Systems Evaluation of Refuse as a Low Sulfur Fuel

Part II-Steam Generator Aspects

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Part 2 is the second part of a series which summarizes results of a study to assess the extent to which municipal refuse, when used as a fuel to generate steam for power generation, can aid in reducing the atmospheric emission of sulfur dioxide. In this part, the basic premise is that refuse is a low sulfur, low grade fuel which imposes rather restrictive limitations on steam generator design. It is shown that it is technically possible to burn refuse in combination with fossil fuels to generate power with substantial benefits to the environment. The basic of the work in this study derives to a large extent from European experience, especially from Germany, and was applied to U.S. conditions in a design study. Preliminary designs for new steam generators and modifications of existing steam generators were prepared representing various combinations of refuse-burning systems. Examples of some of these designs are described.

INTRODUCTION

This is one part of a three part series summarizing the results of a study of burning municipal refuse for power generation and deals with the steam generator aspects. The first part summarizes resource recovery values and the third deals with air pollution aspects [7,3]. When one thinks of refuse the usual descriptive terms are "rubbish," "food wastes," and "noncombustibles." The basic premise of this study is that refuse is a fuel. As a fuel, it compares favorably with other fossil fuels that have been successfully applied for power generation as shown in Table 1. Refuse is not as good as premium fuels, such as oil or natural gas. However, it is a volatile fuel with a heating value of about half that of bituminous coal, and it has a relatively low-sulfur content of about 0.15 percent sulfur (0.3 lb/10^6 Btu).

Large urban areas have high levels of sulfur dioxide in the atmosphere, derived in large part from power plant emissions. These same areas typically have solid waste disposal problems. In many areas, the present practice for waste disposal is landfill—sanitary or unsanitary. In many cities, there are incinerators which are the worst point sources of air pollution.

In this study, refuse was treated as a fuel and its heat content utilized in generating steam to be delivered to a turbine. As with other solid fossil fuels, the heat-transfer surface formed the furnace enclosure. On this basis, it became more appropriate to describe the combustion process as burning, i.e., giving forth heat during combustion, rather than incinerating, i.e., burning to ashes or consuming without heat utilization. With this distinction, the priority was the production of heat with the mass and volume reduction of refuse being secondary. This is not to imply that other characteristics of refuse, such as nonhomogeniety and potential corrosive aspects, were ignored. Much emphasis was placed on the undesirable aspects of buring refuse as a fuel.

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TABLE 1. FUEL PROPERTIES

Fuel	Bituminous Coal	Anthracite	Lignite	Peat	Refuse
Proximate Analyses, Percent					
Moisture	7.8	18.3	36.4	40.0	27.1
Volatile Matter	41.1	5.0	28.7	18.4	44.5
Fixed Carbon	41.1	56.5	28.0	35.4	6.7
Ash	10.0	20.2	6.9	6.2	21.7
Higher Heating Value (HHV), Btu/lb	12,022	8,845	6,750	5,290	4,460

14625 14382 11905 9833 8710

EUROPEAN EXPERIENCE

The concept of burning refuse to recover heat is not a new one. In recent years, the trend to this concept has become a reality in Europe where many such plants are in operation. The plants in the Federal Republic of Germany (West Germany) are most worthy of mention because they epitomize the overall European art. The waste disposal technique practiced on a commercial basis in Germany includes pulverization combined with landfill, composting, and refuse burning (Müllverbrennung). Since 1960, but especially since 1964, a series of refuse burning installations have gone into operation, generally with relatively high disposal capacities, and these plants provide some rather surprising statistics. As of February 1969 (the most recent data available during the study period), 13 refuse burning installations were in operation with seven more under construction with 1971 service dates. All are equipped with steam heat-recovery systems. The 13 plants handle the refuse of about 7.5 million inhabitants, i.e., about 12.5 percent of the total population. This amounts to 37 percent of the refuse in the large cities where the plants are located. With the seven new installations, as well as two installations in the planning stages, the number of inhabitants whose refuse is burned will be increased to more than 11 million. This number could easily reach 14 to 15 million by the mid 1970's. This will correspond to almost a quarter of the total population of Germany [8].

The majority of the German units burn refuse and recover the heat by generating steam. The utilization of the steam varies considerably, ranging from running plant auxiliary equipment to district heating and power generation [9]. In considering steam generating power plants, economic considerations dictate high steam pressures (> 1000 psig) and high superheat temperatures (> 950 F). The number of plants burning large amounts of refuse and generating high-pressure steam for power generation are relatively few and are found mainly in Germany [10]. Refuse is either fired in a separate furnace cell or in the same furnace, or refuse is burned to heat only a portion of the feedwater-steam loop. These plants have one thing in common: Whenever high pressure steam is used in generating power with refuse firing, fossil fuel is always used somewhere in the steam cycle. Because of the nonhomogeniety of refuse, combustion gas temperature and composition fluctuate rapidly and erratically within the furnace. Outside the furnace, these fluctuations are manifested by variations in steam pressure, temperature, and flow. By combining the contribution of the nonhomogeneous fuel (refuse) with the homogeneous fuel (fossil fuel), the effect of these fluctuations is minimized. Shown later are the various, specific techniques by which this is accomplished.

One of the aspects of this program was to select several of these units for detailed study. In choosing these plants, nonagitating grates (e.g., horizontal traveling grates) and units previously firing fossil fuel, modified to burn refuse, were excluded. The five units selected assure consideration of the best examples of inclined grate and boiler design, and include Düsseldorf-Flingern Unit No. 1, Stuttgart-Münster Unit Nos. 28 and 29, and Munich North Unit Nos. 1 and 2.

Düsseldorf-Flingern

The four identical units of this plant were put into service in late 1965. Each natural circulation steam generator is designed to deliver 25,500 to 35,200 lb/hr of steam at 1280 psig and 932 F as

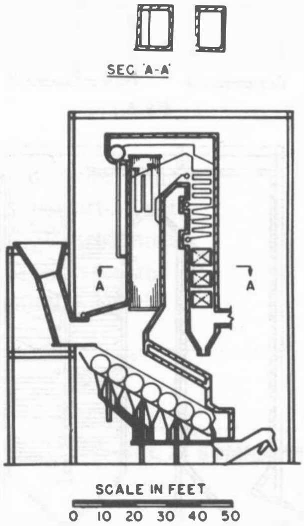

FIG. 1. DÜSSELDORF-FLINGERN

shown in Fig. 1. (Figs. 1 through 4 and Fig. 6 depict general arrangement drawings of the various units and are all shown to the same scale). Refuse is fired on a roller grate at a rate of 22,050 lb/hr (260 tpd). The roller grate was developed by the City of Düsseldorf in conjunction with manufacturers [11]. Auxiliary oil guns are used for start-up. The steam is used in conjunction with the Flingern Power Plant located nearby. Steam from the four refuse-burning steam generators is delivered to a header to which four coal-fired steam generators are also connected. The steam is then delivered to two high- and low-pressure turbogenerators. Steam can also be taken from the outlet of the high-pressure turbine and delivered to a district heating system. The four refuse units comprise only 13.5 percent of the steam generating capacity of the system. The steam pressure and temperature of the refuse-fired units are controlled uniformly, but the steam flow variation is quite erratic. The four refuse units, connected in parallel, comprise only a small percentage of the total steam capacity, resulting in negligible variations in total steam flow at the inlet to the turbines. Space for two additional units was provided in the original plant planning and construction is underway.

Stuttgart-Münster

The two refuse burning units at this plant are nearly identical (differing only in the type of grate used to burn the refuse) and were put into service in 1965. Both units have an oil-fired furnace and a refuse-fired furnace with flue gases combining before entering the convection sections as shown in Fig. 2. Unit No. 28 is equipped with a backward reciprocating grate (Martin) and Unit No. 29 with a roller grate (VKW). Each of these natural circulation steam generators is designed to deliver 204,600 lb/hr steam at 925 psig 977 F. The refuse is burned at a rate of 40,920 lb/hr (490 tpd) which constitutes about 40 percent of the heat input.* Steam from the two combined fired steam generators is delivered to a header to which several coal-fired steam generators are also connected. The steam is then delivered to seven turbogenerator sets (155 MW) with extraction points for a district heating system. The refuse-fired portion of these two combined units comprise less than 15 percent of the steam generating capacity of the system. The steam pressure and temperature of the combined units is uniformly controlled, but there is considerable variation in steam flow. The amount of steam generated by the combined-fired units comprises a small percentage of the total steam capacity, resulting in negligible variations in total steam flow at the inlet to the turbines. One additional combined-fired unit is being added to the plant. As in Düsseldorf, initial plans provided space for this additional unit.

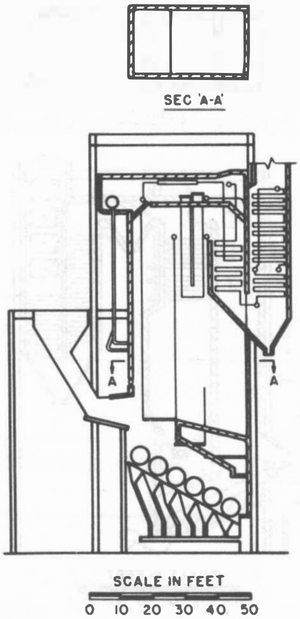

FIG. 2. STUTTGART-MÜNSTER UNIT NO. 29

MUNICH NORTH

Unit No. 1. This unit consists of two identical steam generators (Boiler Nos. 1A and 1B) in parallel connected directly to a turbine and was placed in service in 1964. Each steam generator has a pulverized coal-fired furnace and a refuse-fired furnace with the

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*Heat input is based on United States practice of using higher heating value, contrary to the European use of lower heating value.

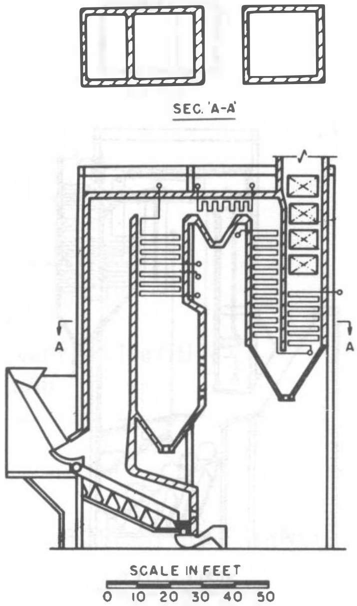


FIG. 3. MUNICH NORTH UNIT NO. 1A

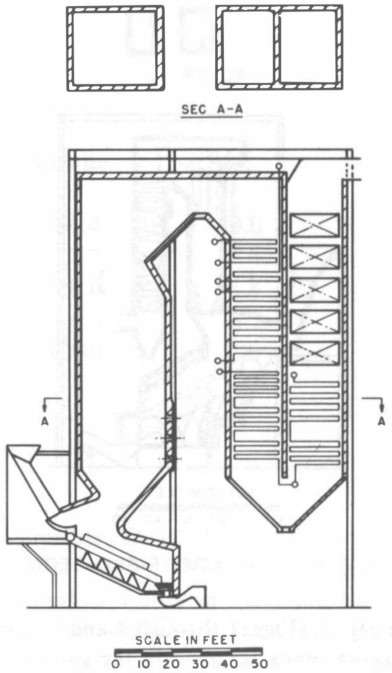


FIG. 4. MUNICH NORTH UNIT NO. 2

flue gases combining before entering the convection sections as shown in Fig. 3. Each of these forced circulation steam generators is designed to deliver 220,000 lb/hr steam at 2600 psig and 1004 F/1004 F superheat and reheat temperatures, respectively. Refuse is fired on each backward reciprocating grate (Martin) at a rate of 55,000 lb/hr (660/tpd), which constitutes about 54 percent of the heat input. Steam is delivered directly to a 68 MW turbo-generator with extraction points for district heating. The steam pressure and temperature of each unit is controlled uniformly, and there are only slight variations in steam flow. Some damping of flow variations is obtained by the parallel arrangement of the twin steam generators. The remaining fluctuations are also present in the electric generator output, but are small in comparison to the system generation (550 MW).

Unit No. 2. This unit, first put into service in 1966, consists of a single steam generator connected directly to a turbine. The steam generator is a forced circulation type designed to deliver 800,000 lb/hr steam at 2600 psig/1004 F/ 1004 F. It has a single furnace with separate refuse and pulverized coal firing equipment as shown in Fig. 4. Refuse is fired on a single backward reciprocating grate (Martin) at a rate of 88,500 lb/hr (1060 tpd) which constitutes about 30 percent of the heat input. Full load can be achieved firing only coal, or refuse and coal in combination. Refuse alone may be fired for district heating but not for power generation. The steam pressure and temperature, and flow are controlled uniformly, permitting the plant to operate on system demand.

TÜV Performance Tests

Performance test data for the steam generator and accessory equipment of each of the selected plants were made available. These tests were performed by the Technischer Überwachungs-Verein. The TÜV was organized about 100 years ago by boiler owners at the request of local authorities to provide test certificates for steam generators. Presently, there are TÜV offices in each of the principal industrial regions. They provide expert certification service for industrial equipment. Both plant owners and manufacturers bear the expense of the performance tests. There is no comparable service available in the United States. Use of these performance test results for this study required approval of the plant owners and all manufacturers, to whom a great debt of gratitude is extended.

The TÜV conducted thorough evaluations of the performance of the five selected units at various test conditions. Table 2 is a summary of the 15 test conditions used for detailed study, firing either fuel alone or in combination. Several tests with fossil fuel only at partial loads were also included in the original TÜV reports.

The original intent of these reports was to demonstrate whether the equipment tested has met guar-

TABLE 2. SUMMARY OF 15 TEST CONDITIONS USED FOR DETAILED STUDY OF FIVE UNITS

Plant	Unit No.	Refuse	Fossil Fuel	Refuse + Fossil Fuel
Düsseldorf-Flingern	1	1	–	–
Stuttgart-Münster	28	–	1	2
Stuttgart-Münster	29	–	1	2
Munich North	1A	1	1	1
Munich North	2	1	1	3

TABLE 3. SUMMARY OF PERFORMANCE DATA FROM MUNICH NORTH, UNIT NO. 2

TÜV TEST NO. 5		
Steam	M lb/hr	774.8
Pressure superheater outlet	Psig	2688
Temperature steam superheater outlet	F	1000
Temperature steam reheater outlet	F	1004
Temperature air entering unit	F	37
Temperature air leaving air heater	F	513
Temperature gas entering air heater	F	618
Temperature gas leaving air heater	F	329
Excess air entering air heater	%	38*
Wet gas entering air heater	M lb/hr	1163
Air leaving air heater	M lb/hr	1047
Fuel fired (Refuse)	M lb/hr	94.1
Fuel fired (Coal)	M lb/hr	57.3
Efficiency	%	81.69

*TÜV Method

anteed specifications. In the context of this study, these reports were used as documentation to determine the feasibility of using refuse as a fuel and to determine what effect such a process would have on air pollution, specifically on the emission of sulfur oxides.

That the equipment met specifications is a tribute to the designers, manufacturers, and operators. The first large refuse-fired installation (264 tpd) was put in service in 1960 at the Essen Karnap Plant. This was a re-vamp of existing pulverized coal-fired steam generators to include combined refuse fossil-fuel firing [12]. It is quite remarkable that by 1964-1966, combined refuse-fossil fuel plants were being put into service on a performance-guaranteed basis. The TÜV reports presented a unique opportunity to evaluate performance data. Of course, their practical value for United States conditions required not only translation from German and the conversion from metric units, but also the conversion of heat liberation from the lower heating value (LHV) basis to the higher heating value (HHV) basis. This is the first time such an evaluation has been made on the higher heating value basis. An evaluation of the sulfur oxides emission was made by sulfur balances. Results of one particular TÜV test are summarized in Table 3, and Fig. 5 illustrates the mass and sulfur balance. The results of sulfur balances of all units surveyed are summarized in Table 4. The data in Table 4 are encouraging, because they indicate that a small amount of the sulfur in the refuse is carried out in the flue gas. Most of the sulfur is retained in the residue.

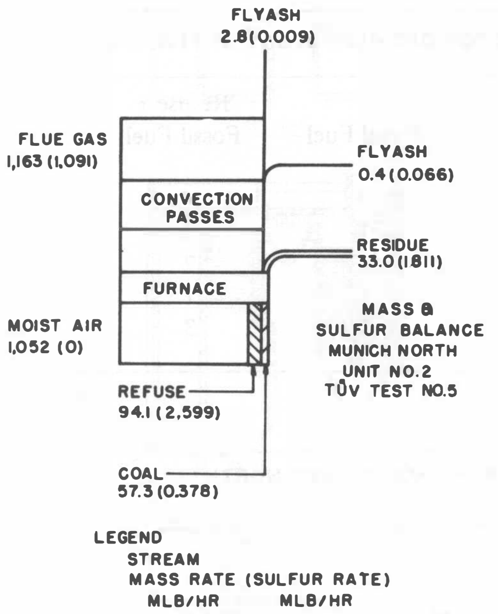


FIG. 5 MASS AND SULFUR BALANCE, MUNICH NORTH, UNIT NO. 2, TÜV TEST NO. 5

TABLE 4. SUMMARY OF RESULTS OF SULFUR BALANCES

Refuse Only	15 to 30 per cent of the entering sulfur appears in the flue gas.
Combined Firing	With (high sulfur) oil, 13 to 18 per cent of the entering sulfur appears in the flue gas. With (low sulfur) coal, 32 to 36 per cent of the sulfur appears in the flue gas.
Fossil Fuel Only	Over 92 per cent of the entering sulfur appears in the flue gas.

TUBE WASTAGE

An especially important part of the program was a study of refuse fireside deposition and corrosion. This involved a comprehensive examination of the literature on ash deposits and corrosion in conjunction with laboratory analyses and physical examination of ash deposits on tubes from the five selected units, and an evaluation of their relationship to corrosion in waterwall refuse-fired units [13]. The corrosion and deposition problem was initially brought out as a result of the publication of a series of articles in Europe in 1966-1967, describing severe corrosion in the furnace and high-temperature gas passes of refuse-fired steam generators (primarily the new German units) shortly after being put into operation. The initial rather disturbing reports were followed by numerous papers which now indicate that corrosion, although still understood only to a limited degree, has subsided or been brought under control [14-16].

As a result of this detailed study and discussions with plant designers and operators, the present situation may be summarized as follows:

- The exact mechanism of corrosion in refuse-fired steam generators is not fully known, and the proposed explanations are based upon surmise.
- Corrosion in refuse boilers is mainly a nuisance at present, rather than a critical problem, and poses no serious threat in Europe to existing installations. As a result, only minor attention is being given to elucidating the causes of corrosion.

These comments should counteract the unfortunate impression, still widespread in the United States, that high-performance, refuse-fired steam generators in Europe continue to experience intolerable corrosion problems. From a design point of view, it must be acknowledged that more detailed information is desirable. However, as a result of this study, the main danger points have been established which permit the designer to avoid the persistent problems incurred in Europe. For example, the experience indicates that corrosion occurs in convection passes when tube metals exceed threshold temperatures between 850 and 950 F, in almost all cases in the presence of ash deposits. In addition to fouling, and like ash corrosion from fossil fuels at comparable temperatures, corrosion due to refuse appears to be accelerated by the presence of sodium, potassium, chlorine, zinc, and lead [17, 18]. Localized reducing conditions can lower these threshold temperatures. This effect can be remedied by proper design and also by operating procedures. Full cognizance of this wealth of information was taken in the design of units for domestic conditions illustrated later in this paper.

MUNICH SOUTH

No survey of European experience on burning refuse for power generation would be complete without including the Munich South Plant. This is the most recent installation, having been put into service in late 1969. At the time the European plants were evaluated, no TÜV reports on this plant were available, and there most likely will not be a formal performance test because the unit has been so successful.

Unit No. 5 (Fig. 6) consists of a refuse-fired economizer and a natural gas- and/or oil-fired steam generator. Feed-water heated in the refuse-fired econ-

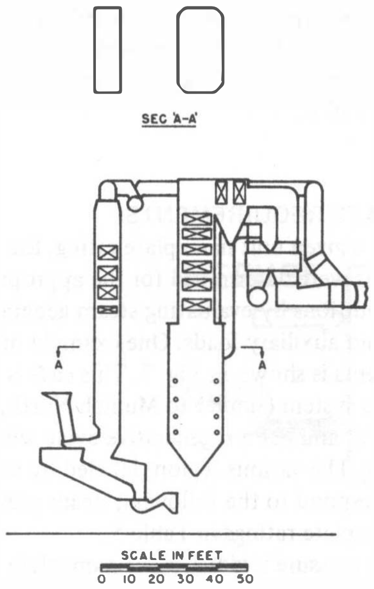


FIG. 6. MUNICH SOUTH UNIT NO. 5

omizer is transferred to the steam generator which is designed to deliver 805,000-lb/hr steam at 2600 psig and 1004 F/1004 F. Refuse is fired on a backward reciprocating grate (Martin) at a rate of 84,000 lb/hr (700 tpd) which constitutes about 20 percent of the heat input. Steam from the main steam generator is delivered directly to a 124 MW turbo-generator with extraction points for district heating. Regulation of steam pressure, temperature, and flow is controlled uniformly, comparable to a unit fired only with fossil fuel. Provision has been made for the future addition of coal pulverizers. Room has been provided for a duplicate unit (Unit No. 4), tentatively planned for a 1971 service date.

The work of Dr. M. Andritzky, formerly the Director of the Munich Electricity Works (now retired and a consultant to this program), and his successors is a model of planning, construction, and operation [19-23]. In the coming years, refuse burning will ultimately provide about 10 percent of the total power requirements of the City of Munich. However, the success in Munich has only been achieved because the city administration and the utility are partners in a joint venture with financial benefits accruing to both partners [22].

DOMESTIC EXPERIENCE

In the United States, there are presently no refuse burning plants designed and built for power generation. The first modern refuse-fired steam generator in the United States was built at the U.S. Naval Base at Norfolk, Virginia [24, 25]. This unit and subsequent units at Montreal, Chicago, Harrisburg, Braintree, Hamilton (Ontario), and Rochester are industrial size steam generators with the steam being used for industrial purposes or simply being condensed. The planned modification to Unit No. 1 at the Meramec Station of Union Electric in St. Louis is the first large-scale refuse burning demonstration for power generation [6]. However, by comparison to the European plants and the designs developed in this program, the refuse rate is small–amounting to only about 10 percent of the heat input.

An additional challenge imposed on domestic applications is that the heating value of municipal refuse is increasing each year as is the total amount of refuse produced. A steam generator is essentially designed for a fixed heat input. As the refuse heating value increases, the amount of refuse fired must be decreased to provide a constant heat input. Steam generator design is also based on fuel characteristics. If the fuel varies either by degradation or improvement, performance can be adversely effected. In Europe, refuse heating value has increased and, to some degree, has been a contributing factor to some of the operational difficulties reported.

CATALOG OF CANDIDATE SYSTEMS

An important task of this program has been the development of engineering and cost data on possible steam generator configurations fired by refuse. The catalog of such candidates was then systematically analyzed to identify those design forms which offer favorable bases for optimization. The selection of such systems was based on a state-of-the-art survey of steam generator designs and a detailed analysis of the characteristics of refuse. The aim in developing the catalog was to propose two classes of designs, one for new plants and one for modifying existing plants to accommodate refuse burning. Ten candidate designs were developed for new plants and five for existing plants.

DESIGN PARAMETERS

In order to develop the catalog, certain assumptions and design constraints were imposed. Typical analyses and heating value were assumed for refuse and coal. Candidate systems using grates were limited to a refuse rate of 1000 tpd. Those not using grates were limited to 2000 tpd. Refuse rates of 20 to 60 percent of the total heat input were generally sought.

Plant economy is adversely affected at lower refuse proportions, especially for new plants, while at levels above 60 percent, steam fluctuations become increasingly difficult to control. An upper limit of 500 MW was used. Four steam conditions were used in different plant sizes based on a survey of utility equipment purchasing over a three-year period ending in 1968. Only natural circulation steam generators were considered, based on the economy of this type compared to forced circulation. (Here there is a basic difference between United States and European practice). The flue gas exit temperature for firing refuse alone or in direct combination with coal firing was set at 450 F. It was chosen on the basis of electrostatic precipitators being a viable candidate for dust collection.

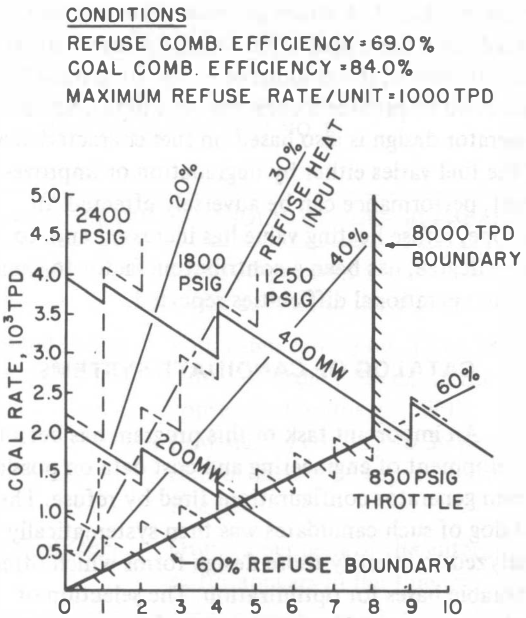


FIG. 7. FUEL REQUIREMENTS FOR BLENDED FLUE GASES

Another design parameter was that when burning refuse only (especially on a grate without size reduction), the maximum allowable steam temperature would be 750 F.

FUEL RATE REQUIREMENTS

For a given unit nameplate rating, the fuel requirements were determined for the appropriate steam conditions by evaluating steam generator efficiencies and auxiliary loads. One example of the fuel requirements is shown in Fig. 7. This case is for blended flue gas system (similar to Munich North, Unit Nos. 1 or 2) and has a regenerative cycle with or without reheat. The various regions labeled by steam pressures correspond to the following steam pressures and plant nameplate ratings in Table 5.

The pressure regions, plant nameplate ratings, and the allowable refuse rate per furnace determined the number of steam turbines and the number of steam generators. The discontinuities of fuel requirements at steam pressure region boundaries are basically due to differences in cycle efficiencies, the number of turbines and steam generators for a given nameplate rating, and the maximum allowable refuse rate per steam generator. Also shown is a boundary following 60 percent refuse heat input and 8000 tpd refuse rate. This system includes a grate and, therefore, the 1000 tpd per refuse furnace limit. Therefore, the refuse rate in 1000 tpd corresponds to the number of refuse furnaces. Thus, at a plant rate of 8000 tpd, there would be eight refuse furnaces in parallel. In burning more than 60 percent refuse, the number of refuse furnaces required was significantly increased. In addition, many multiple furnaces firing less than 40 percent coal required extremely costly duplication of fossil-fuel burning equipment. The catalog of candidate systems consists of combinations of various refuse-firing methods.

TABLE 5. STEAM PRESSURES AND NAMEPLATE RATINGS CORRESPONDING TO VARIOUS REGIONS IN FIG. 7.

Steam Conditions	Turbine Nameplate Rating
Throttle (Psig)/Superheat (F)/Reheat (F)	MW
2400/1000/1000	216-500
1800/1000/1000	86-215
1250/950/-	41-85
850/900/-	≤40

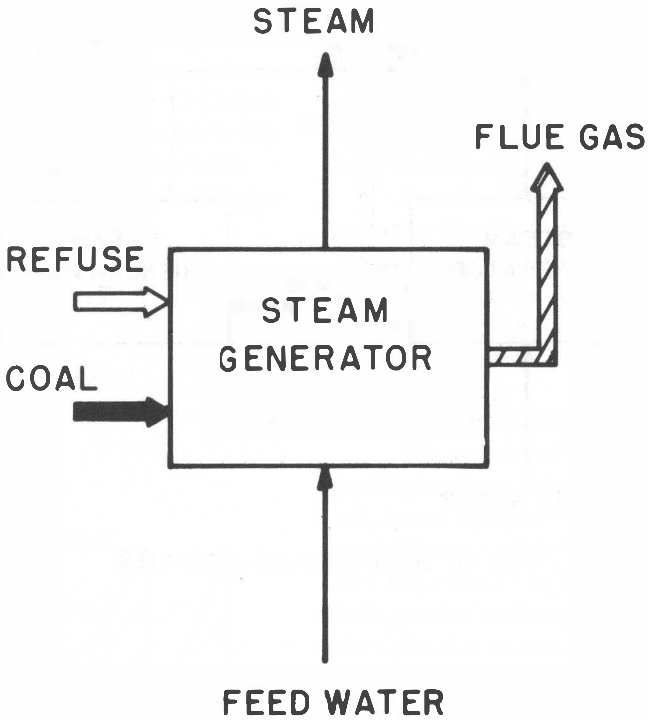


FIG. 8. BLENDED FLUE GAS SYSTEM

HEAT-RELEASE METHODS

One method of burning refuse to generate steam would be to burn refuse only and generate superheated steam delivered directly to a steam turbine. However, this presents difficulties in the control of fluctuations in steam flow and would result in steam temperature above 750 F with correspondingly higher metal temperatures and the potential of tube wastage. Such a method could be used in parallel with coal-fired units, where the amount of steam generated by refuse would be small enough so that variations in steam flow would be minimized, e.g. as at Düsseldorf. However, for the reheat cycle, the potential of tube wastage was sufficient to delete this method from the catalog.

Another method consists of firing refuse and coal in combination (blended flue gas) as shown schematically in Fig. 8. On a temperature-entropy plot, the area under the path of state is approximately the heat input as shown for a reheat cycle in Fig. 9. In this method, refuse and coal could be fired in separate furnaces (Stuttgart, Munich North, Unit No. 1) or in the same furnace (Munich North, Unit No. 2).

Yet another method would be to fire refuse only with the steam temperature held below 750 F as shown in Fig. 10. This method permits the designer a wide latitude. The refuse may be used to merely heat

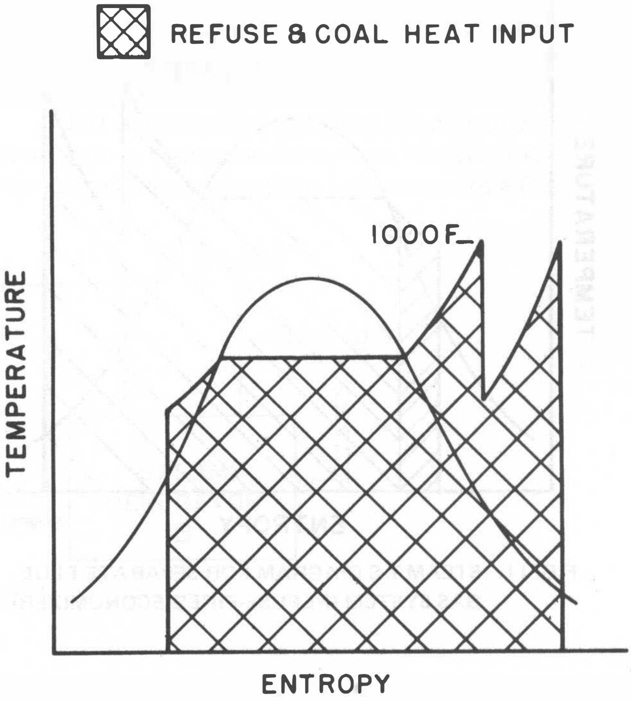


FIG. 9. STEAM T-S DIAGRAM FOR BLENDED FLUE GAS SYSTEM

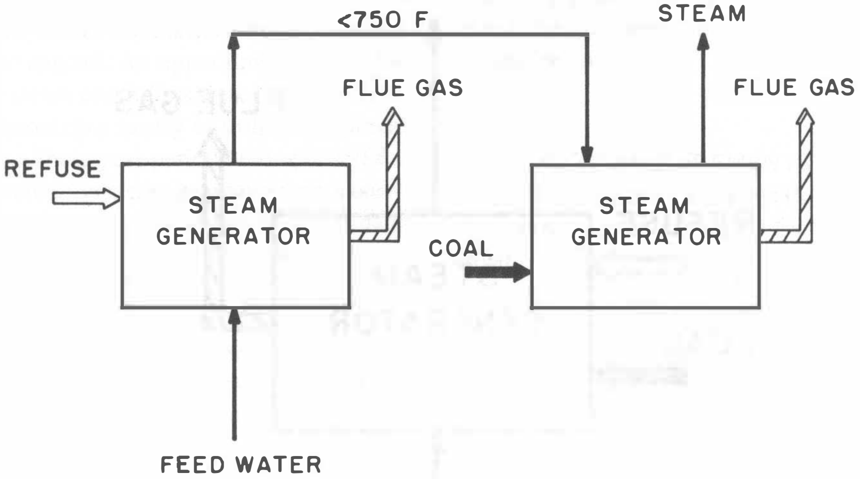


FIG. 10. SEPARATE FLUE GAS SYSTEM

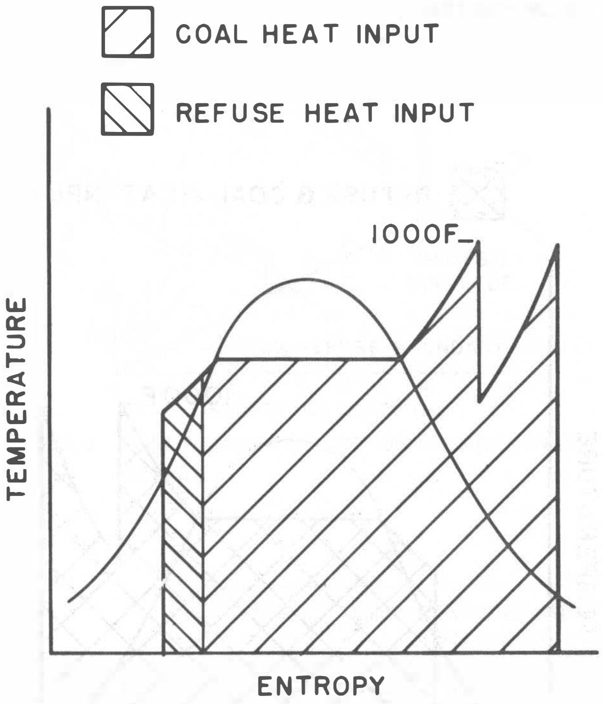


FIG. 11. STEAM T-S DIAGRAM FOR SEPARATE FLUE GAS SYSTEM (REFUSE-FIRED ECONOMIZER)

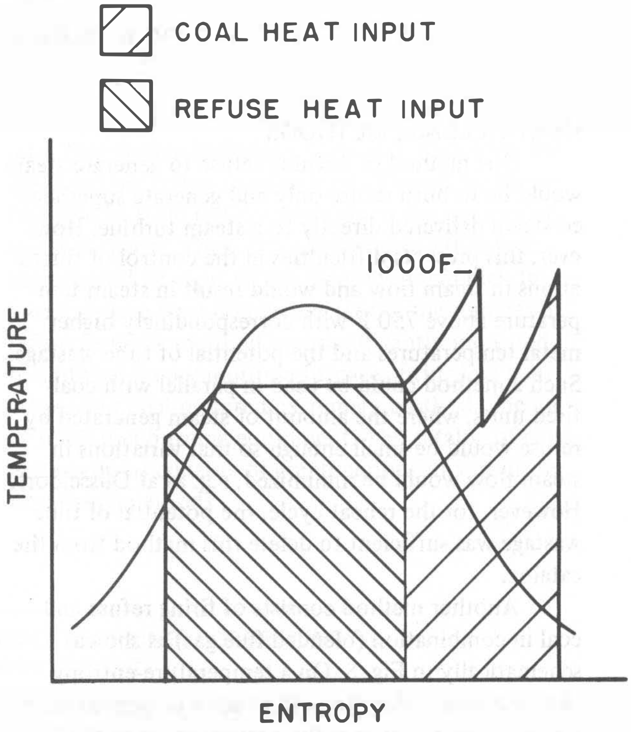


FIG. 12. STEAM T-S DIAGRAM FOR SEPARATE FLUE GAS SYSTEM (REFUSE FIRED TO SATURATED STEAM)

feedwater, normally the duty of the economizer of a conventional steam generator as shown in Fig. 11 (Munich South). The refuse may be used to heat steam to saturated vapor as shown in Fig. 12 [26] or to partially superheat steam (750 F) as shown in Fig. 13. In these instances, superheating and reheating would be accomplished in a separate coal-fired superheater (reheater). Such a method has been used for nuclear plants where saturated steam from the steam generator of the reactor was superheated in a separate, oil-fired superheater [27]. It has also been considered for a combined refuse-oil firing system where steam is used for industrial purposes [28].

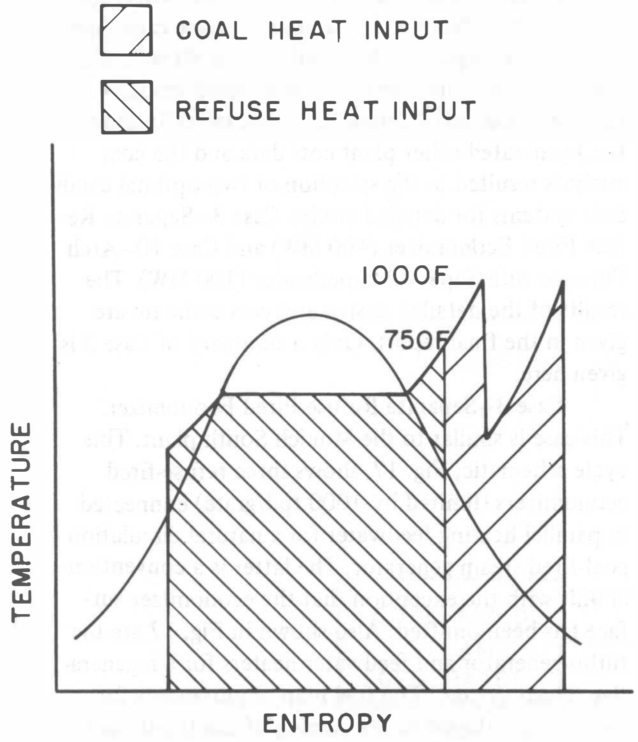


FIG. 13. STEAM T-S DIAGRAM FOR SEPARATE FLUE GAS SYSTEM (REFUSE FIRED TO PARTIAL SUPERHEATED STEAM)

A method combining the last two methods is shown in Fig. 14. Such a method would be used to generate saturated steam as shown in Fig. 15 or may be used to generate superheated steam. As shown in the following, this method is dependent on the firing method to some degree.

REFUSE-FIRING METHODS

The method of firing refuse considered in the catalog has been summarized in Fig. 16. Various manufacturers' equipment may vary in detail. For optimum service, each method requires size preparation. Size reduction of bulky waste is required even for agitating grates. In Europe, this procedure is built into the collection system either by preventing bulky refuse from entering the plants (Munich) or by having separate receiving and shredding facilities for bulky refuse (Düsseldorf and Stuttgart). Metals can be passed through the furnace and separated from the ash for scrap. However, at the Essen Karnap plant, metals are removed prior to firing. It is noted this plant has had no tube wastage and deposition problems. Prior removal of magnetic metal, which also removes most of the lead and zinc, may be the reason. Lead and zinc are two of the suspected temperature-dependent deposition and corrosion accelerators.

Just as commercial coal firing has progressed from grate to suspension firing, there is a real incentive to apply suspension firing to burning refuse for

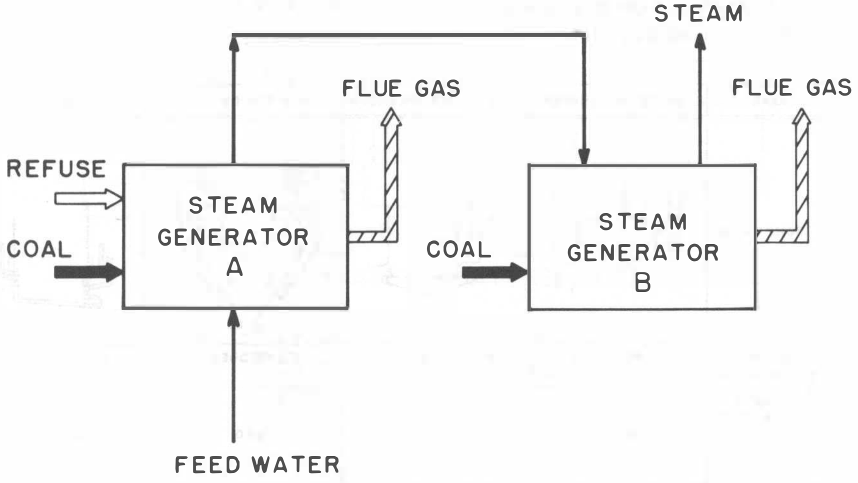


FIG. 14. BLENDED-SEPARATE FLUE GAS SYSTEM

power generation. Grates have structural limitations, and hence a single furnace enclosure is limited to about 1000 tpd. Firing pulverized refuse in suspension certainly would eliminate the need for cumbersome grates and, hence, would permit greater amounts of refuse to be fired. For such a system, a limitation of 2000 tpd was imposed in the catalog. This resulted in a significant change in the fuel requirements map in comparison to grate firing (Fig. 7). The basic difficulty to be resolved is to assure complete burnout of the refuse. One such method is illustrated later in this paper.

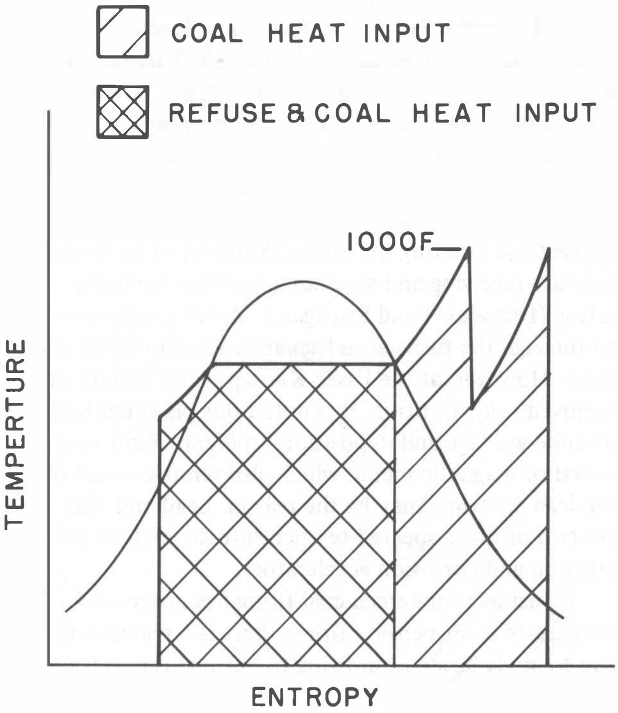


FIG. 15. STEAM T-S DIAGRAM FOR BLENDED-SEPARATE FLUE GAS SYSTEM

NEW PLANTS

A total of ten different candidate steam generator designs that were synthesized are shown in Table 6. Class 1 through 4 involve the use of a conventional agitating grate, such as the backward reciprocating, forward reciprocating, roller or tilting grate. Cases 5 through 10 require special refuse-firing equipment. These cases were subjected to preliminary designs and cost estimates in sizes up to 500 MW and, where applicable, over the complete range of refuse rates (percentage heat input) with a total of over 80 separate cost estimates being derived. Team members (Envirogenics Co. and Cottrell Environmental Systems, Inc.) generated other plant cost data and the cost analysis resulted in the selection of two optimal candidate systems for detailed study: Case 3—Separate Refuse Fired Economizer (400 MW) and Case 10—Arch Furnace with Separate Superheater (100 MW). The results of the detailed design and cost estimate are given in the final report. Only a summary of Case 3 is given here.

Case 3—Separate Refuse Fired Economizer. This case is similar to the Munich South plant. This cycle schematic, Fig. 17, shows three refuse-fired economizers (limited by 1000 tpd/grate) connected in parallel heating feedwater for a natural circulation coal-fired steam generator. The latter is a conventional unit with the exception that the economizer surface has been omitted. Also shown in Fig. 17 are the turbo-generator and feedwater heaters for a regenerative-reheat system. The fuel map requirements for this case developed in the catalog of candidates are shown in Fig. 18, along with the design point resulting from the detailed design. A cross-sectional arrangement of the economizers and steam generator is shown in Fig. 19, and the summary performance is shown in Table 7.

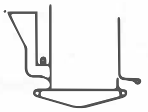
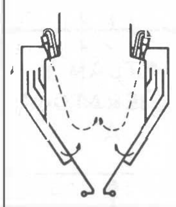
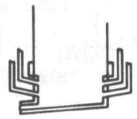
TYPE	AGITATING GRATES	AIR BLOWN SPREADER	SUSPENSION	SLAGGING
SCHEMATIC				
REFUSE PREPARATION	AS RECEIVED	4" SHREDDED	2" SHREDDED	2" SHREDDED
MAXIMUM ALLOWABLE REFUSE RATE PER GRATE TPD	1000	1000	2000	1000

FIG. 16. REFUSE FIRING METHODS

TABLE 6. SYNTHESIZED STEAM GENERATOR DESIGN CANDIDATES

Case	Designation
1	Separate Furnace
2	Combined Furnace
3	Separate Refuse-Fired Enconomizer
4	Saturated Steam Unit with Separate Superheater
5	Partial Superheater Unit with Separate Final Superheater
6	Suspension Furnace
7	Spreader Stoker
8	Slagging Furnace
9	Arch Furnace
10	Arch Furnace with Separate Superheater

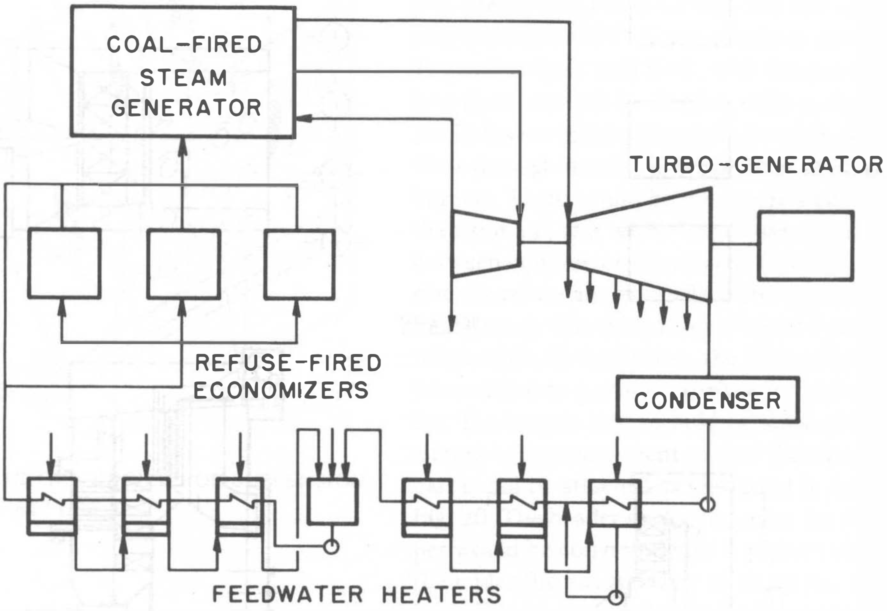


FIG. 17. STEAM CYCLE SCHEMATIC
CASE 3 – SEPARATE REFUSE – FIRED ECONOMIZER

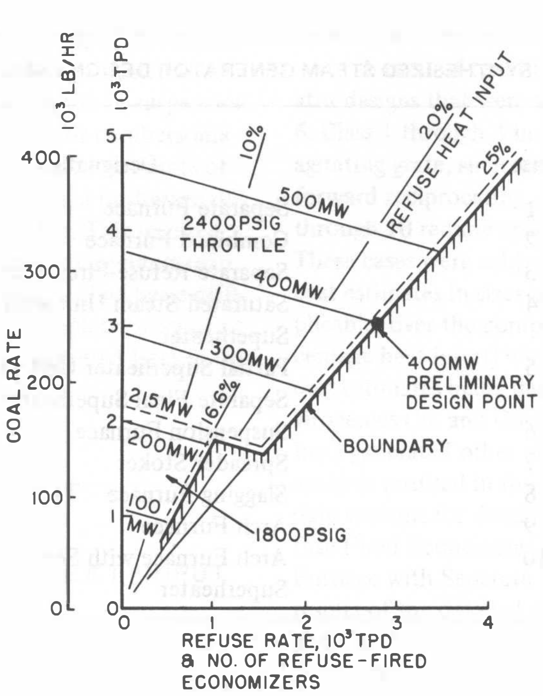


FIG. 18. PLANT FUEL REQUIREMENTS
CASE 3 – SEPARATE REFUSE – FIRED
ECONOMIZER

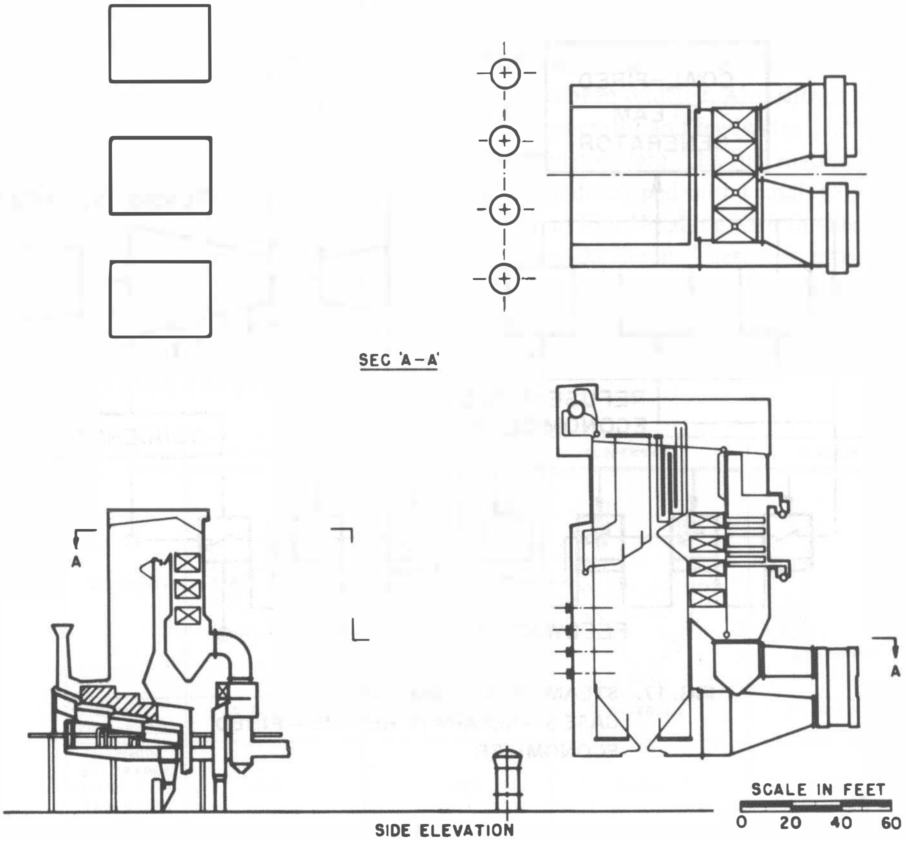


FIG. 19. GENERAL ARRANGEMENT
CASE 3 – SEPARATE REFUSE – FIRED ECONOMIZER

TABLE 7. SUMMARY PERFORMANCE DATA FOR CASE 3—SEPARATE REFUSE-FIRED ECONOMIZER (DESIGN DATA)

Refuse			Coal		
Feedwater	M lb/hr	933	Steam	M lb/hr	2800
Pressure at outlet	Psig	2600	Pressure superheater outlet	Psig	2520
Temperature feedwater outlet	F	657	Temperature steam superheater outlet	F	1000
Temperature feed entering unit	F	470	Temperature steam reheater outlet	F	1000
Temperature air entering unit	F	80	Temperature air entering unit	F	80
Temperature air leaving air heater	F	316	Temperature air leaving air heater	F	764
Temperature gas entering air heater	F	766	Temperature gas entering air heater	F	825
Temperature gas leaving air heater	F	575	Temperature gas leaving air heater	F	325
Excess air entering air heater	%	50	Excess air entering air heater	%	18
Wet gas entering air heater	M lb/hr	435.5	Wet gas entering air heater	M lb/hr	3004
Air entering air heater	M lb/hr	368.9	Air leaving air heater	M lb/hr	2740
Fuel fired	M lb/hr	232.6	Fuel fired	M lb/hr	250.7
	tpd	930		tpd	3008
Efficiency	%	66.22	Efficiency	%	87.42

Combined Efficiency %81.93

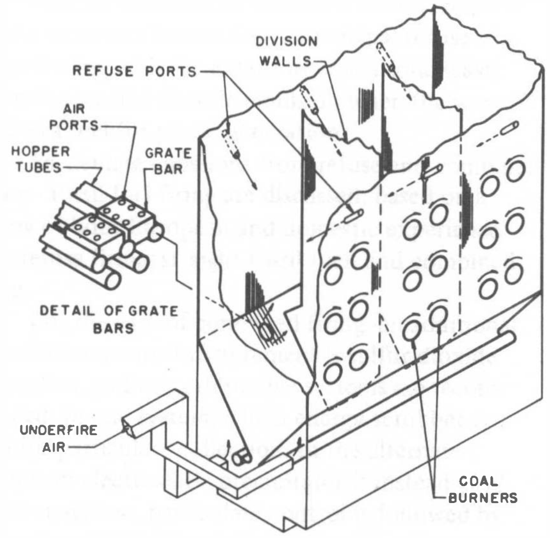


FIG. 20. EXISTING UNIT MODIFIED FOR SUSPENSION FIRING OF REFUSE

Existing Plants

Modifications to candidate plants followed the procedures used for new plants. Obviously, there was a limit to the heat absorption and firing methods that could be employed. The obvious modifications consisted of conversions to Cases 1 and 2 type furnaces with agitating grates or spreader stokers. Suspension firing was considered appropriate for a unit recommended by others for combined refuse and coal firing [6]. Steam conditions for this 300 MW unit are 2200 psig/1010 F/1010 F. It was placed in service in 1961. The unit is front wall fired, with the furnace divided into three sections by division walls as shown in Fig. 20. Refuse would be injected into each of these sections through nozzles located above the top row of burners. There would be two nozzles per section on the front and rear walls. The refuse would be injected between counterrotational coal burners tending to give the refuse an extremely turbulent burning path. In the event that there is insufficient burnout of refuse while in suspension, the furnace hopper could be modified to provide a surface for additional burning. The hopper tubes would be replaced by a slightly altered tube arrangement so that the stationary grate bars could be attached as illustrated in the insert in Fig. 20. The header enclosure under the furnace hopper would be converted into a plenum chamber for the under-fire air. An array of steam jets on the hopper would be operated periodically to remove ash deposits from the grate bars. The refuse rate has been set at 775 tpd, which is equivalent to 10 percent of the heat input. At this rate, existing fans could be used. Additional soot blowers have been included, but at this refuse rate and with magnetic metals removed from the refuse, no fouling would be anticipated.

CONCLUSIONS

It has been shown that the European experience of burning refuse in combination with fossil fuel for power generation is fully developed and based on a sound engineering approach. The more recent plants are well planned and are virtually operated with the same availability and reliability as conventional fossil-fuel-fired plants. Their confidence is well documented by the continued committment of new units. It has also been shown that the European experience is applicable to the United States conditions. The companion papers to this paper demonstrate that there are economic and environmental incentives to generate power from refuse. What is required here in the United States is the same approach that has been applied in Europe, the cooperation of the public, municipal governments, and electric utility companies to burn refuse to produce kilowatts–a reasonable challenge.

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