# Systems Evaluation of Refuse as a Low Sulfur Fuel
# Part I-The Value of Refuse Energy and the Cost of its Recovery

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Part 1 is the first part in a series dealing with utilization of municipal solid waste as an auxiliary fuel for utility class steam generators. It considers the resource characteristics of refuse as a fuel and the economics of such use in comparison with conventional disposal techniques. The primary objective was to establish the impact such refuse use would have, if extensively practiced in waste management operations, on the reduction of sulfur oxide emissions. Accordingly, mixed municipal refuse was parameterized as a fuel material; this included the development of projections dealing with future inventories, compositions, and calorific values. A design and performance analysis was then made of a number of steam generator configurations having demonstrated or potential application for refuse-firing. This part presents cost data for the turbo-electric systems regarded as optimum in this systems analysis. The conclusion drawn is that the refuse-fired steam generator will become, if it has not already, the most cost effective means for waste disposal for most of the large metropolitan areas of the United States.

## INTRODUCTION

A limited number of strategies are available with which to manage the burgeoning solid waste problem. The existing practices of burning or burying solid wastes may seem primitive, but the recognized alternatives (e.g., composting) have already been shown to be either economically unattractive or so difficult of implementation that few municipalities are willing to adopt them. We thus find ourselves in a period ot intensive solution-seeking, as yet accompanied by relatively few innovative application efforts of any significant scale. It is the opinion of the authors that as solutions are found and applied, the Environmental Protection Agency will have had a dominant role in the support of critical analyses and process development. Their sponsorship under Contract CPA 22-69-22 (1) led to the studies on which this three-part paper (Parts 2, 3) is based. It deals with a subject that is now receiving ever-increasing attention from engineers involved in the disposal of refuse by combustion—the firing of refuse in utility-grade boilers. The work, on which this series of papers is based, attempts to evaluate the basic concept in a comprehensive manner, dealing particularly with such process attributes as its functional effectiveness in relationship to its cost (cost-effectiveness), immediate technical feasibility, and environmental benefit. The conclusion derived is that for those urban centers generating certain minimum quantities of solid wastes, the firing of refuse in utility-class steam generators is doubtlessly to be preferred, in the long run, over prevalent solid waste disposal practices.

During the course of the overall subject study, all aspects of mixed refuse characteristics were examined to ascertain their effects on design features and costs of appropriate steam-generating combustion facilities. European and domestic experience was surveyed, discussions held with leading authorities, fire-

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side corrosion and fouling deposits obtained and chemically analyzed, material balance data compiled, and particulate and gaseous pollutant properties determined where needed for design of control systems. Detailed cost models were then developed for alternative refuse-firing systems. Finally, conclusions were formulated as to the technical and economic feasibility of employing water-walled incinerators in the United States for refuse volume reduction, and five-year R&D plans were recommended.

That refuse, of even a lower calorific value than is available in this country, can be used to fuel turbo-electric steam plants has been more than adequately proved in Europe. Considerable attention has also focused on the corrosive nature of refuse when fired in water-wall furnaces. Yet, the consensus, as opposed to some narrower views, is that the effect is short-lived and more of a nuisance than a problem if the design is correct (2). That is, if the refuse is fired separately in a compartment where fireside tube temperatures are maintained at moderate levels so as to produce feedwater or even superheated steam, corrosion will be minimized and final steam temperatures can then be produced in a fossil-fuel-fired boiler operated in tandem. Thus, the questions are:

- How much energy can be extracted from refuse in such systems?
- How do the economics of such an energy-contributing process, assuming it is properly designed, compare with other waste disposal methods?

Other questions that can be considered (2, 3) include:

- How does the enthalpy of the output steam from a refuse-fired steam generator vary, and can it be adequately controlled?
- What is the combination of steam generator configuration and fuel mixture (and form) that will utilize the energy available from refuse in the most cost-effective manner?
- How will such a dispoal process benefit our air sheds?

## REFUSE AS A BOILER FUEL

The energy available from the solid wastes being produced in this country is, of course, a function of quantity and composition, both of which are dynamic properties. In 1970, there were about 200 million tons of mixed municipal refuse collected. Based on typical calorific and compositional values of refuse and the boiler efficiencies that would result from firing such material, this quantity of solid waste would be sufficient to satisfy the (continuous full load) input energy requirements of some 15 thousand megawatts of plant capacity. The power output from this amount of installed capacity would, at continuous full load, represent about 8 percent of the total power that is estimated (1700 x $10^9$ kwhr) to be consumed in this country in 1971.

The collection of refuse is not only increasing with population growth, but with the affluence of our society. It is safe to estimate that the annual refuse collection rate is increasing about 1.5 percent from each of these factors. This is an exponential process, and our present refuse burden can be expected to double in about 23 years. Our annual increase in energy demand (7.0 percent) is over twice this rate, but nuclear plants, in spite of current reassessments, will still probably satisfy over half of this increase. It is thus possible that refuse, if used as a boiler fuel, could absorb a substantial portion of the energy-demand increase now projected for fossil fuels. An important aspect of this is that the composition of mixed municipal refuse will change

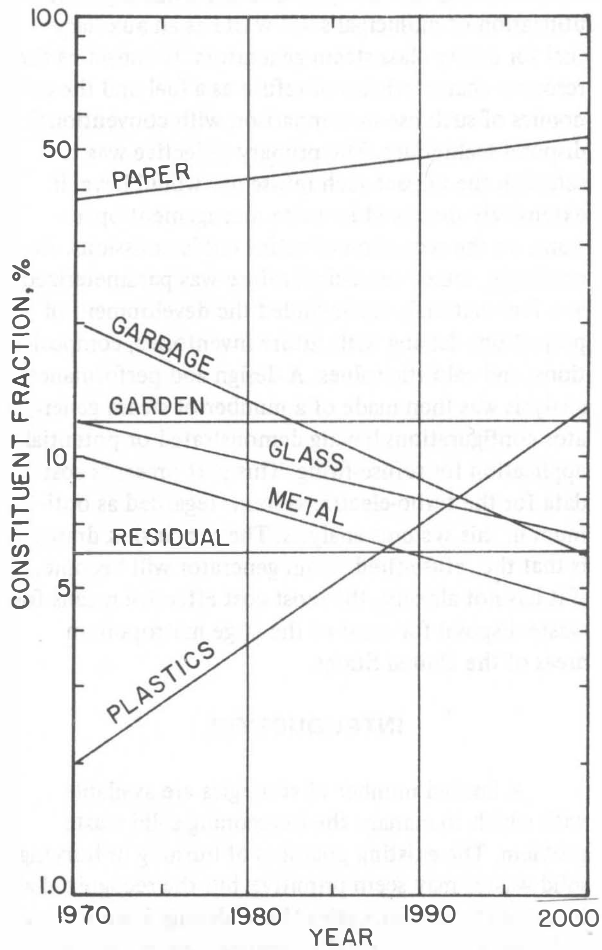


FIG. 1. PROJECTED COMPOSITIONAL CHANGES IN URBAN REFUSE

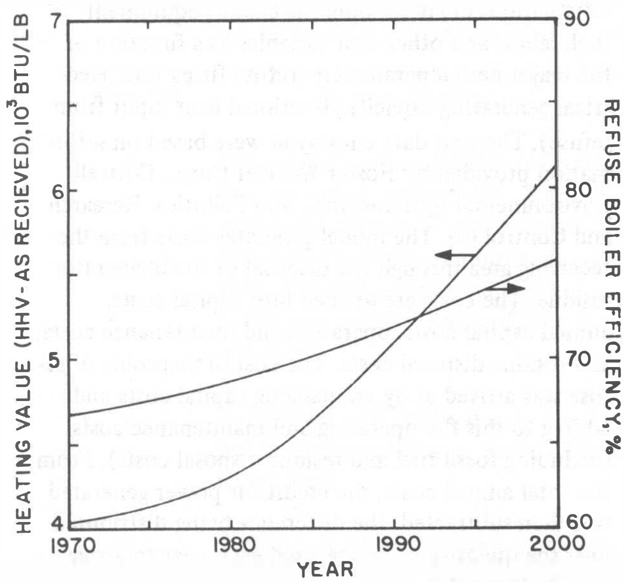


FIG. 2. REFUSE HEATING VALUE PROJECTIONS

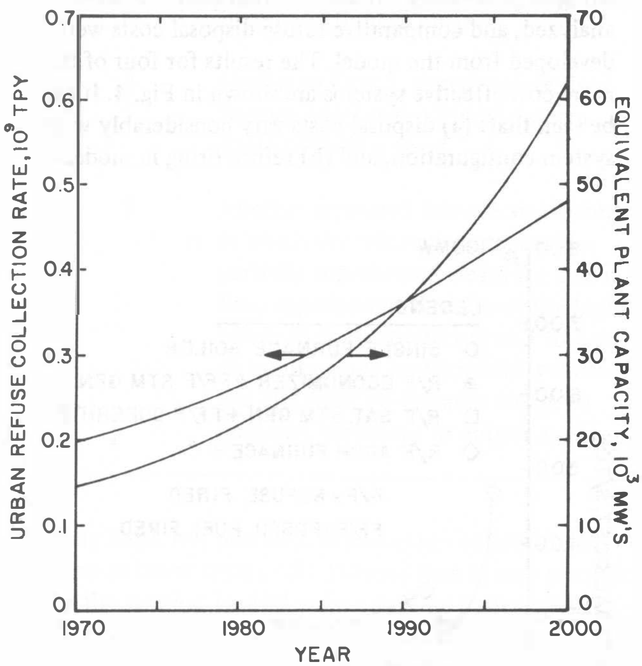


FIG. 3. PROJECTED AVAILABLE REFUSE INVENTORIES AND ENERGY

with time and so will its calorific value and the efficiency of the steam generator in which it is fired.

Fig. 1 shows the compositional changes that can be expected in household refuse over the next 30 years. These trend projections are based on a number of analyses published over the years (4,5) and data provided by the EPA. A result of such compositional changes will be a significant increase in fuel heating value (Fig. 2) and an attendant increase in the efficiency of boilers in which refuse is fired, largely because of reduced heat losses to inerts and free water. When these factors are applied to the projected quantities of refuse that will be collected over the next few decades (Fig. 3), an impressive amount of available energy can be recognized. The question is; can one utilize this "resource" as a fuel in a more cost-effective manner than is available from conventional disposal techniques? The answer to this question will clearly define the viability of the concept.

Another key issue, of course, is the effect the firing of refuse in steam generators would have on the air pollution burden. This matter is dealt with more fully elsewhere (3), but, in general, the following observations can be offered:

1) Refuse contains considerably less (0.1 to 0.2 wt-percent) sulfur than residual oil or coal, and 50 to 75 percent of this sulfur does not appear in the flue gas.

2) On an equivalent energy basis, refuse fired on agitating grates produces less flyash than pulverized coal, and stack emissions can be controlled to 0.01 to 0.03 grain/scf (at 12 percent $CO_2$).

3) The emission of oxides of nitrogen from refuse firing is about the same as for an equivalent amount of fossil fuel energy. Thus, if used as a substitute fuel, no increase in $NO_x$ emissions should result.

4) Hydrocarbon and carbon monoxide emissions from (European) combination (refuse + fossil fuel) fired steam generators are minimal.

5) Halogen emissions (largely as HCl) are not a problem when firing present-day refuse, but may require control if the concentration of polyvinyl chloride plastics in refuse increases significantly.

## PROCESS COST ANALYSIS

The now predominantly utilized method of refuse disposal is some form of dumping, including increasing trends toward sanitary landfill. Average sanitary landfill disposal cost over the nation is about $1.50/ton, exluding the cost of transporting the full refuse load from the collection route to the site and returning the carrier equipment. The use of landfill is largely an irreversible process, which must continuously be moved farther away from its source of supply. Thus, transportation costs will steadily increase, even if all other cost factors somehow remain fixed. The refuse-fired steam generator, by virtue of its function, can often be strategically located within, or at least very near to, a large metropolitan area. Although furnace residues must still be hauled to landfills, the volume, after firing, is less than a tenth of the original bulk. At the present time, transportation costs to landfill sites in many large metropolitan areas equal or exceed disposal costs and will, with time, surely make the method unacceptable in most major metropolitan areas.

In contrast, however, the firing of refuse in suitably designed steam generators can be shown to be as cost-effective a disposal method as the landfill approach. This type of system can involve, however, a considerable capital investment in comparison with other disposal methods, and potential cost benefits are highly influenced by such factors as station size, the cost of the fossil fuel displaced, the blend of fossil fuel and refuse used, the refuse preparation requirements, and, as suggested in the foregoing, the nature of the steam generator design.

A cost model was, therefore, developed to examine such functions. It was assumed that the power company using refuse as a fossil fuel substitute would be a regulated public utility with privately owned equity financing and subject to all applicable Federal, state, and local taxes. One of the most important parameters in determining the net cost of disposal in a refuse-fossil fuel plant is the value assigned to the power generator. This can be done in several different ways, depending on whether the additional power furnished by a new, combination (refuse plus fossil fuel) fired system was fully needed. Because most utilities are faced with increasing power demands, it was assumed that such a system would be built only as an alternative to constructing a needed conventional plant or unit of the same size. Thus, the value of power generated by the various combination-fired systems analyzed was considered to be equal to that of such equivalent, conventional systems. This required, of course, that complete cost analyses be made on both types of systems. The base date for these computations was July 1969.

The capital annualization rate used ranged between 14 and 16 percent, based on then current values for interest rates, insurance, taxes, and equipment life. A plant factor of 80 percent was used, in that it was assumed that the facility would be operated as a base load plant.

Three basic cost models were developed: (a) combined firing plant, (b) conventional firing plant, and (c) a transportation model. The last model, which is not considered here, is described in the report by Roberts et al. [1]. Each model was derived as a series of equations (1) describing the cost of equipment, fuel, labor, and other cost variables as a function of the major design parameters (refuse firing rate, electrical generating capacity, fractional heat input from refuse). The cost data employed were based on information provided by Foster Wheeler Corp., Cottrell Environmental Systems, Inc., and Pollution Research and Control Co. The model generates costs from the receiving area through the disposal of the incinerator residue. The costs are divided into capital costs, annual capital costs, operation and maintenance costs, and residue disposal costs. The cost of disposing of refuse was arrived at by annualizing capital costs and adding to this the operating and maintenance costs (including fossil fuel and residue disposal costs). From the total annual costs, the credit for power generated was then subtracted, the difference being distributed over the quantity of refuse fired each year to arrive at unit disposal cost.

Ten specific candidate designs (Table 1), which have been shown (1,2) to be suitable for combination firing or potentially suitable for that purpose, were analyzed, and comparative refuse disposal costs were developed from the model. The results for four of the more cost-effective systems are shown in Fig. 4. It can be seen that: (a) disposal costs vary considerably with system configuration, and (b) refuse firing in moder-

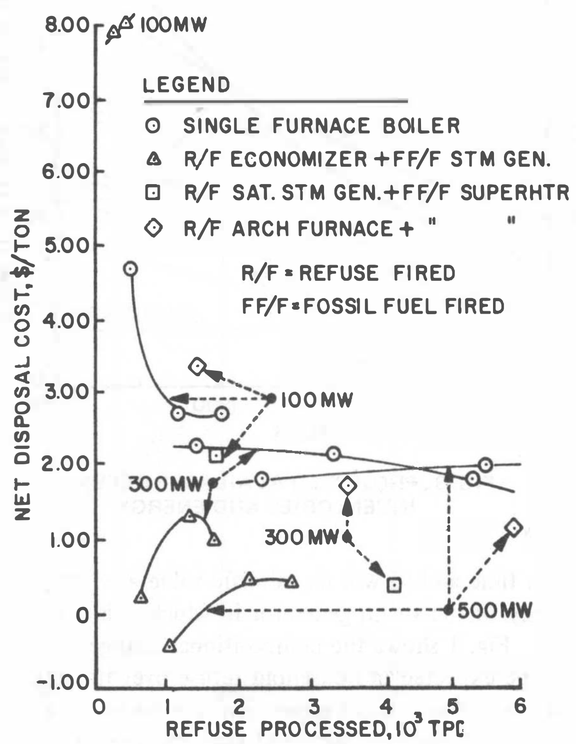

FIG. 4. DISPOSAL COSTS OF SELECTED SYSTEMS

TABLE 1. CATALOG OF CANDIDATE SYSTEMS ANALYZED FOR COST EFFECTIVENESS

| Case No. | System Description | Case No. | System Description |
|---|---|---|---|
| 1 | Refuse and coal are fired in separate furnaces using, respectively, agitating grates and pulverized coal burners. The flue gases from the two furnaces are combined and passed over common convective surface. Ratio of fuels is not fixed. | 6 | Similar to the Case 2, combined furnace arrangement, this system has a dump-grate at the bottom and shredded refuse is blown in to burn in suspension with pulverized coal. Fuel ratio is not fixed. |
| 2 | Refuse and coal are fired as in Case 1, but in the same furnace. Ratio of fuels is not fixed. | 7 | Another combined furnace configuration in which suspension burning is achieved by the use of a spreader stoker. Fuel ratio is not fixed. |
| 3 | Refuse is fired on agitating grates of a furnace which serves as the economizer for a separate, pulverized-coal-fired, steam generator. Flue gases from the two systems are not blended. Ratio of fuels has a limited range. | 8 | A combined furnace system in which the fuels are fired to induce slagging. Molten ash is tapped to yield high density residue. Fuel ratio is limited. |
| 4 | Similar to Case 3, except refuse fired furnace sends over saturated steam. Ratio of fuels is fixed. | 9 | A combined system in which fuels are fired in suspension in an arch furnace arrangement similar to that used for anthracite coal firing. Fuel ratio is not fixed. |
| 5 | Another separated furnace arrangement, in which the refuse system provides partially superheated steam for a coal-fired superheater. Because of the high refuse to coal ratio (fixed at 3 to 1 on an input energy basis) refuse is shredded and fired by spreader-stoker to minimize variations in output steam conditions. | 10 | Shredded refuse is fired in an arch furnace to produce superheated steam that is further superheated in a separate pulverized-coal-fired furnace. Flue gases of two systems are not blended. Fuel ratio is fixed. |

ately large, but practical, utility-grade boilers can be done at lower costs (<$1.50/ton) than is now possible by the sanitary landfill approach. One boiler configuration, in the lower left of Fig. 4 (500 MW capacity and a waste rate of 1000 tpd), would actually involve a credit for refuse disposal ($0.50/ton). This particular design (2) consists of a water-walled furnace firing straight refuse on reciprocating grates to produce high enthalpy feed water. This is sent to a tandem, fossil-fuel-fired steam generator of conventional design (except for economizer surfaces), which brings the working fluid to turbine inlet conditions. Because the systems analysis identified this particular design to be of superior cost-effectiveness, it was subjected to more detailed design and cost analysis and for a fixed set of operating conditions. These included a nameplate rating of 400 MW and a refuse rate of 2800 tpd, based on the use of three refuse-fired economizers producing feedwater for a single fossil-fuel-fired steam generator. In this further analysis, Foster Wheeler design engineers found that, by altering the standby burner arrangement in the refuse-fired economizer, they could significantly reduce the furnace volume of the fossil-fuel-fired steam generator. Thus, this iterative analysis resulted in the detection of a significant cost savings opportunity. The resulting cost breakdown is shown in Table 2, again in July 1969 dollars. The summary performance characteristics for this particular system are shown in Table 3. Because the cost data are based on comparisons with contemporary

TABLE 2. COST BREAKDOWN FOR 400 MW COMBINATION-FIRED (2800 TPD) PLANT OF OPTIMUM DESIGN

| FPC Codes | Description | Cost, $10^6$ $ |
|---|---|---|
| | **CAPITAL COSTS** | |
| 310 | Land and Land Rights | 0.69 |
| 311 | Structures and Improvements | 5.47 |
| 312 | Boiler Plant Equipment | 31.72 |
| 314 | Turbine-Generator Equipment | 13.75 |
| 315 | Accessory Electrical Equipment | 2.87 |
| 316 | Misc. Power Plant Equipment | 0.59 |
| | Air Pollution Control Equipment | 4.04 |
| | Waste Handling Equipment | 1.81 |
| | Engineering and Inspection | 2.44 |
| | Total Capital Cost | 63.38 |
| | **ANNUAL COSTS** | |
| | Annual Capital Cost, $10^6$ $ | 9.25 |
| | (Effective Annualization Rate, 14.6%) | |
| | Water Cost, $10^6$ $ | 0.01 |
| | Operating Labor, $10^6$ $ | 0.62 |
| | Maintenance, $10^6$ $ | 1.73 |
| | Coal Cost, $10^6$ $ | 6.76 |
| | Residue Disposal, $10^6$ $ | 0.36 |
| | Total Annual Costs, $10^6$ $ | 18.73 |
| | Annual Credit for Power Generated, $10^6$ $ | 18.76 |
| | Quantity of Waste Burned, $10^3$ ton/yr | 815 |
| | Disposal Cost, $/ton | –0.04 |

TABLE 3. SUMMARY PERFORMANCE SPECIFICATIONS FOR 400 MW REFUSE FIRING SYSTEM

| Item | Refuse-Fired Economizers | Coal-Fired Steam Generator |
|---|---|---|
| Fuel Rate, tpd | 2790 | 3008 |
| Combustion Air Input, $10^3$ lb/hr | 1040 (50% excess) | 2639 (18% excess) |
| Wet Flue Gas Produced, $10^3$ lb/hr | 1230 | 2898 |
| System Efficiency, % | 66.2 | 87.4 |
| Working Fluid Output, $10^3$ lb/hr | 2800 | 2800 |
| Working Fluid Conditions, psig/F | | |
| Feedwater out | 2600/657 | – |
| Feedwater in | 2640/470 | 2600/657 |
| Superheater outlet | – | 2520/1000 |
| Reheater inlet | – | 577/640 |
| Reheater outlet | – | 518/1000 |
| Gas Temperatures, F | | |
| Air leaving air heater | 316 | 764 |
| Flue gas leaving furnace | 1800 | 2260 |
| Flue gas entering air heater | 766 | 825 |
| Flue gas leaving air heater | 575 | 325 |

costs for operating conventionally fired utility steam generators, the principal distortion that enters with cost escalation is in the cost of the fossil fuel that is displaced by the refuse fuel. As this increases, refuse disposal costs will commensurately decrease. The cost model was based on fossil fuel costs of $\$0.31/10^6$ Btu. In some areas, costs for low-sulfur oil are now running well over twice this amount.

## MODIFICATION OF EXISTING PLANTS

Heretofore, the discussion has been limited to the consideration of systems involving completely new construction; the modification or "retrofit" of existing installations is another possible approach (6). Four units, whose starting service dates ranged from 1949 to 1961, was selected for analysis. All four fire or are capable of firing pulverized coal. Three of the units were chosen because they are fairly representative of the design and operating conditions for similarly sized units built over the past 15 years. One of the units has a somewhat unusual design in having the coal burners on the back wall of the furnace, was selected because it could be modified to produce the arrangement described in Case 1 in Table 1. Information on these four units and the five modifications thereof that were analyzed is given in Table 4.

In developing costs for the retrofit boiler plant equipment, costs were included for the removal of tubing, insulation, and support steel. To keep the costs representative of a type of unit rather than a specific unit, the cost of moving boiler house equipment was not included. The new-material costs include all material and equipment furnished by the steam generator manufacturer, shop work, engineering, overhead, and profit for the items covered in that category. A fixed fee was also included for the erection of the equipment; this includes tools and erection equipment, expendables, erection supervision, and profit for the erection.

All of the other items in the retrofit cost breakdown were based on the derivations developed for the cost model. Additional capital costs were included for new land to accommodate waste handling equipment, new structures pertaining thereto and to the retrofit boiler, add-on accessory electrical equipment, and extra APC facilities. The last cost item was based on the increased volume of flue gas that would be experienced when the design level of refuse is fired in the modified system. This fractional treatment may appear to be an unrealistic approach, but is the only logical way of apportioning APC costs between the actual (fuel) sources of the pollutants generated. The results of this costing are shown in Table 5 which, of course, does not include any of the existing capital or annual costs associated with the unmodified plant.

It can be seen by comparing the costs shown in Table 5 and those roughly extrapolated from the data presented in Fig. 4 that the disposal costs for retrofitted plants would be generally lower than those for new construction plants of corresponding size and configuration. This results from several reasons. In determining disposal costs for new construction plants, the energy credit assigned is based on conventional electricity production costs. The refuse-fired power plant, however, is less competitive, in that it must be designed to handle a less efficient fuel, operate at less economical steam conditions, and include, preferably, features (e.g., separated refuse and coal furnaces) that would be unnecessary in a conventional plant. Thus, unlike a retrofitted plant, a part of the basic power plant capital costs (FPC Code 312) are reflected in the disposal cost of a new construction plant.

While this factor tends to favor the adoption of the retrofit approach, another consideration should be taken into account. The plant factor used in calculating Table 5 was 80 percent, the same value used for the new construction systems. This value was selected to permit a more direct comparison of the two types of systems, but it may not be entirely realistic. The

TABLE 4. CHARACTERISTICS OF EXISTING STEAM GENERATORS SELECTED FOR MODIFICATION

| Modification No. | Nameplate Rating MW | Steam Conditions psig/°F/°F | Steam Flow $10^3$ lb/hr | Service Date | Corresponding Design (Table 1), Case No. |
|---|---|---|---|---|---|
| 1 | 60 | 900/900/- | 600 | 1949 | 2 |
| 2 | 150 | 2035/1050/1000 | 1,100 | 1959 | 1 |
| 3 & 4 | 44 | 1350/950/- | 445 | 1957 | 7 & 2 |
| 5 | 300 | 2200/1010/1010 | 2,310 | 1961 | 6 |

TABLE 5. COSTS FOR RETROFIT SYSTEMS

| Description | Additional Capital Costs, $10^3$ $ | | | | |
|---|---|---|---|---|---|
| | Mod. 1 | Mod. 2 | Mod. 3 | Mod. 4 | Mod. 5 |
| New Land | 19.0 | 20.0 | 17.0 | 13.5 | 15.5 |
| New Structures | 292.0 | 905.0 | 228.0 | 276.0 | 218.0 |
| Retrofit Boiler Plant Equipment | 1,465.0 | 4,529.0 | 1,144.0 | 1,380.0 | 1,091.0 |
| Accessory Electrical Equipment | 146.0 | 453.0 | 1,144.0 | 138.0 | 109.0 |
| APC Equipment | 60.0 | 52.0 | 60.0 | 43.0 | 60.0 |
| Waste Handling Equipment | 734.0 | 816.0 | 2,080.0 | 524.0 | 2,940.0 |
| Engineering & Inspection | 203.0 | 477.0 | 259.0 | 170.0 | 310.0 |
| Total Additional Capital Costs | 2,919.0 | 7,252.0 | 3,903.0 | 2,544.0 | 4,743.0 |
| | Additional Annual Costs, $10^3$ $ | | | | |
| Annual Capital Costs | 423.0 | 1,050.0 | 586.0 | 370.0 | 710.0 |
| Operating Labor | 95.0 | 95.0 | 119.0 | 85.0 | 119.0 |
| Maintenance | 95.0 | 95.0 | 229.0 | 85.0 | 339.0 |
| Residue Disposal | 129.0 | 145.0 | 112.0 | 92.0 | 120.0 |
| Total Additional Annual Costs | 742.0 | 1,385.0 | 1,046.0 | 632.0 | 1,288.0 |
| Annual Credit for Coal, $10^3$ $ | 560.0 | 545.0 | 517.0 | 420.0 | 283.0 |
| Refuse Fired, $10^3$ tons/year | 278.0 | 292.0 | 247.0 | 198.0 | 226.0 |
| Disposal Cost, $/ton | 0.65 | 2.87 | 2.14 | 1.07 | 4.44 |

TABLE 6. SENSITIVITY OF DISPOSAL COST TO PLANT AVAILABILITY

| Plant Factor, % | Total Net Disposal Cost, $/ton | | | | |
|---|---|---|---|---|---|
| | Mod. 1 | Mod. 2 | Mod. 3 | Mod. 4 | Mod. 5 |
| 80 | 2.15 | 4.37 | 3.59 | 2.52 | 5.89 |
| 70 | 2.54 | 5.07 | 4.19 | 2.98 | 6.70 |
| 60 | 3.05 | 5.96 | 5.00 | 3.59 | 7.80 |

availability of the retrofit system may well prove to be considerably lower than that of a newly constructed facility. This could result not only from the fact that the retrofit plant would tend to experience more downtime due to age, but also because the mode of firing would be more conducive to furnace problems. All of the retrofit designs (except Modification No. 2) would yield steam temperatures in excess of 750 F in furnaces in which refuse would be fired. Thus, a lower plant factor should be anticipated due to increased corrosion and fouling problems.

As plant factor is reduced, the amount of refuse fired and of coal displaced are also lowered. This results in a significant increase (13 to 20 percent for each 10 percent (relative) drop in plant factor) in the total net disposal cost, as shown in Table 6.

It will be important, in considering the retrofit approach, to review carefully the past availability of the unit selected for modification and to allow appropriate compensation for the effect that refuse firing will have on plant factor.

## CONCLUSIONS

The firing of refuse in utility class steam generators of optimum design constitutes a method of disposal that is technically practical (2), low in cost, conservative of land and mineral resources, and conducive to the lowering of sulfur oxide emissions (3). As energy resource, mixed municipal refuse is steadily growing in both heating value and production rate. Its use as a fuel represents a definite form of resource recovery, one that is not incompatible with but, rather, highly complementary to certain forms of recycle, such as the salvage of glass and metals.

Although it has gained wide acceptance in Europe over the past dozen years, the concept of firing refuse in utility class boilers is being adopted rather slowly in this country. Although the present year will see many refuse-fired steam generators operating in North America, only one will generate electricity. Nonetheless, that particular steam generator (St. Louis, Missouri) and some of the non-electric plants, such as at East Hamilton, Ontario, and Rochester, New York, represent innovative steps forward in combustion technology. Stimulated by the examples thus set, a quickened pace in new construction starts of similar systems can be expected.