlier stage of development and was likely to be the more cost-effective after further research. Neither had favorable conversion economics in 1990. The authors point out that there is a considerable quantity of solid material left after hydrolysis that, after dewatering, could be used as a solid fuel.

Gasification. The most promising methods of burning coal (and, potentially, solid wastes) in gas turbines appear to involve the use of gasifiers (e.g., the Lurgi), which have been long established. They can be air-blown or oxygen-fed; the latter brings a large increase in the capital cost and a large decrease in the quantity of gas to be cleaned. Further reduction in cleaning requirements can be brought about by incorporating catalytic cracking to convert the tars and other heavy constituents to lighter fractions, according to Ghezzi et al. (22). These authors state that the technology is as-yet experimental for municipal solid wastes. Emsperger and Karg (6) claim that gasification (in the integrated gasification combined cycle, described below) could be implemented in 1996 for the large quantities of oil-refinery wastes.

Alternative Cycles for the Efficient Conversion of Clean Fuels (23)

Combined Cycles. The combined cycle is the most-used variation of the basic gas-turbine cycle in the last few years of the twentieth century. The simplest form is the combined-heat-and-power plant, or CHP (Fig. 8). A gas-turbine engine exhausts hot gas into a heat-recovery steam generator (HRSG). The steam from the HRSG is led to a process application (for instance, a paper-making plant) or to building or district heating. In a true combined-cycle plant the steam operates a steam-turbine plant (Fig. 9), and the plant is sometimes called a *CCGT* plant, for "combined-cycle gas turbine," although manufacturers like to devise their own names for their particular offerings. (For instance, GE uses "STAG," for steam and gas.) Sometimes the gas-turbine part is called the *topping cycle* and the steam-turbine portion the *bottoming cycle*. Most of the new generating plant being built around the world is designed to this cycle. Efficiencies of the small plants are in the range of 50%, while for the larger plants it can go as high as 60%.

This high efficiency is likely to be first achieved by turbines produced by ABB (a Swiss–Swedish company) working on a combined cycle. In the company's GT24 and GT26 gas turbines the output and efficiency are increased through the use of a "reheat" combustor. This increases the gas temperature after the gas has expanded through the first turbine stage. There is more heat in the exhaust, and therefore more power is delivered by a turbine running on the steam generated from this heat.

There is sufficient oxygen in the exhaust of a simple-cycle gas turbine to support additional combustion. However, most combined-cycle plants do not have supplementary firing. The temperature of the steam at the stop-valve of large steam turbines is around 840 K, a temperature limit set by the increasing presence of free radicals that cause corrosive degradation of the steels used in the steam-generator superheaters. It is desirable that the steam reach, but not exceed, this temperature. The increasing turbine-inlet temperatures of modern gas-turbine plant match the required steam conditions without the need for further combustion. There is also benefit in increasing the output of the gas turbine by incorporating intercooling and reheat (which is the incorporation of secondary combustors along the path of the turbine expansion, between stages), thereby also increasing the temperature of the turbine exhaust gases.

Integrated-Gasification Combined Cycle. Another variation is the integrated-gasification combined cycle (IGCC) that incorporates a system producing gas from coal. Where the gasifier is oxygen-fed the system must include an oxygen plant in addition to the gasification plant, leading to a capital cost reported as approximately three times that of a CCGT fired by natural gas. The ability to use a low-cost fuel, coal, in an environmentally benign manner will justify the additional capital cost in certain circumstances in the 1990s, and presumably in more circumstances later when natural-gas prices are certain to rise. The 250 MW Demkolec plant in the Netherlands started trial operation in 1994, and the Wabash River plant in Indiana started trials in 1995. The capital cost of larger plants in the United States was estimated at about \$1600/kW; several other IGCC plants are in the advanced planning stage (24).

CCGT and PFB. Coal is also being used to power combined-cycle gas turbines by using pressurized fluidized beds for combustion, initially in Spain, Japan, and the United States. The beds contain limestone and other sorbents that, together with slag-melting on the walls and base of the bed, produce a hot gas that can pass through a gas-turbine expander without causing more than minor erosion, corrosion, or deposition.

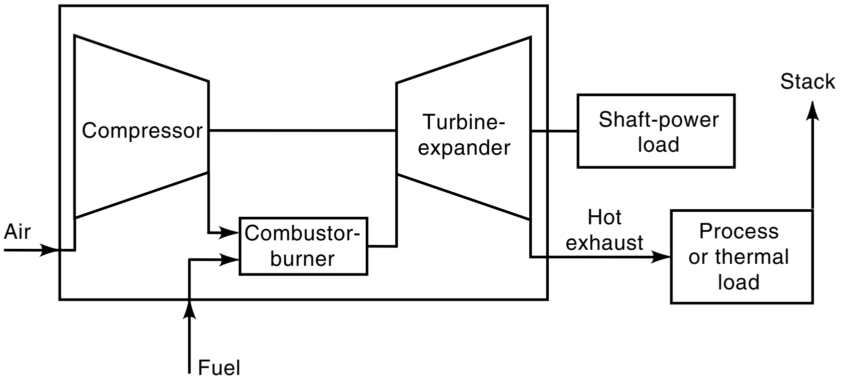

Figure 8. Combined heat and power (CHP) plant. (From Ref. 23.) As shown, this is a plant for "clean" fuel, oil or gas. The hot exhaust can raise steam for process plants or for district heating.

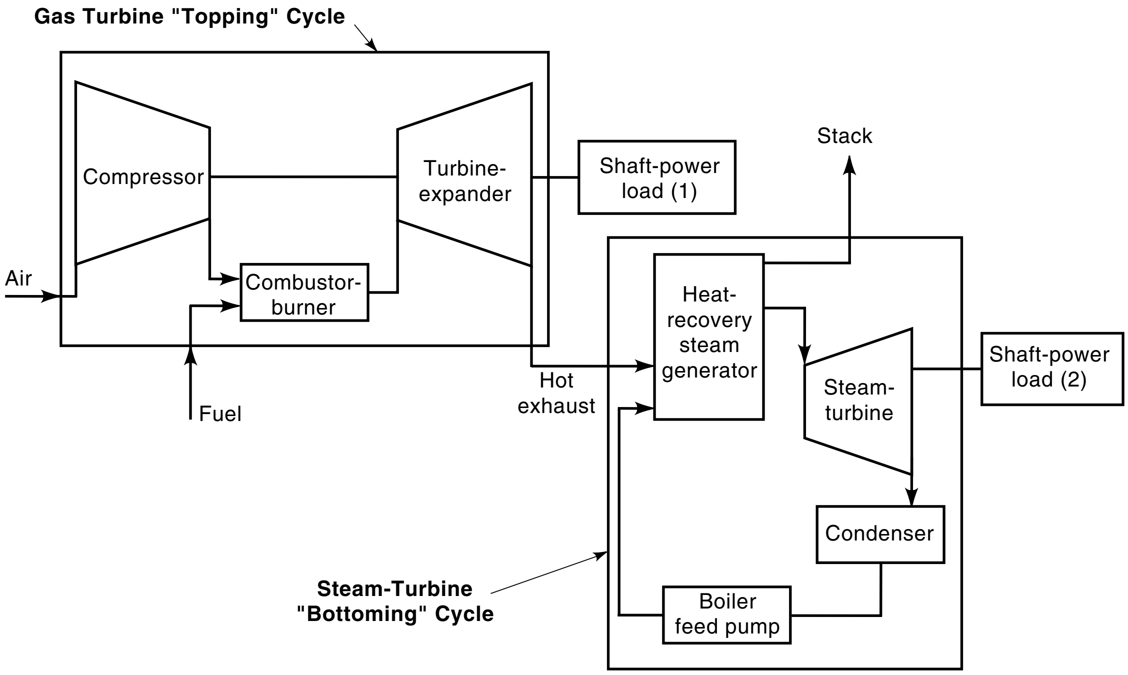

Figure 9. Combined cycle plant. (From Ref. 23.) This is another plant using a "clean" fuel. In this case, the steam raised in a heat-recovery steam generator is fed to a steam turbine, increasing the power output and thermal efficiency.

The prices forecast for the plants are 75% of those for the IGCC plants.

Steam-Injection Gas Turbines. Steam injection in a location where it will expand through the turbine blading with the combustion gases is a third use (besides expansion in a steam turbine and, in advanced plants, cooling of the turbine blades) of the steam generated in a HRSG. Steam may be injected upstream of or into the combustion chamber, or into the turbine nozzles anywhere along the expansion. The steam does less work the further along the expansion it is injected. In comparison with the combined cycle, the steam-injected cycle has the following advantages. A substantial increase in power can be obtained from the gas-turbine engine with no modification in the configuration of the expansion turbine itself. The part-load efficiency is improved. The production of NO_x is reduced. In a review of the status of steam-injected gas turbines, Tuzson (25) stated that combined-cycle turbines have demonstrated the highest power-generation efficiencies and the lowest cost in sizes above 50 MW (although he also quotes a study giving the power level below which steam-injection systems become more attractive than combined cycles as 150 MW). At lower power levels the steam-injected gas turbine becomes attractive because of the avoidance of the large cost of the steam turbine. A typical power gain from steam injection for a GE LM5000 gas-turbine engine was quoted as increasing the engine output for 34 MW to 49 MW, together with an efficiency increase from 37% (simple cycle) to 41%. GE analyzed the gains that would be obtained from a combination of intercooling and steam injection for its LM5000 gas-turbine engine: a power increase from 34 MW to 110 MW and an efficiency improvement from 37% to 55%. The water-purification requirements are more demanding for steam injection than for the combined cycle because virtually all the water is normally lost in the exhaust rather than being circulated in a closed system and because the specifications are more stringent. Any dissolved solids that become deposited on the turbine blades or elsewhere could form corrosion sites or potential blockages. However, Tuzson states that water-purification cost is of the order of 5% of the fuel cost and is not, therefore, a decisive factor. The reliability of early steam-injected units has been high—for instance, 99.5%. Rather surprisingly, combustor-liner durability has been found to increase.

One of the advanced gas-turbine systems being developed in Japan uses an intercooled-reheated gas turbine (the intercooler is a water-spray direct-contact type) in which the steam raised in the HRSG can power a conventional steam turbine, or the steam can be injected into the gas turbine (26). The output, 400 MW, and the predicted efficiency, 54.3%, place it outside Tuzson's guidelines above.

A gas turbine is a good candidate for steam injection if the compressor has a wide range of operation because the increased flow creates a higher back pressure. A high pressure ratio and a high turbine-inlet temperature are also desirable. These conditions seem to favor the aircraft-derivative turbine. However, Tuzson points out that heavy-duty industrial turbines can accommodate concentrations of contaminants about five times higher than can the aircraft-derivative turbines.

There are many variations of these relatively simple forms of water/steam injection. El-Masri (27) proposed an intercooled-recuperative cycle in which the intercooler and an aftercooler are direct-contact water-injected evaporative units and there is subsequent water injection into the recuperator (Fig. 10). There is no steam generator. The results of his analysis show considerably higher efficiencies over the conven-

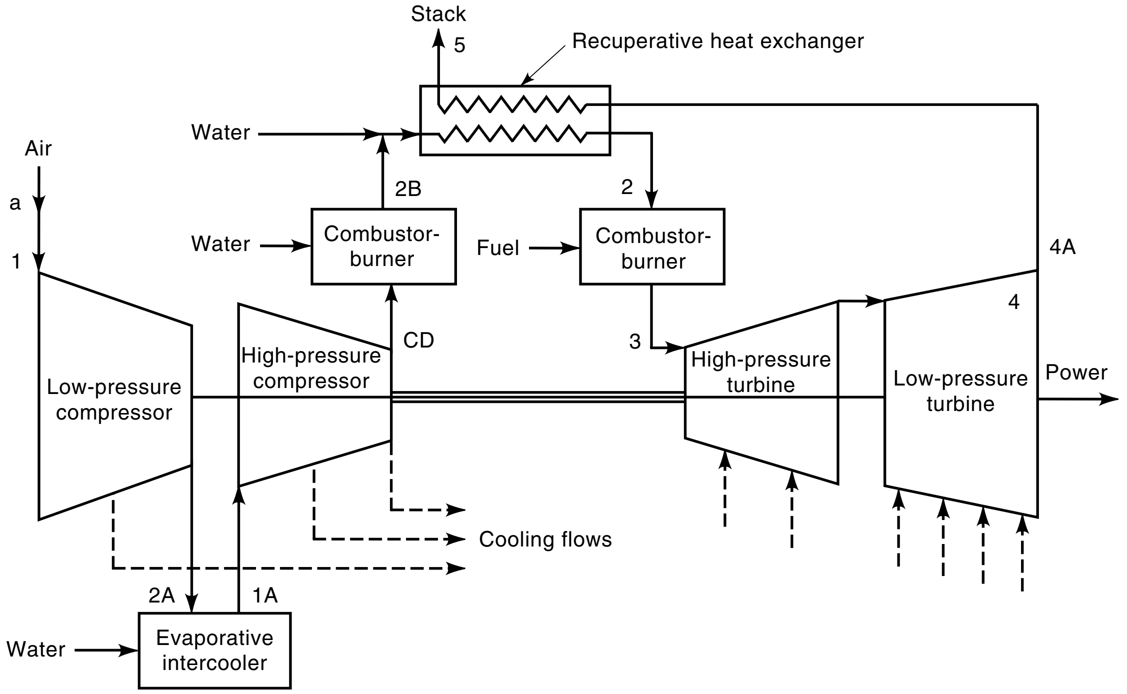

Figure 10. El-Masri intercooled recuperative cycle. (From Ref. 23.) In this cycle, water is injected into the airstream instead of using an intercooler, and water is also injected into the combustor and into the recuperator. Thus power output and efficiency are simultaneously increased at very low cost.

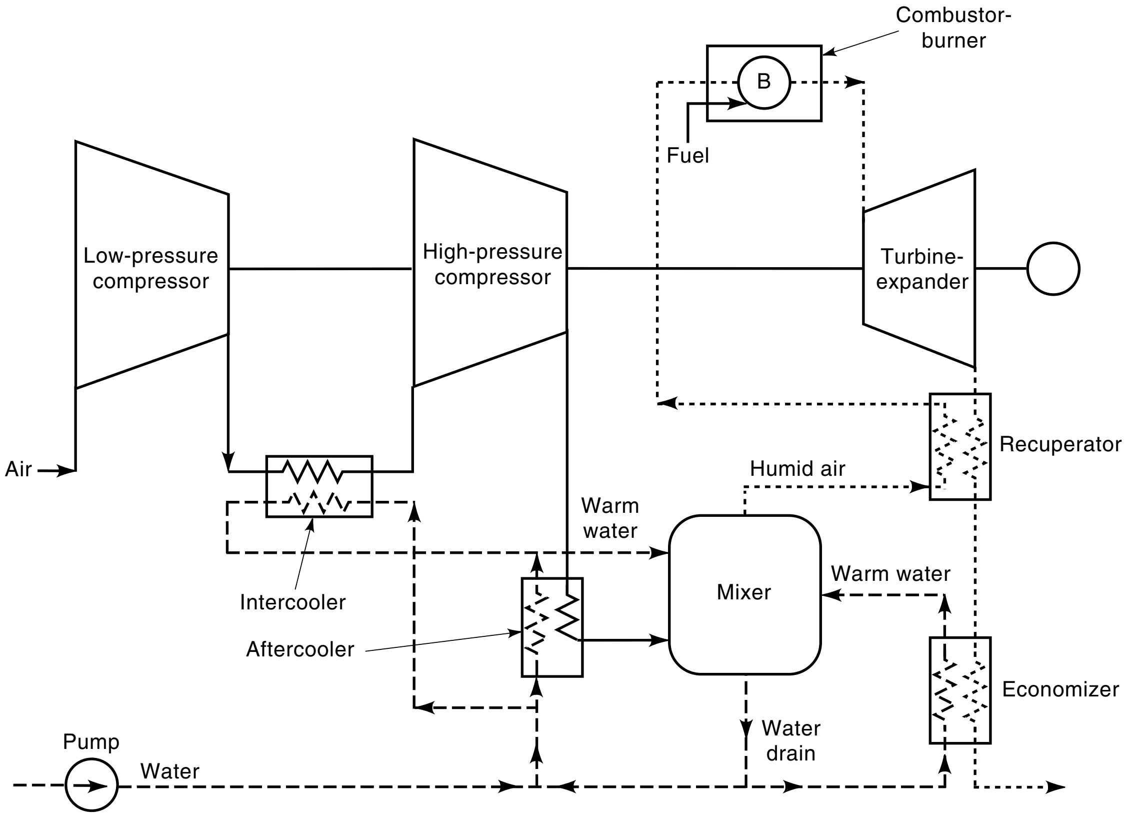

Figure 11. Humid-air cycle. (From Ref. 23.) Water is injected downstream of the compressor, increasing the mass flow through the turbine and recuperator, and raising the efficiency and power output.

tional intercooled-recuperative cycle and over steam-injected cycles. D. D. Rao (cited in Ref. 28) proposed the *humid-air cycle* (Fig. 11) in 1990: it incorporates a water-cooled surface intercooler and a similar aftercooler, followed by a water-injection evaporator, a recuperator, and a combustor. Rao believes that the cycle has advantages over the steam-injected cycles.

Chemical Recuperation. Energy can be recovered from the turbine exhaust by means other than heat transfer to the compressed-air flow. A chemically recuperated gas turbine (CRGT) has been proposed by Kesser et al. (29) in which a simple-cycle gas turbine passes its exhaust to a heat-recovery methane-steam reformer. This takes the place of an HRSG in a steam-injected plant. "The tubes in the reformer (unlike the tubes in the HRSG superheater) are filled with a nickel-based catalyst that promotes a chemical reaction between steam and methane." The gaseous fuel that results is a mixture of CO, H_2, and CO_2 and is assumed to produce NO_x emissions as low as 1 ppm (versus 25 ppm for a steam-injected system). The authors calculated the thermal efficiency of the cycle (at around 47%) as less than the combined cycle but better than the steam-injected cycles for the power level of interest.

Inlet-Cooling Cycles. A somewhat similar approach to chemical recuperation is to use the exhaust heat via an HRSG to operate an absorption chiller that can be used to cool the compressor-inlet air [Ebeling et al. (30)]. However, a more widespread practice is to use power off-peak-load (in the case of the Butler–Warner plant in Fayetteville, NC, having eight GE Frame-5 units, 4.3 MW is used off-peak, 148 hours per week) to operate a vapor-compression ice-making system. Ice is melted during power peaks for four hours per day, five days per week. An increase of hot-weather capacity of 29% was given for the plant quoted. The modification paid for itself in under a year.

CONCLUSION

If the energy in wastes is converted to heat to produce steam, the design of the steam turbine is almost solely a function of the size of the plant. The larger the power output, the more measures are worth taking to improve the efficiency (including increasing the steam pressure and temperature). If the wastes are converted to a clean fuel, however, a higher efficiency and lower plant cost will occur if a plant based on a gas turbine, or a combination of gas and steam turbines, is chosen. Here there are many potential alternatives, including the possibility of burning the waste as RDF directly in one cycle. Only some of the alternatives were fully developed and viable in the mid-1990s. The brief descriptions given will, it is hoped, allow the reader to recognize and evaluate the promise of future developments.

If the definition of wastes is expanded to include wastes occurring in nature, the mixing of fresh water and salt water at the mouth of rivers like the Amazon and at the edge of polar ice sheets could, theoretically, produce vast flows of energy. The reader merely has to imagine the power required in desalination plants to accomplish the reverse process, and to divide this number by two or three to allow for thermodynamic and practical irreversibilities, to arrive at an estimate of the potential power production.

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