INTRODUCTION

A number of American waste-to-energy conversion plants suffered serious technical problems upon start-up which required considerable modifications of equipment and procedures. As a result, multi-year delays were encountered before these plants would achieve maturity in operations. In this regard, the Nashville, Saugus, Akron and Hempstead plants have been widely publicized.

In sharp contrast to these unfortunate developments, the waste-fired district heating station and resource recovery facility (RRF) in Kiel, West Germany, started full scale operations in 1975, i.e., at approximately the same time as Nashville and Saugus. The Kiel facility was delivered on schedule, and it accomplished a high annual plant capacity factor for the refuse burning grate, or PCFG, of 93 percent during its first operating year. (The letter “G” refers to the grates, because, as will be explained later in this paper, there is a different annual plant capacity factor, PCFB, which refers to the boilers.) During subsequent years, the PCFG reached or exceeded 100 percent, a feat which is most remarkable even by German standards.

Besides the high PCFG, the Kiel facility had the distinction of being the first plant built in accordance with the new guidelines for air pollution control (TA Luft 74) promulgated by the German EPA in 1974, see Ref. [1]. As a result, Kiel features electrostatic precipitators in combination with wet scrubbers and provisions for flue gas re-heating.

It is the purpose of this paper to introduce the American audience to the Kiel success story by describing, documenting and discussing the developments outlined above.

PROJECT HISTORY

Discussions concerning construction of a refuse fired district heating station commenced in Kiel during 1963. After considering several alternatives, the city council decided to build a facility which could dispose of refuse and recover energy for district heating. The most convincing argument was the unavailability of new landfill space in or near the city.

It took several years to perform a feasibility study, select a suitable site and to obtain the necessary permits. Because of the need to be close to its residential and commercial customers, the Kiel RRF had to be sited in the inner city. Detailed engineering, construction and start-up took place between 1972 and 1975, requiring approximately 36 months.

The Kiel RRF was organized as a nonprofit corporation with limited liability called “Müllverbrennung Kiel GmbH” (Kiel Refuse Incineration Company). Its shares are completely owned by the City of Kiel and operations are based on an annual budget which must balance expenses against revenues.

In the pursuit of its business, i.e., the disposal of wastes and the recovery of energy, the Kiel plant must interface with two other important municipal entities.
One is the City Department of Sanitation which is responsible for waste collection, transportation and disposal. The Department of Sanitation, together with private carters, delivers refuse, i.e., the fuel, to the RRF.

The other is the Municipal Power Company which supplies electricity, gas, water and district heat to large parts of the city. The Municipal Power Company, because of the existence of an extensive district heating network (DHN), appeared to be an excellent choice as a long term energy customer. This company is also owned by the City of Kiel. It is the custom in many German cities for the Municipal Power Company to be owned by the city itself.

In order to bind all the parties together, a four-part contract was concluded between the RRF and the Municipal Power Company which called for the Power Company to:

1. Operate the RRF on an annual budget basis.
2. Provide engineering services, including design, construction supervision, start-up and testing.
3. Purchase the recovered energy in the form of heat for district heating.
4. Supply the utilities, such as electricity and water.

In accordance with this contract, all skilled personnel in both the technical and business branches are furnished by the Power Company.

Thus the RRF — as a company — has only a minimal staff which consists of two general managers and some secretarial support. Both of these managers are appointed on a part time basis, since they hold other offices as well. In line with the objective of working towards a common goal, these appointments are made on a functional basis.

The “General Business Manager” for the RRF is also the head of the City Department of Sanitation. Similarly, the “General Technical Manager” is also the head of the Cogeneration Department in the Municipal Power Company.

During the first phase of construction, two grate systems of 5.5 stph (5 X 10³ kg/hr) refuse burning capacity each and two boiler systems of 17.6 stph (1.6 X 10⁴ kg/hr) or 20,200 lb/hr steaming capacity each were installed. The thermal characteristics of the grates and boilers were matched in order to permit accommodation of a wide range of heating values. Thus refuse with a lower heating value, between 1,440 and 4,500 Btu/lb (3,350-10,468 kJ/kg), can be burned. However, the following conditions must be met: satisfactory burn-out of the residue, safe thermal loading of the grate and acceptable heat input to the boiler.

The grate boiler combinations were designed for a maximum, or theoretical specific steaming rate (SSR) of 17.6/5.5 = 3.20 ST steam/ST refuse (t steam/t refuse), or lb steam/lb refuse.

Electrical power generation was ruled out, because generally larger systems operating at high conditions of temperature and pressure are required. Instead, smaller units with a modest pressure of 203 psi (1.40 X 10⁶ Pa or 14 bar) were selected for the sole purpose of generating saturated steam. This choice is expected to combine a minimum of corrosion with high equipment availability.

After 4 weeks of testing each boiler, commercial operations of the phase I facility started in June 1975. Even during this test period, all available capacity was fully utilized. Soon it was realized that the supply of refuse from the city and its surroundings would grow further. Consequently, during phase II construction, a larger system was added with the following ratings: grate refuse burning capacity 11.0 stph (1.0 X 10⁴ kg/hr), boiler steaming capacity 35.2 stph (3.2 X 10⁴ kg/hr) or 70,400 lb/hr, and an SSR = 35.2/11.0 = 3.20. Steam parameters are identical to the older units. Commercial operation of the third system started in August 1980. Once again, start-up was an instant success as will be discussed later in this paper under equipment utilization. Also, a roto-shear was installed for size reducing bulky wastes with high Btu values, a provision which — for the long run — should improve the fuel mix.

The Kiel RRF is configured in a manner which permits continuous, year-round feeding of the steam produced to the Kiel District Heating Network (DHN). Any excess energy which cannot be accepted by the DHN during the summer months is rejected by means of air condensers from the rooftop of the RRF.

Investment costs for phase I were about $14 million (DM 30 million in 1975) and for phase II about $14 million (DM 30 million in 1980). For the better part, these monies were borrowed on the open capital market and have to be repaid at commercial interest rates.

Figure 1 shows an aerial view of the Kiel RRF which is located directly at the inner city freeway, thus allowing easy access for refuse and residue transportation. The facility is surrounded by apartment houses, a major shopping center, five schools and one old folks’ home, all within a 2,300 ft radius. The distance to the nearest residential structure is approximately 490 ft. According to the German regulatory procedure, public participation
is invited during permit review. Given the close­
ness of the Kiel RRF to residential areas, it does
not come as much of a surprise to learn that near­
ly 2,000 objections were filed which had to be
dealt with by the permitting agency. All of these
circumstances mitigated towards tough environ­
mental controls, as is discussed in a later section
of this paper.

FACILITY DESCRIPTION

Figure 2 presents a cross-section of the Kiel
RRF. The principal elements of tipping boxes,
refuse storage bunker and feed hoppers are similar
to the ones used in other facilities elsewhere.
Combustion takes place on a Duesseldorf grate
system which is manufactured by Vereinigte Kes­
selwerke A.G., or VKW. This grate consists of six
cylindrical and sequential drums or rollers of
equal diameter and width. The latter are mounted
inside a framework which is inclined by 30 degrees
against the horizontal plane. Below the framework,
six individual sheet metal compartments are ar­
ranged to supply underfire combustion air in such
a way that one flow zone is established for each
roller. Each roller has its own independent speed
and air flow controls. Since both can be varied
continuously over a wide range, it is possible to
tailor the combustion process according to the
quality of the refuse fired.

Fuel oil burners are installed in the sides of the
furnace chamber for start-up purposes and also for

FIG. 1 AERIAL VIEW OF THE KIEL RRF – THE SUD DISTRICT HEATING STATION AND THE
RESOURCE RECOVERY FACILITY ARE INTEGRATED AT THE SAME INNER-CITY SITE INTO A
SINGLE COMPLEX.
supplemental firing in case of abnormally low heating values in the refuse. An additional fuel oil burner is installed in the front wall to ensure that the furnace temperature will never fall below 1,472 F (800 C), a minimum temperature which is necessary for effective odor control.

The boiler itself consists of three passes: the first is the radiation shaft, the second is the evaporator section, and the third is the economizer section. The latter serves to lower the exit temperature for increased boiler efficiency. In true water-wall fashion, membrane walls are extended into the furnace to a line just above the roller grates.

The heat transfer surfaces in the boiler are periodically cleaned with compressed air in order to avoid the corrosion often associated with steam powered soot blowers.

In order to clean the flue gases exiting from the boiler, two field electrostatic precipitators are provided. From there, forced draft fans push the flue gases through venturi scrubbers into a stack. This air pollution control system is described in detail in a subsequent section of this paper.

Two oil fired, packaged standby boilers are available, in case of either unusual winter peak demands or unexpected downtime of the refuse fired systems. As the later section on operating statistics will show, these oil fired boilers are hardly ever used.

THE ENERGY CUSTOMER

The Kiel District Heating Network (DHN) consists of a hot water section and a steam section. The first operates with a supply temperature of 266 F (130 C) and return temperature of 158 F (70 C). The second operates with a pressure of 44 psig (3.03 X 10^5 Pa, or 3 bar).

The Kiel DHN was started in 1905 and is one of the oldest installations of this type in Germany. In terms of its service area, the Kiel DHN stretches 4.1 miles (6.5 km) in the North-South direction and 2.8 miles (4.5 km) in the East-West direction.

As illustrated in Fig. 5, the Kiel DHN comprises seven service districts and four energy supply facilities, one of which is the Kiel RRF.
1979, 31,500 housing units out of a total of 112,000 were connected. This corresponds to an average capture rate of 0.281. An additional 3,500 housing units are presently being connected, so that by 1983 an average capture rate of 0.313 is expected, see Ref. [2]. Capture rates in the inner city, i.e., in districts 1, 2, 5 and 7, are substantially higher. Capture rates between 50 and 100 percent and supply densities of 160 to 288 MW/square-
mile indicate that service saturation has been reached in some areas.

In terms of structures near currently installed piping, already 3,100 out of 6,200 buildings suitable for district heating are connected, for a connection rate of 0.500. From a marketing point of view, it is desirable to increase the length of the existing DHN from 67 miles (107 km) to somewhat over 76 miles (122 km). This increase should

Service Districts:
1. Nord
2. Humboldtstrasse
3. Klinikum u. Landeshaus
4. Tannenberg
5. Hettenhof
7. Süd

![Map of the Kiel District Heating Network](image)

**FIG. 3 MAP OF THE KIEL DISTRICT HEATING NETWORK**
accomplish an optimum in service density and operating economics. Besides housing units, government buildings, shopping centers, office and industrial buildings, a university and several hospitals are provided with district heating. In terms of connected capacity, institutional use accounts for about 42 percent versus 58 percent for residential use. In terms of the heat transfer medium, steam capacity accounts for about 44 percent and hot water for 56 percent. The trend is to build up the hot water system and reduce the low pressure steam system, because the electrical power part of cogeneration works more efficiently with a hot water system than with a steam system.

Table 1 presents the overall performance of the Kiel DHN for the 1975 to 1980 period during which the Kiel RRF has been in operation. While total heat sent out seems to have reached a plateau of about 309 billion Btu (1,055 GWhr), the share of the Kiel RRF shows a continued increase from 11.7 billion Btu (40 GWhr) to 39.6 billion (135 GWhr). This gain corresponds to about 100 percent over a six year period, if annualized data is used for 1975.

In terms of fuel usage, the Municipal Power Company is fortunate to have access to a wide variety of fuels which is the result of geographic location and superb marketing. Being a Baltic seaport allows Kiel to buy and ship coal at competitive prices from suppliers near and far (Ruhr District in Germany, Poland, Soviet Union, Norway, China and Africa). Likewise, Kiel is connected to domestic gas fields as well as to the Norwegian Ekofisk fields in the North Sea. In addition, Kiel stores gas in the form of Butane in underground caverns for winter peaks.

During 1980, Kiel’s supply of primary energy was split among the following sources: 52.3 percent from coal, 39.0 percent from gas, 4.5 percent from refuse and 3.9 percent from oil, see Ref. [3]. While refuse contributed only 4.5 percent to the primary energy supply, it contributed 12.9 percent to the District Heating Network thus offsetting mostly foreign oil.

Table 1 also reveals that the largest portion of Kiel’s district heat, about 75 percent in 1980, was the by-product of electrical power generation, or cogeneration. In terms of fuels, about 48 percent of this heat was derived from gas, about 37 percent from coal and the remaining 15 percent from refuse and oil.

Against this background of total energy marketing, refuse derived energy in Kiel faces stiff competition as will be discussed in the economics section later on.

The Kiel RRF comprises a refuse fired steaming capacity of $2 \times 17.6$ stph + $1 \times 35.2$ stph = 70.4 stph and an oil fired steaming capacity of $2 \times 27.8$ stph = 55.6 stph for a total nameplate capacity of 126 stph ($1.15 \times 10^6$ kg/hr) or 252,000 lb/hr. This capacity can be further expanded by 25.3 stph on the refuse side and 83.4 stph on the oil side for a final total nameplate capacity of 245 stph ($2.22 \times 10^6$ kg/hr) or 490,000 lb/hr. It should be emphasized that since the existence of the Kiel RRF essentially all its heat output has been derived from refuse firing (99.7 percent).

This positive trend is expected to continue, provided the refuse heating value remains high and the supply of refuse continues to increase. While there is promise that the refuse firing capacity can be further expanded in the future by offering waste disposal services to a wide number of neighboring communities, it is not very likely that additional oil firing capacity will be required at the Kiel RRF. This is especially true in view of the excellent performance record of the refuse fired systems.

However, since district heating sales demonstrated strong, continued growth in the hot water sector, the Kiel RRF is now being equipped with a hot water supply system so that its thermal output can be sold either in the form of low pressure steam or in the form of hot water.

**TECHNICAL OPERATING RESULTS**

For a consecutive 7-year reporting period from 1975 through 1981, the general operating statistics are delineated in Table 2. The two parameters which are most important to revenue generation, i.e., the amounts of refuse processed and heat sold to the DHN, increased from year to year with regularity.

Several other parameters showed a less pronounced but nevertheless clear upward trend. These are residue generation, plant heat consumption and heat rejection. The consumptions of water, oil and electricity show a less definitive trend.

Figure 4 further illustrates these trends diagrammatically and, since it is based on monthly entries, it also displays certain seasonal variations. Most noticeable among these is a repetitive dip which occurs every year during the June to August period. This dip coincides with annual minimum demand for district heat. Consequently, the plant
<table>
<thead>
<tr>
<th>Operating Year</th>
<th>Total Sendout (2) for DH Network</th>
<th>Cogeneration Plant Humboldtstrasse (Fuel: Mostly gas, little oil)</th>
<th>Cogeneration Plant Wik (Fuel: Basically coal)</th>
<th>District Heating Station Mettenhof (Fuel: Almost exclusively gas)</th>
<th>Resource Recovery Plant Süd (3)(4) (Fuel: Almost exclusively refuse)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>805.6</td>
<td>335.9</td>
<td>41.7</td>
<td>311.5</td>
<td>38.7</td>
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<tr>
<td>(1975*)</td>
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<tr>
<td>1976</td>
<td>902.6</td>
<td>323.2</td>
<td>35.8</td>
<td>344.2</td>
<td>38.1</td>
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<tr>
<td>1977</td>
<td>941.8</td>
<td>311.4</td>
<td>33.0</td>
<td>382.6</td>
<td>40.6</td>
</tr>
<tr>
<td>1978</td>
<td>1,033.9</td>
<td>329.6</td>
<td>31.9</td>
<td>442.8</td>
<td>42.8</td>
</tr>
<tr>
<td>1979</td>
<td>1,075.6</td>
<td>383.7</td>
<td>35.7</td>
<td>417.3</td>
<td>38.8</td>
</tr>
<tr>
<td>1980</td>
<td>1,053.5</td>
<td>381.7</td>
<td>36.3</td>
<td>403.0</td>
<td>38.3</td>
</tr>
<tr>
<td>T</td>
<td>5,813.0</td>
<td>2,065.5</td>
<td>36.3</td>
<td>2,301.4</td>
<td>39.6</td>
</tr>
</tbody>
</table>

Notes: (1) In working with the original plant records, 1 GWh = 860 Gcal, or 1GWh = 0.860 Tcal, was used for conversion in order to achieve uniformity. Another useful conversion is 1GWh = 3.413 x 10^9 Btu (or billion Btu).
(2) During 6 years, the network's sendout increased approximately 30%, or 5% per annum.
(3) During 6 years, the resource recovery plant contribution increased approximately 50%, or 8% per annum using annualized data for 1975 (see connotation with *).
(4) Includes 0.1-0.3 GWh from oil fired packaged boilers.
TABLE 2 KIEL RRF - GENERAL OPERATING STATISTICS(1)(2)

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</thead>
<tbody>
<tr>
<td>Year</td>
<td>STPY</td>
<td>STPY</td>
<td>STPY</td>
<td>x10^6 kwh/y</td>
<td>x10^6 kwh/y</td>
<td>x10^6 kwh/y</td>
<td>x10^6 kwh/y</td>
<td>x10^6 kwh/y</td>
<td>x10^6 kwh/y</td>
<td>x10^6 kwh/y</td>
<td>x10^6 kwh/y</td>
</tr>
<tr>
<td>1975(1)(2)</td>
<td>52,209</td>
<td>98,889</td>
<td>23,177</td>
<td>87.6</td>
<td>62.5</td>
<td>9.9</td>
<td>12.2</td>
<td>40.4</td>
<td>3.15</td>
<td>(133.10)</td>
<td>11.16</td>
</tr>
<tr>
<td>(1975)</td>
<td>(169,110*</td>
<td>(39,978*)</td>
<td>(149.8*)</td>
<td>(106.9*)</td>
<td>(16.9*)</td>
<td>(20.9*)</td>
<td>(69.1*)</td>
<td>(5.9*)</td>
<td>(162.6*)</td>
<td>(1.67)</td>
<td>(9.19)</td>
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<td>1976</td>
<td>93,447</td>
<td>188,815</td>
<td>45,033</td>
<td>167.9</td>
<td>123.8</td>
<td>18.1</td>
<td>10.8</td>
<td>95.1</td>
<td>6.75</td>
<td>(162.6')</td>
<td>32.66</td>
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<td>1977</td>
<td>90,968</td>
<td>186,437</td>
<td>41,460</td>
<td>170.2</td>
<td>133.9</td>
<td>15.6</td>
<td>8.4</td>
<td>99.9</td>
<td>6.04</td>
<td>11.98</td>
<td>5.05</td>
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<tr>
<td>1978</td>
<td>101,791</td>
<td>219,968</td>
<td>43,915</td>
<td>222.4</td>
<td>133.3</td>
<td>9.9</td>
<td>9.3</td>
<td>116.1</td>
<td>6.14</td>
<td>7.63</td>
<td>0.37</td>
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<tr>
<td>1979</td>
<td>103,999</td>
<td>230,648</td>
<td>48,127</td>
<td>244.8</td>
<td>148.7</td>
<td>17.0</td>
<td>8.9</td>
<td>122.8</td>
<td>6.19</td>
<td>7.63</td>
<td>0.37</td>
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<tr>
<td>1980(1)(2)</td>
<td>117,477</td>
<td>268,399</td>
<td>50,111</td>
<td>279.5</td>
<td>174.9</td>
<td>26.0</td>
<td>13.8</td>
<td>139.1</td>
<td>7.32</td>
<td>17.16</td>
<td>0.77</td>
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<tr>
<td>1981</td>
<td>132,491</td>
<td>317,099</td>
<td>55,440</td>
<td>297.3</td>
<td>207.6</td>
<td>29.7</td>
<td>22.6</td>
<td>155.5</td>
<td>7.97</td>
<td>17.16</td>
<td>0.72</td>
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<tr>
<td>7-Year Totals</td>
<td>664,332</td>
<td>1,310,275</td>
<td>307,955</td>
<td>1,405.7</td>
<td>974.7</td>
<td>126.2</td>
<td>85.8</td>
<td>762.9</td>
<td>43.76</td>
<td>338.66</td>
<td>16.94</td>
</tr>
</tbody>
</table>

7-YEAR STATISTICS(3)

<table>
<thead>
<tr>
<th>Meas.</th>
<th>x10^6 kwh/y</th>
<th>x10^6 kwh/y</th>
<th>x10^6 kwh/y</th>
<th>x10^6 kwh/y</th>
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<tbody>
<tr>
<td>Min.</td>
<td>98,889</td>
<td>23,177</td>
<td>87.6</td>
<td>62.5</td>
</tr>
<tr>
<td>Max.</td>
<td>219,968</td>
<td>43,915</td>
<td>222.4</td>
<td>133.3</td>
</tr>
<tr>
<td>Mean.</td>
<td>132,491</td>
<td>50,111</td>
<td>279.5</td>
<td>174.9</td>
</tr>
<tr>
<td>CV%</td>
<td>41</td>
<td>21</td>
<td>15.6</td>
<td>9.9</td>
</tr>
</tbody>
</table>

Notes:
(1) The figures listed represent annual totals regardless which processing lines were in operation. STPY stands for short tons per year.
(2) For conversion use: 1 ton = 1,848 kwh; 1 ton = 0.008,293.23 kWh; 1 gal heavy oil = 63.0 kWh.
(3) Includes about 12% wt. ferrous scrap most of which is sold, 5% wt. asphalt most of which is used in road construction, 8% wt. residuals which are landfilled. Also included are solids settled out from the scrubber systems.
(4) For startup and standby operations the first two years were excluded from statistical treatment because of their atypical nature. The figures involved are marked with a.
(5) Phase I plant operations commenced in June 1975 with the first two units installed: 2x3.3 stth, or 3.3 MW, of initial nameplate grate capacity and 2x17.6 stth, or 4.6 MW, of initial nameplate boiler capacity. Operations lasted only 7 months. STPY, minus short tons per day on a 7-day a week basis.
(6) In order to reduce bias during statistical treatment, the actual figures were annualized by multiplication with the factor 52/7 = 1.17. The annualized figures are marked with * and were used as such.
(7) Phase II plant operations commenced in August 1980 with the third unit installed: 1x1.0 stth, or 3.6 MW, of additional nameplate grate capacity and 1x17.6 stth, or 4.6 MW, of additional nameplate boiler capacity.
(8) Annualized data for 1975 is used. The oil figures for 1975 and 1976 were deleted. See notes (4) and (5) above.
(9) Arithmetic average for 7-year period (unless denoted by the), calculated as \( \bar{x} = \frac{\sum x_i}{n} \), where \( x_i \) is the individual value and \( n \) is the number of values.
(10) Percentage change over 7-year period (unless denoted by the), calculated as \( \% = \frac{x_{new} - x_{old}}{x_{old}} \times 100\% \).
(11) Coefficient of variability for 7-year period (unless denoted by the), calculated as \( CV = \frac{\text{Range}}{\text{Mean}} \).

operator tries to schedule equipment inspection and maintenance for this same period. This results in a temporary reduction of waste processed and steam generated. In spite of these precautionary moves, excess steam is temporarily generated which must be condensed in air cooled condensers.

Figure 4 projects continued and substantial growth for refuse processing and steam generation, a highly positive result. However, it also indicates that heat rejection during the summer months is likely to increase. Unlike many urban areas in the U.S., Kiel enjoys a moderate climate which calls for little by way of air conditioning during the summer. For the near future, the prospects of finding major new customers with high summer loads are poor and therefore increased heat rejection must be accepted as an unfortunate, but nevertheless permanent condition.

Because tipping fees are much higher than steam prices, the economic impact of this energy wastage is less dramatic than it would appear on first sight. This will be explained in a later section.

From the aforementioned Table 2, specific operating statistics have been calculated for presentation in Table 3. The results can be subdivided into two major observation periods. The first spans the first five operating years and the second spans the last two operating years.

During the first period, the refuse heating value and the specific steam rate showed a steady increase while the other parameters, such as heat sales, plant heat consumption, electrical and water
consumption and residue generation rate, remained essentially stable.

In contrast, during the second period almost all of the parameters investigated changed, mostly as a result of equipment modification and plant expansion. The steaming rate increased while the heating value declined which, if taken on first sight, appears to be a paradox. The average annual heating value appears to have declined at least temporarily. In this context it should be remembered that the annual lower heating value (LHV) is not the result of laboratory tests, but is determined by using the boilers as “living calorimeters”. Heat balances are then set up with an assumed thermodynamic efficiency. The final result is a calculated heating value, the accuracy of which depends on the assumptions made. Originally an efficiency of 65 percent was used. After investigation by the testing service and the manufacturer, it was decided to increase the assumed efficiency to 75 percent, which resulted in a lower heating value. At the same time, larger boiler equipment is used more often, allowing for some economy of scale. In addition, improvements are being made in the accounting system, making steam measurements more accurate both in terms of actual send-out and actual condensate return (special computer-controlled analyzers are being installed).

Other parameters, such as oil consumption, electrical consumption, water consumption and heat losses, show discernible improvements. While some of these improvements may indeed be related to economics of scale, others are either the result of new design features, or gains in equipment reliability, or both.

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<tbody>
<tr>
<td></td>
<td>Btu/Lb</td>
<td>ST/ST</td>
<td>kWh/ST</td>
<td>Gal/ST</td>
<td>kWh/ST</td>
<td>kWh/ST</td>
<td>kWh/ST</td>
<td>kWh/ST</td>
<td>kWh/ST</td>
<td>kWh/ST</td>
<td>St/ST</td>
</tr>
<tr>
<td>Year</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1975</td>
<td>2,857</td>
<td>1.90</td>
<td>1,675</td>
<td>(2.58)</td>
<td>107.3</td>
<td>60.1</td>
<td>169.3</td>
<td>233.3</td>
<td>777</td>
<td>633</td>
<td>217</td>
</tr>
<tr>
<td>1976</td>
<td>3,064</td>
<td>2.03</td>
<td>1,797</td>
<td>(1.73)</td>
<td>72.12</td>
<td>66.3</td>
<td>193.7</td>
<td>115.6</td>
<td>1,018</td>
<td>608</td>
<td>350</td>
</tr>
<tr>
<td>1977</td>
<td>3,195</td>
<td>2.05</td>
<td>1,873</td>
<td>0.13</td>
<td>5.4</td>
<td>66.0</td>
<td>171.7</td>
<td>92.5</td>
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<td>581</td>
<td>745</td>
</tr>
<tr>
<td>1978</td>
<td>3,726</td>
<td>2.16</td>
<td>2,185</td>
<td>0.07</td>
<td>2.9</td>
<td>59.9</td>
<td>97.3</td>
<td>91.4</td>
<td>1,121</td>
<td>938</td>
<td>379</td>
</tr>
<tr>
<td>1979</td>
<td>4,003</td>
<td>2.17</td>
<td>2,347</td>
<td>0.07</td>
<td>2.9</td>
<td>58.5</td>
<td>160.4</td>
<td>84.0</td>
<td>1,159</td>
<td>1,006</td>
<td>276</td>
</tr>
<tr>
<td>1980</td>
<td>4,231</td>
<td>2.29</td>
<td>2,481</td>
<td>0.15</td>
<td>6.2</td>
<td>63.8</td>
<td>221.3</td>
<td>117.5</td>
<td>1,150</td>
<td>1,062</td>
<td>347</td>
</tr>
<tr>
<td>1981</td>
<td>3,620</td>
<td>2.39</td>
<td>2,244</td>
<td>0.13</td>
<td>5.4</td>
<td>60.1</td>
<td>224.2</td>
<td>169.1</td>
<td>1,174</td>
<td>743</td>
<td>289</td>
</tr>
</tbody>
</table>

Notes:
1. Averages for all three processing lines, per ST of refuse processed.
2. Lower heating value. For approximate conversion use LHV = HHV - 1,040 (w), where LHV = Lower Heating Value (Btu/Lb), HHV = Higher Heating Value (Btu/Lb), w = Water Content of Refuse (lb/lb).
3. Includes scrubber operations, but excludes materials recovery by private contractor and DH pumping.
4. Mostly air condenser operation during summer period and for load balancing.
5. Includes standby boilers.
6. Includes scrubber operations.
7. Includes standby boilers.
8. Includes scrubber sludge disposal.
9. Includes scrubber operations.
10. Includes scrubber sludge disposal.
11. Arithmetic average for 7-year period, calculated as \( \bar{X} = \frac{\sum X_i}{7} \) 
12. Percentage change over 7-year period, calculated as \( \frac{X_{81} - X_{75}}{X_{75}} \times 100\% \)
13. Coefficient of variability for 7-year period, calculated as \( \frac{\max - \bar{X}}{\bar{X}} \times 100\% \)
the capacity increase previously discussed, the third processing line is quite different from the two older ones. Since the third line started operating during 1980, its effects have been felt in many ways. For example, less oil is used for start-ups, due to better reliability and fewer shutdowns. Heat losses have been trimmed and less electricity is used because the number 3 furnace is equipped with a newly designed piston extractor. Unlike the older drag conveyors, the piston extractor is able to retain more of the quench water, thus yielding a residue with a lower moisture content and hauling weight. The plant's water consumption has been further cut by the introduction of a totally new scrubber concept which will be treated in the environmental section which follows.

Equipment has always been worked hard in the Kiel RRF. The evidence for this statement can be gleaned from Table 4. Annual equipment utilization, while averaging 73 percent, has peaked at 92 percent. The annual load factors for the grates, or LFG, has averaged 127 percent, and for the boilers, (LFB), has averaged 85 percent. These observations clearly indicate that the grate-boiler systems are forgiving to the point where they can be overloaded for extended periods of time. Since the refuse heating value remained well below its upper design limit, the only other limiting factor was the ability of the air pollution control system to keep up with increased volumetric flow and particulate loadings. Some of these events and their interactions are discussed elsewhere in the literature. See Refs. [4-6].

Like equipment utilization and load factors,

<table>
<thead>
<tr>
<th>Table 4 Kiel RRF – Annual Equipment Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Year</strong></td>
</tr>
<tr>
<td>1975(6)</td>
</tr>
<tr>
<td>(7)</td>
</tr>
<tr>
<td>1976</td>
</tr>
<tr>
<td>1977(8)</td>
</tr>
<tr>
<td>1978</td>
</tr>
<tr>
<td>1979</td>
</tr>
<tr>
<td>1980(9)</td>
</tr>
<tr>
<td>1981</td>
</tr>
<tr>
<td><strong>7-Year Totals</strong></td>
</tr>
<tr>
<td><strong>7-Year Statistics</strong>(10)</td>
</tr>
<tr>
<td><em>Hin.</em></td>
</tr>
<tr>
<td><strong>Avg.</strong></td>
</tr>
<tr>
<td><strong>Max.</strong></td>
</tr>
<tr>
<td><strong>A(%)</strong></td>
</tr>
<tr>
<td><strong>CV(%)</strong></td>
</tr>
</tbody>
</table>

Notes:
(1) Average for all units installed.
(2) Actual operating time divided by total time.
(3) Actual annual capacity used, divided by both the operating hours per year times the installed hourly capacity. The average annual load factor for the grate is denoted by LFG, while average annual load factor for the boiler is denoted by LFB.
(4) Actual annual capacity used in StP/ST divided by installed nameplate capacity in StP/ST. This also corresponds to the annual average capacity factor in StP/ST/h. The annual plant capacity factor for the grate burning capacity is denoted by PCFC, while the annual plant capacity factor for boiler steaming capacity is denoted by PCFB.
(5) Average actual steaming capacity in StP/ST divided by design steaming capacity in StP/ST. The design steaming rate is 3.20 St of steam per St of refuse.
(6) Units 1 and 2 were operated for only 7 months upon completion of Phase 1 construction.
(7) In order to reduce bias during statistical treatment, the actual figures were annualized by multiplication with the factor 1.71. The annualized figures are marked with an * and were used accordingly.
(8) Major repairs of stack necessitated use of a provisional stack.
(9) Unit 3 operated for only 5 months upon completion of Phase II construction.
(10) See previous tables for definition of terminology.
the high annual capacity factors are equally impressive when judged by industry standards. See Ref. [7]. The averages are a PCFG = 94 percent for the grates and PCFB = 62 percent for the boilers. A recent drop during 1981 seems to indicate that there are some difficulties with refuse logistics in catching up with the newly expanded plant capacity. These difficulties are believed to be of a temporary nature, as resumed growth is expected for the near future.

The last column in Table 4, entitled "capacity matching," shows a consecutive improvement for every year in each observation period. This development reflects a maturing of plant operations both from technical and management points of view. The first category embraces rising heating values and steaming rates. The second involves upgraded operating strategies and maintenance procedures. However, as long as there is a wide disparity between tipping fees and energy revenues, there is no need to accomplish the perfect match. To express it in order of priority, it is simply more important to push grate performance than boiler performance. This is by no means a universal statement, and it must be viewed against the narrow specifics of the Kiel situation. A nearly perfect match has been reported for at least one other German plant. See Ref. [7]. In this case, tipping fees and energy revenues are nearly equal, and the actual steaming rate is almost identical with the design steaming rate.

Since energy recovery, and its efficiency, is

\[ \text{Defininition of Annual Energy Budget}^{(2)} \]
\[ \text{Annual Total} \left( \times 10^6 \text{ kWh} \right) = \text{Energy Inputs} \left( \times 10^6 \text{ kWh} \right) - \text{Energy Outputs} \left( \times 10^6 \text{ kWh} \right) \]
wherein Energy Inputs = Plant Use + Rejection + Sales + Losses

\[ \text{Defininition of Energy Efficiencnes:} \]
\[ \text{Energy Thermal Efficiency} = \frac{\text{Plant Use} + \text{Rejection} + \text{Sales} \times 100}{\text{Refuse + Oil}} \]
\[ \text{Energy Utilization Efficiency}^{(3)} = \frac{\text{Sales} \times 100}{\text{Refuse + Oil + Electrical}} \]

\[ \text{Notes:} \]
1. For 1981, assume 100% condensate return at 113°F (45°C). Thus a net heat input of 0.655 MWh/ST of steam (0.720 MWh/MT of steam) is required for steam generation.
2. No credits are taken for materials recovery, i.e., the recycling of ferrous scrap and aggregate which is accomplished by a private contractor off-site.
3. No credit is taken for the energy requirement of waste disposal by ordinary incineration. Such consideration would require additional analysis to determine which part of electrical consumption is associated with refuse incineration only and which part is associated with steam generation only. A conventional, oil fired package boiler might serve as the basis of such comparison.

\[ \text{FIG. 5 KIEL RRF - MODEL FOR ANNUAL ENERGY BALANCE} \]
<table>
<thead>
<tr>
<th>Operating Year</th>
<th>Refuse</th>
<th>Oil</th>
<th>Electrical</th>
<th>Annual Total</th>
<th>Plant Use</th>
<th>Rejection</th>
<th>Sales</th>
<th>Losses</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>87.6</td>
<td>90.9</td>
<td>5.62</td>
<td>5.86</td>
<td>31.15</td>
<td>6.58</td>
<td>2.16</td>
<td>10.0</td>
<td>7.06</td>
</tr>
<tr>
<td>(1975)</td>
<td>186.9</td>
<td>186.9</td>
<td>186.9</td>
<td>186.9</td>
<td>186.9</td>
<td>186.9</td>
<td>186.9</td>
<td>186.9</td>
<td>186.9</td>
</tr>
<tr>
<td>1976</td>
<td>162.9</td>
<td>162.9</td>
<td>162.9</td>
<td>162.9</td>
<td>162.9</td>
<td>162.9</td>
<td>162.9</td>
<td>162.9</td>
<td>162.9</td>
</tr>
<tr>
<td>1977</td>
<td>170.2</td>
<td>170.2</td>
<td>170.2</td>
<td>170.2</td>
<td>170.2</td>
<td>170.2</td>
<td>170.2</td>
<td>170.2</td>
<td>170.2</td>
</tr>
<tr>
<td>1978</td>
<td>222.4</td>
<td>222.4</td>
<td>222.4</td>
<td>222.4</td>
<td>222.4</td>
<td>222.4</td>
<td>222.4</td>
<td>222.4</td>
<td>222.4</td>
</tr>
<tr>
<td>1979</td>
<td>248.8</td>
<td>248.8</td>
<td>248.8</td>
<td>248.8</td>
<td>248.8</td>
<td>248.8</td>
<td>248.8</td>
<td>248.8</td>
<td>248.8</td>
</tr>
<tr>
<td>1980</td>
<td>291.5</td>
<td>291.5</td>
<td>291.5</td>
<td>291.5</td>
<td>291.5</td>
<td>291.5</td>
<td>291.5</td>
<td>291.5</td>
<td>291.5</td>
</tr>
<tr>
<td>1981</td>
<td>297.3</td>
<td>297.3</td>
<td>297.3</td>
<td>297.3</td>
<td>297.3</td>
<td>297.3</td>
<td>297.3</td>
<td>297.3</td>
<td>297.3</td>
</tr>
<tr>
<td>7-Year Totals</td>
<td>1,485.7</td>
<td>1,485.7</td>
<td>1,485.7</td>
<td>1,485.7</td>
<td>1,485.7</td>
<td>1,485.7</td>
<td>1,485.7</td>
<td>1,485.7</td>
<td>1,485.7</td>
</tr>
</tbody>
</table>

| Min.            | 149.8 | 149.8| 149.8     | 149.8        | 149.8     | 149.8     | 149.8 | 149.8  | 149.8      |
| Avg.            | 221.1 | 221.1| 221.1     | 221.1        | 221.1     | 221.1     | 221.1 | 221.1  | 221.1      |
| Max.            | 297.3 | 297.3| 297.3     | 297.3        | 297.3     | 297.3     | 297.3 | 297.3  | 297.3      |
| CV(%)           | 267   | 267   | 267       | 267          | 267       | 267       | 267   | 267    | 267        |

Notes: (1) The format of this tabulation is based on Figure 5, "Kiel RRF—Model for Annual Energy Balance". (2) In working with the original plant records, the unit of kWh was retained for uniformity. For conversion purposes, use 1068 = 3,412 Btu. Depending on the amount and the temperature of the condensate returned, the net heat input required for steam generation may vary between 0.5% THM/ST of steam (0.450 MWh/MMT of steam) and 0.5% HH/M of steam (0.720 MWh/MMT of steam). (3) Figures for 1975* and 1976 were included in this statistical treatment, even though due to start-up and testing oil consumption was abnormally high. This was necessary in order to complete the energy balance. (4) For definitions, see Figure 5. (5) The statistical treatment conforms to the methods used in previous tables, i.e., the actual figures for 1975 were annualized by multiplication with the factor 1.71 marked with an * and used as such.
central to the theme of this paper, a detailed model was developed in Fig. 5 in order to establish representative annual energy balances. This model also contains the definitions used for the characterization of energy efficiencies.

A significant variable in this model is the amount of net heat required for steam generation. This depends to a large extent on the amount and the temperature of the condensate returned. No credit is claimed for energy conserved by ferrous scrap and aggregate recovery which is handled separately by a private contractor off-site. Neither is credit claimed for thermal waste reduction, which is part of ordinary waste disposal, i.e., the energy difference between operating a conventional boiler and a refuse incinerator. On the debit side, no entries were made concerning the pumping of condensate and/or water through the DHN.

Based on the aforementioned caveats, the annual energy balances were calculated. The results were fitted into standard format and entered in Table 5.

While the oil and electrical inputs showed little or no growth, the refuse input showed a dramatic boost of 86 percent over 7 years. On the output side — if taken on a percentage basis — plant use, heat rejection and heat losses experienced only minor changes. The big winner is heat sales which went up by 126 percent on the absolute scale and a solid 20 percent on the relative scale.

For quick reference, the 7-year energy budgets were summarized and are displayed in Fig. 6, using the pie chart format.

---

OPERATING ECONOMICS

Every year in March, the RRF management presents its official operating report to the City of Kiel. This report contains a full accounting for the previous year. At this writing, the 1981 report had not yet been issued and therefore the analysis of operating economics had to be confined to 6 years rather than seven. (However, 1981 economics should be available for the discussion part of the conference.)

Other complicating factors in such international comparisons concern monetary exchange rates and inflation rates. To make matters worse, neither one is constant. Consequently, to simplify matters, an average but constant conversion rate was used.

Budget details for each of the 6 observation years, in terms of expenditures and revenues, have been assembled in Table 6.

On the expenditure side, materials and taxes pretty much held the line, while labor showed significant gains on both the absolute and relative scales. Capital service, if taken on a unit cost basis, i.e., $/ST refuse for repayment of principal and interest declined steadily as the plant’s output increased. The sole exception is 1981, when refinancing for plant modification and/or expansion interfered with this downward trend.

For 1981, typical values are $13.51/ST for capital service, $10.52/ST for labor, $10.80/ST for materials and $0.77/ST for taxes. This adds up to a gross processing cost of $35.68/ST. In this
regard it is important to remember that the Kiel RRF has at least two handicaps. One is the original installation of rather small processing lines. The other deals with the relatively high cost of installing and operating a very modern air pollution control system. Some pertinent details on the latter subject will be presented in the subsequent environmental section.

Because of the nonprofit nature of the Kiel RRF and the need to maintain a balanced budget, a reserve fund has been set up to accommodate small surpluses and shortages on a year-to-year basis.

On the revenue side, the most remarkable fact is that the tipping fee remained virtually constant during the entire observation period. A tipping fee or net disposal fee of $25.80/ST may be considered high by current U.S. standards, but one should bear in mind that an inner-city plant is involved. This plant abides by the strictest environmental standards and at the same time shortens hauling distances. This latter condition has made a great deal of difference where most of the emphasis is placed. A private enterprise, on the other hand, might have to consider an alternative concept.

Energy revenues have grown, both on the absolute and on the relative scales. However, when compared with resource recovery facilities in other locations, they appear to be lagging. To a large extent this is due to favorable pricing and the abundance of alternative fuels, most notably gas and coal, as previously mentioned.

During 1980, the equivalent of $8.35/ST of refuse was received for the sale of steam. This price could have been about 7.3 percent higher, or $8.96/ST, if it had not been for the rejection of excess heat during the summer. Using the specific steaming rate SSR = 2.29 as reported in Table 3, the resultant steam price would be $3.91/ST steam, or $1.96/1,000 lb steam. By U.S. standards, this is not a very good price considering the following IDHA statistics for domestic district heating networks. See Ref. [8].

Average fuel cost $1.60/10^6 Btu for coal
$3.05/10^6 Btu for gas
$4.36/10^6 Btu for oil

Average gross revenue $8.91/1,000 lb steam sold
(For comparison purposes, it takes about 1.117 \times 10^6 Btu in the Kiel RRF to generate 1,000 lb of saturated steam.)

These annual budgets are summarized and graphed in Figure 7. Upon inspection of the revenue pie chart, one immediately identifies the relatively low energy price as the major reason for the relatively high tipping fees. Since in the final analysis, it is the City of Kiel that is responsible for both the Power Works Company and the Department of Sanitation budgets, it may not make a great deal of difference where most of the emphasis is placed. A private enterprise, on the other hand, might have to consider an alternative concept.

### ENERGY MARKETING

For resource recovery facilities, energy marketing is a highly complex and often controversial subject both here in the U.S. and Europe. This is particularly true if the RRF cannot sell its energy directly in the retail market, but instead must sell its entire output through a large utility company. If this utility is a large cogenerator,
then the concerns of electrical marketing rather than thermal marketing may be overriding. Depending on the “must run” decisions of the electrical load dispatcher, certain co-generating turbines may need to be run even if the demand for district heat is rather flat at a particular time. In this case, by-product steam will be cheaply available and it becomes hard for any RRF to compete, especially if fuel replacement cost is to be the sole basis of steam pricing.

Full discussion of these energy marketing issues would go far beyond the scope of this paper. The Kiel experience, however, would seem to suggest that at least five important points should be considered when planning an RRF with the sale of energy to a utility company:

1. What is the established price for fuel replacement based on the utility’s fuel mix?
2. What is the incremental price for steam generation?
3. What is the value of added generation capacity?
4. What is the value of guaranteeing an uninterruptible supply of steam (as in Kiel where oil fired boilers are installed for standby duty)?
5. How large is the utility’s minimum requirement for district heat during the low season, i.e., how much of the RRF’s output can be sold on a year-round basis?

ENVIRONMENTAL PROTECTION

When the permit to construct and operate was granted in 1972, air pollution control requirements were usually based on the older TA Luft 64 (Technical Guidelines for Air Pollution Control promulgated by the West German Federal Government). These guidelines did not call for acid gas scrubbing and even allowed particulate emissions up to 150 mg/Nm³.

The licensing board, when considering Kiel’s application, went considerably beyond these guidelines by writing into the permit the condition “...that a scrubber system for hydrochloric acid (HCl) must be installed which will limit emissions to 100 mg HCl/Nm³...”

Three conditions contributed to this strict decision:

1. The LIB (State Institute for Atmospheric Research) had performed a study which predicted a 2.5 fold rise in HCl emission from refuse incineration for the 1970-1980 period (up to 1,000 mg/Nm³).
2. The Federal Ministry of the Interior had already started to work on a revision to TA Luft 64, indicating that acid gas scrubbing might be required in the future.
3. The closeness of the proposed RRF to residential areas.

The height of the exhaust stack was also a subject of intense discussion. The TüV (National Testing Service), acting as a project consultant, had recommended 256 ft (78 m) while the LIB thought that 354 ft (108 m) would be necessary in order to limit ground level concentrations to less than 0.15 mg HCl/m³. An additional consideration in stack sizing was the possibility of
failure in the scrubbers. Therefore, stack sizing was completed without taking credit for the expected scrubber benefits.

The licensing board sided with the LIB and the 354 ft (108 m) stack was prescribed which, in effect, raised the top of the stack to 430 ft (131 m) above sea level (compared to the rooftops of nearby residential buildings which are at 223 ft (68 m) above sea level). These determinations include an allowance of up to 98 ft (30 m) for the height of the RRF buildings.

In return for this rather high stack, the licensing board conceded that the scrubbers could be bypassed on a temporary basis. This concession would permit scrubber maintenance without disrupting the RRF's basic waste disposal services.

A further condition of the permit was that the scrubber should assist with the task of particulate removal in case of partial failure of the electrostatic precipitators.

In response to these conditions, venturi type scrubbers were selected. The stack was to be cast in concrete with three individual flues on the inside in order to allow for a wide range of operating conditions. These flues were to be constructed of ceramic pipes.

It was also decided to reheat the saturated flue gases after they left the scrubbers in order to minimize condensation and corrosion problems in the stack. Furthermore, reheating would help to keep up sufficient draft on the stack and reduce visible plume formation.

While the Kiel RRF was under construction, the Federal Government actually issued the new TA Luft 74 which mandated acid gas cleaning and lowered the particulate limit to 100 mg/Nm³.

### TABLE 7a KIEL RRF — ACCEPTANCE TESTING OF ORIGINAL APC SYSTEM

<table>
<thead>
<tr>
<th>Pollutants Tested</th>
<th>Particulates(1)(2)</th>
<th>HCl(1)</th>
<th>HCl(3)</th>
<th>HCl(4)</th>
<th>HF(1)</th>
<th>SO₂ (11)(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Points:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>mg/m³</td>
<td>4</td>
<td>24</td>
<td>90</td>
<td>126</td>
<td>24</td>
</tr>
<tr>
<td>After Boiler</td>
<td>mg/m³</td>
<td>5,200 min, 13,000 max</td>
<td>8,100 avg</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>After ESP</td>
<td>mg/m³</td>
<td>7% CO₂, wet</td>
<td>89 min, 267 max</td>
<td>1,170 avg</td>
<td>998 avg</td>
<td>940 avg</td>
</tr>
<tr>
<td>After Scrubber</td>
<td>mg/m³</td>
<td>11% O₂, wet</td>
<td>15.6 min, 25.8 max</td>
<td>19.3 avg</td>
<td>-</td>
<td>0.4 avg</td>
</tr>
<tr>
<td>Average Scrubber Efficiency</td>
<td>%</td>
<td>89.3</td>
<td>98</td>
<td>-</td>
<td>96.0</td>
<td>80.9</td>
</tr>
<tr>
<td>Original Permit Requirement(6)</td>
<td>mg/m³</td>
<td>11% O₂</td>
<td>150</td>
<td>100</td>
<td>-</td>
<td>None</td>
</tr>
<tr>
<td>(1972 Status)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TA Luft 74</td>
<td>mg/m³</td>
<td>11% O₂</td>
<td>100</td>
<td>100</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>Requirement(7)</td>
<td>(1976 Status)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100 (8)</td>
</tr>
</tbody>
</table>

Notes:
(1) Testing was performed by the National Testing Service (TÜV) during May 1976 as part of the RRF's acceptance testing on Units #1 and #2.
(2) Particulate loadings were unusually high due to overloading of the grate systems which were running with LF=1.45. As a result, the ESP's exceeded their design ratings.
(3) Additional testing was performed by the TÜV during August to December 1977. The #3 unit has already been tested, but the official report has not been filed as yet.
(4) Additional testing during the period August 1977 to August 1978.
(5) The test method used for SO₂ determinations was a standard method. It is believed, however, that this method is susceptible to interference from chemicals which may be present in refuse derived flue gases with the iodine solution used. Therefore, these results must be viewed with caution.
(6) The original permit was based on TA Luft 64 and determinations by the LIB (State Institute for Atmospheric Research).
(7) As construction got underway, the German Federal Government promulgated TA Luft 74 (Technical Guidelines for Air Quality Control). TA Luft 74 is not a law, but an administrative procedure which is used by the local licensing boards for implementing the Bundesemissionschutzgesetz (Federal Clean Air Act).
(8) Optional requirement at the discretion of the local licensing boards. (Several industrial cities like Hamburg and Krefeld are enforcing this requirement.)
<table>
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<tr>
<th>Component</th>
<th>Symbol</th>
<th>Average Concentration Levels</th>
<th>Scrubber Recirculation Fluid mg/L</th>
<th>Wastewater Overflow from Setting Tank(2) mg/L</th>
<th>Regulatory Requirement for Sewer Acceptance(3) mg/L</th>
<th>Sludge from Setting Tank Wt %</th>
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Notes: (1) 5 individual measurements were performed by the Municipal Analytical Laboratory during the January-March 1976 period. (2) After neutralization. (3) Source: Arbeitsblatt #90, December 1970, "Hinweise für das Einleiten von Abwasser aus gewerblichen u. industriellen Betrieben in eine öffentliche Abwasseranlage".

Figure 8 identifies the major building blocks of the air pollution control system as it was installed during Phase I construction. Table 7a shows the results of the acceptance tests which were performed by the TüV. These tests indicated compliance with both the original permit and the newer requirements of TA Luft 74. What is more, compliance was accomplished under conditions of severe overloading, a fact which explains the relatively high particulate loadings downstream of the precipitators and upstream of the scrubbers (The LFG was 1.45).

The problem of potential heavy metals emissions was not overlooked. During testing in 1976 it was observed that the oxides of Cadmium, Chromium, Copper, Lead, Nickel and Zinc are removed by the electrostatic precipitators with a fractional efficiency ranging from 93-97 percent. The small, remaining fraction of particulates is further reduced by the scrubber, as Table 7b indicates. This is particularly effective during periods when the precipitators are either overloaded, or partially disabled. But, because of high acidity and elevated temperature of the
scrubbing fluid, many of these remaining heavy metals go into solution.

Fortunately, they can be settled out easily after neutralization. Laboratory tests showed that at a pH of 8, about 90 percent of the solids settled out within 10 min. Some of these test data are summarized in Table 7b and they indicate compliance with the criteria of the local sewer district. These criteria had been part of the permit.

In view of these observations, a state of interdependency can be formulated for the precipitators and scrubbers working in unison: the precipitators lower the solids load, especially that of soluble heavy metals, on the wastewater treatment system. The scrubbers, on the other hand, take over where the precipitators leave off and further clean the effluent gas stream.

What effect has acid gas scrubbing had on ambient air quality? A final answer cannot be given because some research is still in progress. However, the occasion of a complete scrubber shutdown during 1977 (when the stack was rebuilt), was used to perform extensive air quality measurements, without the benefit of acid gas scrubbing. Upon completion of the new stack, acid gas scrubbing was resumed and the air quality measurements were repeated.

The results have already been reported in detail elsewhere, see Ref. [10]. However, in order to put acid gas scrubbing at the Kiel RRF into its proper perspective, a summary is put forth in Table 7c. Examination of mean HCl concentrations in the ambient air permits the following conclusions to be drawn from these measurements:

1. HCl emissions from the RRF have a measurable impact on ambient air quality within a 3 km radius.
2. HCl concentrations are well below the allowable standard regardless of RRF operations.
3. Because of the high stack, the impact of HCl emissions is minor even if the scrubbers are bypassed (about a 36 percent increase of mean ambient concentrations with scrubbers versus a 45 percent increase of mean ambient concentrations without scrubbers).
4. Fluctuations in the background levels are of nearly the same magnitude as the changes due to scrubbing.
5. There appears to be interference from the nearby Baltic Sea, i.e., depending on wind conditions, airborne chlorides were being carried off into the test area.
6. Raw gas HCl emissions did not rise to the levels initially predicted during the permitting

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<tr>
<th>Operating Conditions</th>
<th>Radial Distance from Stack</th>
<th>Number of Measurements</th>
<th>Mean Concentrations mg HCl/Nm³</th>
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<td>Standard</td>
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Notes: (1) Measurements were performed by Kiel Municipal Analytical Laboratory during 1977.
(2) In the absence of a standard, the test procedures actually followed were cleared with the TüV (National Testing Service) North-Rine Westphalia.
(3) North-East direction, Baltic Sea location.
process. In fact, they have been declining at Kiel in recent years. See Table 7a.

7. Depending on RRF siting, scrubbers may be considered more of a precautionary measure than a hard requirement. In any event, they may be an investment for the future, because refuse composition and ambient air quality conditions may change. This is especially true for RRF’s which are planned with lower stack heights.

In 1975, the capital cost of the two scrubbers was put at $0.98 million (DM 2.1 million) with $0.33 million (DM 0.7 million) for the civil part and $0.65 million (DM 1.4 million) for the mechanical part. O & M costs were estimated at 2 percent per annum of capital cost for the civil part and 8 percent per annum of capital cost for the mechanical part. To this must be added the cost of steam, water, electricity and chemicals.

Depending on annual throughput, the following estimates were made for total costs:

- 82,500 STPY ($7.50 \times 10^4 \text{ kg/year}) $4.65/\text{ST (DM11.00/t)}
- 99,000 STPY ($9.00 \times 10^4 \text{ kg/year}) $4.22/\text{ST (DM 10.00/t)}

For 1981, on the basis of 137,000 STPY of refuse processed, a figure of $5.07/\text{ST (DM 12.00/t)} was considered to be more realistic, although this does not yet include the cost of scrubber sludge disposal. (At present, this sludge is simply added to the bottom ash for disposal.) It is significant to note that this figure represents about 18 percent of a tipping fee of approximately $27.90/\text{ST (DM 66.00/t)}.

During the first years of operation, a number of serious problems were encountered which caused a fair amount of downtime, see Refs. [4, 8, and 9].
Three major problems need to be mentioned:

1. The saturation or cooling chamber of the scrubber inlet corroded out after a brief period. The substitution of Hastelloy as a new construction material was the answer.

2. The scrubber's high degree of particulate removal led to abrasion in the piping and controls of the washing loop. Since overloading was the major cause, refuse processing rates were reduced. Also the induced draft fans were attacked. This was remedied by modifications of the inlet shroud and the rotor blading.

3. In spite of reheating, the stack had to be operated with positive pressure (3 mbar) because of insufficient thermal draft. As a result, acid gases leaked out of the ceramic flues and condensed upon the concrete outer shell. The resultant corrosion attacked structural elements and ultimately would have destroyed the stack. The original stack was redesigned and rebuilt while the plant continued to operate with a temporary stack. Since there was not enough space left inside the concrete shell for enlargement of the individual flues, the three ceramic

---

FIG. 9 KIEL RRF – IMPROVED AIR POLLUTION CONTROL SYSTEM
### TABLE 8: KIEL RRF - GENERAL SCRUBBER OPERATING DATA (1)

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<tr>
<th>Boilers Number(2)</th>
<th>Scrubber Utilization</th>
<th>Refuse Processed</th>
<th>Steam Generated</th>
<th>Steam Used</th>
<th>Water Used</th>
<th>Electricity Used</th>
<th>Boiler Utilization</th>
<th>Scrubber Utilization</th>
<th>Refuse Processed</th>
<th>Steam Generated</th>
<th>Water Used</th>
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<td>1+2 h</td>
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<td>1+2 STx10^3</td>
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<td>1+2 kWhx10^3</td>
<td>3 h</td>
<td>3 STx10^3</td>
<td>3 STx10^3</td>
<td>3 galx10^5</td>
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**PROGRAM STATISTICS**

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<td>26.13</td>
<td>695</td>
<td>695</td>
<td>8,599</td>
<td>20.90</td>
<td>2.038</td>
</tr>
<tr>
<td>Range, R</td>
<td>1,112</td>
<td>1,187</td>
<td>7,733</td>
<td>15.09</td>
<td>950</td>
<td>2.564</td>
<td>12.24</td>
<td>333</td>
<td>382</td>
<td>3.417</td>
<td>9.76</td>
<td>1.637</td>
</tr>
<tr>
<td>Coeff. of Variability, CV%</td>
<td>119</td>
<td>194</td>
<td>138</td>
<td>127</td>
<td>188</td>
<td>188</td>
<td>58</td>
<td>92</td>
<td>67</td>
<td>56</td>
<td>58</td>
<td>156</td>
</tr>
</tbody>
</table>

**Notes:**
1. Data source: plant operating records, based on monthly recordings. Not all parameters were measured for each individual boiler during the course of this scrubber test and observation program.
2. Boilers #1 and #2 belong to the "original air pollution control system" depicted in Figure 8. Boiler #3 belongs to the "improved air pollution control system" depicted in Figure 9.
3. Boilers #1 and #2 had already been in service since June 1975. Some repairs and/or modifications were made prior to January 1980 in order to improve operational reliability.
4. Boiler #3 started up in August 1980 upon completion of plant expansion. It uses a completely redesigned scrubber system for increased reliability and reduced operating costs.
pipes were replaced by a single, maximum
diameter flue which once again was clad with
ceramic materials. In addition, an orifice was
installed in the stack exit plane and the ceramic
center pipe was elevated by another 16 ft (5 m)
above the concrete outer shell.

In addition to these problems, it was recog­
ized that the consumption of steam and water
by the scrubbers was costly. Also, more residue
had to be handled and disposed.

With this experience as a background, a totally
new air pollution control system was designed
upon plant expansion for the number 3 proces­
sing line. Figure 9 depicts this system in block
diagram. The most important innovation is the
new flue gas-to-flue gas heat exchanger between
the induced draft fan and the venturi scrubber.

This arrangement provides flue gas reheating
without the expenditure of precious steam. In
a related development, water consumption was
dramatically cut by lowering the scrubbers’ tem­
perature regime. The temperature differential for
the old scrubbers was 518 F - 149 F = 369 F
(270 C - 65 C = 205 C) compared to 302 F -
147 F = 155 F (150 C - 64 C = 86 C) for the
new one. The result was a reduction in evapora­
tive losses, but at the same time solubility was
reduced. This apparent drawback was alleviated
by lowering the pH factor of the scrubbing fluid
from 1.0 to 0.5. Now the designers faced the
new challenge as to how to cope with a highly
acidic environment for heat exchanger materials.
The answer was found by resorting to newly de­
veloped glass tube heat exchangers. The operat­
ing results of over 1½ years of operations indi­
cate that this was an excellent choice.

In order to obtain a better understanding of
the operational differences between the original
and the improved air pollution control systems,
a two year observation and test program was
commissioned, the results of which are reported
in Table 8.

From the basic data, specific and comparative
statistics have been worked up which are listed
in Table 9. Inspection of this table reveals three
striking accomplishments:
1. Scrubber equipment utilization has increased
to the point where it nearly equals that of the
boiler-grate combination, i.e., 0.791 hr/hr versus
0.800 hr/hr.
2. Water usage has been reduced from 321 gal/
ST refuse (1.215 m³/t refuse) for the original
scrubbers to 154 gal/ST refuse (0.583 m³/t refuse)
for the improved scrubber.
3. By eliminating the use of steam for reheat­
ing, an additional 5 percent of gross steam pro­
duction is available for sale to the DHN.

<table>
<thead>
<tr>
<th>TABLE 9</th>
<th>KIEL RRF — SPECIFIC SCRUBBER OPERATING DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <strong>Equipment Utilization:</strong></td>
<td></td>
</tr>
<tr>
<td>(a) Processing Lines #1 and #2</td>
<td></td>
</tr>
<tr>
<td>• Crate/Boiler Combinations</td>
<td></td>
</tr>
<tr>
<td>[ U_{GB}^{1,2} = \frac{12,238 \text{ hr}}{2 \times 24 \text{ months} \times 30 \text{ days} \times 24 \text{ hr}} = 0.557 \text{ hr} ]</td>
<td></td>
</tr>
<tr>
<td>• Scrubbers</td>
<td></td>
</tr>
<tr>
<td>[ U_{S}^{1,2} = \frac{14,670 \text{ hr}}{2 \times 24 \text{ months} \times 30 \text{ days} \times 24 \text{ hr}} = 0.424 \text{ hr} ]</td>
<td></td>
</tr>
<tr>
<td>• Utilization Quotient</td>
<td></td>
</tr>
<tr>
<td>[ U_{Q}^{1,2} = \frac{U_{S}^{1,2}}{U_{GB}^{1,2}} = \frac{0.424}{0.557} = 0.761 \text{ hr} ]</td>
<td></td>
</tr>
<tr>
<td>(b) Processing Line #3</td>
<td></td>
</tr>
<tr>
<td>• Crate/Boiler Combination</td>
<td></td>
</tr>
<tr>
<td>[ U_{GB}^{3} = \frac{9,793 \text{ hr}}{1 \times 17 \text{ months} \times 30 \text{ days} \times 24 \text{ hr}} = 0.800 \text{ hr} ]</td>
<td></td>
</tr>
</tbody>
</table>
II. Plant Capacity Factors:

(a) Processing Lines #1 and #2

- Grates

\[ PCFG_{1,2} = \frac{134,367 \text{ ST}}{2 \times 24 \text{ months} \times 30 \text{ days} \times 24 \text{ hr}} \times 5.5 \text{ stph} = 0.707 \text{ ST Refuse} \]

- Boilers

\[ PCFB_{1,2} = \frac{299,013 \text{ ST}}{2 \times 24 \text{ months} \times 30 \text{ days} \times 24 \text{ hr}} \times 17.6 \text{ stph} = 0.492 \text{ ST Steam} \]

(b) Processing Line #3

- Grate

\[ PCFG_3 = \frac{115,792 \text{ ST}}{1 \times 17 \text{ months} \times 30 \text{ days} \times 24 \text{ hr}} \times 11.0 \text{ stph} = 0.860 \text{ ST Refuse} \]

- Boiler

\[ PCFB_3 = \frac{286,685 \text{ ST}}{1 \times 17 \text{ months} \times 30 \text{ days} \times 24 \text{ hr}} \times 35.2 \text{ stph} = 0.665 \text{ ST Steam} \]

III. Specific Steaming Rates:

(a) Processing Lines #1 and #2 (24-month average)

\[ SSR_{1,2} = \frac{299,871 \text{ ST Steam}}{134,367 \text{ ST Refuse}} = 2.23 \text{ ST Steam or 2.23 Lb Steam} \]

(b) Processing Line #3 (17-month average)

\[ SSR_3 = \frac{286,686 \text{ ST Steam}}{115,792 \text{ ST Refuse}} = 2.48 \text{ ST Steam or 2.48 Lb Steam} \]

IV. Load Factors:

(a) Processing Lines #1 and #2

- Grates

\[ LFG = \frac{134,367 \text{ ST}}{19,238 \text{ hr} \times 5.5 \text{ stph}} = 1.270 \text{ ST Refuse} \]

- Boilers

\[ LFB = \frac{299,013 \text{ ST}}{19,238 \text{ hr} \times 17.6 \text{ stph}} = 0.883 \text{ ST Steam} \]

(b) Processing Line #3

- Grate

\[ LFC_3 = \frac{115,792 \text{ ST}}{9,793 \text{ hr} \times 11.0 \text{ stph}} = 1.075 \text{ ST Refuse} \]
### Table 9: Kiel RRF — Specific Scrubber Operating Data (Cont'd)

<table>
<thead>
<tr>
<th>Boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>$LFB_3 = \frac{286,685 \text{ ST}}{9,793 \text{ hr} \times 35.2 \text{ stph}} = 0.832 \text{ ST Steam}$</td>
</tr>
</tbody>
</table>

### V. Water Usage:

(a) Process Lines #1 and #2

\[
\frac{32.81 \times 10^6 \text{ gal}}{0.761 \times 134,367 \text{ ST}} = 321 \text{ gal/ST refuse}
\]

(b) Process Line #3

\[
\frac{17.67 \times 10^6 \text{ gal}}{0.989 \times 115,792 \text{ ST}} = 154 \text{ gal/ST refuse}
\]

(c) Water Use Reduction (#1 and #2) versus (#3)

\[
\frac{321 - 154}{321} \times 100\% = -52\%
\]

which is approximately \(\frac{321 - 154}{299} \times 100\% = 56\%\) of the plant's total usage

### VI. Electrical Usage:

(Incremental usage for scrubber system exclusive of ESP's and ID fans.)

(a) Process Lines #1 and #2

\[
\frac{465,538 \text{ kWh}}{0.761 \times 134,367 \text{ ST}} = 4.55 \text{ kWh/ST Refuse}
\]

which is approximately \(\frac{4.6}{62.1} \times 100\% = 7\%\) of the plant's total usage

(b) Process Line #3: no separate data, assumed to resemble #1 and #2

### VII. Steam Usage:

(a) Process Lines #1 and #2

\[
\frac{12,139 \text{ ST}}{0.761 \times 299,871 \text{ ST}} = 0.0532 \text{ ST of Steam Lost}
\]

which is approximately \(\frac{12,139}{228,202} \times 100\% = 5.32\%\) of the steam generated by lines #1 and #2

(b) Process Line #3: no steam required

### VIII. Chemicals Usage ( Lime):

Processing Lines #1, #2 and #3

\[
\frac{852.3 \text{ ST}}{0.761 \times 134,367 \text{ ST Refuse} + 0.989 \times 115,792 \text{ ST Refuse}} = 0.00393 \frac{\text{ST Lime}}{\text{ST Refuse}} \text{ or } 7.86 \frac{\text{Lb Lime}}{\text{ST Refuse}}
\]

### Conclusions and Recommendations

The Kiel experience proves that a refuse fired district heating station can easily be integrated with a large and modern utility system. The skill with which the Kiel team operates its facility compares favorably with the professionalism usually encountered in the utility industry. Although start-up of the Kiel RRF was not totally without surprises, the dependability and predictability of the mass burning and steam raising technology was amply demonstrated once again.
The Kiel project was delivered on schedule and its performance, in terms of waste disposal and energy recovery, matured in barely one year. The RRF has never been shutdown and, since expansion of its capacity in 1980, has put an end to the landfilling of raw waste in the city. Prior to this expansion, the combustion system showed its ruggedness by being able to accept overloads for extended periods of time without serious damage to its vital parts.

The near-term prospects are good for acquiring additional refuse from neighboring communities. In concert with growth and improvements in the district heating network, the Kiel plant should show a continued strong upward trend. In fact, by the end of this year, conservation of the first million barrels of crude oil should be accomplished and the Kiel RRF is sure to remain an important factor in the long range planning of the city's energy supply.

In the area of advanced air pollution control, Kiel did much of the pioneering work. While modifications had to be made, they were completed without any disruption to ongoing operations. Kiel has shouldered this development burden without the benefit of customary government R & D grants. The Kiel RRF is a ready-made test bed for developing valuable additional information, especially with regard to heavy metals, dioxins, fractional sizing of flyash, micro-pollutant analysis, etc.

With the recently expressed interest in acid gas scrubbing by such states as California, New Jersey and Oregon, it might be appropriate to suggest the continuation of such efforts on the basis of international cooperation.

REFERENCES


Key Words
Disposal
Efficiency
Incinerator
Operation
Refuse
Steam
Waterwall

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