Characterization of Industrial Process Waste Heat and Input Heat Streams

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CHARACTERIZATION OF INDUSTRIAL
PROCESS WASTE HEAT AND INPUT
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EXECUTIVE SUMMARY

Approximately one-third of the energy consumed in the U.S. is consumed by the manufacturing sector of the economy. Although considerable progress has been made toward increasing energy efficiency in manufacturing, many opportunities for further improvements remain. The greatest opportunities include the use of more efficient process equipment and the recovery and use of industrial waste heat.

The U.S. Department of Energy's (DOE) industrial energy conservation strategy emphasizes high-payoff, long-term, high-risk generic research and development programs. In support of this emphasis, the Pacific Northwest Laboratory was contracted to provide management planning information for the DOE's Waste Heat Recovery Branch.

This report identifies the nature and extent of industrial waste heat associated with the manufacturing sector of the U.S. economy. Specifically, this report addresses the following questions:

- What U.S. industries purchase large amounts of energy?
- What industrial processes generate large amounts of waste heat?
- Which unit operations and types of equipment discharge waste heat streams within these industrial processes?
- What is the energy content of these waste heat streams?
- What are the candidate uses for energy recovered from these waste heat streams?
- Does the temperature of the waste heat need to be reduced or elevated to be useful to candidate users?
- When the energy contained in waste heat streams at T_1 is compared with candidate energy needs at T_2 , how much energy can be matched up?

Industries purchasing energy at market prices have considerable interest in implementing advanced waste heat recovery equipment to reduce purchased energy costs. In 1980, total manufacturing purchases were estimated to be \$48.2 billion for some 11.9 quadrillion Btu. Review of industry purchases of

energy shows that one-third of all purchased energy by the manufacturing sector is purchased by 4 of some 450 four-digit SIC industries. The top 10 four-digit industries account for one-half of all energy purchases.

This report reviews industry energy information, and for planning purposes, estimates the energy content in waste heat streams emanating from 108 energy-intensive industrial processes. In total, these 108 industrial processes account for approximately 70% of the energy purchased by the manufacturing sector. The energy content in gaseous, liquid, and steam waste streams above 75⁰F is estimated to be nearly 7 quadrillion Btu for the industries addressed.

Of the 108 industrial processes evaluated, the 5 industries with the largest energy content in their gaseous, liquid, and steam waste streams are Petroleum Refining, Blast Furnaces and Steel Mills, Integrated Paper Board Mills, Integrated Paper Mills, and Hydraulic Cement.

Generic types of process equipment are identified in this report and the energy content in gaseous, liquid, and steam waste streams emanating from this equipment are evaluated. The equipment with the largest energy content in output streams includes furnaces, distillation equipment, drying equipment, boilers, and thermal-chemical reactor equipment.

The usefulness of any energy recovered from these waste steams depends largely on the immediate energy input needs of other unit operations in the plant. Thus, the emphasis of this report is to identify matchups between the energy content of waste heat streams and candidate uses. In this assessment only temperature difference and energy content were considered in the matchups.

The temperature spectrum from 80-2300+⁰F is divided into 16 temperature ranges, and the energy content in waste heat and candidate input heat streams is estimated using an industrial energy flow data base. The three temperature ranges containing the largest waste heat are: 80-119⁰F (2,522 trillion Btu/yr), 400-499⁰F (598 trillion Btu/yr), and 600-799⁰F (571 trillion Btu/yr). The temperature ranges of the three candidate uses having the largest thermal input needs are: 250-299⁰F (1,244 trillion Btu/yr), 400-499⁰F (592 trillion Btu/yr), and 600-799⁰F (137 trillion Btu/yr).

In this report, the (thermal) energy of the waste heat stream is compared with candidate input heat requirements. Matrices are developed to compare this energy by temperature ranges. The resultant matrix identifies 256 source/sink (waste heat/candidate input heat) temperature combinations. The maximum amount of energy that can be transferred from a source to a sink is the lesser of the input energy and the output energy for that source/sink combination. The maximum energy transferable and the temperature differential between the source and sink is useful when considering the applicability of specific waste heat recovery technologies.

Tables summarizing the maximum energy transferable from source to sink are provided for three classes of heat streams:

- liquid and gaseous heat streams combined
- liquid heat streams only
- gaseous heat streams only.

For each of these classes, the source/sink temperature combination with the largest energy matchup is evaluated to identify contributing industrial processes and generic types of equipment.

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CHARACTERIZATION OF INDUSTRIAL PROCESS WASTE HEAT AND INPUT HEAT STREAMS

1.0 INTRODUCTION

OBJECTIVES

The research discussed herein addresses five objectives: 1) review the 1979 Drexel industrial data base and specify its strengths and weaknesses; 2) update the data base with 1980 data; 3) extend the data base with industry production information; 4) estimate the energy content of waste heat streams within a set of temperature ranges; and 5) identify for specific industries the unit operations that make the most important energy contribution to the liquid and gaseous waste stream totals. All of these objectives were met and are discussed fully in this report. The report also identifies candidate energy uses (sinks) that may use energy received from waste heat streams and matches these thermal energy needs to the thermal energy present in waste heat streams.

BACKGROUND

In 1974, the manufacturing sector purchased an estimated 13.5 quadrillion Btu (13.5 quads). Since the oil embargo of 1973-74 and its related energy shortages and higher prices, the manufacturing sector has aggressively pursued energy conservation. In 1980, total manufacturing sector purchases dropped to an estimated 11.9 quads, about 1.6 quads below the 1974 level (Department of Commerce 1982).

The immediate reaction to the energy shortage was to curtail unnecessary energy use, for example, curtailing nonessential energy uses. However, industry has since moved toward improving the management of energy systems by using the available energy more efficiently rather than "doing without." The results have been significant, and many companies have found that through conscientious management, energy requirements can be reduced by 10 to 30% without major capital investments or reduced production. Although most industries have tried some form of energy management, many opportunities for further improvements

remain. In the long term, the greatest opportunities for improving energy efficiency are to substitute more energy-efficient equipment in industrial processes and to more fully use process waste heat, the subject of this report. Waste heat herein is defined to be the thermal energy from streams of hot air, hot exhaust gases, and hot liquids that leave industrial processes and enter the environment at temperatures high enough above the ambient temperature to permit the recovery of some fraction of that energy for useful purposes.

The Department of Energy's (DOE) revised R&D strategy emphasizes high-payoff, long-term, high-risk generic R&D programs. In support of this emphasis, the Pacific Northwest Laboratory (PNL) was contracted to provide management planning information for the Waste Heat Recovery Branch. This new planning effort revealed that in general the existing literature did not have the readily available data required to identify additional long-term R&D opportunities for industrial waste heat recovery. This information is necessary, however, to identify future technology development programs that will significantly impact a wide spectrum of industries and to insure that federal research does not duplicate privately sponsored research.

REPORT ORGANIZATION

This project, Waste Heat Recovery Analysis, consists of two tasks. The purpose of Task 1 is to identify and evaluate waste heat streams from industrial processes, to estimate, for planning purposes, the energy content in waste streams and to match this energy with candidate uses. To obtain these estimates, many data bases were reviewed and the Drexel data base was selected. The purpose of Task 2 is to provide information on the availability of commercial waste heat recovery equipment and to identify recent trends in the equipment design and operation.

This Task 1 report provides an overview of the energy content of waste heat streams for specific industrial processes. By analyzing the energy content of waste heat streams (source) and the thermal energy input requirements for specific processes (sink), we estimate the relative magnitude of the energy that could be used through waste heat recovery technology. Although

this assessment contains several assumptions and caveats, the energy source/energy sink information provides new insights into the opportunities for waste heat recovery equipment.

This report is organized into seven chapters and six appendices. Chapter 2.0 describes the approach used in the assessment and discusses several limitations and caveats to be considered when using the data to estimate waste heat recovery opportunities. Review of energy use and industrial energy flow data bases is discussed in Chapter 3.0. Chapter 4.0 discusses the selection of the Drexel data base and its subsequent update, expansion and adjustment for use in this assessment. Chapter 5.0 identifies the temperature ranges used in compiling energy content data; compiles energy content data by type of waste stream, type of equipment and by industrial process; and describes the process for matching up the energy content of waste heat streams with input heat streams. Chapter 6.0 summarizes the source/sink information across 108 industry processes (these processes are estimated to represent approximately 70% of the energy purchased by industry). Chapter 7.0 looks at specific high-energy-content sources/sink situations and identifies the key industries and generic types of equipment involved.

The appendices are separated into discussions of six industries: Chemicals; Petroleum Refining and Related Industries; Primary Metal Industries; Paper and Allied Products; Stone, Clay and Glass; and Textiles. Each appendix provides a process description, a discussion of major heat transfer operations, and a characterization of waste heat streams within that industry.

2.0 APPROACH

Approximately one-third of the energy used in the U.S. is consumed by manufacturing processes. To evaluate how energy is used in industry and to estimate the extent to which advanced waste heat recovery technology may be applicable is complex and difficult. The manufacturing sector covers a broad spectrum of industries and products encompassing hundreds of thousands of establishments, each having its own set of process and management characteristics.

In this chapter, the four levels of the Standard Industrial Classification (SIC) system used to classify the thousands of establishments are explained as they relate to the manufacturing sector. Also, the approach used in assessing the energy content of waste heat streams is discussed. Finally, our assumptions and the limitations that should be considered when using the data to identify potential research opportunities for waste heat recovery are discussed.

CLASSIFICATION OF INDUSTRIAL ACTIVITY

Various classification systems have been developed to organize information on the broad spectrum of manufacturing activities, including systems for classifying according to products, occupations, and enterprises. The Standard Industrial Classification (SIC) of Establishments, however, is especially useful when addressing industrial processes because it classifies manufacturing establishments by their types of activities.

Three principals are used to classify establishments having similar activities (Department of Commerce 1972).

1. The classification structure should conform to the existing structure of American industry.
2. Establishments should be classified according to their primary activity.
3. The group of establishments constituting a classification category must be statistically significant in the number of persons employed, the volume of business done, and other measures of economic activity.

Because the SIC system is broadly based and well defined, it is widely used in tabulating industry information. Its organizational structure

facilitates the collection, tabulation, presentation and analysis of industrial activity information. As such, the SIC code is used by various U.S. government agencies, state agencies, trade associations and private research organizations. For example, the U.S. Department of Commerce compiles manufacturing sector information at the two-, three- and four-digit level for its Census of Manufactures and for its Annual Survey of Manufactures publications.

In the SIC system, each manufacturing establishment is assigned an industry code (usually at the four-digit level) on the basis of its primary activity. The primary activity is determined by its principal product or group of products. The coding system has been set up so that all establishments primarily engaged in the same kind of economic activity are classified in the same four-digit industry, regardless of their type of ownership. The SIC coding scheme is hierarchical, consisting of two-, three-, and four-digit codes providing increasingly detailed industrial classification.

The manufacturing sector is identified by 20 major industrial groups defined by the two-digit SIC numbers 20 through 39 (Table 2.1). Each of these major groups of industries contains 5 or more three-digit industries. For example, Food and Kindred Products (Major Group 20) is subdivided into 9 three-digit industries:

- 201 Meat Products
- 202 Dairy Products
- 203 Canned and Preserved Fruits and Vegetables
- 204 Grain Mill Products
- 205 Bakery Products
- 206 Sugar and Confectionary Products
- 207 Fats and Oils
- 208 Beverages
- 209 Miscellaneous Food Preparation and Kindred Products.

The digit "9" in the third or fourth position of the SIC code designates residual establishments whose activities are not homogeneous with the other specified activities identified within the three- or four-digit group of industries.

TABLE 2.1 The 20 Major SIC Divisions

Major Group 20.	Food and kindred products
Major Group 21.	Tobacco manufactures
Major Group 22.	Textile mill products
Major Group 23.	Apparel and other finished products made from fabrics and similar materials
Major Group 24.	Lumber and wood products, except furniture
Major Group 25.	Furniture and fixtures
Major Group 26.	Paper and allied products
Major Group 27.	Printing, publishing, and allied industries
Major Group 28.	Chemicals and allied products
Major Group 29.	Petroleum refining and related industries
Major Group 30.	Rubber and miscellaneous plastics products
Major Group 31.	Leather and leather products
Major Group 32.	Stone, clay, glass and concrete products
Major Group 33.	Primary metal industries
Major Group 34.	Fabricated metal products, except machinery and transportation equipment
Major Group 35.	Machinery, except electrical
Major Group 36.	Electrical and electronic machinery, equipment, and supplies
Major Group 37.	Transportation equipment
Major Group 38.	Measuring, analyzing, and controlling instruments; photographic, medical and optical goods; watches and clocks
Major Group 39.	Miscellaneous manufacturing industries

The four-digit level of classification is fairly narrow and specifically defined. An example of four-digit activities are those that comprise SIC 201-Meat Products:

2011 Meat packing

2013 Sausage and other prepared meat products

2016 Poultry dressing plants

2017 Poultry and egg processing.

In this example, meat packing plants (SIC 2011) are defined as establishments primarily engaged in the slaughtering, for their own account or on a contract basis for the trade, of cattle, hogs, sheep, lambs, and calves for meat to be

sold or to be used on the same premises in canning and curing, and in making sausage, lard and other products (Department of Commerce 1972). Establishments primarily engaged in killing, dressing, and packing poultry, rabbits, and other small game animals would not be included in SIC 2011, but are classified as Industry 2016. Also, the establishments primarily engaged in killing and processing horses and other nonfood animals would not be included in 2011, but are classified as SIC 2047, which is outside of the 201 series. Establishments primarily engaged in manufacturing sausages and meat specialties from purchased meats are classified in Industry 2013, and establishments primarily engaged in canning meat for baby food are classified 2032, which is from another three-digit SIC category, Canning and Preserving Fruits and Vegetables.

The four-digit level of the SIC code provides the lowest level of industry detail covered by the censuses and surveys of manufacturers. However, below this level of industry detail we can identify individual processes used to produce specific products and, within a particular process, the unit operations that make up a process. For example, there are three active processes for the production of pulp, SIC 2611 - Pulp mills (manufacture of pulp from wood or from other materials such as rags, linters, waste paper, and straws). In the data base that was selected for this assessment, different processes are identified by suffixing a fifth digit to the four-digit SIC number, for example as follows:

- 2611-1 Pulp mills - Kraft process
- 2611-2 Pulp mills - sulfite process
- 2611-3 Pulp mills - mechanical process.

Information at the process level is required to assess the usefulness of energy in waste heat streams. However, information even below the process level is also important. At this level, the specific unit operation level, energy streams take on specific characteristics that must be evaluated to identify opportunities for waste heat recovery. Figure 2.1 shows seventeen unit operations that are identified with the Kraft process method of producing pulp (Drexel University 1980).

FIGURE 2.1 Process Flow - Pulp Mills, SIC 2611-1 (DOE 1980)

ENERGY INFORMATION

As discussed above, an industrial process can be defined as a set of unit operations combined to process raw material into finished products. Each unit operation performs a specific function in the process. The material and energy stream flows coming into and out of each unit operation describe the nature of that process step. Outlet flow streams that contain heat above 80°F and that are released to the environment are classified as waste heat energy streams. Examples of waste heat streams are boiler stack gases (unit operation 16 in Figure 2.1), dryer exhaust (unit operation 15), dewatering water (unit operation 14), evaporator steam (unit operation 8), etc. In this study, the procedure used to evaluate waste streams at the unit operation level is to quantify the energy content of these energy streams for a typical plant.

For this planning assessment, we need to estimate for a full year the energy content of waste heat streams (sources) and input heat streams (sinks). Therefore, typical plant energy flow information (in Btus per unit operation) must be combined with industry production information at the national level to obtain annual energy flow information. We used industry production information provided by the Census of Manufactures and the DOE (discussed in Chapter 4.0). To estimate annual energy content of waste heat streams, energy flow information for typical plants at the four-digit SIC level was compiled in a data base. This PNL-modified data base provides the annual energy content for individual industry energy streams and forms the basis of our analysis on the energy content in waste and input heat streams.

TYPICAL PLANT OPERATIONS

Unfortunately, the diversity of industrial operations even at the four-digit SIC level makes an analysis of intra-industry energy flow extremely complex and difficult. Not only are there many plants to be considered, but most manufacturing plants have unique characteristics that influence energy flow patterns. The problem is compounded by the lack of reliable data and the difficulties in getting access to individual plants to develop primary data. Thus,

even at the four-digit level, the lowest level of industry information, plants vary significantly in size, structure, operating procedures and energy flow.

A common approach to conducting broad based industry evaluations has been to develop a model by describing the operation of a typical plant for the industry. Our literature review has not produced an alternative to using a "typical plant" in broadly assessing the operation of an industry or particular process. Typical plant information generally substitutes for specific plant data because collecting data for every major industrial plant is restricted by cost and legal access constraints.

Thus, typical plant data provide the best information available for analyzing, generically, the energy flow patterns of industry, although the findings of such an analysis may be only partially valid for any specific plant. The typical plant approach is applicable when assessing for program planning purpose the energy content for waste heat and input heat streams within general temperature ranges. This temperature range information can be used to identify potential matchups between waste heat and input heat needs. The matchup (utilization) information can then be used to identify unit operations where opportunities may exist for using advanced waste heat recovery technology. Based on this information, specific plant engineering studies can be used to gather engineering data for waste heat recovery equipment design and operation information. The data in this assessment describing a typical plant's operation is, of course, not adequate nor intended to be used for detailed engineering design of heat recovery equipment. Engineering design of information can only be obtained through a site-specific engineering assessment.

COMPILATION OF ENERGY DATA BY TEMPERATURE RANGE

The usefulness of recovered energy from waste heat streams depends largely on the need of that energy in nearby unit operations. Recovered energy from waste heat may displace part of or all of the energy input needs for a specific unit operation within an industrial plant. The temperature differential between waste heat streams and input heat streams that must be overcome to make the energy in waste heat streams useful is one factor addressed in this assessment.

The information about the temperature differential between sources of energy and sinks for reclaimed energy is useful when considering the applicability of specific waste heat recovery technologies. Thus, our research approach involved identifying temperature differences between waste heat and input heat streams and assessing the maximum amount of energy that might be transferred. These two parameters, temperature difference and energy transfer, are key factors in evaluating specific heat recovery opportunities.

Sixteen temperature ranges were selected for analysis and the waste heat data base was queried to obtain the energy content of waste heat streams and input energy streams within each temperature range.

ENERGY SOURCE/SINK INFORMATION

The energy content of waste heat streams and energy input needs within each of the 16 temperature ranges is the basis for our evaluating the uses of recovered waste heat. To identify situations where energy from waste heat streams may be substituted for input heat energy, 108 industrial processes were examined. For each process separate matrices were developed that match up waste heat energy sources with input heat sinks across the 16 temperature ranges. Matrices were developed for three classes of heat streams:

- liquid and gaseous input and output heat streams combined
- liquid input and output heat streams only
- gaseous input and output heat streams only.

As Chapter 6.0 will discuss, the use of waste heat energy identified for each specific process is summed across all industries. This summary represents the maximum amount of waste heat that can be used in each of 256 matrix cells defined by a source and sink temperature. Chapter 6.0 concentrates on those cells in the summary tables having the highest energy content. Because these cells have high energy content, it is valuable to know which industries, and which unit operations within those industries contribute importantly to the cells energy content value. Chapter 6.0 ends with the provision of this information.

3.0 INDUSTRY ENERGY INFORMATION

In this chapter, energy use by the manufacturing sector is reviewed in terms of purchased fuels. Also, operation and energy-use characteristics of 6 two-digit SIC industries are summarized based on an extensive literature review. A more detailed write up for each of these 6 industries is provided in Appendices A through F. Finally, various industry-oriented energy data bases are briefly reviewed.

The 1980 Annual Survey of Manufactures (Department of Commerce 1982) indicates that 11.9 quads of purchased fuels were consumed by the manufacturing sector in 1980. These purchases were from a variety of primary and secondary energy sources including natural gas, crude petroleum products, coal, and hydro and nuclear power. Table 3.1 shows the relative importance of each energy source. Natural gas is by far the largest source of energy for the manufacturing sector. It contributed 51% of energy purchased in 1980, whereas electricity provided 19% of the energy purchased. Comparing the right hand column of the table to the 1980 value shows how the mix of fuel has changed since 1974.

TABLE 3.1 Percent of Total Energy Consumed by All Manufacturing Industries for Selected Fuels and Purchased Electric Energy (U.S. Department of Commerce 1982)

<u>Type of Fuel</u>	<u>Percent of Total Energy Purchased</u>	
	<u>1980</u>	<u>1974</u>
Residual fuel oil	8	9
Bituminous coal, lignite, & anthracite	12	10
Coke and breeze	4	3
Distillate fuel oil	2	5
Natural gas	51	54
Purchased electric energy	19	15
Other fuels (includes liquefied petroleum gases)	4	3

Total energy purchased by the manufacturing sector in 1974 was 13.5 quads or 1.6 quads above the 1980 purchases. Over this six-year period, purchased fuels have favored electricity and coal, whereas the relative energy purchases of natural gas and fuel oil have declined.

An analysis of the functional end uses of the primary fuels consumed by the manufacturing sector in 1974 indicates that industrial process heat is by far the most important end use in the manufacturing sector (SRC 1980). Of the total energy consumed in 1974, 26.3% was used for direct heat, 21.0% was used for process steam, and 19.2% for feed stocks (Table 3.2). Although industry consumption of purchased fuels has changed somewhat since 1974, direct heat, process steam and fuel feed stocks end uses still account for the majority of the fuels consumed by the manufacturing sector.

SPECIFIC INDUSTRY ENERGY INFORMATION

As discussed in Chapter 2.0, the manufacturing sector of the U.S. economy includes a broad spectrum of industries and products. The SIC code subdivides the manufacturing sector into 20 major groups identified by two-digit SIC numbers, 20 through 39. (SIC numbers and titles for these major groups are shown in Table 3.3.) Each of the major groups of industries is subdivided into the three-digit SIC divisions, and each of these divisions is subdivided further, identifying the four-digit SIC industries. The four-digit level provides the finest industry detail. A total of 452 four-digit SIC industries are identified within the SIC coding system.

Sector-Wide Information

Table 3.3 shows energy purchases by two-digit level industries. Of the 11.9 quads of energy purchased in 1980 by the manufacturing sector, Chemicals (SIC 28), Primary Metals (SIC 33), and Paper and Allied Products (SIC 26) accounted for 52.8%. As the table shows, the top 10 two-digit industries accounted for 91.4% of all energy purchased by the manufacturing sector.

One-third of all purchased energy is purchased by 4 of the 452 four-digit industries. The top 10 four-digit industries account for one-half of all energy purchased by the manufacturing sector. Table 3.4 shows the purchased

TABLE 3.2 U.S. Manufacturing 1974 Energy Consumption by Primary Fuel and Functional End Use (SERI/SRC 1980)

Functional End Use	Coal	Coke	Dist. Fuel Oil	Res. Fuel Oil	Misc. Petro. Products	LPG	Natural Gas	Other Gas	Hydro	Elec.	Other Energy	Total
Space heating	0.1		1.1	0.5			0.6			0.1		0.3
Space cooling										1.3		0.2
Space conditioning										0.1		NS
NSK/NEC												
Lighting										1.8		0.2
Total direct heat	6.5	1.8	26.2	38.7	32.0	2.6	38.1	80.7	1.7	4.3	3.1	26.3
below 600°F			3.4	3.8		0.5	3.6	12.4				2.5
600°F to 1000°F			5.2	10.6		1.6	9.0	43.7				7.0
1000°F to 1500°F			1.4	0.7	31.2	0.1	3.3	2.9		1.5	1.3	3.6
above 1500°F			2.3	1.1			1.8			0.1		0.8
Direct heat, NSK		1.8	13.9	18.0	0.9	0.2	19.3	21.7	1.7	2.7	1.8	11.8
Raw Material		88.7			67.8	91.0	6.7				2.8	19.3
Process steam	15.0	0.1	25.6	37.1		0.8	23.9	21.5			50.5	21.0
Electricity generation	6.3	0.2	2.3	6.7	0.1	0.1	5.3	4.1	-100.0	-12.3	2.3	2.5
Coke production	64.9	-98.8	0.6				NS	-21.0		0.3	-6.3	1.8
Machine drive			5.2	1.0	0.1	0.1	1.7	1.5	46.4	34.0		5.0
Electrolyte processes								51.8	15.7		1.9	
Other uses, NSK/NEC	7.2	6.9	38.9	16.0		5.4	23.7	-7.6	0.1	42.5	41.4	21.4
Total	100.0	-1.2	100.0	100.0	100.0	100.0	100.0	79.4	0.0	87.7	93.7	100.0

TABLE 3.3 Energy Purchases by Two-Digit Level Industries

Rank	SIC	Industry	Purchased Fuels and Electricity (10 ¹² Btu/yr)	% of Total	Cumulative %
1	28	Chemicals	2716.7	22.9	22.9
2	33	Primary Metals	2276.8	19.2	42.1
3	26	Paper & Allied Products	1278.4	10.8	52.8
4	29	Petroleum & Coal	1177.9	9.9	62.7
5	32	Stone, Clay & Glass	1122.3	9.5	72.2
6	20	Food & Kindred Products	948.0	8.0	80.2
7	34	Fabricated Metal	359.4	3.0	83.2
8	37	Transportation Equipment	343.8	2.9	86.1
9	35	Machinery	333.7	2.8	88.9
10	22	Textiles	294.9	2.5	91.4
11	36	Electrical, Electronic	239.9	2.0	93.4
12	30	Rubber, Miscellaneous Plastics	223.0	1.9	95.3
13	24	Lumber & Wood	199.3	1.7	97.0
14	27	Printing & Publishing	88.2	0.7	97.7
15	38	Instruments	79.7	0.7	98.4
16	23	Apparel	58.2	0.5	98.9
17	25	Furniture & Fixtures	47.1	0.4	99.3
18	39	Miscellaneous	45.0	0.4	99.7
19	21	Tobacco	22.4	0.2	99.8
20	31	Leather	19.0	0.2	100.0
			11,873.9		

energy by industry at the four-digit SIC level for the top 80 energy-purchasing industries.

Individual Industry Information

An extensive literature review was conducted to determine the energy use characteristics of all two-digit SIC industries. Manufacturing processes, heat-transfer operations, and waste heat stream characteristics of six industries are described in detail in Appendices A through F. These industries are: 1) chemicals, 2) petroleum, 3) primary metals, 4) pulp and paper, 5) stone, clay and glass, and 6) textiles. These six industries account for almost 80% of the total energy used by the manufacturing sector. Table 3.5 shows the

TABLE 3.4. Energy Purchases by the Top 80 Four-Digit Level Industries

Rank	SIC	Industry	Purchased Fuels and Electricity (10 ¹² Btu/yr)	% of Total	Cumulative %
1	3312	Blast Furnaces & Steel Mills	1282.1	10.8	10.8
2	2911	Petroleum Refining	1098.5	9.3	20.0
3	2869	Industrial Organic Chemicals	1005.9	8.5	28.5
4	2621	Papermills	583.0	4.9	33.4
5	2631	Paperboard Mills	458.6	3.9	37.3
6	3241	Cement, Hydraulic	390.8	3.3	40.6
7	3334	Primary Aluminum	359.8	3.0	43.6
8	2819	Industrial, Inorganic Chemicals	356.7	3.0	46.6
9	2873	Nitrogenous Fertilizers	258.2	2.2	48.8
10	2821	Plastics Materials & Resins	187.3	1.6	50.4
11	2865	Cyclic Crudes & Intermediates	152.1	1.3	51.7
12	3221	Glass Containers	132.0	1.1	52.8
13	2824	Organic Fibers, Noncellulosic	127.4	1.1	53.9
14	3079	Misc. Plastics Products	121.4	1.0	54.9
15	3321	Gray Iron Foundaries	111.0	0.9	55.8
16	3714	Motor Vehicle Parts, Acc.	110.9	0.9	56.7
17	2812	Alkalies and Chlorine	100.2	0.8	57.5
18	2611	Pulpmills	93.0	0.8	58.3
19	2046	Wet Corn Milling	92.1	0.8	59.1
20	3711	Motor Vehicles & Car Bodies	89.7	0.8	59.9
21	3274	Lime	85.6	0.7	60.6
22	2063	Beet Sugar	71.7	0.6	61.2
23	2011	Meatpacking Plants	69.6	0.6	61.8
24	3353	Aluminum Sheet, Plate & Foil	68.2	0.6	62.4
25	3229	Pressed and Blown Glass	65.7	0.6	63.0
26	2421	Sawmills, Planing Mills	59.2	0.5	63.5
27	2813	Industrial Gases	58.1	0.5	64.0
28	3251	Brick & Structural Clay Tile	57.3	0.5	64.5
29	2823	Cellulosic Manmade Fibers	56.6	0.5	65.0
30	2874	Phosphatic Fertilizers	55.1	0.5	65.5
31	3011	Tires & Inner Tubes	54.0	0.5	66.0
32	3296	Mineral Wool	53.9	0.5	66.5
33	3331	Primary Copper	53.0	0.4	66.9
34	2082	Malt Beverages	52.8	0.4	67.3
35	3273	Ready-Mix Concrete	51.9	0.4	67.7
36	3313	Electrometallurgical Products	51.0	0.4	68.1
37	3211	Flat Glass	50.9	0.4	68.5
38	2899	Chemical Preparations, NEC	49.3	0.4	68.9

TABLE 3.4. (contd)

Rank	SIC	Industry	Purchased Fuels and Electricity (10 ¹² Btu/yr)	% of Total	Cumulative %
39	2075	Soybean Oil Mills	48.0	0.4	69.3
40	2221	Weaving Mills, Manmade Fiber	44.9	0.4	69.7
41	2033	Canned Fruits & Vegetables	44.7	0.4	70.1
42	2822	Synthetic Rubber	42.6	0.4	70.5
43	3275	Gypsum Products	42.5	0.4	70.9
44	2816	Inorganic Pigments	41.2	0.3	71.2
45	2051	Bread, Cake, Related Products	41.0	0.3	71.5
46	2834	Pharmaceutical Preparations	40.0	0.3	71.8
47	3462	Iron & Steel Forgings	40.0	0.3	72.1
48	3341	Secondary Nonferrous Metals	39.3	0.3	72.4
49	3531	Construction Machinery	37.6	0.3	72.7
50	2653	Corrugated Solid Fiber Boxes	36.4	0.3	73.0
51	2211	Weaving Mills, Cotton	35.9	0.3	73.3
52	2951	Paving Mixtures & Blocks	35.4	0.3	73.6
53	3721	Aircraft	34.4	0.3	73.9
54	2411	Logging Camps, Log Contractors	33.6	0.3	74.2
55	2262	Finishing Plants, Manmade Fiber	33.3	0.3	74.5
56	2026	Fluid Milk	32.9	0.3	74.8
57	2099	Food Preparations, NEC	32.8	0.3	75.1
58	2499	Wood Products, NEC	32.8	0.3	75.4
59	3339	Primary Nonferrous Metals, NEC	32.8	0.3	75.7
60	2062	Cane Sugar Refining	32.2	0.3	76.0
61	2037	Frozen Fruits & Vegetables	32.0	0.3	76.3
62	2833	Medicinals & Botanicals	31.4	0.3	76.6
63	3523	Farm Machinery & Equipment	30.3	0.3	76.9
64	2077	Animal & Marine Fats & Oils	28.9	0.2	77.1
65	3069	Fabricated Rubber Products, NEC	28.4	0.2	77.3
66	2079	Shortening & Cooling Oils	28.0	0.2	77.5
67	3361	Aluminum Foundaries	27.8	0.2	77.7
68	3465	Automotive Stampings	27.7	0.2	77.9
69	3295	Minerals, Ground or Treated	27.6	0.2	78.1
70	3599	Machinery, except Electrical, NEC	27.5	0.2	78.3
71	3411	Metal Cans	27.1	0.2	78.5
72	2272	Tufted Carpets & Rugs	26.8	0.2	78.2
73	2661	Building Paper & Board Mills	26.8	0.2	78.9
74	2048	Prepared Foods, NEC	26.1	0.2	79.1
75	2022	Cheese, Natural & Processed	25.9	0.2	79.3
76	2261	Finishing Plants, Cotton	25.9	0.2	79.5

TABLE 3.4 (contd.)

<u>Rank</u>	<u>SIC</u>	<u>Industry</u>	<u>Purchased Fuels and Electricity (10¹² Btu/yr)</u>	<u>% of Total</u>	<u>Cumulative %</u>
77	3585	Refrigeration, Heating Equipment	25.5	0.2	79.7
78	2879	Agricultural Chemicals, NEC	25.4	0.2	79.9
79	2436	Softwood Veneer & Plywood	24.7	0.2	80.1
80	2752	Commercial Printing, Lithograph	24.2	0.2	80.3

Table 3.5 1982 Industrial Energy Consumption
(adopted from DOE 1983)

<u>SIC</u>	<u>Industry</u>	<u>Energy Use^(a) (10¹² Btu/yr)</u>	<u>% of Total</u>
28	Chemicals	5636.6	24.5
29	Petroleum	5551.1	24.1
33	Primary metals	3747.9	16.3
26	Pulp and paper	1813.7	7.9
32	Stone, clay and glass	1148.1	5.0
22	Textiles	452.6	2.0
	Others	<u>4665.2</u>	<u>20.2</u>
	Total	23,015.2	100.0

(a) Includes captive fuels, purchased fuels, and fuels used to generate purchased electricity.

energy use for these six industries in 1982 on an absolute and percentage basis. These energy use figures include internally generated (captive) fuels, purchased fuels, and energy conservation losses in generating purchased electricity. Summaries of the waste heat stream information gathered for these six industries are provided in the following sections.

Chemicals

The chemical industry encompasses the manufacture of thousands of organic and inorganic chemicals by a variety of processes. The chemical industry is the largest user of energy in the manufacturing sector. Four 3-digit SIC product groups consume more than 90% of the energy consumed by the chemical

industry: 1) SIC 281--Industrial Inorganic Chemicals, 2) SIC 282--Plastics and Synthetics, 3) SIC 286--Industrial Organic Chemicals, and 4) SIC 287--Agricultural Chemicals.

Table 3.6 lists the waste heat potential for the chemical industry by source. The waste heat stream information collected for specific chemical processes within the four top energy-consuming classifications is summarized below.

Industrial Inorganic Chemicals

The following industrial inorganic chemicals are examined in detail in the Appendix A:

- Chlorine
- Soda Ash
- Nitrogen
- Elemental phosphorus
- Caustic Soda
- Oxygen
- Sulfuric acid
- Phosphoric acid

Table 3.7 summarizes the waste heat temperatures and quantities for these chemicals. No significant waste heat streams were identified for the sulfuric acid

TABLE 3.6 Waste Heat Potential in the Chemical Industry
(10^{12} /Btu/yr) (Nydick 1976)

Source	Temperature °F				Total
	<150	150-300	300-600	>600	
Flue gas	--	--	350	60	410
Engine exhaust	--	--	10	10	20
Waste steam	--	--	--	--	--
Gas cooling and gas to liquid condensation	20	700	300	10	1030
Solid products and effluents	--	10	--	20	30
Liquid products and effluents	120	190	--	--	310
Subtotal	140	900	660	100	1800
Radiation/convection/conduction losses					200
Total heat releases					2000

TABLE 3.7 Waste Heat Stream Characteristics of Industrial Inorganic Chemical Processes

10 ⁶ Btu/ton of product (temperature, °F)			
<u>Process</u>	<u>Flue Gases</u>	<u>Cooling Water</u>	<u>Radiative</u>
Chlorine	--	0.24 (190)	2.2
Caustic soda	4.5 (120)	0.40 (180)	0.1
Soda ash	1.22 (400-500)	0.16	0.3
Oxygen/nitrogen	--	0.57 (100-120)	--

process. Two unit operations in this process are exothermic: sulfur burning and catalytic conversion of sulfur dioxide to sulfur trioxide. Waste heat is recovered from these operations to generate steam that is used either elsewhere in the plant or is exported. Little information was available on the waste heat from phosphorus and phosphoric acid production.

Plastics and Synthetics

The following plastics and synthetic materials were reviewed:

- low-density polyethylene
- high-density polyethylene
- polyvinyl chloride
- polystyrene
- polyester
- nylon
- acrylic

These processes are all characterized exothermic polymerization reactions, which may require high temperatures to initiate. Most of the process heat is provided in the form of steam and the condensate is returned to the boilers. The most important source of waste heat in these industries is cooling water, both contact and noncontact. Cooling water discharged from the high-density polyethylene process is the waste stream sufficiently large enough for waste heat recovery. The temperature of this cooling water typically ranges from 100 and 120°F. The other source of waste heat is the flue gas from boilers used to generate process steam. These gases are at temperatures of about 400°F.

Industrial Organics

The following industrial organic chemicals are described in Appendix A:

- polyester
- acrylic
- phenol
- nylon
- styrene
- ethylene

The most significant process in terms of waste heat discharged is the styrene process. Between 0.6 and 0.7 million Btu of waste heat is discharged per ton of styrene produced in flue gases at temperatures between 400 and 500°F (Latour 1981, UTC 1980). However, almost 50 times more waste heat is discharged in the cooling water from the styrene process, or 28.98 million Btu per ton of styrene at 100 to 120°F (Latour 1981). About 1.86 million Btu per ton of ethylene are discharged in flue gases at temperatures around 400°F (Reding et al. 1975). The polyester process discharges flue gases in the range of 90 to 110°F, although information on the quantity discharged was not available. Cooling water from polyester and nylon production ranges from 100 to 120°F, again with no estimate of the quantities available.

Nitrogenous Fertilizers

The most significant chemical in this category is ammonia. This chemical accounts for most of the production of agricultural fertilizers and many of the remaining fertilizers are derived from this. Table 3.8 summarizes the waste heat temperatures and quantities associated with ammonia production.

TABLE 3.8 Waste Heat Streams from Ammonia Production

<u>Source</u>	<u>Temperature (°F)</u>	<u>Quantity (10⁶ Btu/ton)</u>
Reformer flue gas	400	2.4 ^(a)
Compressor cooling water	100-120	0.5 ^(a)
Boiler blowdown	200 ^(b)	0.03
Cooling tower blowdown	20 ^(b)	0.2
Process condensate	70 ^(b)	0.2

(a) Estimate based on information for 1200 ton/day plant.

(b) Temperature above ambient.

Petroleum

There are only two significant sources of waste heat in a petroleum refinery: 1) hot flue gases from fired heaters, and 2) hot liquid product streams that are currently cooled to safe storage temperatures by water or air. Table 3.9 summarizes the sources and temperatures of these waste streams.

Primary Metals

A significant amount of waste heat is rejected in the primary metals industries, both in flue gases and in waste cooling and process water. Estimates of the total waste heat rejected in flue gas as waste water for the top four energy-consuming industries are provided in Table 3.10. Almost half of

TABLE 3.9 Sources of Refinery Waste Heat

<u>Source</u>	<u>Temperature (^oF)</u>	<u>10³ Btu/bbl of Oil Charge</u>
Heater and boilerstacks		105
• Crude distillation	700-900 ^o F	--
• Catalytic reforming	700-950 ^o F	--
• Coking	800-1000 ^o F	--
• Hydrocracking	700-900 ^o F	--
• Hydrogen production	600-1000 ^o F	--
• Others	300-1000 ^o F	--
Air coolers	250-350 ^o F	174
Water coolers	150-250 ^o F	137

TABLE 3.10 Annual Waste Heat Discharged by Primary Metals Industries (Latour 1981)

	<u>10¹² Btu/yr</u>
Blast furnaces and steel mills	1414.2
Gray iron foundaries	73.4
Primary copper	76.4
Primary aluminum	58.4

the energy is rejected by these four processes is at temperatures less than 125⁰F (mostly cooling and process water). About 25% is at temperatures from 125 to 500⁰F, 20% is between 500 and 1000⁰F, and the remainder is above 1000⁰F.

Paper and Allied Products

Waste waters and saturated vapors at temperatures less than 350⁰F are the most significant waste heat streams discharged from pulp mills (Labour 1981). Table 3.11 summarizes for pulp mills the types of waste heat sources and their heat content. The most significant sources of waste heat in paper and paper-board mills are 1) hot, moist air containing about 3.1×10^6 Btu/BDT, and 2) hot water containing about 0.69×10^6 Btu/BDT at about 250⁰F.

Stone, Clay and Glass

The major products in this classification are cement, glass (flat, container, pressed and blown), gypsum, brick and structural clay, mineral wool, and ready-mix concrete. With the exception of ready-mix concrete, the production process for each of these products is characterized by a high-temperature, direct-heat operation. Three of these industries, cement, lime, and glass

TABLE 3.11 Waste Heat Streams - Pulp Mills
(Latour 1981; UTC CTAS 1980;
Palmer et al. 1980)

<u>Source</u>	<u>Medium</u>	<u>Reported Theoretical Heat Content (10⁶ Btu/BDT)</u>
1. Ground wood bleaching	Bleaching effluent	1.1
2. Digestor blowdown	Steam	2.8
3. Kraft bleaching	Bleach effluent	0.4-1.2
4. Multiple effect evaporators	Steam Foul condensate	3.3 1.9
5. Recovery boilers	Flue gases	5.4
6. Kiln	Off gases	0.82

Sources: Latour 1981; UTC CTAS 1980; Palmer 1980.

(including flat glass, container glass, pressed and blown glass, and mineral wool) consume 70% of the energy used by this industry classification. These three industries reject almost 0.4 quads (393×10^{12} Btu) of waste heat each year in kiln and furnace exhausts (Latour 1981).

Sources and temperatures of waste heat are summarized in Table 3.12 and quantities of waste heat are summarized in Table 3.13 for cement, glass and lime.

Textiles

Sources and approximate temperatures of waste heat streams from textile operations are summarized in Table 3.14. A large portion of the energy is

TABLE 3.12 Sources and Temperatures of Waste Heat from Stone, Clay and Glass Industries

<u>Process</u>	<u>Source</u>	<u>Temperature (°F)</u>
Cement	Kiln exhaust - wet	150
	dry	700
	preheater	500-700
	bypass	1700-2000
	Clinker cooler - wet	150-250
	dry	300-450
	preheater	300-450
	Finishing mill	160
Glass	Cooling water	<100
	Melting furnace	2000-2800
	Primary regenerator	1200-1500
	Secondary regenerator	800-1000
	Metallic recuperator	1600-1800
	Annealing lehrs	1000-1200
	Cooling water	<125
Lime	Kiln exhaust	1800-2000
	Preheater exhaust	450-550
	Cooling water	<100
Gypsum	Calcining kettles	700-1100
	Dryers	<200
Brick & clay	Kilns	300-400

TABLE 3.13 Quantity of Waste Heat Discharged from Cement, Lime and Glass Production

	<u>10⁶ Btu/ton</u>
Cement	
Kiln exit gases	2.40
Clinker cooling air	0.54
Cooling water	0.05
Shell losses	0.90
Glass	
Melter exit gases	1.40
Wall losses	3.40
Lime	
Kiln exit gases	1.63
Product cooling air	1.14

TABLE 3.14 Sources of Waste Heat from Textile Mill Operations

<u>Type</u>	<u>Source</u>	<u>Temperature (°F)</u>
Exhaust gas	Boilers	400-600
	Singeing ovens	390-400
	Tenter-frame dryers	250-400
Process water	Slashing, bleaching, washing, mercerizing, dyeing	100-120
Non-contact cooling water	Product cooling	140

rejected from batch operations, such as drying. Exhausts from fabric ovens and dryers contain moisture, lint and finishing chemicals.

DATA BASE REVIEW

Information characterizing the industrial sector has been collected for years through censuses and surveys of manufacturers. Annual surveys of the fuels and electric energy purchased by industry are conducted by the U.S. Department of Commerce, Bureau of Census. Thus, considerable information is

TABLE 3.15. Twenty-Five Industrial Energy Data Bases and Summary of SERI Report Findings (SERI 1980)

1. Federal Energy Administration (FEA) Energy Conservation Data Base for nine industries, developed by Gordian Associates, Inc. (1975)
2. Dow Chemical Company's Survey of Industrial Energy Use (1977)
3. DOE's End-Use Energy Consumption Data Base (ECDB) (1978b)
4. The data base associated with the Industrial Sector Technology Use Model (ISTUM)(Energy and Environmental Analyses, Inc. 1978)
5. The Industrial Process Energy Data Base of the Drexel University Industrial Applications Study (Hamel et al., 1979)
6. The Industrial Plant, Energy Profiles (IPEP) Data Base developed by General Energy Associates (1979)--a derivative of the Drexel data base
7. The Facility Energy Utilization Data System (FEUDS) developed by Ultra-systems, Inc. (undated)
8. Industrial Process Energy Data Base developed by Intertechnology Corporation (ITC 1977)
9. Industrial Process Heat Data Base developed by Battelle Columbus Laboratories (1977)
10. The Industrial Process Heat Data Base developed by SERI under the Industrial Energy Data Collection cooperative effort (Green 1979)
11. Ongoing efforts at the Oak Ridge National Laboratory to develop a data base on industrial steam use (Barnes 1980)
12. The Environmental Protection Agency's (EPA) National Emissions Data System (1976)
13. Characterization of industrial process energy services by the Institute for Energy Analysis of Oak Ridge Associated Universities (1979)
14. Energy price distribution studies performed by Grumman Energy Data Systems (1979)
15. DOE's Price Data Base (1978) as part of the Federal Energy Data System
16. DOE's Major Fuel-Burning Installations (MFBI) Data Base (1975)
17. The Boiler Data Base available from the American Boiler Manufacturers Association (ABMA, 1979)
18. Current DOE efforts to conduct a large-scale survey of industrial plants to obtain detailed end-use information (Wotecki 1980)
19. Other special studies resulting in data bases:
 - Studies of industrial cogeneration by the Rocket Research Company (1978) for the Pacific Northwest
 - Studies of industrial energy consumption in Missouri by Synergic Resources Corporation (1980c)
 - Studies by Thermo Electron Corporation (1976) of industrial cogeneration
 - Study by Resource Planning Associates (RPA, 1977) of industrial cogeneration for DOE
 - Case studies of industrial cogeneration conducted by Synergic Resources Corporation (1980a) for the Electric Power Research Institute (EPRI)
 - The industrial energy reporting system at DOE

TABLE 3.15. (contd)

Major Findings

- Many data bases on industrial energy end use exist, but generally, the information reported was inconsistent.
- With the exception of ITC's and Battelle Laboratories' data bases, which were developed specifically to study solar industrial applications, none provide the information required for evaluating solar energy.
- Most data bases that report end-use information by quality and quantity of energy used represent only hypothetical or reference plants.
- Most data bases that have real plant data do not provide the detail required on the quality and quantity of energy end uses.
- No single data base can be considered uniformly better than any other.
- The Drexel University Industrial Process Energy Data Base, which details data on 108 industrial processes and uses the ITC and Battelle Information, is the most detailed data source for end uses at the 4-digit SIC level.
- The data bases vary significantly, perhaps corresponding to the variant energy consumption patterns throughout the U.S. Unfortunately, no attempt has been made to provide statistical measures of the actual variation in existing plants.
- Although considerable time and resources have been expended in developing the data bases, little effort has been devoted to verifying or validating the data.
- A considerable gap exists between what these data bases claim to provide and what they actually provide.
- A significant need exists for site-specific energy consumption data that can be used to develop realistic case studies on industrial solar energy applications. DOE is conducting a large-scale survey to develop such a data base, but it probably will not be available for several years.

available on purchased energy inputs to manufacturing. However, for less information is available describing the flow of purchased and self-generated energy within industrial processes. Chapter 2.0 briefly discussed the problems of collecting energy flow data at the plant level and the complexity of the problem because of the diversity of industrial processes. This section reviews the work of others to establish industry energy data bases.

In recent years a number of independent studies have been conducted on the use of energy in industry. Many of the data bases associated with these studies have been reviewed by Synergic Resources Corporation (SRC) in conjunction with Solar Energy Research Institute (SERI) and for the Electric Power Research Institute (EPRI). The SERI/SRC evaluation (SERI/SRC 1980) investigated the application of several industrial energy data bases to obtain information for 1) industrial process heat market assessments, and 2) comparative evaluation of solar thermal systems for industrial process heat applications. A similar study conducted for EPRI (SRC 1982) focused on the needs of the electrical utility industry for information addressing the following items:

- end-use data
- type and size of loads
- technological changes
- time of day
- process demand profiles
- fuel substitution opportunities
- electricity conservation and cogeneration potential
- load management
- economic data.

The focus of these two reviews of industrial energy data bases are somewhat different from the focus for this report, which is to identify opportunities for using waste heat recovery technology. However, their discussion of the strengths and weaknesses of various data bases is applicable to this study.

The SERI/SRC (1980) report identifies 24 data bases. These data bases and the major findings of the review are identified in Table 3.15. In the

study two years later for EPRI, SRC (1982) reviewed in detail 11 major energy consumption data bases and concluded that none provided energy data in a form that would satisfy all the requirements of utilities. Table 3.16 identifies the 11 data bases reviewed in that study and the major findings (SRC 1982).

Each of these data bases were found by SRC to have significant weaknesses. Generally, they found that verification of data is a weakness of all data bases and that data bases were limited in providing detailed plant specific and geographic information.

From our review and SRC's, PNL determined that the Drexel University Industrial Process Energy Data Base had the best overall design capacity to handle the project needs. This data base is discussed in more detail in the next chapter.

TABLE 3.16. Eleven Industrial Energy Data Bases and Summary
of EPRI Report Findings (SRC 1982)

<u>Industrial Energy Data Bases</u>	
1.	The Potential for Energy Conservation in Nine Selected Industries: The Data Base, prepared for the Federal Energy Administration by Gordian Associates, June 1974.
2.	Evaluation of the Theoretical Potential in Energy Conservation in Seven Basic Industries, prepared for the Federal Energy Administration by Battelle Columbus Laboratories, July 1975.
3.	Energy Consumption: Fuel Utilization and Conservation in Industry, prepared for the Environmental Protection Agency by Dow Chemical Company, September 1975.
4.	Environmental Considerations of Selected Energy Conservation Manufacturing Process Options, 15 volumes prepared for the Environmental Protection Agency by Aruthur D. Little, Inc., December 1976.
5.	Survey of the Applications of Solar Energy Systems to Industrial Process Heat, Final Report, prepared for the Energy Research and Development Administration by Battelle Columbus Laboratories, January 1977.
6.	Analysis of the Economic Potential of Solar Thermal Energy to Provide Industrial Process Heat, Final Report, prepared for the Energy Research and Development Administration by InterTechnology Corporation (ITC), February 1977.
7.	Energy Consumption Data Base, prepared for the Federal Energy Administration by Energy and Environmental Analysis (EEA), June 1977.
8.	Energy Analysis of 108 Industrial Processes, prepared by Drexel University for the U.S. Department of Energy, June 1979.
9.	Cogeneration Technology Alternative Study (CTAS), Volume II, Industrial Process Characteristics, Final Report, prepared for the U.S. Department of Energy NASA by United Technologies Corporation, January 1980.
10.	Industrial Energy Data Book, prepared by Oak Ridge Associated Universities (ORAU) for the U.S. Department of Energy.
11.	Industrial Plant Energy Profiles (IPEP), a proprietary data base developed by General Energy Associates (GEA).

Major Findings

- The data bases were not designed to fulfill utility requirements for detail concerning electrical end uses--in fact, many of the data bases tend to ignore electrical end uses.
- Generally the data bases were developed to provide input for studies or models. This required that a wide range of data for plants with different characteristics be reduced to values for a "representative plant" because of the significant plant-to-plant variation within an industry. Such data are not useful when analyzing specific utility service areas.

4.0 APPLICATION OF SELECTED DATA BASE

This chapter discusses the data base used in our analysis. Several steps were followed to implement an industrial energy-flow data base:

- After review of many data bases (Chapter 3.0), Drexel University's Industrial Process Energy Data Base was selected.
- The Drexel data base was updated from a 1979 data tape to incorporate 1980 data-base information.
- The Drexel data base was expanded to account for annual industry production.
- Calculated energy content values were adjusted to account for obvious limitations.

Our review and SRC's review of industrial energy data bases indicate that the data base with the best overall design capacity for handling the information needs of this waste heat recovery assessment is the Drexel University Industrial Process Energy Data Base. This data base's design at the unit operation level gives it the capacity to handle detailed energy flow information more comprehensively than other data bases. For example, the data base allows for collection of unit operation temperature, inlet and outlet stream flow temperature, and mass and energy content data. Figure 4.1 shows a blowup of this information for a unit operation from the process flow diagram shown in Figure 2.1 of Chapter 2.0.

FIGURE 4.1 Evaporator Operation

The Drexel data base includes typical process flow configurations for 108 industrial processes. These processes account for approximately 75% of U.S. industry purchased energy and fall within 61 four-digit SIC industries and 13 two-digit SIC industrial groups.

The 108 process flow configurations used in the Drexel data base are for typical plant operations for each process. The typical plant configurations developed are reported to be based on available references (engineering texts and handbooks, studies performed by private organizations and government agencies), limited on-site visits and consultant information (SERI/SRC 1980, p. 12). These data sources were used to develop heat and mass flow data on a per-pound-of-product basis for each unit operation in an industrial process. Because the Drexel data base is designed to handle detailed data at the unit operation level, it is the most capable data base to address waste heat recovery source and sink questions.

Generally, the design of the Drexel data base matches well with the assessment needs of this study. The main criticism of the Drexel data base is that the data-base values are not documented. Review of Drexel data-base information indicates that it is not possible to determine the sources used to develop energy and mass balances for particular industries and that it is difficult to determine implicit assumptions contained in the data.

SRC's review of the Drexel data was based on three sources: Hamel et al. 1979; Hedman and Brown 1980; and 1980 computer printouts of unit operation flow charts. As part of their review, SRC evaluated one process and noted several questions that could not be resolved. In their overall review of the Drexel data base, SRC identified four limitations: 1) only hypothetical or reference plants are represented without any variation in energy-use patterns by geographic region or by plant size; 2) no systematic validation has been performed; 3) some relevant 4-digit groups are not covered; and 4) the quality and reliability of information used to compile the data vary significantly. Despite these limitations, SRC concluded that the end-use data provided by the Drexel can be valuable, particularly if some primary data are available to compare, to validate, or to modify the typical plant data. SRC also concluded that the data base represents the most detailed end-use data available on industrial energy

consumption and is the only data base that provides information for a large number of 4-digit SIC industries.

Since the SRC review, Drexel University has published an additional document that considerably changes several industry process flow diagrams and changes many industry stream flow values (Drexel University 1980). These changes are discussed in some detail later. Although this latest report does provide considerable changes to the data in the Drexel data base, it still does not provide the additional documentation required. As a result, the Drexel data base as presently documented still has significant limitations placed on its usefulness.

Our review of the Drexel data base and its limitations indicates that the data base is not adequate for engineering level detail analysis nor for industry detailed analysis. The data base is most useful in assessing the general extent to which waste heat streams exit, their expected temperature ranges, and areas where recovered energy from waste heat streams may be used. Because this study's needs were for planning information, the Drexel data base was considered appropriate. Therefore, the 1979 data tape was placed on a System 2000 data base management system for review and updating. Once the data were updated, information for all 108 industrial processes was compiled. The data base was then expanded to calculate energy flow information over a one-year period and, where necessary, adjustments to these values were made.

DATA BASE FILES

Under contract with DOE, Drexel University had developed the industrial energy data base and placed the data base on computer tapes. That issue of the Drexel data base is herein referred to as the 1979 Drexel data base. The data tape as obtained from DOE came without instructions. Drexel University and others familiar with the Drexel data base were contacted for information about operating the data base. The information we were able to obtain was helpful but was not complete. We then spent considerable time in developing a program to read the 1979 data tape and in implementing a data base management system. Once the data base became operational, the 1979 data tape and the 1980 edition of the data base were compared, and the 1979 data base was upgraded.

Updating Drexel Industrial Data Files

The updated 1979 Drexel industrial data files are stored on computer disk files and backed up on magnetic tape on the UNIVAC 1100/44 computer at the Hanford site. The industrial data files consist of three types of records: General Industry Information Records, Unit Operation Records, and Flow Stream Records. Update changes were made to the Unit Operation Records and Flow Stream Records for each of the 108 five-digit SIC industries to make them agree with the 1980 Drexel documentation.

For the 14 industrial processes shown in Table 4.1, significant changes were made to the process flow diagram or to the energy flow values. For each of these processes, significant changes were made to the character of the process. For each of the 108 industrial processes, Table 4.2 identifies the kind of changes made to update the data tape.

TABLE 4.1 Process Industries With Significant Changes Between 1979 Tape and 1980 Drexel Manual

22	<u>TEXTILE MILL PRODUCTS</u>
2221-1	Weaving Mills, Man-Made Fibers
2262-1	Finishing Plants, Man-Made Fibers
24	<u>LUMBER AND WOOD PRODUCTS</u>
2411-1	Logging Camps, Log Contracts
2499-1	Wood Products, Fiberboard - Changed unit operation configuration
28	<u>CHEMICALS</u>
2812-1	Alkalies and Chlorine (Caustic Soda and Chlorine - Diaphragm Cell)
2822-2	Synthetic Rubbers (Butyl Rubber)
2865-1	Cyclic Crudes and Intermediates (Styrene and Ethylbenzene)
2869-1	Industrial Organic Chemicals (Ethylene) - Changed unit operation configuration
2869-2	Industrial Organic Chemicals (Methanol) - Changed unit operation configuration
29	<u>PETROLEUM</u>
2911-1	Petroleum Refining
33	<u>PRIMARY METALS</u>
3312-1	Blast Furnaces and Steel Mills - Changed unit operation configuration
3313-1	Electrometallurgical Products
3331-1	Primary Copper
3334-1	Primary Aluminum

TABLE 4.2. Changes Made to Update the 1979 Drexel Data Tape

20 FOOD AND KINDRED PRODUCTS

2011-1 Meat Packing Plants

Several changes to fuels used. Air conditioning and utility are deleted as separate unit operations.

2026-1 Fluid Milk

Several changes to fuels used. Space cooling and utility are deleted as separate unit operations.

2033-1 Canned Fuits and Vegetables (Canned Fruits)

Several changes to fuels used. Space cooling and utility are deleted as separate unit operations.

2033-2 Canned Fruits and Vegetables (Canned Vegetables)

Several label changes and changes to fuels used. Air conditioning and utility are deleted as separate unit operations.

2033-3 Canned Fruits and Vegetables (Canned Juices & Drinks)

Several changes to fuels used. Air conditioning and utility are deleted as separate unit operations.

2046-1 Wet Corn Milling

Several changes to fuels used. Space conditioning and utility are deleted as separate unit operations.

2051-1 Bread, Cake and Related Products (Bread)

Several changes to fuels used. Air conditioning and utility are deleted as separate unit operations.

2051-2 Bread, Cake, and Related Products (Cakes & Pies)

Several changes to fuels used. Air conditioning and utility are deleted as separate unit operations.

2062-1 Cane Sugar Refining

Several label changes and changes to fuels used. Utility is deleted as a separate unit operation.

2063-1 Beet Sugar

Several changes to fuels used. Utility is deleted as a separate unit operation.

2075-1 Soybean Oil Mills

Seven unit operations are missing from the 1980 Manual on Page 47. Several changes to fuels used. Utility is deleted as a separate unit operation.

TABLE 4.2. (contd)

2082-1 Malt Beverages

Eight unit operations are missing from the 1980 Manual on Page 48. Several changes to fuels used. Utility is deleted as a separate unit operation.

22 TEXTILE MILL PRODUCTS

2221-1 Weaving Mills, Man-Made Fibers

Massive numerical changes and label changes to many flow streams. Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.

2262-1 Finishing Plants Man-Made Fabrics

Massive numerical changes to flow streams. Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.

24 LUMBER AND WOOD PRODUCTS

2411-1 Logging Camps, Log Contracts

About one dozen numeric changes to flow streams. Several changes to fuels used. Utility is deleted as a separate unit operation.

2421-1 Saw Mills & Planning Mills

One label change to flow stream name. Several changes to fuels used.

2499-1 Wood Products (Fiber Board)

Previously called Wood Products (Miscellaneous). Massive label and numerical changes to many unit operations and flow streams. Recode completely from 1980 Manual, Page 63.

26 PAPER AND ALLIED PRODUCTS

2611-1 Pulp Mills (Kraft Process)

Minor label changes to flow stream names. Several changes to fuels used. Unit operations of space heating, space cooling, and utility are deleted as separate unit operations.

2611-2 Pulp Mills (Sulfite Process)

Several minor label changes to flow stream names. Several changes to fuels used. Unit operations of space heating, space cooling, and utility are deleted as separate unit operations.

2611-3 Pulp Mills (Mechanical Process)

Several dozen label changes to flow stream names. Several changes to fuels used. Unit operations of space heating, space cooling, and utility are deleted as separate unit operations.

2621-1 Paper Mills (Finishing Plant)

Several changes to fuels used. Unit operations of space heating, space cooling, and utility are deleted as separate unit operations.

TABLE 4.2. (contd)

- 2621-2 Paper Mill (Integrated Mills)
Several changes to fuels used. Unit operations of space heating, space cooling, and utility are deleted as separate unit operations.
- 2631-1 Paperboard Mills (Finishing Plant)
Several changes to fuels used. Unit operations of space heating, space cooling, and utility are deleted as separate unit operations.
- 2631-2 Paperboard Mills (Integrated Plant)
Several changes to fuels used. Unit operations of space heating, space cooling, and utility are deleted as separate unit operations.
- 2653-1 Corrugated Solid Fiber Boxes
Several changes to fuels used. Unit operations of space cooling and utility are deleted as separate unit operations.
- 2661-1 Building Paper and Board Mills
Several changes to fuels used. Unit operation of space heating, space cooling, and utility are deleted as separate unit operations.
- 2661-2 Building Paper & Board Mills Integrated Plant
Several changes to fuels used. Unit operations of space heating, space cooling, and utility are deleted as separate unit operations.
- 28 CHEMICALS
- 2812-1 Alkalies and Chlorine (Caustic Soda and Chlorine-Diaphragm Cell)
Massive changes to numeric fields and labels of many unit operations and flow streams. Space heating, space cooling, and utility are deleted as separate unit operations.
- 2812-2 Alkalies and Chlorine (NaOH, Cl₂--Mercury Process)
Card missing on tape for first flow stream (salt) for first unit operation -- Brine Preparation. Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 2812-3 Alkalies and Chlorine (Soda Ash-Solvay Process)
Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 2812-4 Alkalies and Chlorine (Soda Ash-Trona Deposits)
Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 2813-1 Inorganic Gases (N₂, O₂)
Space heating, space cooling, and utility are deleted as separate unit operations.

TABLE 4.2. (contd)

2813-2	<u>Inorganic Gases (H₂-Steam Reform)</u>
	Several minor label changes and numeric changes to fuels used. Utility is deleted as a separate unit operation.
2813-2	<u>Inorganic Gases (Acetylene)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2813-3	<u>Inorganic Pigments (TiO₂-Chloride Process)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2816-1	<u>Inorganic Pigments (TiO₂-Sulfate Process)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2816-2	<u>Inorganic Pigments (ZnO-French Process)</u>
	Several changes to fuels used. Space heating and utility are deleted as separate unit operations.
2816-3	<u>Inorganic Pigments (ZnO-American Process)</u>
	One set of changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2816-5	<u>Inorganic Pigments (ZnO-Electrothermal Process)</u>
	One set of changes to fuels used. Space heating, space cooling and utility are deleted as separate unit operations.
2819-1	<u>Industrial Inorganic Chemicals (Al₂O₃)</u>
	Several changes to fuels used. Utility is deleted as a separate unit operation.
2819-2	<u>Industrial Inorganic Chemicals (Sulfuric Acid)</u>
	Several label changes and utility is deleted as a separate unit operation.
2819-3	<u>Industrial Inorganic Chemicals (Phosphorus)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2819-4	<u>Industrial Inorganic Chemicals (Potash-Flotation Method)</u>
	Several changes to fuels used. Utility is deleted as a separate unit operation.
2819-5	<u>Industrial Inorganic Chemicals (Sodium Metal)</u>
	Several changes to fuels used. Space cooling and utility are deleted as separate unit operations.

TABLE 4.2. (contd)

2821-1	<u>Plastic Materials and Resins (PVC-Suspension Process)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2821-2	<u>Plastic Materials and Resins (Polystyrene-Mass Process)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2821-3	<u>Plastic Materials and Resins (LOPE)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
28214	<u>Plastic Materials and Resins (HDPE-Slurry Process)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2821-5	<u>Plastic Materials and Resins (HDPE-Solution Process)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2822-1	<u>Synthetic Rubbers (SBR)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2822-2	<u>Synthetic Rubbers (Butyl Rubber)</u>
	Several flow streams added to two unit operations. Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2822-3	<u>Synthetic Rubbers (Polybutadiene Rubber)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2822-4	<u>Synthetic Rubbers (Polyisoprene)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2822-5	<u>Synthetic Rubbers (EP Rubber)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2823-1	<u>Cellulosic Man-Made Fibers (Rayon)</u>
	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.

TABLE 4.2. (contd)

2823-2	<u>Cellulosic Man-Made Fibers (Cellose Acetate)</u>	Several label changes to flow streams and changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2824-1	<u>Organic Fibers, Non-Cellulosic (Polyester)</u>	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2824-2	<u>Organic Fibers, Non-Cellulosic (Polypropylene Fibers)</u>	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2824-3	<u>Organic Fibers, Non-Cellulosic (Acrylics)</u>	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2824-4	<u>Organic Fibers, Non-Cellulosic (Nylon 6, 6)</u>	Several changes to fuels used. Utility is deleted as a separate unit operation.
2824-5	<u>Organic Fibers, Non-Cellulosic (Nylon 6)</u>	Several changes to fuels used. Space cooling and utility are deleted as separate unit operations.
2834-1	<u>Pharmaceutical Preparations</u>	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2865-1	<u>Cyclic Crudes and Intermediates (Styrene and Ethylbenzene)</u>	Massive changes to numeric values for many unit operations and flow streams. Space heating and utility are deleted as separate unit operations.
2865-2	<u>Cyclic Crudes and Intermediates (Cumene and Phenol)</u>	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2865-3	<u>Cyclic Crudes and Intermediates (Cyclohexane)</u>	Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
2869-1	<u>Industrial Organic Chemicals (Ethylene)</u>	Massive label and numerical changes to many unit operations and flow streams. Recode completely from 1980 Manual, Pages 203-204. Space heating and utility are deleted as separate unit operations.

TABLE 4.2. (contd)

- 2869-2 Industrial Organic Chemicals (Methanol)
Massive label and numerical changes to many unit operations and flow streams. Recode completely from 1980 Manual, Pages 206-207. Space heating, space cooling, and utility are deleted as separate unit operations.
- 2869-3 Industrial Organic Chemicals (Formaldehyde)
Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 2873-1 Nitrogenous Fertilizers (Ammonia)
Several label changes to flow streams. Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 2874-1 Phosphatic Fertilizers (Phosphoric Acid-Wet Process)
Several label changes to flow streams. Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 2874-2 Phosphatic Fertilizers (Phosphoric Acid-Oxidation Method)
Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 2874-3 Phosphatic Fertilizers (Superphosphates)
Several changes to labels of flow streams and to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 2874-4 Phosphatic Fertilizers (Ammonium Phosphates)
Several changes to labels of flow streams and to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 2899-1 Chemical Preparations, NEC (Salt)
Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 2899-2 Chemical Preparations, NEC (Fatty Acids-Continuous Process)
Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 29 PETROLEUM
- 2911-1 Petroleum Refining
Dozens of numeric changes and some label changes to flow streams. Utility is deleted as a separate unit operation. Several changes to fuels used.
- 2951-1 Paving Mixtures and Blocks
Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.

TABLE 4.2. (contd)

30 RUBBER AND MISCELLANEOUS PLASTIC PRODUCTS

3011-1 Tires and Inner Tubes

Several changes to fuels used. Space cooling, space heating, and utility are deleted as separate unit operations.

3069-1 Fabricated Rubber Products, NEC (Dipped Latex)

Several label changes and changes to fuels used. Space cooling, space heating, and utility are deleted as separate unit operations.

3069-2 Fabricated Rubber Products, NEC (Molded Latex)

Several label changes and changes to fuels used. Space cooling, space heating, and utility are deleted as separate unit operations.

3069-3 Fabricated Rubber Products, NEC (Molded Products)

One label change and one change to fuels used. Space cooling and utility are deleted as separate unit operations.

3079-1 Miscellaneous Plastic Products

Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.

32 STONE, CLAY, AND GLASS

3211-1 Flat Glass

One numeric change to flow stream temperature. Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.

3221-1 Glass Containers

Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.

3229-1 Pressed & Blown Glass

Twenty-six minor label changes to flow stream names. Unit operations of space heating, space cooling, and utility are deleted. Several changes to fuels used.

3241-1 Cement, Hydraulic

Unit operations of space cooling, space heating, and utility are deleted. Several changes to fuels used.

3251-1 Brick and Structural Clay Tile

Fourteen minor label changes to flow stream names. Unit operations of space heating, space cooling, and utility are deleted. Several changes to fuels used.

3273-1 Ready Mix Cement

Five minor label changes to flow stream names. Unit operations of space cooling, space heating and utility are deleted. Several changes to fuels used.

TABLE 4.2. (contd)

3274-1	<u>Lime</u>	Eighteen minor label changes to flow stream names. Unit operations of space heating, space cooling, and utility are deleted. Several changes to fuels used.
3275-1	<u>Gypsum Products</u>	Two minor label changes to flow stream names. Unit operations of space heating, space cooling, and utility are deleted. Several changes to fuels used.
3296-1	<u>Mineral Wool</u>	Three minor label changes to flow stream names. Unit operations of space heating, space cooling, and utility are deleted. Several changes to fuels used.
33	<u>PRIMARY METALS</u>	
3312-1	<u>Blast Furnaces and Steel Mills</u>	Massive label and numeric changes to many unit operations and flow streams. One dozen old unit operations are deleted. Redo completely from 1980 manual, Pages 268-272.
3313-1	<u>Electrometallurgical Products</u>	Several dozen changes to numeric data and labels of flow streams. Unit operations of space heating, space cooling, and utility are deleted. Several changes to fuels used.
3321-1	<u>Gray Iron Foundries</u>	Unit operation of utility is deleted. Several changes to fuels used.
3331-1	<u>Primary Copper</u>	Several dozen changes to numeric data and labels of flow streams. Unit operation of utility is deleted. Several changes to fuel used.
3334-1	<u>Primary Aluminum</u>	About one dozen changes to numeric data and labels of flow streams. Unit operation of utility is deleted. Several changes to fuels used.
3341-1	<u>Secondary Non Ferrous Metals-Aluminum</u>	Minor label changes to flow streams. Unit operation of utility is deleted. Several changes to fuels used.
3341-2	<u>Secondary Non Ferrous Metals (Lead)</u>	Minor changes to labels of flow streams. Utility operation is deleted. Several changes to fuels used.

TABLE 4.2. (contd)

- 3341-3 Secondary Non Ferrous Metals (Zinc)
Minor changes to labels of flow streams. Utility operation is deleted. Several changes to fuels used.
- 3341-4 Secondary Non Ferrous Metals (Copper)
Utility operation is deleted. Several changes to fuels used.
- 3353-1 Aluminum Sheet Plate Foil
Minor label changes to flow streams. Utility operation is deleted. Several changes to fuels used.
- 34 FABRICATED METALS
- 3462-1 Iron and Steel Forging
Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 35 MACHINERY, EXCEPT ELECTRICAL
- 3523-1 Farm Machinery and Equipment
Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 3531-1 Construction Machinery
Several changes to fuels used. Utility is deleted as a separate unit operation.
- 37 TRANSPORTATION EQUIPMENT
- 3711-1 Motor Vehicles and Car Bodies
Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 3714-1 Motor Vehicle Parts and Accessories
Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.
- 38 INSTRUMENTS AND RELATED PRODUCTS
- 3861-1 Photographic Film
Several changes to fuels used. Space cooling, space heating, and utility are deleted as separate unit operations.
- 3861-2 Photographic Equipment
Several changes to fuels used. Space heating, space cooling, and utility are deleted as separate unit operations.

Record Layout

The record layout for the Unit Operation Records in the Drexel industrial data files was slightly revised to incorporate a new data element called "Total Fuels Used." Figure 4.2 shows the revised record layout for the Drexel industrial data files.

The data elements are defined in Table 4.3 and the codes for specific elements are shown in Table 4.4. The new data element, "Total Fuels Used," was inserted into the third card-image data record of the Unit Operation Records in columns 51-60. The rationale for adding the new data element is discussed below.

Research analysts at Drexel University originally itemized fuel consumption in each of the five-digit SIC process codes by five categories: coal, distilled oil, residual oil, natural gas, and other fuels. However, it was noticed that the consumption of natural gas, distilled oil, and residual oil always followed one of two ratios:

1. 50% by natural gas, 25% by distilled oil, and 25% by residual oil, or
2. 75% by natural gas, 12.5% by distilled oil, and 12.5% by residual oil.

No documentation was provided by Drexel University to justify this "assumed" pattern of fuel consumption for natural gas, distilled oil, and residual oil across the 108 five-digit codes. Consequently, the updated files (as well as the 1980 Drexel report) provide only a total fuel consumption value for each industry. Energy consumption is no longer reported by subtotals for natural gas, distilled oil, residual oil, coal and other fuels; however, the electrical consumption and unrecoverable losses are still reported separately in the updated files. This format follows the 1980 Drexel document.

Space heating, space cooling, and utility operations were also dropped as separate unit operations in the updated files to conform to the 1980 Drexel document. The boiler operation and electric generation operation were retained, both in the 1980 Drexel document and the updated files.

80 - 80																				REQUESTED BY										DATE										PROBLEM NO.																																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
GENERAL INDUSTRY INFORMATION RECORD																																																																															
SIC CODE					INDUSTRY NAME (UP TO 40 CHARACTERS)															TOTAL COOLING AVAILABLE										NO. OF UNIT OPERATIONS																																																	
					A40															F10.0										15																																																	
UNIT OPERATION RECORDS (Report for each unit operation within industry)																																																																															
SIC CODE					OPERATION NAME (20 char.)															OPERATION CODE					NO. OF # LOOPS																																																						
					A20															F5.0					15																																																						
SIC CODE					SHAFT POWER					OPERATION EFFICIENCY					OPERATION TEMPERATURE					OPERATION PRESSURE					ENDOTHERMIC					EXOTHERMIC					COAL USED																																												
					2					F10.0					F10.0					F10.0					F10.0					F10.0					F10.0																																												
SIC CODE					DISTILLED OIL USED					RESIDUAL OIL USED					NATURAL GAS USED					OTHER FUELS					TOTAL FUELS USED					ELECTRIC USED					UNRECOVERABLE LOSSES																																												
					3					F10.0					F10.0					F10.0					F10.0					F10.0					F10.0																																												
FLOW STREAM RECORDS (Repeat for each flow stream associated with the above unit operation)																																																																															
SIC CODE					FLOW NAME (10 char.)					FLOW TYPE					UNIT OPER TO 1300M					REPLACEMENT BY RECOVERED ENERGY					SOLIDS CONC.					LIQUIDS CONC.					PARTICLE SIZE					ABRASIVENESS					SOLID 3/4 IN FORMING					CORROSIVITY LIQUID					CORROSIVITY GAS					FLAMMABLE ?					PASSABLE THROUGH HEAT														
					1					A10					F5.0					F5.0					35.0					F5.0					F5.0					F5.0					F5.0					F5.0					F5.0					F5.0																			
SIC CODE					FLOW TEMPERATURE					FLOW PRESSURE					MASS FLOW RATE					ENERGY CONTENT					SP. HEAT					MOISTURE CONC.															HIGHER HEATING VALUE																																		
					2					F10.0					F10.0					F10.0					F10.0					F5.0					F5.0										F5.0																																		
NOTE: Most units are in Btu per unit of production. Temperatures are in °F. Pressure is in PSIA. Mass flow rate is in pounds per unit of production. Energy content is in Btu per unit of production.																																																																															

54-3000-263 (9-56)

FIGURE 4.2 Record Layout for Drexel Industrial Data Files Loaded into System 2000 DBMS

TABLE 4.3 Definition of Drexel Data Elements

General Industry Information Record--Description of Inputs

Industry name:	The name used to identify the industry/process on reports. Up to 40 characters.
Cooling tower availability:	Cooling tower availability in Btus per unit of production.
Number of 3-unit operations:	The number of unit operations in this industry.

Unit Operation Records--Description of Inputs

SIC code:	Full five-digit SIC code. Append a "1" on the right if only a four-digit code is used to identify the process.
Unit operation seq. no.:	Sequence number for the unit operation. Should start with 1 for the first unit operation, 2 for the second, (in one industry).
Flow seq. no.:	Sequence number for flows in process. Should start with 1 for the first flow in process, 2 for the second, etc.
Operation code:	Code indicating the type of unit operation. See Table 4.4.
No. of flows:	The number of flow streams associated with this unit operation.
Average size of shaft power unit:	Used only when shaft power is an input to the unit operation.

Flow Stream Records--Description of Inputs

Flow type code:	Code indicating the type of flow. See Table 4.4.
Unit operation to/from:	The unit operation a flow comes from (for inlet flows) or goes to (for outlet flows). Flows with exogenous sources should be coded with a -1., flows with exogenous destinations should be coded with a 99.

The updated Drexel industrial data files for the 108 five-digit codes were then loaded into the System 2000 Data Base Management System (DBMS) on the UNIVAC 1100/44 computer at the Hanford site. This data base was used for on-line query, updating, and report generation by using System 2000 DBMS commands at our computer terminals. The definition of the records and data elements ("schema") for the resulting System 2000 data base is shown in Table 4.5. Simple English-like commands, described in the next subsection, were used to query, sort, select, and update data from the System 2000 data base.

TABLE 4.4 Drexel Data Element Codes^(a)

Unit Operation Code

Mechanical (1-19)

1. Compressor	10. Centrifuge
2. Refrigeration	11. Pumps
3. Mixing	12. Major mech. proc. (misc.)
4. Crushing, grinding	13. Packaging
5. Separation	14. Filling
6. Filter	15. Settling
7. Extruding	16. Spinning, weaving
8. Rolling	17. Storage, holding tank
9. Cutting, trimming	18. Misc.

Thermal (20-40)

20. Furnace	31. Condenser
21. Drying	32. Distillation
22. Cooking	33. Flash separator
23. Ovens	34. Prime mover, elect.
24. Washing	35. Prime mover, mech.
25. Evaporation	36. Turbine
26. Annealing	37. Cooling tower
27. Pasteurizing	38. Cooling
28. Casting, molding	39. Heating
29. Boiler	40. Misc.
30. Heat exchangers	

Thermal-Chemical (41-49)

41. Reactors	45. Absorbing
42. Coking	46. Stripping
43. Electrolytic cells	47. Leaching
44. Extraction	48. Crystallization

Misc. (50-59)

50. Feedstocks	53. Space heating
51. Transportation	54. Space cooling
52. Lighting	55. Electricity
	56. Misc.

(a) Other data elements in Figure 3.2 are self-explanatory.

TABLE 4.4 (contd)

<u>Inlet Flows</u>		<u>Outlet Flows</u>	
1.0	Electrical	21.0	Waste gas
2.0	Shaft power	22.0	Waste water
3.1	Process hot air	23.0	Waste steam
3.2	Process hot water	24.0	Solid waste
3.3	Process steam	25.0	Return condensate
4.1	Process cool air	26.0	Gas product
4.2	Process cool water	27.0	Liquid product
6.0	Refrigeration	28.0	Solid product
7.0	Space heating	29.0	Process steam
8.0	Space cooling	30.0	Electricity
9.1	Product gas	31.0	Undefined losses
9.2	Product liquid		
9.3	Product solid		
9.4	Return Condensate		

Stream Flow Characteristics

Solids concentration:

- 1 clean
- 2 low
- 3 moderate
- 4 high

Liquid concentration:

- 1 clean
- 2 low
- 3 moderate
- 4 high

Particle size:

- 1 minute
- 2 small
- 3 medium
- 4 large

Abrasive:

- 1 Yes
- 2 No

Flammability

- 1 Yes
- 2 No

Solid film forming:

- 1 Yes
- 2 No

Corrosivity (liquid):

- 1 ph: >13
- 2 ph: 9-13
- 3 ph: 7-9
- 4 ph: 7
- 5 ph: 5-7
- 6 ph: 2-5
- 7 ph: 2

Corrosivity (gas):
(acid or base-forming
gas - Mole%)

- 1 0.1
- 2 0.1-1.0
- 3 1.0-10.0
- 4 10.0

Passable through
heat exchanger

- 1 Yes
- 2 No

TABLE 4.5. Schema for Updated System 2000 Drexel Data Base

```

1* SIC (INTEGER 9(5)):
2* GEN SEQ (NON-KEY INTEGER 9(2)):
3* INDUSTRY NAME (CHAR X(40)):
4* COOLING TOWER (DECIMAL 9(8).9(3)):
5* NO OPERS (INTEGER 9(2)):
6* ANNUAL PRODUCTION (DECIMAL NUMBER 9(5).9(8)):
7* ANNUAL HOURS (DECIMAL NUMBER 9999.):
8* NUMBER OF PLANTS (DECIMAL NUMBER 9(5).):
9* ANNUAL FUEL USAGE (DECIMAL NUMBER 9(5).9(8)):
10* ADJUST FACTOR (DECIMAL NUMBER 9(5).9(8)):
11* UNITS OF PRODUCTION (NON-KEY CHAR X(10)):
20* UNIT OPERATIONS (RECORD):
    21* SIC1 (INTEGER 9(5) IN 20):
    22* OPER SEQ (NON-KEY INTEGER 9(2) IN 20):
    23* OPER NAME (CHAR X(20) IN 20):
    24* OPER CODE (DECIMAL 9(4). IN 20):
    25* PROFILE CODE (DECIMAL 9(4). IN 20):
    26* NO FLOWS (INTEGER 9(2) IN 20):
    27* SIZE SHAFT POWER (DECIMAL 9(8).9(3) IN 20):
    28* OPER EFF (DECIMAL 9(3).9(3) IN 20):
    29* OPER TEMP (DECIMAL 9(5). IN 20):
    30* OPER PRES (DECIMAL 9(5).9(3) IN 20):
    31* ENDOTHERMIC (DECIMAL 9(8).9(3) IN 20):
    32* EXOTHERMIC (DECIMAL 9(8).9(3) IN 20):
    33* COAL USED (DECIMAL 9(8).9(3) IN 20):
    34* DIS OIL USED (DECIMAL 9(8).9(3) IN 20):
    35* RES OIL USED (DECIMAL 9(8).9(3) IN 20):
    36* NAT GAS USED (DECIMAL 9(8).9(3) IN 20):
    37* OTHER FUELS USED (DECIMAL 9(8).9(3) IN 20):
    38* TOTAL FUELS USED (DECIMAL 9(8).9(3) IN 20):
    39* ELECTR USED (DECIMAL 9(8).9(3) IN 20):
    40* UNRECOVER LOSSES (DECIMAL 9(8).9(3) IN 20):
    50* FLOW DATA (RECORD IN 20):
        51* SIC2 (INTEGER 9(5) IN 50):
        52* OPER SEQ1 (NON-KEY INTEGER 9(2) IN 50):
        53* FLOW SEQ (NON-KEY INTEGER 9(2) IN 50):
        54* FLOW NAME (CHAR X(8) IN 50):
        55* FLOW TYPE (DECIMAL 9(4).9 IN 50):
        56* UN OPER TO FROM (DECIMAL 9(4).9 IN 50):
        57* REPLACE (DECIMAL 9. IN 50):
        58* SOLIDS CONC (DECIMAL 9. IN 50):
        59* LIQUIDS CONC (DECIMAL 9. IN 50):
        60* PART SIZE (DECIMAL 9. IN 50):
        61* ABRASIVE (DECIMAL 9. IN 50):
        62* SOLID FILM FORM (DECIMAL 9. IN 50):
        63* COR LIQUID (DECIMAL 9. IN 50):
        64* COR GAS (DECIMAL 9. IN 50):
        65* FLAM (DECIMAL 9. IN 50):
        66* PASS HXER (DECIMAL 9. IN 50):
        67* FLOW TEMP (DECIMAL 9(5). IN 50):
        68* FLOW PRES (DECIMAL 9(8).9(3) IN 50):
        69* FLOW RATE (DECIMAL 9(8).9(3) IN 50):
        70* ENERGY CONTENT (DECIMAL 9(8).9(3) IN 50):
        71* SP HEAT (DECIMAL 9(8).9(3) IN 50):
        72* MOISTURE CONC (DECIMAL 9(8).9(3) IN 50):
        73* HHEATV (DECIMAL 9(8).9(3) IN 50):
        74* FLOW LABEL (CHAR X(7) IN 50):
        75* FLOW IN-OUT (CHAR XXX IN 50):

```

GENERAL CAPABILITIES OF SYSTEM 2000 DBMS

System 2000 is a Data Base Management System that was developed and is maintained by Intel Corporation in Austin, Texas. The system operates on IBM, Univac, Amdahl, and CDC large-scale computers. Most of the information on System 2000 described in this section was obtained from Intel's System 2000 Professional User's Guide.

System 2000 contains multiple modules, i.e., English-like command languages, to provide the user with commands to name, organize, load, archive, query, sort, update, and release data bases. Some of the key modules of System 2000 are shown in Table 4.6.

Users can dial into an on-line System 2000 data base located at a host computer site that has the System 2000 DBMS, such as the DOE headquarters or the Hanford site, through the FTS telephone network or through some other commercially available time-sharing network. Because the QUEST language is the module that users would most frequently use at their terminal to access information and to browse through a System 2000 data base, the remainder of the discussion in this subsection will focus on this module.

Commands in the QUEST language are easy to learn and use. The most frequently used QUEST commands for data retrieval and data browsing are DESCRIBE, TALLY, PRINT, and LIST. Each of these commands is discussed briefly below.

DESCRIBE shows the user the data base definition. This includes the names of the data items, their data type (numeric or alphanumeric), their maximum number of anticipated digits or characters (their "picture"), the relationships among the data records, and various other attributes.

TALLY is used to count the distinct values of a data item, to determine the number of times each distinct value occurs in the data base, and to display the minimum and maximum values for each item.

PRINT will display requested data values. Either the entire data base or a subset of the data base can be scanned with this command.

LIST will produce columns of data with either default or user-specified column headings. Again, either the entire data base or a subset can be scanned.

TABLE 4.6 Modules of System 2000

<u>Module</u>	<u>Purpose</u>
DEFINE language	To specify the names of the data items, the types of data, and the relationships among the data records in a data base (i.e., the data base definition).
CONTROL language	To save or to restore a data base and to provide security.
QUEST (immediate access) language	To load, query, retrieve, sort, and update a data base.
REPORT language	To generate reports.
PLEX (programming language extension)	To load and retrieve large volumes of data through a programming language such FORTRAN, COBOL, PL/1, or Assembler.
Genius	To generate reports and graphic charts through a series of conversational prompts and user responses from a terminal.
Quex	To enter and retrieve data interactively from terminal.

A wide variety of options are available with each of these four main commands. The user can select a subset of data items to be displayed by specifying a where-clause and selection criteria in the PRINT or LIST commands. The user can also sort the output by giving an ordering-clause whenever a where-clause is given in a PRINT or LIST command.

The following commands in the QUEST language can be used to update the data base:

ADD is used to add an item value where none currently exists.

ASSIGN is used to assign a value to an existing data item.

CHANGE is used to change an existing item value.

REMOVE deletes an item value.

INSERT TREE inserts a new data tree of records and values.

REMOVE TREE deletes a data tree of records and values.

Detailed information on each of these commands, including examples, and information on each of the above modules is available through the following publications by Intel:

Language Specification Manuals

DEFINE language

QUEST language, including the QUEUE option

Programming Facility (PLEX)

Administrative Facilities, including CONTROL language

Messages and Codes (MAC)

CREATE facility

User's Guides

System 2000 Professional User's Guide

Genius

Quex

Pocket Guides

Syntex Guide

Glossary

DATA BASE EXPANSION/ADJUSTMENTS

At this point the data base was operational, and the energy flow information associated with the unit operations of selected industrial processes was specified in Btus per unit of production. To estimate the annual energy content embodied in these various heat streams, annual production information developed for a prior DOE report (G.E. 1981) was compared to information from the 1977 Census of Manufactures. The relationship among industrial processes characterized in the Drexel data base and the industries characterized in the Census of Manufactures is not always direct. Differences occurred in three areas:

1. The Drexel data base often divides SIC codes into subunits based on the different types of processes used to produce a product (i.e., three types of pulp mills), whereas the 1977 Census of Manufactures divides the SIC codes by types of goods--not processes. This makes it difficult to assign Census of Manufactures production levels to some Drexel processes.
2. In several cases, the production units used by Drexel and the Census of Manufactures were not the same.

3. In some industries, Census of Manufactures estimates of annual production were unavailable or undisclosed.

Industry Production Information

The Drexel data base provides energy flow information in Btus per pound of product for typical industrial processes. To estimate the quantity of waste heat energy that a plant or industry might generate annually, industrial production information must be incorporated into the Drexel data base. Using G.E. and Census of Manufactures data, production values for each of the 108 processes characterized by the Drexel data base were compiled.

Efforts were made to independently relate the Drexel industrial processes to the Census of Manufactures product data. Where the Census of Manufactures data was used, the results are reported in Table 4.7. The first two columns of the table shows the Drexel data base code used for all 108 industrial processes and the production units used in describing stream flows. Column three reports the production units used in the Census of Manufactures. Column four provides the conversion factor for converting Drexel data base production unit to the production unit used in the Census of Manufactures. Column five identifies the 1977 estimates of production obtained from the Census of Manufactures and column six provides the multiplier used for converting Drexel data base stream flow information into annual data.

This assessment uses the G.E. values as the basic estimate of production and modifies them based on the 1977 Census of Manufactures data. The revised values are close to G.E.'s original values, except for processes 2262-1, 2951-1, and 3273-1. In the case of Process 2262-1, the conversion factor used to convert linear feet of material to pounds is corrected. For Process 2951-1 and 3273-1, differences appear to stem from different interpretations of Census of Manufactures information and possibly different conversion factors.

Table 4.8 compares the U.S. industrial production estimate used in this report to those used by G.E.

TABLE 4.7 Industry Production Information for Use in
Converting Drexel Data to Annual Data

Drexel Industry Code	Drexel Units of Production	Census of Manufacturers Units of Production	Conversion from Drexel Units to CM ^(a) Units	1977 CM ^(a) Production	Multiplier for Converting Drexel Data to Annual Data
2011-1	Pounds	Million pounds	1,000,000	31,675.1	$31,675 \times 10^6$
2026-1	Pounds	Million pounds	1,000,000	15,816.4	
2026-1	Pounds	Million quarts	2.0825×10^6	22,065.4	
2026 total	Pounds				$61,786 \times 10^6$
2033-1	Case	1,000 cases	1,000	150,748	151×10^6
2033-2	Case	1,000 cases	1,000	251.127	251×10^6
2033-3	Case	1,000 cases	1,000	157,000	157×10^6
2046-1	Pound of corn input	Million pounds	1,000,000	15,180	15.18×10^9
2051-1	100 pounds	Million pounds	10,000	10,883	109×10^6
2051-2	100 pounds	Million pounds	10,000	6,300	63×10^6
2062-1	100 pounds	1000 s tons	20,000	7,250	145×10^6
2063-1	Pound of input	1000 s tons	2,000,000	23,279	$46,558 \times 10^6$
2075-1	Pound of oil	Million pounds	1,000,000	16,512	$16,512 \times 10^6$
2082-1	Pound	1000 bbl	2.624×10^5		$40,962 \times 10^6$
2221-1	Pound	Million linear yards	2.29×10^6	6,568	$15,040 \times 10^6$
2262-1	Pound	Million finished linear yard	2.29×10^6	6,731	$15,413 \times 10^6$
2411-1	Pound rough cut	Million feet (log scale)	4.99×10^6	16,776	$83,711 \times 10^6$
2421-1	Pounds	Million board feet	2×10^6	37,096	$74,192 \times 10^6$
2499-1	Square feet	Million square feet	1,000,000	506.3	506×10^6
2611-1	Pound	1000 s tons	2,000,000	4,717	$9,435 \times 10^6$
2611-2	Pound	1000 s tons	2,000,000	726	$1,452 \times 10^6$
2611-3	Pound	1000 s tons	2,000,000	122	244×10^6
2621-1	Pound	1000 s tons	2,000,000		$8,900 \times 10^6$
2621-2	Pound	1000 s tons	2,000,000	20,150	$40,300 \times 10^6$
2631-1	Pound	1000 s tons	2,000,000		$9,400 \times 10^6$

TABLE 4.7 (contd)

Drexel Industry Code	Drexel Units of Production	Census of Manufacturers Units of Production	Conversion from Drexel Units to CM ^(a) Units	1977 CM ^(a) Production	Multiplier for Converting Drexel Data to Annual Data
2631-2	Pound	1000 s tons	2,000,000		$54,800 \times 10^6$
2653-1	Square foot	1000 s tons	$13,888.87 \times 10^3$	15,449.2	$214,572 \times 10^6$
2661-1	Pound	1000 s tons	2,000,000		$3,600 \times 10^6$
2661-2	Pound	1000 s tons	2,000,000		$7,000 \times 10^6$
2812-1	Pound	1000 s tons	2,000,000		$17,000 \times 10^6$
2812-2	Pound	1000 s tons	2,000,000		$4,300 \times 10^6$
2812-3	Pound	1000 s tons	2,000,000		$8,100 \times 10^6$
2812-4	Pound	Million pounds	2,000,000		$8,000 \times 10^6$
2813-1	Pound	Million ft ³	89,200		$31,600 \times 10^6$
2813-2	Pound	Million ft ³	5,610		445×10^6
2813-3	Pound	Million ft ³	84,160		405×10^6
2816-1	Pound	1000 s tons	2,000,000		750×10^6
2816-2	Pound	1000 s tons	2,000,000		750×10^6
2816-3	Pound	1000 s tons	2,000,000		130×10^6
2816-4	Pound	1000 s tons	2,000,000		130×10^6
2816-5	Pound	1000 s tons	2,000,000		130×10^6
2819-1	Pound	1000 s tons	2,000,000		$11,900 \times 10^6$
2819-2	Ton	1000 s tons	1,000		36×10^6
2819-3	Pound	1000 s tons	2,000,000		800×10^6
2819-4	Pound	1000 s tons	2,000,000		4900×10^6
2819-5	Pound	1000 s tons	2,000,000		320×10^6
2821-1	Pound	Million pounds	1,000,000		$5,200 \times 10^6$
2821-2	Pound	Million pounds	1,000,000		$5,400 \times 10^6$
2821-3	Pound	Million pounds	1,000,000		$6,500 \times 10^6$
2821-4	Pound	Million pounds	1,000,000		$1,800 \times 10^6$
2821-5	Pound	Million pounds	1,000,000		$1,800 \times 10^6$
2822-1	Pound	Million pounds	1,000,000		$3,080 \times 10^6$
2822-2	Pound	1000 s tons	2,000,000		330×10^6
2822-3	Pound	Million pounds	1,000,000		790×10^6
2822-4	Pound	Million pounds	1,000,000		140×10^6

TABLE 4.7 (contd)

Drexel Industry Code	Drexel Units of Production	Census of Manufacturers Units of Production	Conversion from Drexel Units to CM ^(a) Units	1977 CM ^(a) Production	Multiplier for Converting Drexel Data to Annual Data
2822-5	Pound	Million pounds	1,000,000		158×10^6
2823-1	Pound	Million pounds	1,000,000		606×10^6
2823-2	Pound	Million pounds	1,000,000		324×10^6
2824-1	Pound	Million pounds	1,000,000		$4,200 \times 10^6$
2824-2	Pound	Million pounds	1,000,000	3,800.0	$3,800 \times 10^6$
2824-3	Pound	Million pounds	1,000,000		761×10^6
2824-4	Pound	Million pounds	1,000,000	1900	$1,900 \times 10^6$
2824-5	Pound	Million pounds	1,000,000	600	600×10^6
2834-1	\$ sales	Million \$ shipments	1.0	9,639	$9,640 \times 10^6$
2865-1	Pound	Billion pounds	10^9		$6,900 \times 10^6$
2865-2	Pound	Billion pounds	10^9		$2,600 \times 10^6$
2865-3	Pound	Billion pounds	10^9		$2,300 \times 10^6$
2869-1	Pound	Billion pounds	10^9		$25,200 \times 10^6$
2869-2	Pound	Billion pounds	10^9		$6,500 \times 10^6$
2869-3	Pound	Billion pounds	10^9		$6,000 \times 10^6$
2873-1	Pound	1000 s tons	2,000,000		$38,800 \times 10^6$
2874-1	Pound	1000 s tons	2,000,000		$15,200 \times 10^6$
2874-2	Pound	1000 s tons	1,000,000		$1,700 \times 10^6$
2874-3	Pound	1000 s tons	2,000,000		$4,000 \times 10^6$
2874-4	Tons	1000 s tons	1,000		$9,600 \times 10^6$
2899-1	Pound	Million s tons	2×10^9		$1,030 \times 10^6$
2899-2	Pound	Million s tons	2×10^9		$1,030 \times 10^6$
2911-1	Pound of crude oil	Million BBL crude oil	308×10^6	5,108.5	$1,578 \times 10^9$
2951-1	Pound	1000 s tons	2,000,000	58,013	$116,027 \times 10^6$
3011-1	Pound	Million pounds	1,000,000	8,946	$8,946 \times 10^6$
3069-1	Pound	Million pounds	1,000,000		505×10^6
3069-2	Pound	Million pounds	1,000,000		506×10^6
3069-3	Pound	Million pounds	1,000,000		$1,990 \times 10^6$
3079-1	Pound	Million pounds	1,000,000	16,633	$16,633 \times 10^6$

TABLE 4.7. (contd)

Drexel Industry Code	Drexel Units of Production	Census of Manufacturers Units of Production	Conversion from Drexel Units to CM ^(a) Units	1977 CM ^(a) Production	Multiplier for Converting Drexel Data to Annual Data
3211-1	Pound	1000 s tons	2,000,000	2,900	$5,800 \times 10^6$
3221-1	Pound	1000 s tons	2,000,000	15,120	$30,240 \times 10^6$
3229-1	Pound	1000 s tons	2,000,000	1635	$3,270 \times 10^6$
3241-1	Pound	Million s tons	2×10^9	77.9	$155,800 \times 10^6$
3251-1	Pound	1000 s tons	2,000,000	9,895	$19,790 \times 10^6$
3273-1	Pound	Million yards ³	2.54×10^9	203.4	$516,600 \times 10^6$
3274-1	Pound	1000 s tons	2,000,000	1395.3	$2,790 \times 10^6$
3275-1	Pound	1000 s tons	2,000,000	13,300	$26,600 \times 10^6$
3296-1	Pound	1000 s tons	2,000,000	1630	$3,260 \times 10^6$
3312-1	Pound	1000 s tons	2,000,000		$290,000 \times 10^6$
3313-1	Pound	1000 s tons	2,000,000		$4,360 \times 10^6$
3321-1	Pound	1000 s tons	2,000,000		$25,000 \times 10^6$
3331-1	Pound	1000 s tons	2,000,000		$7,160 \times 10^6$
3334-1	Pound	1000 s tons	2,000,000		$9,280 \times 10^6$
3341-1	Pound	1000 s tons	2,000,000		$2,300 \times 10^6$
3341-2	Pound	1000 s tons	2,000,000		1570×10^6
3341-3	Pound	1000 s tons	2,000,000		442×10^6
3341-4	Pound	1000 s tons	2,000,000		918×10^6
3353-1	Pound	1000 s tons	2,000,000		$8,240 \times 10^6$
3462-1	Pound	1000 s tons	2,000,000		$2,500 \times 10^6$
3523-1	# sales	Million \$ shipments	1,000,000	\$9548.9	$9,550 \times 10^6$
3531-1	\$ sales	Million \$ shipments	1,000,000	\$11,569.9	$11,570 \times 10^6$
3711-1	Pounds	Million pounds	1,000,000		$16,600 \times 10^6$
3714-1	Pounds	Million pounds	1,000,000		$32,100 \times 10^6$
3861-1	Pounds	Million pounds	1,000,000		$1,200 \times 10^6$
3861-2	\$ of sales	Million \$ sales	1,000,000	\$1104	$1,104 \times 10^6$

TABLE 4.8 Comparison of Industrial Production Estimates
(G.E. 1981)

Drexel Code	SIC Code	Units In Millions	U.S. Production Estimate		Value Used/GE
			Value Used	GE ⁽¹⁾	
2011-1	2011	Pounds	31,675	25,000	1.27
2026-1	2026	Pounds	61,768	52,000	1.19
2033-1	2033	Cases	151	230	0.66
2033-2	2033	Cases	251	295	0.85
2033-3	2033	Cases	157	220	0.71
2046-1	2046	Pounds	15,180	22,000	0.69
2051-1	2051	Hundred Wt.	109	109	1.00
2051-2	2051	Hundred Wt.	63	67	0.94
2062-1	2062	Hundred Wt.	145	145	1.00
2063-1	2063	Pounds	46,558	11,110	4.19
2075-1	2075	Pounds	16,512	9,500	1.74
2082-1	2082	Pounds	40,962	38,000	1.08
2221-1	2221	Pounds	15,040	1,900	7.92
2262-1	2262	Pounds	15,413	1,000	15.4
2411-1	2411	Pounds	83,711	101 Cords	--
2421-1	2421	Pounds	74,192	41,000	1.81
2499-1	2499	sq. ft.	506	594	0.85
2611-1	2611	Pounds	9,435	5,400	1.89
2611-2	2611	Pounds	1,452	1,100	1.32
2611-3	2611	Pounds	244	700	0.35
2621-1	2621	Pounds	8,900	8,900	1.00
2621-2	2621	Pounds	40,300	40,300	1.00
2631-1	2631	Pounds	9,400	9,400	1.00
2631-2	2631	Pounds	54,800	54,800	1.00
2653-1	2653	sq. ft.	214,572	260,600	0.83
2661-1	2661	Pounds	3,600	3,600	1.00
2661-2	2661	Pounds	7,000	7,000	1.00
2812-1	2812	Pounds	17,000	17,000	1.00
2812-2	2812	Pounds	4,300	4,300	1.00
2812-3	2812	Pounds	8,100	8,100	1.00
2812-4	2812	Pounds	8,000	8,000	1.00
2813-1	2813	Pounds	31,600	31,600	1.00
2813-2	2813	Pounds	445	445	1.00
2813-3	2813	Pounds	405	405	1.00
2816-1	2816	Pounds	750	750	1.00
2816-2	2816	Pounds	750	750	1.00
2816-3	2816	Pounds	130	130	1.00

(1) Industrial Process Heat Pump Service Study prepared by General Electric Company for U.S. Department of Energy April 1981.

TABLE 4.8 (contd)

Drexel Code	SIC Code	Units In Millions	U.S. Production Estimate		Value Used/GE
			Value Used	GE ⁽¹⁾	
2816-4	2816	Pounds	130	130	1.00
2816-5	2816	Pounds	130	130	1.00
2819-1	2819	Pounds	11,900	11,900	1.00
2819-2	2819	Tons	36	36	1.00
2819-3	2819	Pounds	800	800	1.00
2819-4	2819	Pounds	4,900	4,900	1.00
2819-5	2819	Pounds	320	320	1.00
2821-1	2821	Pounds	5,200	5,200	1.00
2821-2	2821	Pounds	5,400	5,400	1.00
2821-3	2821	Pounds	6,500	6,500	1.00
2821-4	2821	Pounds	1,800	1,800	1.00
2821-5	2821	Pounds	1,800	1,800	1.00
2822-1	2822	Pounds	3080	3080	1.00
2822-2	2822	Pounds	330	330	1.00
2822-3	2822	Pounds	790	790	1.00
2822-4	2822	Pounds	140	140	1.00
2822-5	2822	Pounds	158	158	1.00
2823-1	2823	Pounds	606	606	1.00
2823-2	2823	Pounds	324	324	1.00
2824-1	2824	Pounds	4,200	4,200	1.00
2824-2	2824	Pounds	3,800	3,800	1.00
2824-3	2824	Pounds	761	761	1.00
2824-4	2824	Pounds	1,900	1,900	1.00
2824-5	2824	Pounds	600	600	1.00
2834-1	2834	\$ sales	9,640	79 Btu E12	--
2865-1	2865	Pounds	6,900	6,900	1.00
2865-2	2865	Pounds	2,600	2,600	1.00
2865-3	2865	Pounds	2,300	2,300	1.00
2869-1	2869	Pounds	25,200	25,200	1.00
2869-2	2869	Pounds	6,500	6,500	1.00
2869-3	2869	Pounds	6,000	6,000	1.00
2873-1	2873	Pounds	38,800	38,800	1.00
2874-1	2874	Pounds	15,200	15,200	1.00
2874-2	2874	Pounds	1,700	1,700	1.00
2874-3	2874	Pounds	4,000	4,000	1.00
2874-4	2874	Pounds	9,600	9,600	1.00
2899-1	2899	Pounds	1,030	1,030	1.00

TABLE 4.8 (contd)

Drexel Code	SIC Code	Units In Millions	U.S. Production Estimate		Value Used/GE
			Value Used	GE ⁽¹⁾	
2899-2	2899	Pounds	1,030	1,030	1.00
2911-1	2911	Pounds	1,578,000	1,46,000	1.00
2951-1	2951	Pounds	116,027	9,300	12.5
3011-1	3011	Pounds	8,946	10,200	0.88
3069-1	3069	Pounds	505	505	1.00
3069-2	3069	Pounds	506	506	1.00
3069-3	3069	Pounds	1990	1,990	1.00
3079-1	3079	Pounds	16,633	15,800	1.05
3211-1	3211	Pounds	5,800	12,700	0.69
3221-1	3221	Pounds	30,240	23,400	1.29
3229-1	3229	Pounds	3,270	2,440	1.34
3241-1	3241	Pounds	155,800	168,000	0.93
3251-1	3251	Pounds	19,790	54,400	0.36
3273-1	3273	Pounds	516,600	34,400	15.0
3274-1	3274	Pounds	2,790	29,200	0.10
3275-1	3275	Pounds	26,600	33,600	0.79
3296-1	3296	Pounds	3,260	3,660	0.89
3312-1	3312	Pounds	290,000	290,000	1.00
3313-1	3313	Pounds	4,360	4,360	1.00
3321-1	3321	Pounds	25,000	25,000	1.00
3331-1	3331	Pounds	7,160	7,160	1.00
3334-1	3334	Pounds	9,280	9,280	1.00
3341-1	3341	Pounds	2,300	2,300	1.00
3341-2	3341	Pounds	1570	1,570	1.00
3341-3	3341	Pounds	442	442	1.00
3341-4	3341	Pounds	918	918	1.00
3353-1	3353	Pounds	8,240	8,240	1.00
3462-1	3462	Pounds	2,500	2,500	1.00
3523-1	3523	\$ sales	9,550	5,800 lbs	--
3531-1	3531	\$ sales	11,570	13 units	--
3711-1	3711	Pounds	16,600	16,600	1.00
3714-1	3714	Pounds	32,100	32,100	1.00
3861-1	3861	Pounds	1,200	1,200	1.00
3861-2	3861	\$ sales	1,104	18 units	--

Adjustment Factors

Review of the waste heat stream energy content data, calculated by multiplying Drexel process data by the production multipliers, indicated that for 12 specific processes the calculated energy content appears to be unreasonably high. Therefore, specific adjustment factors for each of these processes were developed. The adjustment factor and the basis for its value is shown in Table 4.9. For processes 2411-1 and 2874-4, adjustments are necessary to correct the production unit discrepancies between those initially indicated by the Drexel data base and the one actually used. The other processes required

TABLE 4.9 Adjustment Factors

<u>Process Number</u>	<u>Adjustment Factor</u>	<u>Basis for Adjustment</u>
2221-1	.20	Adjustment, waste heat energy = $.70 \times$ purchased fuels 1980
2262-1	.11	Adjustment, waste heat energy = $.70 \times$ purchased fuels 1980
2411-1	.0002	Adjustment, unit of production is in cords instead of pounds
2611-1	.51	Adjustment, waste heat energy = $.70 \times$ purchased fuels
2611-2	.51	Adjustment, waste heat energy = $.70 \times$ purchased fuels
2611-3	.51	Adjustment, waste heat energy = $.70 \times$ purchased fuels
2812-1	.29	Adjustment, waste heat energy = $.70 \times$ purchased fuels
2812-2	.29	Adjustment, waste heat energy = $.70 \times$ purchased fuels
2812-3	.29	Adjustment, waste heat energy = $.70 \times$ purchased fuels
2812-4	.29	Adjustment, waste heat energy = $.70 \times$ purchased fuels
2874-4	.0005	Adjustment, unit of production is in tons instead of pounds
3312-1	.53	Adjustment, waste heat energy = $.70 \times$ purchased fuels

adjustments to more closely relate expected waste heat stream energy content with industry input energy as specified by the 1980 Survey of Manufactures information on purchased fuels. For some industries, the comparison of purchased fuels to waste heat is not a good one because the industry may generate energy from feedstock materials. However, for these 10 industries the developed adjustment factors appear reasonable.

WASTE HEAT STREAM ENERGY CONTENT

The industry energy flow data base as discussed above estimates the annual energy content in specific waste heat streams (gas, water, and steam) and specific input heat streams (process air, water, and steam).

Waste heat stream and energy input stream information was compiled for all 108 industrial processes. Each industrial process contains an average of 15 unit operations and each unit operation often contains more than one energy stream. Table 4.10 illustrates the type of information available from the industry energy flow data base. The header for Table 4.10 includes process number and name. The first four digits of the code relate to the SIC code (for example, 2011 - Meat Packing Plant) and the fifth digit reflects the number of the process addressed. The table header also gives the number of plants classified under the five-digit process code (2580), the expected annual hours of operation (2100), and the annual production (31.7 billion pounds). The table contains the following information:

- o process flow, input or waste
- o type of heat stream, e.g., gas, liquid
- o the temperature of the stream. Temperatures are arranged from lowest to highest within each stream type.
- o energy content of the stream in Btu per unit of product. (The unit of product is given in the header information.)
- o total energy content of each stream in trillions of Btu annually. This number is calculated by multiplying the energy content per unit of product by the annual production rate. (Annual production information is also given in the table header.)

TABLE 4.10 Steam Flow Energy Content Data

SIC number is: 2011-1
 Industry: meat packing plants
 Number of plants: 2580
 Annual hours: 2100
 Annual production: 31.7 billion
 Units of production: pounds

<u>Process</u> <u>Energy Flows</u> <u>Input/Waste</u>	<u>Stream</u>	<u>Temp (F)</u>	<u>Energy Content</u> <u>(Btu/Unit</u> <u>Production)</u>	<u>Total Energy</u> <u>(10¹² Btu/yr)</u>
Input	Gas	250	73.0	2.31
			83.4	2.64
			127.8	4.05
			511.0	16.19
			73.0	2.31
			31.3	0.99
			Total	28.49
	Liquid	140	85.2	2.70
			170.3	5.39
			Total	8.09
Waste	Gas	212	19.5	0.62
			82.4	2.61
			Total	3.23
		220	57.7	1.83
			Total	1.83
		400	123.2	3.90
			Total	3.90
	Liquid	500	38.4	1.22
			590.5	18.70
			Total	19.92
		95	420.5	13.32
			Total	13.32
		120	69.5	2.20
			138.2	4.38
			Total	6.58

- the total energy in the input/output stream(s) for each temperature. Within a particular process, several energy input streams may have the same temperature value. For example, a stream at 250°F may be used in several unit operations. Similarly, several unit operations may exhaust gas at, for example, 500°F.

Waste Heat by Industry

The industry energy flow data base was used to estimate the energy content for each waste heat stream within an industrial process and to total these

values for all gaseous and liquid waste streams with temperatures above 80°F. Table 4.11 estimates the annual waste heat rejected by each of the 108 industrial processes. The total energy content of waste heat streams for all 108 industrial processes is estimated to be 6,670.1 trillion Btu (6.7 quad). The five processes with the highest waste heat stream energy content are Petroleum Refining (1,740.7), Blast Furnaces (898.4), Integrated Paper Board Mills (575.6), Integrated Paper Mills (490.8), and Cement (251.3)(units are 10^{12} Btu).

Waste Heat by Type of Equipment

The terms used in describing various unit operations within the 108 industrial processes are not narrowly defined. For example, Furnaces are classified to include the following unit operations: Autoclave, Blast Furnace, Burner, Distillation Furnace, Electric Furnace, Furnace, Induction Furnace, Kettle Furnace, Kiln, Melting Furnace, Open Hearth Furnace, Recovery Furnace, Reforming Furnace, Reheat Furnace, Rotary Furnace, Smelting Furnace, Sweating Furnace and Others. Given that the description of the unit operation and its related equipment is broadly defined, Table 4.12 estimates the level of waste heat associated with each generic type of equipment. The five generic types of equipment having the largest waste heat energy streams are Furnaces (1,217.4), Distillation Equipment (939.7), Drying Equipment (778.4), Boilers (575.2), and Thermal-Chemical Reactors (486.2)(units are 10^{12} Btu).

TABLE 4.11. Estimate of Waste Heat by Industry

Process Number	Industry	Trillion Btu
SIC 2011-1	Meat Packing	48.8
SIC 2026-1	Fluid Milk	21.4
SIC 2033-1	Canned Fruits	4.7
SIC 2033-2	Canned Vegetables	8.1
SIC 2033-3	Fruit and Vegetable Juices	3.6
SIC 2046-1	Wet Corn Milling	37.2
SIC 2051-1	Bread Baking	4.7
SIC 2051-2	Cakes and Pies Baking	2.4
SIC 2062-1	Cane Sugar Refining	29.2
SIC 2063-1	Beet Sugar Refining	53.2
SIC 2075-1	Soybean Oil Mills	36.2
SIC 2082-1	Malt Beverages	41.9
SIC 2221-1	Weaving Mills, Man-Made Fibers	31.6
SIC 2262-1	Finishing Mills, Man-Made Fibers	23.5
SIC 2411-1	Logging Camps	0.3
SIC 2421-1	Sawmills and Planing Mills	144.7
SIC 2499-1	Wood Products, NEC (Fiberboard)	4.1
SIC 2611-1	Pulp Mills (Sulfate or Kraft)	59.0
SIC 2611-2	Pulp Mills (Sulfite, NSCC)	5.3
SIC 2611-3	Pulp Mills (Mechanical)	0.9
SIC 2621-1	Paper Mills (Finishing)	42.3
SIC 2621-2	Paper Mills (Integrated)	490.8
SIC 2631-1	Paper Board Mills (Finishing)	49.8
SIC 2631-2	Paper Board Mills (Integrated)	575.6
SIC 2653-1	Corrugated, Solid Fiber Boxes	15.4
SIC 2661-1	Building Paper (Finishing)	14.4
SIC 2661-2	Building Paper (Integrated)	30.0
SIC 2812-1	Alkalies and Chlorine (Caustic Soda and Chlorine-Diaphragm Cell)	49.8
SIC 2812-2	Alkalies and Chlorine (Caustic Soda and Chlorine-Mercury Cell)	6.7
SIC 2812-3	Alkalies and Chlorine (Soda Ash-Solvay Process)	5.8
SIC 2812-4	Alkalies and Chlorine (Soda Ash-Trona Process)	7.8
SIC 2813-1	Inorganic Gases (N + O - Air Separation)	19.8
SIC 2813-2	Inorganic Gases (H - Steam Reforming)	36.2
SIC 2813-3	Inorganic Gases (Acetylene - from Natural Gas)	19.0
SIC 2816-1	Inorganic Pigments (TiO - Chloride Process)	2.6
SIC 2816-2	Inorganic Pigments (TiO - Sulfate Process)	14.7
SIC 2816-3	Inorganic Pigments (ZnO - French Process)	1.3
SIC 2816-4	Inorganic Pigments (ZnO - American Process)	3.9
SIC 2816-5	Inorganic Pigments (ZnO - Electro Process)	1.6
SIC 2819-1	Industrial Inorganic Chemicals (Alumina-Bauxite Refining)	84.4
SIC 2819-2	Industrial Inorganic Chemicals (Sulfuric Acid - Contact Process)	2.3

TABLE 4.11. (contd)

Process Number	Industry	Trillion Btu
SIC 2819-3	Industrial Inorganic Chemicals (Phosphorous-Elect Furnace)	6.9
SIC 2819-4	Industrial Inorganic Chemicals (Potash-Flotation Method)	5.6
SIC 2819-5	Industrial Inorganic Chemicals (Sodium Metal - Electrolysis)	1.1
SIC 2821-1	Plastic Materials and Resins (PVC) Suspension	5.8
SIC 2821-2	Plastic Materials and Resins (Polystyrene) Mass	3.2
SIC 2821-3	Plastic Materials and Resins (LDPE)	26.2
SIC 2821-4	Plastic Materials and Resins (HDPE) Slurry Process	3.4
SIC 2821-5	Plastic Materials and Resins (HDPE) Solution Process	3.9
SIC 2822-1	Synthetic Rubbers (SBR)	8.8
SIC 2822-2	Synthetic Rubbers (Butyl)	5.3
SIC 2822-3	Synthetic Rubbers (Polybutadiene)	11.3
SIC 2822-4	Synthetic Rubbers (Polyisoprene)	1.7
SIC 2822-5	Synthetic Rubbers (EP Rubber)	1.8
SIC 2823-1	Cellulosic Man-Made Fibers (Rayon)	20.5
SIC 2823-2	Cellulosic Man-Made Fibers (Acetate)	4.9
SIC 2824-1	Organic Fibers, Non-Cellulosic (Polyester)	56.7
SIC 2824-2	Organic Fibers, Non-Cellulosic (Polypropylene)	48.4
SIC 2824-3	Organic Fibers, Non-Cellulosic (Acrylics)	21.7
SIC 2824-4	Organic Fibers, Non-Cellulosic (Nylon, 6,6)	17.6
SIC 2824-5	Organic Fibers, Non-Cellulosic (Nylon 6)	4.4
SIC 2834-1	Pharmaceutical Preparations	6.1
SIC 2865-1	Cyclic Crudes and Intermediates (Ethylbenzene and Styrene)	97.2
SIC 2865-2	Cyclic Crudes and Intermediates (Cumene and Phenol)	28.1
SIC 2865-3	Cyclic Crudes and Intermediates (Cyclohexane)	6.1
SIC 2869-1	Industrial Organic Chemicals (Ethylene)	198.3
SIC 2869-2	Industrial Organic Chemicals (Methanol)	33.4
SIC 2869-3	Industrial Organic Chemicals (Formaldehyde)	7.4
SIC 2873-1	Nitrogenous Fertilizers (Ammonia-Gas Reforming)	247.2
SIC 2874-1	Phosphatic Fertilizers (Phosphoric Acid-Wet Digestion)	28.3
SIC 2874-2	Phosphatic Fertilizers (Phosphoric Acid-Furnace)	28.6
SIC 2874-3	Phosphatic Fertilizers (TSP-Superphosphates)	3.0
SIC 2874-4	Phosphatic Fertilizers (Ammonium-Phosphates)	2.8

TABLE 4.11. (contd)

Process Number	Industry	Trillion Btu
SIC 2899-1	Chemical Preparations, NEC (Salts)	1.4
SIC 2899-2	Chemical Preparations (Fatty Acids)	1.7
SIC 2911-1	Petroleum Refining	1,740.7
SIC 2951-1	Paving Mixtures and Blocks	7.2
SIC 3011-1	Tires and Inner Tubes	9.3
SIC 3069-1	Fabricated Rubber Products, NEC (Dipped Latex)	9.7
SIC 3069-2	Fabricated Rubber Products, NEC (Molded Latex)	9.6
SIC 3069-3	Fabricated Rubber Products, NEC (Molded Rubber)	10.7
SIC 3079-1	Miscellaneous Plastic Products	35.6
SIC 3211-1	Flat Glass	12.9
SIC 3221-1	Glass Containers	89.2
SIC 3229-1	Pressed and Blown Glass	11.0
SIC 3241-1	Cement, Hydraulic	251.3
SIC 3251-1	Brick and Structural Clay Tile	32.9
SIC 3273-1	Ready Mix Cement	1.2
SIC 3274-1	Lime	3.8
SIC 3275-1	Gypsum Products	27.3
SIC 3296-1	Mineral Wood	18.8
SIC 3312-1	Blast Furnaces and Steel Mills	898.4
SIC 3313-1	Electrometallurgical Products	16.5
SIC 3321-1	Gray Iron Foundries	117.7
SIC 3331-1	Primary Copper	46.5
SIC 3334-1	Primary Aluminum	89.6
SIC 3341-1	Secondary Non-Ferrous Metals (Aluminum)	3.7
SIC 3341-2	Secondary Non-Ferrous Metals (Lead)	0.5
SIC 3341-3	Secondary Non-Ferrous Metals (Zinc)	0.7
SIC 3341-4	Secondary Non-Ferrous Metals (Copper)	1.0
SIC 3353-1	Aluminum Finish Forming	21.8
SIC 3462-1	Iron and Steel Forging	32.8
SIC 3523-1	Farm Machinery and Equipment	30.7
SIC 3531-1	Construction Machinery	32.3
SIC 3711-1	Motor Vehicles and Car Bodies	44.4
SIC 3714-1	Motor Vehicles Parts and Accessories	74.2
SIC 3861-1	Photographic Film	0.5
SIC 3861-2	Photographic Equipment - Fabrication and Assembly	3.5
Total for all 108 processes		6,670.1
(Total may differ from sum of process values due to rounding.)		

TABLE 4.12. Estimate of Waste Heat by
Type of Process Equipment

<u>Type of Equipment</u>	<u>Trillion Btu</u>
Absorption	70.3
Annealing	93.3
Boiler	575.2
Casting, molding	51.8
Centrifuge	1.1
Coking	34.4
Compressor	82.4
Condenser	53.0
Cooking	18.2
Cooling	202.2
Crystallization	6.9
Crushing, grinding	16.0
Cutting, trimming	1.0
Distillation	939.7
Drying	778.4
Electrical generation	358.1
Electrolytic cells	27.0
Extraction	12.7
Extruding	0.8
Flash separator	1.4
Filter	9.1
Furnace	1,217.4
Heat exchanger	85.3
Heating	93.1
Leaching	13.5
Mechanical prime mover	83.8
Mechanical processing	0.8
Mixing	7.8
Ovens	259.5
Packaging	2.4
Pasturizing	8.3
Rolling	157.8
Separation	68.4
Settling	3.0
Storage, holding tank	126.9
Thermal-chemical reactors	486.2
Washing	26.6
Other equipment	696.3
Total	<u>6,670.1</u>

5.0 SUBSTITUTING WASTE HEAT FOR PROCESS HEAT NEEDS

The usefulness (utility) of any energy recovered from waste heat streams depends largely on the immediate energy input needs of the plant or process from which the heat emanates. However, the energy supplied by waste heat recovery technology does not need to match the time of need exactly. Using existing or advanced technology, the energy can be stored.

Recovered waste heat can displace part or all of the energy input needs for specific unit operations within an industrial plant. A broad spectrum of advanced energy recovery technologies exist that could be used in recovering energy from waste heat streams. The various waste heat recovery equipment available, or soon to be available, is discussed in the Task 2 report for this project. Government and industry also are studying advanced waste heat recovery materials, components and systems that could be available in the future.

This analysis of waste heat streams and the recoverable energy is generic in that it is not tied to any particular recovery technology. Looking across industries, the emphasis of this report is on identifying matchups between the energy available in waste heat streams and the thermal energy inputs to process operations. No attempt has been made to evaluate how much energy loss would take place in transferring energy from waste heat sources to energy input uses. This thermodynamic analysis must be done in conjunction with specific heat recovery and transfer technology assessments.

This chapter discusses the selection of the temperature ranges used to assess the applicability of energy recovery. The compilation of energy stream data by temperature range for 3 types of waste heat streams, 40 generic types of process equipment, and 108 industrial processes is presented. Matchup of waste and input heat streams is also addressed.

SELECTION OF TEMPERATURE RANGES

One key factor in assessing the applicability of energy recovery technology is the temperature difference between the waste heat stream and process input stream (the source and sink, respectively). The industrial energy flow

data base associates specific temperatures with energy streams. Waste heat streams can have temperatures from slightly above ambient to over 2000°F. Energy streams at ambient conditions are assumed to have a temperature of 75°F. Researchers involved in assessing the applicability of advanced energy recovery indicated that the full spectrum of waste heat temperatures should be subdivided.

Sixteen temperature ranges were selected for this assessment. The 16 ranges span the temperature spectrum from 80°F to 2300+°F. Table 5.1 identifies the temperatures associated with each range. Temperature ranges at the lower end of this spectrum are relatively small compared to those at the higher temperature end of the spectrum. After the industry energy flow data were evaluated with participants in DOE's Chemical Heat Pump Program, it was agreed that the same temperature ranges for classifying waste heat stream temperatures should also be applied to input stream temperatures.

TABLE 5.1 Waste Heat/Input Energy Temperature Ranges

<u>Temperature Range</u>	<u>Degrees Fahrenheit</u>
1	80 - 119
2	120 - 139
3	140 - 211
4	212 - 249
5	250 - 299
6	300 - 349
7	350 - 399
8	400 - 499
9	500 - 599
10	600 - 799
11	800 - 999
12	1000 - 1199
13	1200 - 1499
14	1500 - 1899
15	1900 - 2299
16	2300+

ENERGY STREAM DATA

In this section, heat stream data by temperature range are presented in three different ways: by type of waste stream (liquid and gaseous streams combined, liquid only, and gaseous only), by generic type of equipment (40 types), and by industrial process (two examples).

Compiled by Type of Waste Stream

The annual energy content for the waste heat streams and for the energy input streams within each of the 16 temperature ranges was compiled for each of the 108 industrial processes. Three classes of streams were compiled: liquid and gaseous waste and input heat streams combined, only liquid waste and input heat streams, and only gaseous waste and input heat streams. The separation of these streams into three classes can be useful for specific technology applications. Table 5.2 summarizes for all 108 processes the estimated energy content of heat streams in each of the 16 temperature ranges. Estimated values in trillions of Btu are shown for all these classes. The waste heat streams are grouped together as are the process input heat streams. As expected, the majority of the liquid waste heat streams are in the three lowest temperature ranges, whereas gaseous waste heat streams span the full temperature range spectrum.

TABLE 5.2 Energy Content of Heat Streams by Temperature Range

Temperature Range F	Waste Heat - Trillion Btu			Input Heat - Trillion Btu		
	Liquid & Gaseous	Liquid	Gaseous	Liquid & Gaseous	Liquid	Gaseous
80-119	2,522.0	2473.1	48.9	29.7	0.0	29.7
120-139	124.7	100.6	24.2	6.1	6.1	0.0
140-211	533.2	337.9	195.3	48.7	48.7	0.0
212-249	562.3	9.5	552.8	53.1	1.4	51.6
250-299	103.5	0.0	103.5	1244.0	0.0	1244.0
300-349	299.4	1.1	298.3	420.8	0.0	420.8
350-399	140.3	0.3	140.0	228.6	23.3	205.3
400-499	597.6	0.0	597.6	592.1	0.0	592.1
500-599	191.5	0.0	191.5	80.8	0.0	80.8
600-799	571.1	0.0	571.1	137.1	0.0	137.1
800-999	269.7	0.0	269.7	81.1	0.0	81.1
1000-1199	119.6	0.0	119.6	119.3	0.0	119.3
1200-1499	327.2	0.0	327.2	65.8	0.0	65.8
1500-1899	115.3	0.0	115.3	124.6	0.0	124.6
1900-2299	192.5	0.0	192.5	0.0	0.0	0.0
2300-+	0.2	0.0	0.2	0.0	0.0	0.0

Compiled by Type of Equipment

The annual energy content of gas, liquid and steam waste heat streams were compiled for 40 types of process equipment. The results of the combined liquid and gaseous waste heat streams are shown in Table 5.3. Distillation (727.8) and chemical reactors (334.6) have very large waste heat streams in the 80-119°F temperature range. Boiler waste stream temperatures center around 400-499°F, whereas furnace waste stream temperatures are more spread out because of the use of combustion preheat in some industries.

Compiled by Process

Table 5.4 provides an example of the data-base information compiled for a single process (2011-1 Meat Packing). In this process, the temperature of the combined liquid and gaseous waste heat streams (column 3) falls into five temperature ranges and process input heat (column 4) falls within two temperature ranges. This pattern is typical of many industrial processes. An industrial process seldom has more than 7 waste heat temperature ranges or more than 3 input heat temperature ranges. The total annual energy content of the liquid and gaseous waste heat streams (column 3) for this process is estimated to be about 50 trillion Btu. Energy input streams to the meat packing process include direct use of electricity and fossil fuels, as well as heated liquids, heated gases and steam. The input energy streams noted in Table 5.4 are only those associated with thermal energy streams--hot liquids, hot gases and steam. Table 5.5 provides another example of waste heat and input heat stream data, this time for industrial process 2611-1, Pulp Mills (Kraft). Similar data were compiled for all 108 industrial processes.

MATCHUP OF WASTE AND INPUT HEAT STREAMS

As mentioned at the beginning of this chapter, the utility of any energy recovered from waste heat streams depends largely on the immediate energy input needs of unit operations within the process. Table 5.4 indicates that industry process 2011-1 contains waste heat streams in 5 temperature categories, 80-119, 120-139, 212-249, 400-499 and 500-599. The energy content of these streams can be used to displace the process input heat needs in the temperature ranges of 140-211 and 250-299. Table 5.6 shows the waste heat (output energy) values for

TABLE 5.3 Waste Heat Energy By Type of Equipment - 10^{12} Btu/Yr

Type of Process Equipment	80- 119°F	120- 139°F	140- 211°F	212- 249°F	250- 299°F	300- 349°F	350- 399°F	400- 499°F	500- 599°F	600- 799°F	800- 999°F	1000- 1199°F	1200- 1499°F	1500- 1899°F	1900- 2299°F	2300- UP°F	TOTAL
Absorption	13.5		55.2	1.59													70.3
Annealing					51.0					1.71	2.50	9.74	13.6	14.7			93.3
Boiler						0.49	0.81	447.3	74.3	51.1	1.13						575.2
Casting, Molding	3.62		10.4	7.69		29.2			0.84								51.8
Centrifuge	0.47	0.02	0.60														1.1
Coking	27.9											6.47					34.4
Compressor	81.9		0.56														82.5
Condenser	50.9	0.21	0.29	1.65													53.0
Cooking			0.16	2.94				5.41					9.65				18.2
Cooling	89.1	54.3	43.5	1.08	0.81	1.85	0.18		17.3			0.04					208.2
Crushing, Grinding	16.0																16.0
Crystallization	6.31		0.58														6.9
Cutting, Trimming	1.01																1.0
Distillation	727.8		0.28	0.30						68.8	142.5						939.7
Drying	158.1		113.8	215.1	13.5	11.2	106.6	57.4	0.16	92.3		10.2					778.4
Electric Generation	185.2	37.1	13.6				0.73	1.25	0.20	119.9	0.09						358.1
Electrolytic Cells												0.06		26.9			27.0
Evaporation	189.2	0.27	119.3	0.48													309.2
Extraction	3.52	8.12										1.08					12.7
Extruding	0.77																0.8
Filter	5.71		1.00								2.37						9.1

TABLE 5.3. (contd)

Type of Process Equipment	80- 119°F	120- 139°F	140- 211°F	212- 249°F	250- 299°F	300- 349°F	350- 399°F	400- 499°F	500- 599°F	600- 799°F	800- 999°F	1000- 1199°F	1200- 1499°F	1500- 1899°F	1900- 2299°F	2300- UP°F	TOTAL
Flash Separator	0.02		0.22	1.14													1.4
Furnace	168.4		12.5		19.4	204.5		13.3	79.2	44.5	49.4	91.7	296.6	64.4	173.7		1,217.4
Heat Exchangers	79.8		4.69	0.23							0.65						85.3
Heating	27.6			2.69	18.8	4.65	4.47	6.05	3.43	17.2	0.89	0.06		7.03		0.20	93.1
Leaching	11.5		1.93						0.03								13.5
Major Mech. Proc.	0.75		0.10														0.8
Misc. Mechanical	7.41	9.00	21.7	5.11				1.84		2.04							47.1
Mixing	0.51	0.31	5.51			1.50											7.8
Ovens		0.26	74.0	33.6	0.01	0.53	24.2	18.0	0.56	77.4	22.2		2.12		6.61		259.5
Packaging	2.28			0.08	0.08												2.4
Pasteurizing			7.17	1.11													8.3
Prime Mover, Mech.	73.1		7.97						2.22	0.54							83.8
Reactors	334.6		22.6	4.31		0.23	3.26	46.0	10.4	4.26	47.9		0.45		12.3		486.2
Rolling	1.02			154.8						1.98							157.8
Separation	64.2		2.03	0.66		1.51											68.4
Settling			2.14									0.25		0.66			3.0
Storage, Holding Tank				126.9													126.9
Stripping	97.3					37.5											134.8
Washing	2.33	15.1	9.18														26.6
Other	90.10		2.29	0.91		6.18		0.97	2.89	89.28			4.76	1.58			199.0
TOTAL	2,522.0	124.7	533.2	562.3	103.5	299.4	140.3	597.6	191.5	534.1	269.7	119.6	327.2	115.3	192.5	0.20	6,670.1

TABLE 5.4. Energy Content of Waste Heat and Input Heat Streams
for Industrial Process 2011-1, Meat Packing

Temperature Range	Temperature (F)	Energy Content in Trillions of Btu (10^{12})					
		Liquid & Gaseous Streams		Liquid Streams		Gaseous Streams	
		Waste Heat	Input Heat	Waste Heat	Input Heat	Waste Heat	Input Heat
1	80-119	13.32	----	13.32	----	----	----
2	120-139	6.58	----	6.58	----	----	----
3	140-211	----	8.09	----	8.09	----	----
4	212-249	5.05	----	----	----	5.05	----
5	250-299	----	28.49	----	----	----	28.49
6	300-349	----	----	----	----	----	----
7	350-399	----	----	----	----	----	----
8	400-499	3.90	----	----	----	----	----
9	500-599	19.92	----	----	----	----	----
10	600-799	----	----	----	----	----	----
11	800-999	----	----	----	----	----	----
12	1000-1199	----	----	----	----	----	----
13	1200-1499	----	----	----	----	----	----
14	1500-1899	----	----	----	----	----	----
15	1900-2299	----	----	----	----	----	----
16	2300 ⁺	----	----	----	----	----	----

TABLE 5.5. Energy Content of Waste Heat and Input Heat Streams
for Industrial Process 2611-1, Pulp Mills (Kraft)

Energy Content in Trillions of Btu (10^{12})							
Temperature Range	Temperature (F)	Liquid & Gaseous Streams		Liquid Streams		Gaseous Streams	
		Waste Heat	Input Heat	Waste Heat	Input Heat	Waste Heat	Input Heat
1	80-119	20.40	----	20.40	----	----	----
2	120-139	----	----	----	----	----	----
3	140-211	----	----	4.46	----	----	----
4	212-249	4.46	----	----	----	17.79	----
5	250-299	17.79	37.32	----	----	----	37.32
6	300-349	----	10.18	----	----	9.60	10.18
7	350-399	9.60	----	----	----	----	----
8	400-499	----	----	----	----	3.15	----
9	500-599	3.15	----	----	----	----	----
10	600-799	----	----	----	----	1.64	----
11	800-999	1.64	----	----	----	1.98	----
12	1000-1199	1.98	----	----	----	----	----
13	1200-1499	----	----	----	----	----	----
14	1500-1899	----	----	----	----	----	----
15	1900-2299	----	----	----	----	----	----
16	2300 ⁺	----	----	----	----	----	----

TABLE 5.6. Liquid and Gaseous Waste Heat Stream Utility Matrix -
Process 2011-1, Meat Packing

INPUT ENERGY REQUIREMENTS - 10^{12} BTU/YR																	
°F	80-119	120-139	140-211	212-249	250-299	300-349	350-399	400-499	500-599	600-799	800-999	1000-1199	1200-1499	1500-1899	1900-2299	2300-UP	OUTPUT ENERGY
80 - 119																	13.3
120 - 139																	6.58
140 - 211																	
212 - 249																	5.05
250 - 299																	
300 - 349																	
350 - 399																	
400 - 499																	3.90
500 - 599																	19.9
600 - 799																	
800 - 999																	
1000 - 1199																	
1200 - 1499																	
1500 - 1899																	
1900 - 2299																	
2300 - UP																	
INPUT ENERGY			8.09		28.5												

OUTPUT ENERGY AVAILABLE - 10^{12} BTU/YR

each of 5 temperature ranges in the right hand column, and the two input heat (input energy) values in the bottom row. In Table 5.6, no attempt has been made to match source (output energy) with sink (input energy) values. In Table 5.7 the output energy for temperature range 80-119°F (13.3×10^{12} Btu) is compared to the need for heat energy in the 140-211°F temperature range (8.09×10^{12} Btu) and the "input energy" value (the lesser of the two) selected for the cell. The 8.09×10^{12} Btu value was placed in the cell because that is the maximum amount of heat required at temperature range 140-211°F by the process. Table 5.8 next compares the 80-119°F output energy value (13.3×10^{12} Btu) to the input energy requirement for the 250-299°F temperature range (28.5×10^{12} Btu). This time the input energy requirements (28.5×10^{12} Btu) exceed the output energy (13.3×10^{12} Btu) and the 13.3 value is placed in the cell. Table 5.9 shows the utility matrix completed for process 2011-1. The 5 output energy temperature ranges intersect the 2 input energy temperature ranges in 10 of the matrices 256 cells. In cells where an output energy and input energy value intersect the smaller of the 2 values is entered.

Table 5.10 presents the utility matrix for Process 2611-1 (Pulp Mills, Kraft). This process contains waste heat streams that fall within 7 temperature ranges, and input heat requirements that fall within 2 temperature ranges. Note that the full amount of the energy value in the output streams for temperature ranges 140-211°F, 300-349°F, 400-499°F, 600-799°F, and 800-999°F is available to both of the input energy temperature ranges. No attempt is made in these utility matrices to prioritize how waste heat should be used.

The utility value is the maximum amount of input heat energy that could be displaced given 100% efficiency in transferring energy from source to sink. (Of course, the laws of thermodynamics prevents this. These values should be adjusted based on the efficiency of the heat recovery equipment being assessed.)

TABLE 5.7. Liquid and Gaseous Waste Heat Stream Utility Matrix -
Process 2011-1 Meat Packing

INPUT ENERGY REQUIREMENTS - 10 ¹² BTU/YR																	
°F	80-119	120-139	140-211	212-249	250-299	300-349	350-399	400-499	500-599	600-799	800-999	1000-1199	1200-1499	1500-1899	1900-2299	2300-UP	OUTPUT ENERGY
80 - 119			8.09														13.3
120 - 139																	6.58
140 - 211																	
212 - 249																	5.05
250 - 299																	
300 - 349																	
350 - 399																	
400 - 499																	3.90
500 - 599																	19.9
600 - 799																	
800 - 999																	
1000 - 1199																	
1200 - 1499																	
1500 - 1899																	
1900 - 2299																	
2300 - UP																	
INPUT ENERGY			8.09		28.5												

OUTPUT ENERGY AVAILABLE - 10^{12} BTU/YR

TABLE 5.8. Liquid and Gaseous Waste Heat Stream Utility Matrix -
Process 2011-1, Meat Packing

		INPUT ENERGY REQUIREMENTS - 10 ¹² BTU/YR																
°F		80-119	120-139	140-211	212-249	250-299	300-349	350-399	400-499	500-599	600-799	800-999	1000-1199	1200-1499	1500-1899	1900-2299	2300-UP	OUTPUT ENERGY
80 - 119				8.09		13.3												13.3
120 - 139																		6.58
140 - 211																		
212 - 249																		5.05
250 - 299																		
300 - 349																		
350 - 399																		
400 - 499																		3.90
500 - 599																		19.9
600 - 799																		
800 - 999																		
1000 - 1199																		
1200 - 1499																		
1500 - 1899																		
1900 - 2299																		
2300 - UP																		
INPUT ENERGY				8.09		28.5												

OUTPUT ENERGY AVAILABLE - 10^{12} BTU/YR

TABLE 5.9. Liquid and Gaseous Waste Heat Stream Utility Matrix -
Process 2011-1, Meat Packing

INPUT ENERGY REQUIREMENTS - 10 ¹² BTU/YR																	
°F	80-119	120-139	140-211	212-249	250-299	300-349	350-399	400-499	500-599	600-799	800-999	1000-1199	1200-1499	1500-1899	1900-2299	2300-UP	OUTPUT ENERGY
80 - 119			8.09		13.3												13.3
120 - 139			6.58		6.58												6.58
140 - 211																	
212 - 249			5.05		5.05												5.05
250 - 299																	
300 - 349																	
350 - 399																	
400 - 499			3.90		3.90												3.90
500 - 599			8.09		19.9												19.9
600 - 799																	
800 - 999																	
1000 - 1199																	
1200 - 1499																	
1500 - 1899																	
1900 - 2299																	
2300 - UP																	
INPUT ENERGY			8.09		28.5												

OUTPUT ENERGY AVAILABLE - 10¹² BTU/YR

TABLE 5.10. Liquid and Gaseous Waste Heat Stream Utility Matrix -
Process 2611-1, Pulp Mills (Kraft)

INPUT ENERGY REQUIREMENTS - 10 ¹² BTU/YR																	
° F	80-119	120-139	140-211	212-249	250-299	300-349	350-399	400-499	500-599	600-799	800-999	1000-1199	1200-1499	1500-1899	1900-2299	2300-UP	OUTPUT ENERGY
80 - 119					20.40	10.18											20.40
120 - 139																	
140 - 211					4.46	4.46											4.46
212 - 249					17.79	10.18											17.79
250 - 299																	
300 - 349					9.60	9.60											9.60
350 - 399																	
400 - 499					3.15	3.15											3.15
500 - 599																	
600 - 799					1.64	1.64											1.64
800 - 999					1.98	1.98											1.98
1000 - 1199																	
1200 - 1499																	
1500 - 1899																	
1900 - 2299																	
2300 - UP																	
INPUT ENRGY					37.32	10.18											

OUTPUT ENERGY AVAILABLE - 10^{12} BTU/YR

6.0 WASTE HEAT RECOVERY OPPORTUNITIES

Chapter 5.0 described the maximum amount of energy (per year) transferable from energy sources to energy uses in each of 108 industrial processes and the method used to determine source/sink matchup values. For individual industry processes, an energy matchup value was tabulated for each source/sink temperature combination and placed in a 256 cell matrix (defined as a utility matrix). This chapter summarizes the data from all 108 industrial processes addressed and indicates the amount of energy in waste heat streams that can be potentially used. Summary tables of source/sink matchups represent opportunities for waste heat recovery applications across the manufacturing sector of the U.S. economy. In Chapter 5.0 the maximum transferable energy determined from source/sink matchups (comparisons) was presented in utility matrices for specific industrial processes. A separate process utility matrix was developed for each of the 108 industrial processes evaluated.

To summarize the Chapter 5.0 utility matrix data across all 108 industrial processes, the individual matrix values for each source/sink temperature combination were added. For example, a review of all 108 utility matrices indicates that 11 of the 108 industrial processes had utility matrix values for the source/sink temperature combination defined by 80 - 119⁰F source and 140 - 211⁰F sink. These 11 industries are shown in Table 6.1. Figure 6.1 shows how these 11 values were summed and entered into the liquid and gaseous heat stream summary table. This process was repeated for all 256 source/sink temperature combinations in the utility matrices.

The summary of the 108 industrial processes for the liquid and gas waste heat streams combined, gas only waste heat streams, and liquid only waste heat streams are shown in Tables 6.2, 6.3 and 6.4, respectively. Remember that in the industry-specific utility matrices in Chapter 5.0 no attempt was made to apportion the output energy among the input energy streams. The objective was to identify the temperature range matchups that offer the largest energy savings potential. The total energy content of an output stream is therefore assumed to be available to any of the input streams. Therefore, it is

TABLE 6.1 Process Utility Matrix Values for Liquid and Gaseous Waste Heat Streams (source/sink temperature combination 80°F to 119°F/ 140°F to 211°F)

<u>Process #</u>	<u>Industry Name</u>	<u>Cell Utility Value (Btu x 10¹²)</u>
2011-1	Meat packing	8.1
2033-1	Canned fruits	0.50
2033-2	Canned vegetables	1.2
2033-3	Fruit and vegetable juices	0.38
2062-1	Cane sugar refining	9.3
2063-1	Beet sugar refining	2.7
2082-1	Malt beverages	13.1
2822-2	Synthetic rubber (Butyl)	0.14
2823-2	Celluloisic man-made fibers (Acetate)	0.12
2899-2	Chemical preparations (fatty acids)	0.010
3861-1	Photographic film	<u>0.014</u>
		35.6

inappropriate to sum the energy content in rows or columns in either the utility matrices of Chapter 5.0 or in the summary tables presented in Tables 6.2, 6.3, and 6.4.

SUMMARY OF SOURCE/SINK MATCHUPS

Within the temperature range region discussed earlier, waste heat streams and candidate use temperature streams were each grouped into 16 temperature ranges. A total of 256 energy source/sink temperature combinations are possible. Table 6.2 presents a summary across all 108 industrial processes of the energy matchups between potential energy available from waste streams and potential utilization from candidate unit operations. The values in Table 6.2 reflect two basic constraints: 1) the energy available in waste heat streams is not transferred between industrial sites nor industrial processes, and 2) only waste heat energy that can be matched to a candidate use is counted.

As discussed earlier, the total energy content of any waste heat stream is available to any candidate use within an industrial process. Until a specific use actually taps an energy source, the energy source is available to any use.

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Process Number	
2011-1	8.1
2033-1	0.5
2033-3	0.38
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Total	35.6

FIGURE 6.1. Development of the Source/Sink Summation Table
(cell values are the lesser of the input & output energy)

TABLE 6.2 Summary of 108 Source/Sink Matchups: Combined Liquid and Gaseous Heat Streams

°F	INPUT ENERGY REQUIREMENTS - 10^{12} BTU/YR															
	80-119	120-139	140-211	212-249	250-299	300-349	350-399	400-499	500-599	600-799	800-999	1000-1199	1200-1499	1500-1899	1900-2299	2300-UP
80 - 119	1.39	2.46	35.6	42.0	517.5	265.3	150.7	553.4	21.0	61.8	81.1	10.9		123.8		
120 - 139	2.30	3.36	14.1	24.1	27.7	46.7	13.3				0.26	0.01		0.26		
140 - 211	0.85	1.91	21.8	18.2	246.5	195.3	79.6	86.1	1.51	7.48	67.2	10.1		75.7		
212 - 249		1.06	9.51	3.81	449.4	246.3	48.1	5.24	1.69	0.30	42.7	1.60		41.3		
250 - 299	6.43	5.01	1.69		8.89	55.0	31.1	18.8			67.1			70.4		
300 - 349	4.55	4.55	0.23		192.9	213.2	19.4	12.8			14.8			14.8		
350 - 399	23.6	5.01	10.4		30.4	12.3	9.66	2.79		12.7						
400 - 499	5.25	5.01	9.21	46.1	228.2	140.6	87.9	193.1	1.85	24.2	32.6	10.1		32.6		
500 - 599		1.06	21.6	5.22	73.9	64.7	34.4	15.0	20.0	2.34	69.4			77.8		
600 - 799		1.06	13.4	6.76	130.7	132.1	54.7	135.8	38.8	11.5	67.1	3.14	0.01	120.3		
800 - 999				0.08	17.3	48.4	23.4	181.5	0.89		31.5	0.65	0.59	32.3		
1000 - 1199			0.73	1.53	8.13	16.8	33.0	56.8	14.5		17.1	10.0		9.8		
1200 - 1499				0.03	4.76	55.0	23.1		60.2		67.1	0.03		123.8		
1500 - 1899												0.14				
1900 - 2299						6.61			62.8							
2300 - UP																

OUTPUT ENERGY AVAILABLE - 10^{12} BTU/YR

TABLE 6.3 Summary of 108 Source/Sink Matchups: All Gas Heat Streams

°F	INPUT ENERGY REQUIREMENTS - 10^{12} BTU/YR															
	80-119	120-139	140-211	212-249	250-299	300-349	350-399	400-499	500-599	600-799	800-999	1000-1199	1200-1499	1500-1899	1900-2299	2300-UP
80 - 119				0.07	5.05	27.0	5.36	0.36	0.08	1.62	2.95	0.76		2.95		
120 - 139				23.8	0.35	23.8						0.01				
140 - 211				1.44	109.3	8.18	0.91	72.1	0.84	0.19		0.02				
212 - 249				2.37	496.6	238.6	46.5	3.80	0.66	0.30	33.6			33.6		
250 - 299	6.43				7.29	53.4	31.1	18.8			67.1			70.4		
300 - 349	4.54				200.0	214.7	19.4	12.7			14.8			14.8		
350 - 399	9.66				27.8	7.91	9.81	2.54		12.7						
400 - 499	5.24			46.1	234.4	145.0	75.6	192.9	2.66	24.2	32.6	5.83	14.9	32.6		
500 - 599				3.78	73.2	70.7	35.0	15.0	19.5	2.34	69.4		2.34	77.8		
600 - 799				6.67	132.3	126.0	53.5	135.8	40.0	11.5	64.1	29.0	0.01	120.3		
800 - 999				0.08	17.3	48.4	23.4	181.5	1.95		31.5	0.65	0.59	31.5		
1000 - 1199				10.3	9.21	27.0	9.75	66.8	14.5		17.1	0.05		9.75		
1200 - 1499				0.04	5.84	55.0	23.1		60.2		67.1	0.04		123.8		
1500 - 1899				0.03								0.16				
1900 - 2299					1.07	6.61			62.80							
2300 - UP																

OUTPUT ENERGY AVAILABLE - 10^{12} BTU/YR

TABLE 6.4 Summary of 108 Source/Sink Matchups: All Liquid Heat Streams

°F	INPUT ENERGY REQUIREMENTS - 10^{12} BTU/YR															
	80-119	120-139	140-211	212-249	250-299	300-349	350-399	400-499	500-599	600-799	800-999	1000-1199	1200-1499	1500-1899	1900-2299	2300-UP
80 - 119		2.46	34.1				23.3									
120 - 139		3.36	14.1													
140 - 211		1.91	21.6				6.64									
212 - 249			1.44													
250 - 299																
300 - 349																
350 - 399																
400 - 499			0.016													
500 - 599																
600 - 799																
800 - 999																
1000 - 1199																
1200 - 1499																
1500 - 1899																
1900 - 2299																
2300 - UP																

OUTPUT ENERGY AVAILABLE - 10^{12} BTU/YR

The energy values in Table 6.2 represent the maximum matchup between energy source/energy sink values, and thus the maximum waste heat recovery opportunity. In total, 142 of the 256 matrix cells in Table 6.2 show energy values. Energy values range from 10 billion Btu per year to 553 trillion Btu per year.

Nearly half (116 of 256) of the cells in Table 6.3 have non-zero energy values. The values range from 10 billion to 496.6 trillion Btu per year. In the liquid only heat stream summation table (Table 6.4), 10 of the 256 cells in the table have non-zero values. The number of cells is low because most of the liquid streams are water, which vaporizes at a relatively low temperature.

HEAT BOOSTING/HEAT EXCHANGER OPPORTUNITIES

Although this task does not address the specific heat recovery technologies currently available, it is important to note the two major classes of heat recovery equipment - temperature boosting equipment and heat exchangers. The second law of thermodynamics states that for two bodies in thermal contact, energy will flow from the higher temperature body to the lower temperature body. Therefore, to transfer energy from lower temperature waste streams to higher temperature input streams, the temperature of the waste energy must be increased.

Table 6.5 shows the diagonal cells from Table 6.2. The source and sink temperature ranges are the same for these cells. For example, the source energy (waste heat) temperature range for the first cell in the diagonal is 80°F to 119°F. That also is the temperature range of the sink energy (input energy).

Table 6.6 shows the set of cells where source/sink temperature combinations require temperature boosting technology, that is, where the source temperature is less than the sink temperature. An example of a temperature boosting technology is the electrically driven heat pump.

Table 6.7 shows the set of cells where source/sink temperature combinations can use heat exchanger heat recovery technology. In this set of source/sink combinations, the source temperature is above the sink temperature.

TABLE 6.5 Summary of 108 Source/Sink Matchups: Liquid and Gaseous Heat Streams Combined

°F	INPUT ENERGY REQUIREMENTS - 10^{12} BTU/YR															
	80-119	120-139	140-211	212-249	250-299	300-349	350-399	400-499	500-599	600-799	800-999	1000-1199	1200-1499	1500-1899	1900-2299	2300-UP
80 - 119	1.39															
120 - 139		3.36														
140 - 211			21.8													
212 - 249				3.81												
250 - 299					8.89											
300 - 349						213.2										
350 - 399							9.66									
400 - 499								193.1								
500 - 599									20.0							
600 - 799										11.5						
800 - 999											31.5					
1000 - 1199												10.0				
1200 - 1499																
1500 - 1899																
1900 - 2299																
2300 - UP																
INPUT ENERGY																

TABLE 6.6 Summary of 108 Source/Sink Matchups: Liquid and Gaseous Heat Streams Combined

•f	INPUT ENERGY REQUIREMENTS - 10^{12} BTU/YR															
	80-119	120-139	140-211	212-249	250-299	300-349	350-399	400-499	500-599	600-799	800-999	1000-1199	1200-1499	1500-1899	1900-2299	2300-UP
80 - 119		2.46	35.6	42.0	517.5	265.3	150.7	553.4	21.0	61.8	81.1	10.9		123.8		
120 - 139			14.1	24.1	27.7	46.7	13.3				0.26	0.01		0.26		
140 - 211				18.2	246.5	195.3	79.6	86.1	1.51	7.48	67.2	10.1		75.7		
212 - 249					449.4	246.3	48.1	5.24	1.69	0.30	42.7	1.60		41.3		
250 - 299						55.0	31.1	18.8			67.1			70.4		
300 - 349							19.4	12.8			14.8			14.8		
350 - 399								2.79		12.7						
400 - 499									1.85	24.2	32.6	10.1		32.6		
500 - 599										2.34	69.4			77.8		
600 - 799											67.1	3.14	0.01	120.3		
800 - 999												0.65	0.59	32.3		
1000 - 1199														9.8		
1200 - 1499														123.8		
1500 - 1899																
1900 - 2299																
2300 - UP																
INPUT ENERGY																

OUTPUT ENERGY AVAILABLE - 10^{12} BTU/YR

TABLE 6.7 Summary of 108 Source/Sink Matchups: Liquid and Gaseous Heat Streams Combined

°F	INPUT ENERGY REQUIREMENTS - 10^{12} BTU/YR															
	80-119	120-139	140-211	212-249	250-299	300-349	350-399	400-499	500-599	600-799	800-999	1000-1199	1200-1499	1500-1899	1900-2299	2300-UP
80 - 119																
120 - 139	2.30															
140 - 211	0.85	1.91														
212 - 249		1.06	9.51													
250 - 299	6.43	5.01	1.69													
300 - 349	4.55	4.55	0.23		192.9											
350 - 399	23.6	5.01	10.4		30.4	12.3										
400 - 499	5.25	5.01	9.21	46.1	228.2	140.6	87.9									
500 - 599		1.06	21.6	5.22	73.9	64.7	34.4	15.0								
600 - 799		1.06	13.4	6.76	130.7	132.1	54.7	135.8	38.8							
800 - 999				0.08	17.3	48.4	23.4	181.5	0.89							
1000 - 1199			0.73	1.53	8.13	16.8	33.0	66.8	14.5		17.1					
1200 - 1499				0.03	4.76	55.0	23.1		60.2		67.1	0.03				
1500 - 1899												0.14				
1900 - 2299						6.61			62.8							
2300 - UP																
INPUT ENERGY																

OUTPUT ENERGY AVAILABLE - 10^{12} BTU/YR

7.0 CHARACTERIZATION OF HIGH-ENERGY SOURCE/SINK COMBINATIONS

In this chapter the specific source/sink temperature combinations (cells) that have the greatest energy content in the summary matrix discussed in Chapter 6.0 are examined more closely. With these cells identified, the specific industry processes contributing to the highest energy cells are specified and the generic types of equipment involved identified.

Identifying the energy content of these source/sink combinations of energy streams can provide important insight to program planners as they evaluate the need and potential market for advanced waste heat recovery technology.

In the preceding section a summary matrix of source/sink values was developed for each of three classes of waste streams. In this section, the source/sink temperature combinations that have the highest energy content are examined from these summary matrices. Table 7.1 identifies the cells that have the largest energy content for each class of heat stream. This table shows the source (output energy) and the sink (input energy) temperature, the cell's source/sink energy, and the cell's energy content ranked (from 1 to 5).

This assessment will now focus on selected high-energy source/sink combinations for each class of waste stream. Two criteria were used in selecting source/sink combinations to be evaluated. The first criterion was the energy content of source/sink temperature combinations. The second involved recognizing the fundamental difference between equipment that transfers heat from a higher temperature source to a lower temperature sink (heat exchangers) and equipment that thermodynamically boosts process stream temperatures (for example, heat pumps). These criteria suggest addressing two high-energy source/sink combinations from each of the three classes of heat streams. The first source/sink combination to be examined has the source (output) temperature lower than the sink (input) temperature. Candidate source/sink combinations that meet these definitions are located above the diagonal running from the top left hand corner to the lower right hand corner of the summary matrix. The second source/sink combination examined has the source stream temperature above the sink temperature (below the diagonal).

TABLE 7.1 Utility Summary Cells with the Highest Energy Values

LIQUID AND GASEOUS HEAT STREAMS COMBINED

CELL RANK	OUTPUT ENERGY TEMPERATURE RANGE	INPUT ENERGY TEMPERATURE RANGE	UTILITY VALUE (10**12 Btu/Yr)
1	80-119 F	400-499 F	553.42
2	80-119 F	250-299 F	524.39
3	212-249 F	250-299 F	449.39
4	80-119 F	300-349 F	265.26
5	140-211 F	250-299 F	246.45

LIQUID HEAT STREAMS ONLY

CELL RANK	OUTPUT ENERGY TEMPERATURE RANGE	INPUT ENERGY TEMPERATURE RANGE	UTILITY VALUE (10**12 Btu/Yr)
1	80-119 F	140-211 F	34.13
2	80-119 F	350-399 F	23.28
3	140-211 F	140-211 F	21.55
4	120-139 F	140-211 F	14.07
5	140-211 F	350-399 F	6.64

GASEOUS HEAT STREAMS ONLY

CELL RANK	OUTPUT ENERGY TEMPERATURE RANGE	INPUT ENERGY TEMPERATURE RANGE	UTILITY VALUE (10**12 Btu/Yr)
1	212-249 F	250-299 F	496.61
2	400-499 F	250-299 F	234.42
3	300-349 F	300-349 F	214.72
4	300-349 F	250-299 F	199.97
5	400-499 F	400-499 F	192.91

COMBINED LIQUID AND GASEOUS HEAT STREAMS

For combined liquid and gaseous heat streams (Table 6.2), the cell with the highest energy content above the diagonal has the source/sink temperature combination of 80 - 119°F/400 - 499°F (553.4 trillion Btu/yr). Industry processes that contribute substantially to this cell's source/sink value are presented in Table 7.2. Table 7.2 shows the contribution that each industrial process makes to the total energy content of the cell (column 4). The industries are ranked in decreasing order of energy contribution. Cumulative contributions, as a percent of the total, are provided in column 5. Petroleum Refining (2911-1) accounts for nearly 80% of the cell's total energy content. The top two industries (Petroleum Refining and Nitrogenous Fertilizer) account for 96.59% of the total energy content. Eleven industries contribute to this cell of the summary matrix.

The types of process equipment that produce waste heat streams in the 80 - 119°F temperature range and process equipment that require input heat streams in the 400 - 499°F temperature range are listed in Table 7.3 for the top two industries (Petroleum Refining and for Nitrogenous Fertilizers). The

TABLE 7.2 Industry Processes Contributing to the (80-119°F Output Stream)/(400-499°F Input Stream) Cell in the Combined Liquid and Gaseous Heat Stream Utility Matrix Summary

PROCESS NUMBER	INDUSTRY PROCESS	ENERGY CONTRIBUTION (10**12 Btu/Yr)	PER CENT OF TOTAL	CUMULATIVE PER CENT
2911-1	PETROLEUM REFINING	441.52	79.78	79.78
2873-1	NITROGENOUS FERTILIZER	93.00	16.80	96.59
2865-1	ETHYLBENZENE AND STYRENE	4.49	0.81	97.40
2821-3	PLASTICS, LDPE	3.91	0.71	98.11
2865-2	CUMENE AND PHENOL	3.39	0.61	98.72
2869-2	METHANOL	2.60	0.47	99.19
2821-5	PLASTICS, HDPE	2.06	0.37	99.56
	OTHER (4)	2.46	0.44	100.00
		553.4		

TABLE 7.3 Major Unit Operations Supplying the Energy Sources and Sinks for the (80-119°F Output Stream)/(400-499°F Input Stream) Cell in the Combined Liquid and Gaseous Heat Stream Utility Matrix

PROCESS		OUTPUT STREAM 80-119 F			INPUT STREAM 400-499 F		
NUMBER	INDUSTRY	UNIT OPERATION	MEDIUM	TEMP	UNIT OPERATION	MEDIUM	TEMP
2911-1	PETROL REFINING	ATMOSPHERIC DIST	WATER	110	ATMOSPHERIC DIST	STEAM	422
		VACUUM DIST	WATER	110	VACUUM DIST	STEAM	422
		DELAYED COKING	WATER	100	DELAYED COKING	STEAM	422
		CAT CRACKING	WATER	100	DIST REFORMING	STEAM	422
		DIST REFORMING	WATER	100	LUBE OIL PROC	STEAM	422
		LUBE OIL PROC	WATER	100	ASPHALT PROC	STEAM	422
		ASPHALT PROC	WATER	100	HYDROTREATING	STEAM	422
		VISBREAKING	WATER	100	ISOMERIZATION	STEAM	422
		HYDROTREATING	WATER	100	ALKYLATION	STEAM	422
		CAT REFORMING	WATER	100	GAS RECOVERY	STEAM	422
		ISOMERIZATION	WATER	100			
		ALKYLATION	WATER	100			
		GAS RECOVERY	WATER	100			
2873-1	NITROGEN FERT.	CO ₂ ABSORPTION	WATER	100	PRIMARY REFORMER	STEAM	475
		METHANATION	WATER	100			
		COMPRESSOR	WATER	100			
		SYNTH CONVERTER	WATER	100			
		CHILLER	WATER	100			

stream medium (in this case water or steam) and the stream temperature are also shown. Thirteen unit operations in Petroleum Refining produce hot waste water at 100 to 110°F. Ten unit operations require steam at 422°F.

Petroleum refineries typically have available large quantities of relatively low-cost by-product fuels. Justifying the expense of equipment to recover low-level waste heat may be more difficult in Petroleum Refining than in many other industries. For this reason, a second source/sink combination from the set of matrix cells above the diagonal is also examined. The source/sink temperature combination 80 - 119°F/250 - 299°F has an energy content of 517.5 trillion Btu/yr. The principal industries contributing to this total are listed in Table 7.4. Although two industry processes, Integrated Paper Mills (2621-2) and Integrated Paper Board Mills (2631-2), account for almost

TABLE 7.4 Industry Processes Contributing to the (80-119°F Output Stream)/(250-299°F Input Stream) Cell in the Combined Liquid and Gaseous Heat Stream Utility Matrix Summary

PROCESS NUMBER	INDUSTRY PROCESS	ENERGY CONTRIBUTION (10**12 Btu/Yr)	PER CENT OF TOTAL	CUMULATIVE PER CENT
2621-2	INTEGRATED PAPER MILLS	166.40	32.16	32.16
2631-2	INTEGRATED PAPER BOARD	140.29	27.11	59.27
2063-1	BEET SUGAR REFINING	25.66	4.96	64.23
2874-1	PHOSPHATIC FERTILIZER	22.08	4.27	68.49
2611-1	KRAFT PULP MILLS	20.40	3.94	72.43
2046-1	WET CORN MILLING	13.80	2.67	75.10
2865-2	CUMENE AND PHENOL	13.53	2.62	77.71
2011-1	MEAT PACKING	13.32	2.57	80.29
2631-1	PAPER BOARD FINISHING	10.15	1.96	82.25
2062-1	CANE SUGAR REFINING	9.59	1.85	84.10
2869-2	METHANOL	8.74	1.69	85.79
2026-1	FLUID MILK	7.88	1.52	87.31
	OTHER (39)	65.66	12.69	100.00
		817.5		

60% of the energy in this cell, 51 industries have source/sink temperature combinations defined by this cell. The unit operations for the top 5 energy contributors to this cell are listed in Table 7.5. The source streams are typically water or water slurries at 82 to 95°F and the sink streams use steam at 250 to 292°F.

The 400 - 499°F/250 - 299°F cell from the liquid and gas stream summary has the highest energy content (228.2 trillion Btu/yr) of those cells with input stream temperatures less than the output stream temperature (below the diagonal from top left to bottom right). The major industry processes that contribute to this cell are listed in Table 7.6. Of the 28 industries that contribute to this source/sink combination, the top 5 account for 53.74% of the cell's total energy content.

TABLE 7.5 Major Unit Operations Supplying the Energy Sources and Sinks for the (80-119°F Output Stream)/(250-299°F Input Stream) Cell in the Combined Liquid and Gaseous Heat Stream Utility Matrix Summary

PROCESS		OUTPUT STREAM 80-119 F			INPUT STREAM 250-299 F		
NUMBER	INDUSTRY	UNIT OPERATION	MEDIUM	TEMP	UNIT OPERATION	MEDIUM	TEMP
2621-2	INTEG PAPER MILL	MULT EVAP	WATER	95	MULT EVAP	STEAM	292
		BLEACHING	PLP&WTR	85	BLEACHING	STEAM	260
		GENERATOR	WATER	95	DRIER	STEAM	250
2631-2	INTEG PAPER BOARD	MULT EVAP	WATER	95	MULT EVAP	STEAM	292
		WASHING	PLP&WTR	90	DRIER	STEAM	250
		DECKER	PLP&WTR	90			
		REFINING	PLP&WTR	95			
2063-1	BEET SUGAR	VACUUM PANS GENERATOR	WATER	95	DIFFUSION	STEAM	250
			WATER	95	JUICE HTR	STEAM	250
					HEATER	STEAM	250
					EVAPORATOR	STEAM	250
					GRAN. DRIER	STEAM	250
					VACUUM PANS	STEAM	280
2874-1	PHOS. FERTILIZER	FILTER	GYP/WTR	82	EVAPORATOR	STEAM	250
		EVAPORATOR	WATER	92			
		GENERATOR	WATER	95			
2611-1	KRAFT PULP MILL	MULT EVAP	WATER	95	MULT EVAP	STEAM	292
		BLEACHING	PLP&WTR	85	BLEACHING	STEAM	260
		WASHING	PLP&WTR	90	DRIER	STEAM	260
		DEWATERING	WATER	90			
		GENERATOR	WATER	95			

The major unit operations that produce waste heat streams in the 400 - 499°F range and the unit operations that require heat streams in the 250 - 299°F range are listed in Table 7.7. Here, the output streams are primarily stack gases and steam and the input streams are steam.

GASEOUS WASTE HEAT STREAMS

A similar analyses is provided using the summary matrix for gaseous only source/sink combinations. The 212 - 249°F/250 - 299°F combination in the

TABLE 7.6 Industry Processes Contributing to the (400-499°F Output Stream)/(250-299°F Input Stream) Cell in the Combined Liquid and Gaseous Heat Stream Utility Matrix

PROCESS NUMBER	INDUSTRY PROCESS	ENERGY CONTRIBUTION (10**12 Btu/Yr)	PER CENT OF TOTAL	CUMULATIVE PER CENT
2421-1	SAW AND PLANING MILLS	39.22	17.22	17.22
2621-2	INTEGRATED PAPER MILLS	27.61	12.10	29.32
2631-2	INTEGRATED PAPER BOARD	26.58	11.64	40.97
2063-1	BEET SUGAR REFINING	16.94	7.42	48.39
2824-2	POLYPROPYLENE	12.21	5.35	53.74
2824-1	POLYESTER	11.25	4.92	58.65
2221-1	PLASTICS, PVC	10.66	4.67	63.33
2631-1	PAPER BOARD FINISHING	10.01	4.39	67.71
2821-3	PLASTICS, LDPE	8.81	3.86	71.57
2621-1	PAPER MILLS, FINISHING	8.01	3.51	75.08
2026-1	FLUID MILK	7.88	3.45	78.53
2262-1	MAN-MADE FIBERS, FIN.	7.52	3.30	81.83
	OTHER (16)	46.50	18.17	100.00
		228.2		

gaseous only matrix has the highest energy content (496.6 trillion Btu/yr). The industrial processes contributing to this cell are listed in Table 7.8. Of the 21 industrial processes contributing to this cell, Integrated Paper Board Mills (2631-2) and Integrated Paper Mills (2621-2) together account for three-quarters of the energy content. The unit operations for the 5 top energy contributing industries are listed in Table 7.9 with corresponding stream medium and stream temperature.

Similarly, the 400 - 499°F/250 - 299°F source/sink combination in the gas only summary matrix has the highest energy content of cells with output stream temperature greater than input stream temperature (234.4 trillion Btu/yr). There are 35 industry processes in our data base with input and output streams having temperatures defined by this cell. The top 14 industrial

TABLE 7.7 Major Unit Operations Supplying the Energy Sources and Sinks for the (400-499°F Output Stream)/(250-299°F Input Stream) Cell in the Combined Liquid and Gaseous Heat Stream Utility Matrix Summary

PROCESS		OUTPUT STREAM 400-499 F			INPUT STREAM 250-299 F		
NUMBER	INDUSTRY	UNIT PROCESS	MEDIUM	TEMP	UNIT PROCESS	MEDIUM	TEMP
2421-1	SAWMILLS	BOILER	STACK	450	DRIER KILN	STEAM	250
2621-2	INTEG PAPER MILL	EVAPORATOR	STEAM	400	MULT EVAP	STEAM	292
		BOILER	STACK	450	BLEACHING	STEAM	260
					DRIER	STEAM	250
2631-2	INTEG PAPER BOARD	EVAPORATOR	STEAM	400	MULT EVAP	STEAM	292
		KILN	STACK	400	DRIER	STEAM	250
		BOILER	STACK	450			
2063-1	BEET SUGAR	KILN DRIER	STACK	400	DIFFUSION	STEAM	250
		LIMING & CARB.	CO2	400	JUICE HTR	STEAM	250
		GENERATOR	STACK	450	HEATER	STEAM	250
					EVAPORATOR	STEAM	250
					GRAN DRIER	STEAM	250
					VACUUM PANS	STEAM	280
2824-2	POLYPROPYLENE	BOILER	STACK	400	MELTING & EXTR.	STEAM	250

processes contributing to this cell account for 85.37% of the total energy content. These industry processes are listed in Table 7.10. The relevant unit operations for the top five industrial processes in Table 7.10 are given in Table 7.11.

LIQUID WASTE HEAT STREAMS

For the liquid only summary matrix, the 80 - 119°F/140 - 211°F source/sink combination has the highest energy content (34.1 trillion Btu/yr). The 11 industrial processes contributing to this cell are listed in Table 7.12 and the relevant unit operations and stream characteristics for the top three industrial processes (accounting for 85% of the cell's energy content) are presented in Table 7.13.

TABLE 7.8 Industry Process Contributing to the (212-249°F Output Stream)/(250-299°F Input Stream) Cell in the Combined Liquid and Gaseous Heat Stream Utility Matrix Summary

PROCESS NUMBER	INDUSTRY PROCESS	ENERGY CONTRIBUTION (10**12 Btu/Yr)	PER CENT OF TOTAL	CUMULATIVE PER CENT
2631-2	INTEGRATED PAPER BOARD	216.30	43.56	43.56
2621-2	INTEGRATED PAPER MILLS	155.80	31.37	74.92
2631-1	FINISHING PAPER BOARD	25.25	5.08	80.01
2621-1	FINISHING PAPER MILLS	23.59	4.75	84.76
2661-2	INTEGRATED BLDG PAPER	18.55	3.74	88.50
2611-1	KRAFT PAPER MILLS	17.79	3.58	92.08
2075-1	SOYBEAN OIL MILLS	11.01	2.22	94.30
2661-1	BLDG PAPER, FINISHING	9.95	2.00	96.30
2011-1	MEAT PACKING PLANT	5.06	1.02	97.32
2816-2	INORGANIC PIGMENTS	4.56	0.92	98.24
	OTHERS (11)	8.74	1.76	100.00
		496.6		

TABLE 7.9 Major Unit Operations Supplying the Energy Sources and Sinks for the (212-249°F Output Stream)/(250-299°F Input Stream) Cell in the Gas Waste Heat Stream Utility Matrix Summary

PROCESS		OUTPUT STREAM 212-249 F			INPUT STREAM 250-299 F		
NUMBER	INDUSTRY	UNIT OPERATION	MEDIUM	TEMP	UNIT OPERATION	MEDIUM	TEMP
2631-2	INTEG. PAPER BOARD	BLOW TANK	STEAM	220	MULT EVAP	STEAM	292
		DRIER	EXHAUST	240	DRIER	STEAM	250
2621-2	INTEG. PAPER MILLS	BLOW TANK	STEAM	220	MULT EVAP	STEAM	292
		DRIER	EXHAUST	240	BLEACHING	STEAM	260
					DRIER	STEAM	250
2631-1	FIN. PAPER BOARD	DRIER	EXHAUST	240	DRIER	STEAM	250
2621-1	FIN. PAPER MILLS	DRIER	EXHAUST	240	DRIER	STEAM	250
2661-2	INTEG BLDG PAPER	DRIER	EXHAUST	240	DRIER	STEAM	250

TABLE 7.10 Industry Processes Contributing to the (400-499°F Output Stream)/(250-299°F Input Stream) Cell in the Combined Liquid and Gaseous Heat Stream Utility Matrix Summary

PROCESS NUMBER	INDUSTRY PROCESS	ENERGY CONTRIBUTION (10**12 Btu/Yr)	PER CENT OF TOTAL	CUMULATIVE PER CENT
2421-1	SAW & PLANING MILLS	39.222	16.73	16.73
2621-2	INTEG. PAPER MILLS	27.606	11.78	28.51
2631-2	INTEG. PAPERBOARD	26.578	11.34	39.85
2063-1	BEET SUGAR REFINING	16.942	7.23	47.07
2824-2	POLYPROPYLENE	12.209	5.21	52.28
2824-1	POLYESTER	11.245	4.80	57.08
2221-1	WEAVING MILLS	10.661	4.55	61.63
2631-1	FINISHING PAPERBOARD	10.011	4.27	65.90
2821-3	PLASTICS, LDPE	8.808	3.76	69.65
2621-1	FINISHING PAPER MILLS	8.010	3.42	73.07
2026-1	FLUID MILK	7.878	3.36	76.43
2262-1	MAN-MADE FIBERS, FIN.	7.521	3.21	79.64
2062-1	CANE SUGAR REFINING	6.815	2.91	82.55
2661-2	BUILDING PAPER, INTEG.	6.615	2.82	85.37
	OTHER (21)	34.285	14.63	100.00
		234.4		

The 140 - 211°F/140 - 211°F cell of the liquid only summary matrix has the highest energy content (21.6 trillion Btu/yr) of those cells with output stream temperatures greater than or equal to input stream temperatures. The 8 industrial processes contributing to this cell are listed in Table 7.14. The relevant unit operations, stream mediums and stream temperatures are given for the top 3 industries in Table 7.15.

TABLE 7.11 Major Unit Operations Supplying the Energy Sources and Sinks for the (400-499°F Output Stream)/(250-299°F Input Stream) Cell in the Gaseous Waste Heat Stream Utility Matrix Summary

PROCESS		OUTPUT STREAM 400-499 F			INPUT STREAM 250-299 F		
NUMBER	INDUSTRY	UNIT OPERATION	MEDIUM	TEMP	UNIT OPERATION	MEDIUM	TEMP
2421-2	SAWMILLS	BOILER	STACK	450	DRYING KILN	STEAM	250
2621-2	INTEG PAPER MILLS	BOILER	STACK	450	MULT EVAP	STEAM	292
					BLEACHING	STEAM	250
					DRIER	STEAM	250
2631-2	INTEG PAPER BOARD	BOILER	STACK	450	MULT EVAP	STEAM	292
					DRIER	STEAM	250
2063-1	BEET SUGAR	KILN DRIER	STACK	400	DIFFUSION	STEAM	250
		LIMING & CARB.	CO2	400	JUICE HTR	STEAM	250
		GENERATOR	STACK	450	HEATER	STEAM	250
					EVAPORATOR	STEAM	250
					GRAN. DRIER	STEAM	250
					VACUUM PANS	STEAM	280
2824-2	POLYPROPYLENE	BOILER	STACK	400	MELTING & EXTR	STEAM	250

TABLE 7.12 Industry Processes Contributing to the (80-119°F Output Stream)/(140-211°F Input Stream) Cell in the Liquid Heat Stream Utility Matrix Summary

PROCESS NUMBER	INDUSTRY PROCESS	ENERGY CONTRIBUTION (10**12 Btu/Yr)	PER CENT OF TOTAL	CUMULATIVE PER CENT
2082-1	MALT BEVERAGES	11.617	34.04	34.04
2062-1	CANE SUGAR PROCESSING	9.331	27.34	61.38
2011-1	MEAT PACKING PLANT	8.093	23.71	85.09
2063-1	BEET SUGAR	2.700	7.91	93.00
2033-2	CANNED VEGETABLES	1.239	3.63	96.63
2033-1	CANNED FRUITS	0.498	1.46	98.09
2033-3	CANNED DRINKS	0.337	1.10	99.19
2822-2	BUTYL	0.129	0.38	99.57
2823-2	POLYBUTADIENE	0.115	0.34	99.91
3861-1	PHOTOGRAPHIC FILM	0.019	0.06	99.97
2899-2	FATTY ACIDS	0.010	0.03	100.00
		34.1		

TABLE 7.13 Major Unit Operations Supplying the Energy Sources and Sinks for the (80-119°F Output Stream)/(140-211°F Input Stream) Cell in the Liquid Waste Heat Stream Utility Matrix Summary

PROCESS		OUTPUT STREAM 80-140 F			INPUT STREAM 140-211 F		
NUMBER	INDUSTRY	UNIT OPERATION	MEDIUM	TEMP	UNIT OPERATION	MEDIUM	TEMP
2082-1	MALT BEVERAGES	COMPRESSOR	WATER	95	COOKER	WATER	180
		GENERATOR	WATER	95	FILTER TUB	WATER	165
		CHILLER	WATER	95	PASTEURIZATION	WATER	160
					CONTAINER WASH	WATER	180
2062-1	CANE SUGAR	CHARCOAL WASHER	WATER	95	MINGLER	WATER	145
		EVAPORTOR	WATER	95	CENTRIFUGE		
		VACUUM PANS	WATER	95	FILTER	WATER	165
		LIQ SUGAR PROC.	WATER	95	MELTER	WATER	195
		GENERATOR	WATER	95			
2011-1	MEAT PACKING	EVISCKERATION	WATER	120	EVISCKERATION	WATER	140
		VISCERA HANDLING	WATER	120	VISCERA HANDLING	WATER	140

TABLE 7.14 Industry Processes Contributing to the (140-211°F Output Stream)/(140-211°F Input Stream) Cell in the Liquid Heat Stream Utility Matrix Summary

PROCESS NUMBER	INDUSTRY PROCESS	ENERGY CONTRIBUTION (10**12 Btu/Yr)	PER CENT OF TOTAL	CUMULATIVE PER CENT
2062-1	CANE SUGAR	9.331	43.29	43.29
2082-1	MALT BEVERAGES	7.484	34.72	78.01
2824-3	ACRYLICS	2.328	10.80	88.81
2063-1	BEET SUGAR	0.978	4.54	93.35
2823-1	RAYON	0.596	2.77	96.12
2823-2	POLYBUTADIENE	0.376	1.74	97.86
2822-2	BUTYL	0.303	1.41	99.27
2033-2	CANNED VEGETABLES	0.158	0.73	100.00
		21.6		

TABLE 7.15 Major Unit Operations Supplying the Energy Sources and Sinks for the (140-211°F Output Stream)/(140-211°F Input Stream) Cell in the Liquid Waste Heat Stream Utility Matrix Summary

PROCESS		OUTPUT STREAM 140-211 F			INPUT STREAM 140-211 F		
NUMBER	INDUSTRY	UNIT OPERATION	MEDIUM	TEMP	UNIT OPERATION	MEDIUM	TEMP
2062-1	CANE SUGAR	CENTRIFUGE	WATER	145	MINGLER	WATER	145
		EVAPORATOR	COND VAP	170	CENTRIFUGE	WATER	145
		VACUUM PANS	COND VAP	200	FILTER	WATER	165
		MIXER/CENTRIFUGE	WATER	140	MELTER	WATER	195
2082-1	MALT BEVERAGES	CONTAINER WASH	WATER	145	COOKER	WATER	180
		PASTEURIZATION	WATER	150	FILTER TUB	WATER	165
					PASTEURIZATION	WATER	160
					CONTAINER WASH	WATER	180
2824-3	ACRYLICS	HEATED CHAMBER	WATER	160	HEATED CHAMBER	WATER	180
		GENERATOR	WATER	140			

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APPENDICES A - F

APPENDICES

Appendices A through F describe the manufacturing processes, heat-transfer operations, and waste heat characteristics of 35 processes in 6 industrial categories: 1) chemicals, 2) petroleum, 3) primary metals, 4) pulp and paper, 5) stone, clay and glass, and 6) textiles. These 6 industries account for almost 80% of the total energy used by the manufacturing sector.

This information was gathered through an extensive survey of the literature. In general, qualitative process descriptions are readily available in the literature. Much less information is reported on the location and characteristics of sources of waste heat. Almost no information on the quantity of waste heat by process is presented in this literature.

APPENDIX A
CHEMICALS - SIC 28

APPENDIX A
CHEMICALS - SIC 28

The chemicals industry encompasses the manufacture of thousands of organic and inorganic chemicals by a variety of processes. Four product groups consume more than 90% of the total energy used by the chemicals industry: 1) industrial inorganics, 2) plastics and synthetics, 3) industrial organics, and 4) agricultural chemicals. The chemicals industry is the largest user of energy in the manufacturing sector, accounting for 24.5% of total energy use.

This section provides a discussion of the manufacturing processes, heat-transfer operations, and waste heat streams for the industries listed below:

SIC

2812	Alkalies and Chlorine <ul style="list-style-type: none">● chlorine● caustic soda● soda ash
2813	Industrial Gases <ul style="list-style-type: none">● oxygen● nitrogen
2819	Other Industrial Inorganics <ul style="list-style-type: none">● sulfuric acid● elemental phosphorus● phosphoric acid
2821	Plastics Materials and Resins <ul style="list-style-type: none">● low-density polyethylene● high-density polyethylene● polyvinyl chloride● polystyrene
2824	Organic Fibers <ul style="list-style-type: none">● polyester● nylon● acrylic
2865	Cyclic Crudes and Intermediates <ul style="list-style-type: none">● styrene● phenol
2869	Aliphatic Organic Chemicals <ul style="list-style-type: none">● ethylene
2873	Nitrogenous Fertilizers <ul style="list-style-type: none">● ammonia

ALKALIES AND CHLORINE - SIC 2812

The chemicals in this classification include chlorine, caustic soda (NaOH), caustic potash (KOH), soda ash (Na₂CO₃), and other miscellaneous alkalies. Chlorine and caustic soda account for most of the production and most of the energy use. Soda ash ranks third in production volume and energy use.

Process Descriptions

Alkalies and chlorine are manufactured from common salt and trona ore (Na₂CO₃ · NaHCO₃). Chlor-alkali plants range in capacity from about 2000 tons/year for plants captive to the paper industry to over two million tons/year. The typical size of a commercial chlor-alkali plant is about 150,000 tons/year (UTC 1980). The five plants that produce natural soda ash range in capacity from 1000 to 2500 thousand short tons per year (BuMines 1980). The manufacturing steps used to produce chlorine, caustic soda and soda ash are described below.

Chlorine and Caustic Soda

Chlorine and caustic soda are primarily manufactured by the electrolysis of a salt brine solution. Most chlorine and caustic soda is produced using diaphragm cells as shown in Figure A.1. Mercury cells, which accounted for about 25% of the production prior to 1976, are being phased out due to environmental problems (Latour 1981).

The salt in underground deposits is mined by pumping water into the cavity and forcing saturated brine to the surface. Steam is used to preheat the brine, and soda ash and caustic soda are added to precipitate calcium and magnesium, respectively. The purified, filtered brine is further heated to 175 to 200°F by direct steam injection.

In the cell, the application of a direct current dissociates salt and water according to the following reaction:

FIGURE A.1. Chlorine and Caustic Soda Flow Diagram
(Adapted from Sittig 1977)

Chlorine gas is drawn from the top of the cells through a heat exchanger and a drying tower. Chlorine flows countercurrent to strong sulfuric acid in the drying tower, which strips the water from the chlorine product. The chlorine may then be compressed for storage as a gas at 30 to 100 psig or liquified.

By-product hydrogen is drawn off at the cathode, cooled and compressed. The dilute cell liquor overflows to the caustic evaporation process. The cell liquor is concentrated in multiple-effect evaporators from a concentration of about 10 to 50%. Most of the caustic is sold in this form. Some caustic is further concentrated to a 70 to 75% solution in a single-effect evaporator or to anhydrous caustic in evaporators using molten salt or oils as a heat-transfer medium.

Soda Ash

Soda ash is manufactured by two common processes: the Solvay (or synthetic process) and the Trona process. Because of the abundance of natural soda ash in the United States, the Trona process is the most common. Because few Solvay plants are in operation, only the Trona process will be discussed.

Figure A.2 shows the major steps in the Trona process. Crushed trona is calcined in a rotary kiln at 320 to 390°F to drive off carbon dioxide and water as follows:

The calcined ore is then dissolved in water, insolubles are removed, and the solution is filtered and treated with activated carbon to remove impurities. The resulting liquid is concentrated in triple-effect evaporators and sodium carbonate monohydrate ($\text{Na}_2\text{CO}_3 \cdot \text{H}_2\text{O}$) precipitates. The crystals are separated by centrifugation and calcined to remove the water of crystallization. The product is then cooled and screened prior to shipping.

Natural gas is the principal fuel for calcining soda ash. Most natural soda ash facilities have the multiple fuel capabilities of natural gas, fuel oil, and coal (BuMines 1980).

FIGURE A.2. Soda Ash Flow Diagram
(Adapted from Kirk-Othmer)

Heat-Transfer Operations

The major heat-transfer operations in chlorine/caustic and soda ash production are listed in Table A.1. Non-contact operations are those in which the heat-transfer fluid and the medium being heated or cooled are kept separate by a heat-transfer surface. In direct-contact operations, the heat-transfer fluid and the media being heated or cooled come into contact.

Steam is generated by burning fossil fuels, primarily natural gas and coal. It is expected that the industry will shift increasingly to the use of coal as the availability of natural gas diminishes and the price increases. About 80% of the steam is used for caustic evaporation in a triple-effect evaporator. About 7500 lbs/electrochemical unit^(a) is used in the evaporators at about 90 psi (UTC 1980). The first two stages operate at about 140°F

(a) Electrochemical unit (E.C.U.) is one ton of chlorine plus 1.12 tons of caustic in a 50% solution.

TABLE A.1. Heat-Transfer Operations in Chlorine/
Caustic and Soda Ash Production

<u>CHLORINE/CAUSTIC</u>	<u>Type of Heat Transfer</u>	<u>Heat-Transfer Medium</u>
o Steam Generation	non contact	combustion gases
o Brine Heating	direct contact	steam
o Caustic Evaporating	non contact	steam
o Chlorine Cooling	direct contact	water
o Hydrogen Cooling	direct contact	water
<u>SODA ASH</u>		
o Trona Calcining	direct contact	combustion gases
o Evaporation	non contact	steam
o Monohydrate Calcining	non contact	steam
o Product Cooling	direct contact	air

and 200°F. The third stage generally operates above 300°F. Typically, all of the process steam is introduced in the third stage and the steam evaporated from the caustic soda solution provides the process heat for the first two stages. About 1900 lbs/E.C.U. of low-pressure steam is used for brine heating by direct injection.

Chlorine and hydrogen are cooled by direct contact with water. Natural gas is the principal fuel for calcining trona, although most plants now have multiple fuel capability. Calcination takes place in rotary kilns or vertical kilns. Steam is often used to dehydrate the monohydrate in rotary dryers. The dryers utilize finned tubes to enhance heat transfer. The product is air cooled.

Waste Heat Streams

The major sources of waste heat in chlorine and caustic production are listed in Table A.2. The largest source of waste heat is the water vapor evaporated from the cell liquor in the triple-effect evaporators. About 4700 pounds of water vapor are discharged from the evaporators per ton of chlorine produced at about 1.7 psia and 40°F above ambient (Latour 1981).

TABLE A.2. Waste Heat Rejected from Chlorine and Caustic Production (Sittig 1977)

	<u>Temperature (°F)</u>	<u>Heat Rejected (Btu/lb)</u>
Diaphragm Cell:		
• Radiation and Convection	---	1100 ^(a)
• H ₂ By-Product Cooling	190	20 ^(a)
• Chlorine Cooling	190	100 ^(a)
Caustic Evaporators:		
• Radiation and Convection		50 ^(b)
• Water Vapor	120	2250 ^(b)
• Caustic Cooling	180	200 ^(b)

(a) Heat rejected per pound of chlorine

(b) Heat rejected per pound of caustic soda as 100% caustic soda

Cooling water is used to cool process liquids and vapors. Much of this cooling occurs by direct contact with the process stream. Thus, the discharged cooling waters may be contaminated. Table A.3 lists the cooling water sources, temperatures, flow rates, heat content, and composition for a representative 1.5 million pound/day chlorine plant.

The major energy users in the production of soda ash is the calcination of raw trona, evaporation, and product drying. Table A.4 provides a heat balance for the ore kiln and the rotary monohydrate dryer. Table A.5 identifies the waste heat sources, temperatures, and quantities for the trona process. The only liquid waste stream is the condensate from the evaporator. This stream rejects about 156,000 Btu per ton of soda ash (Latour 1981).

INDUSTRIAL GASES - SIC 2813

The production of oxygen and nitrogen accounts for almost 70% of the production of industrial gases and uses almost 60% of the total energy consumed by the industrial gas industry. The production methods, heat-transfer operations, and waste heat streams associated with these chemicals are discussed below.

Process Description

Oxygen and nitrogen are manufactured by the cryogenic air separation process shown in Figure A.3. High-pressure cycles that were commonly used in the 1950s are becoming obsolete and are being replaced by the slightly less energy-efficient and less costly low-pressure plants. The following descriptions will refer to the low-pressure cycle. Equipment required for air separation is classified as that which operates at room temperature and that which operates below room temperature, as shown in Table A.6.

The air is first filtered to remove impurities. Then the air is compressed to approximately 75-85 psi in a centrifugal compressor and is after-cooled. Any liquid water is extracted before the air is sent to a reversing heat exchanger where it is cooled almost to its dew-point temperature. As the air is cooled, first moisture and then carbon dioxide condenses and freezes on

TABLE A.3 Sample Chlorine/Caustic Plant Waste Heat Stream Summary (Schmidt 1978)

Source	Throughput (lb/day)	Flow (10 ³ lb/hr)	Temperature Input (°F)	Composition	Phase/* Disposition	Heat Content (10 ⁷ Btu/Day)	Specific Energy (Btu/lb)
Chlorine/Caustic Plant	1,534,246					426.8	2,782
• Brine heat exchanger		1,152	180/122	25% salt	L/CW	(262.1)	
• Primary hydrogen coolers		3	230/105	Moist H ₂	V/CW	(10.6)	
• Hydrogen compressors		1		Moist H ₂	V/CW	(4.3)	
• Primary chlorine coolers		47	175/100	wet Cl ₂	V/CW	(15.6)	
• Chlorine compressor oil coolers			150/	oil	L/CW	(1.7)	
• Dechlorinating flash tank		2	180/125	Cl ₂ ,air,H ₂ O	V/CW	(11.5)	
• Chlorine liquefaction condensers			105/100		L-V/CW	(41.4)	
• Chlorine liquid freon compressors					CW	(1.5)	
• Caustic coolers		90	230/110	50% caustic	L/CW	(19.9)	
• Sodium hypochlorite cooler		40	150/140		L/CW	(5.1)	
• Compressant intercooler		2	220/110	Cl ₂	V/CW	(6.0)	
• Diamond freon compressors		29	235/105	MW 865	CW	(1.2)	
• Diamond snift compressors		16	250/230	dry Cl ₂	V/CW	(1.2)	
• Diamond freon condensers			230/105		L-V/CW	(12.0)	
• Water chillers		960		H ₂ O	L/CW	(33.31)	

*L = Liquid, V = Vapor, CW = Cooling Water.

TABLE A.4. Heat Balance for Kiln and Rotary Dryer (Sittig 1977)

	<u>Btu/lb</u>	<u>Btu/lb</u>
<u>Lime Kiln</u>		
Energy Input	--	1090
<u>Energy Rejected</u>		
• Radiation and Convection	100	--
• Stack Gases (500 ^o F)	210	--
• Hot Lime (400 ^o F)	50	--
	<u>360</u>	--
Heat of Reaction	730	
	<u>1090</u>	<u>1090</u>
Process Efficiency = 67%		
<u>Rotary Dryer</u>		
Energy Input	--	1050
<u>Energy Rejected</u>		
• Radiation and Convection	50	--
• Hot Soda Ash (400 ^o F)	100	--
• Stack Gases (400 ^o F)	400	--
	<u>550</u>	--
Heat of Reaction	500	
	<u>1050</u>	<u>1050</u>
Process Efficiency = 48%		

TABLE A.5. Sources, Quantities and Temperatures of Waste Heat (Latour 1981)

<u>Source</u>	<u>Type</u>	<u>Temperature (^oF)</u>	<u>Ft³/Ton</u>
Trona Calcination	Flue Gas	405	150,000
Boiler	Stack Gas	370	155,000
Monohydrate Drying	Air & Water Vapor	185	35,900
Soda Ash Cooling	Radiant Heat	300	--

FIGURE A.3 Oxygen and Nitrogen Production
(Sittig 1977)

the walls of the heat exchanger. The air exits the reversing heat exchanger completely dry and with 99% of the carbon dioxide removed (Shen 1980). Fixed-bed absorption is used to remove any remaining carbon dioxide and any hydrocarbons from the air stream.

TABLE A.6. Classification of Air Separation Equipment
(Shen 1980)

Room Temperature:	Compressors Inter-Coolers After-Coolers Oil Separators Water Separators
Below Room Temperature:	Heat Exchangers Cleanup Equipment Expanders Distillation Columns

The air is then fed to the bottom tray of a double-column rectifier. The double-column rectifier is composed of two tray distillation columns that are connected by a heat exchanger as shown in Figure A.4. The heat exchanger is the condenser for the lower column and the reboiler for the upper column. Nitrogen is more volatile than oxygen; thus it ascends the column and oxygen descends. The nitrogen stream is divided as it leaves the condenser/reboiler. A portion of the stream returns to the lower column as reflux and the other is routed to the upper column, through the nitrogen superheater, to serve as reflux in the upper column. The liquefied oxygen stream exiting the lower column is cooled in the nitrogen superheater and becomes the feed for the upper column. The oxygen product is drawn off as a saturated vapor from the top of the upper column. The low-purity waste stream is removed several trays from the top of the column.

Compression is the most energy-intensive step in the production of these industrial gases. Compressors are operated with electricity. Table A.7 summarizes the total energy requirements for producing oxygen and nitrogen.

Oxygen plants range in capacity from 10 tons/day up to 6000 tons/day. The larger plants contain several modules since the technical limit on the capacity of a single module is 2000 tons/day. The average capacity is about 780 tons/day (Palmer 1980).

FIGURE A.4 Double-Column Rectifier
(Shen 1980)

Heat-Transfer Operations

The major heat-transfer operations in industrial gas production are compressor cooling, distillation (condensing and reboiling), oxygen and nitrogen superheating, and air precooling/product heating. The heating and cooling media for each of these heat-transfer operations are listed in Table A.8. Whenever possible, process streams are used to effect heat exchange to save energy.

Reversing heat exchangers are used for air precooling and product heating. These heat exchangers are a sort of combination recuperator and

TABLE A.7. Energy Used to Produce Oxygen and Nitrogen
(Shen 1980)

<u>Process, Product</u>	<u>kWhe/ton</u>
Separation	
Oxygen gas ^(a)	278
Nitrogen gas ^(a)	60
Liquefaction	
Liquid oxygen	525
Liquid nitrogen	582
Separation plus liquefaction ^(b)	
Liquid oxygen	800
Liquid nitrogen	640
Separation plus pressurization	
Oxygen gas at 425 psig	395
Nitrogen gas at 200 psig	163

(a) at 70°F and 14.7 psia

(b) totals not exact due to rounding

TABLE A.8. Heat-Transfer Media in Air Separation Plants

<u>Operation</u>	<u>Heating Medium</u>	<u>Cooling Medium</u>
Compressor Cooling	Waste Heat	Cooling Water
Distillation (Condenser/ Reboiler)	Nitrogen	Oxygen
Air Precooling/Product Heating	Air	Product Oxygen and Nitrogen
Nitrogen Superheating	Oxygen	Nitrogen
Oxygen Superheating	Air	Oxygen

regenerator. The air and the product streams flow countercurrent to each other. The product nitrogen and oxygen flow in separate, nonreversing passages, while the waste nitrogen flows through passages that periodically reverse with the air passages. Extended surfaces are typically used to enhance the heat transfer (Shen 1980).

Heat exchangers are generally compact plate-and-fin exchangers constructed of brazed aluminum. Distillation trays may be either perforated or bubble cap. Construction materials for distillation trays and heat exchangers include aluminum, stainless steel, copper, and copper alloys. Equipment operating below room temperature is assembled in one or more "cold boxes" which are heavily insulated (Shen 1980).

Waste Heat Streams

The only significant source of waste heat from air separation facilities is that rejected by the compressors. It is estimated that about 571,500 Btu/ton of oxygen produced is rejected as hot air at about 250°F (Latour 1981). If cooling water is used as the sink for the waste heat, it is estimated that about 2200 gallons of cooling water would be discharged per ton of oxygen produced at a temperature about 30°F above ambient (Latour, 1981). It is estimated that the compressor cooling water waste stream for a 2000 ton/day oxygen plant is at temperatures between 100 and 120°F and a flow rate of about 700,000 lb/hr (Palmer 1980). Another source estimates that an average of 460 Btu are rejected as waste heat from compressors per pound of oxygen produced (Sittig 1977).

OTHER INDUSTRIAL INORGANICS - SIC 2819

This product category encompasses a large number of inorganic chemicals. One of these, sulfuric acid, is produced in the largest quantity of any chemical in the chemical industry. In this category others that are discussed in this section are elemental phosphorus and phosphoric acid.

Process Description

The processes grouped in this classification are highly varied; thus, similarities in operation between the production of the various chemicals is uncommon. The manufacturing processes for sulfuric acid, phosphorus and phosphoric acid are described in this section.

Sulfuric Acid

The most common method used to manufacture sulfuric acid is the contact process shown in Figure A.5. In this process, atomized sulfur is fed to the

FIGURE A.5 Sulfuric Acid Production Process
(Battelle 1976)

burner along with predried air. In the burner, the sulfur is converted to sulfur dioxide. The exothermic reaction gives off a large quantity of heat. The heat is recovered in waste heat boilers to produce steam for other plant

operations. The cooled gases from the waste heat boilers flow countercurrent to a stream of concentrated sulfuric acid in a tower for purification and drying. The dried and purified gas stream, which consists of sulfur dioxide, oxygen, and nitrogen, passes through a multi-stage, catalytic converter that oxidizes the sulfur dioxide to sulfur trioxide. The catalytic conversion is also an exothermic reaction. Following conversion, the sulfur trioxide is absorbed in 93% sulfuric acid recirculating from the gas purification tower to produce concentrated sulfuric acid. Part of the concentrated sulfuric acid product is recycled to the gas purification tower as needed.

Elemental Phosphorus

Elemental phosphorus is produced exclusively in the U.S. by the electric fusion of phosphate rock, as shown in Figure A.6. Phosphate rock is passed through a rotary kiln or traveling grate at 1400 to 1600°F to form spherical nodules that are between one and five centimeters in diameter. Most of the phosphate rock requires little beneficiation because silica, which is the major impurity, is required for efficient furnace operation. Coke and additional silica are dried, screened and fed to the furnace. When the feed reaches its fusion temperature, the calcium in the phosphate rock reacts with the silica, forming a calcium silicate slag. The carbon from the coke acts as a reducing agent to form phosphorus vapor and carbon monoxide from the P_2O_5 , which is released from the phosphate rock. Iron impurities in the feed react with some of the phosphorus to form molten ferrophosphorus. The calcium silicate slag and the ferrophosphorus are periodically tapped from the furnace.

The gas-phase mixture of phosphorus and carbon monoxide pass through an electrostatic precipitator to remove dust that is carried over from the furnace. The phosphorus is then liquefied in a water-spray tower and the carbon monoxide is drawn off for use as a fuel in the nodulizing process.

Phosphoric Acid

Figure A.7 shows the manufacturing steps in converting phosphate rock to phosphoric acid by digestion with sulfuric acid. This is commonly referred to as the wet-acid process. Following washing and floatation to concentrate the

FIGURE A.6. Phosphorus Flow Diagram (A.D. Little 1976)

FIGURE A.7. Phosphoric Acid Production (Battelle 1976)

phosphorus, the ore is dried in rotary dryers. The ore is then ground and fed to the digestors where it is first treated with dilute phosphoric acid. The phosphate rock and the dilute acid react as follows:

This solution is then acidified with strong sulfuric acid, which reacts with the monocalcium phosphate to precipitate gypsum and to form phosphoric acid as follows:

Total residence time in the digester is about six hours.

The slurry from the digester is processed through a rotary vacuum filter to separate the gypsum for subsequent disposal. The filtrate is phosphoric acid with a concentration of about 30 to 32% (A. D. Little 1976). The weak acid is concentrated to the desired strength by evaporating the water in multi-effect evaporators.

Plants range in capacity from about 50 tons/day to 2000 tons/day with the typical plant producing about 780 tons/day (Palmer 1980).

Heat-Transfer Operations

The major heat-transfer operations are discussed below for each of the processes described earlier.

Sulfuric Acid

Sulfuric acid production requires only a modest amount of electricity for moving gaseous and liquid streams. Both the sulfur burning process and the catalytic conversion process are exothermic, making the overall process a net generator of heat. The majority of the heat-transfer operations recover heat from the product following these exothermic reactions. It is estimated that potentially 3.4×10^6 Btu could be recovered per ton of sulfuric acid produced (Bodine 1980). Heat can be recovered in four places:

1. after the sulfur burner
2. after the first converter pass
3. following catalytic conversion
4. from the hot acid prior to storage.

The hot gases from the sulfur burner contain about 10% by volume sulfur dioxide and are at temperatures of 1740 to 1830⁰F (Bodine 1980). The hot gases are used to produce steam in a fire-tube waste-heat boiler. The steam generated is of sufficient quality to produce power. In more modern plants, most of the steam is used to power pumps and blowers, replacing the need for electricity. After providing for fluid transport, steam is still available for export from the plant.

Heat may be recovered from the gas stream following the first pass through the catalytic converter either by a fire-tube waste-heat boiler or an extended surface superheater. Following the converter, the process gases are further cooled in extended surface economizers. The hot acid product is cooled prior to storage in water-cooled heat exchangers.

Elemental Phosphorus

The major heat-transfer operations in phosphorus production include phosphate ore nodulizing, feedstock drying, phosphorus reduction, slag quenching, and phosphorus condensing. The most energy-intensive process is phosphorus reduction in the electric furnace. About 12,500 kWh/ton of phosphorus are required for furnace operation (Battelle 1976). In addition, the reduction of P_2O_5 is exothermic, adding more heat to the furnace.

In ore nodulizing and feedstock drying the heat-transfer is by direct contact between the hot combustion gases and the ore or feedstock. The carbon monoxide generated in the furnace is burned to provide the heat for nodulizing. Any fuel can be burned to dry the coke and the silica.

Slag quenching and phosphate cooling involve direct contact with cooling water. Lastly, cooling water is used to cool electrode clamps in the furnace and to prevent corrosion of the slag taphole. A water spray cools the outer shell of the furnace.

Phosphoric Acid

Two steps in the production of phosphoric acid require the addition of process heat. These are the drying of P_2O_5 concentrate prior to grinding, and the evaporation of the water to produce concentrated phosphoric acid. The

digestion reaction is strongly exothermic, requiring cooling to maintain the required process temperature.

Any fuel can be used in the concentrate drying process. About 1.21×10^6 Btu are required per ton of P_2O_5 (Battelle 1976). Steam is used for heating and evacuating the multiple-effect evaporators used to concentrate the acid. This step requires about 2100 pounds of steam at 90 psi and $320^{\circ}F$ per ton of P_2O_5 (Battelle 1976). The steam used in the concentration step is the excess steam produced by the captive sulfuric acid plant that provides the acid used in the digester.

Waste Heat Streams

The majority of the waste heat in the manufacture of the inorganic chemicals described in the preceding sections is in the form of waste water. Heat is typically recovered from high-temperature product gases for steam generation or for use as process heat. The waste heat streams for each of the processes are discussed below.

Sulfuric Acid

No significant waste heat streams have been identified in the sulfuric acid production process, despite the fact that it is a net generator, rather than user, of heat. In this process, all of the streams containing waste heat are heat exchanged to successively heat water and then to produce steam. To summarize, the hot acid product is cooled in water-cooled heat exchangers. The water is then routed to the economizers that cool the product gases prior to the absorption process. From there, the steam or water is routed to either a waste-heat boiler or a superheater which recovers additional heat after the first pass through the converter. In addition, the heat in the product stream exiting the sulfur burner is recovered in a waste-heat boiler.

Elemental Phosphorus

The significant sources of waste heat in elemental phosphorus production are the exit gases from the nodulizing kiln and the feedstock dryers, and the waste waters from nodulizer off-gas scrubbing, slag quenching, and phosphorus condensing. Table A.9 gives the nodulizer exit gas parameters for a sample

TABLE A.9. Nodulizer Exit Gas Parameters for Sample Plant
(Cox 1979)

Temperature	1022 ⁰ F
Flow	140,000 ACFM
Dust Load	450 lbs/hr
Corrosive Components	HF, SO

plant. No information was available for the exhausts from the feedstock dryers.

The exit gases from the nodulizing process are at a temperature of about 1022⁰F prior to the scrubbers (Cox 1979). The gases are laden with dust and may contain corrosive components such as hydrogen fluoride and sulfur trioxide. The information in Table A.9 was provided for one plant with a traveling grate nodulizer.

Since the nodulizer exhaust gas is dusty and contains fluorides, pollution control equipment must be used prior to venting to the atmosphere. Typically, scrubbers are used and the water is recycled. The purge stream from the recycle is contaminated with phosphates, sulfates, fluorides, and suspended solids and is acidic (A. D. Little 1976).

The slag quench water is slightly alkaline and contains phosphates, sulfates, fluorides and suspended solids. The "phossey" water from the phosphorus condenser contains a small amount of phosphorus in suspension as a finely divided solid.

The volumes and content of the three waste cooling water streams vary from plant to plant. Table A.10 provides an estimate of the characteristics of the waste water for a 100,000 ton/year phosphorus plant.

Phosphoric Acid

Sources of waste heat from phosphoric acid production include dryer exhausts, digester vent gas, and evaporation system vent gas. The exhaust gases are scrubbed with a water spray to remove any gaseous fluorine. No information on the temperatures, volumes, or heat contents of these waste streams was found.

TABLE A.10 Phosphorus Wastewater Characteristics (A. D. Little 1976)

Basis: 100,000 tpy production (as P_4)
330 operating days/year

Wastewater Characteristics	Nodulizer		Phosphorus		Slag		Combined Wastewater	
	Scrubber Liquor*	Liquor*	Condenser Plus	Other Phosphy Water	Quenching Water	Quenching Water	(mg/l)	(lb/day)
	(mg/l)	(lb/day)	(mg/l)	(lb/day)	(mg/l)	(lb/day)		
Total suspended solids	280	5,100	135	8,190	820	12,450	273	25,740
Phosphorus (P_4)	-	-	90	5,460	-	-	58	-
Phosphate (PO_4)	70	1,270	220	13,350	40	610	162	15,230
Sulfate (SO_4)	1,200	21,830	-	-	3,000	45,560	717	67,390
Fluoride (F)	730	13,280	270	16,380	180	2,730	344	32,390
Total Acidity (as $CaCO_3$)	2,000	36,380	-	-	-	-	351	33,040
Total Alkalinity (as $CaCO_3$)	-	-	-	-	220	3,340	-	-
Wastewater Flow Rate	2.18 mgd		7.27 mgd		1.82 mgd		11.27 mgd	

*Assumes scrubber liquor is recirculated with a 10% blowdown.

PLASTICS MATERIALS AND RESINS - SIC 2821

The manufacture of plastics and resin materials in the United States involves the production of thermoplastic and thermosetting polymers and thermoplastic elastomers. Four of these account for 60% of the total production of plastics and resins (Battelle 1976):

- low-density polyethylene (LDPE)
- high-density polyethylene (HDPE)
- polyvinyl chloride (PVC)
- polystyrene.

The manufacturing processes, heat-transfer operations and waste heat streams are analyzed below for these four representatives of the plastics industry.

Process Description

Low-Density Polyethylene

LDPE is the largest-volume plastic material manufactured and is the largest single product produced from ethylene. There are two basic processes used to manufacture LDPE: the autoclave reactor process and the tubular reactor process. With the exception of the type of reactor, these processes are similar. Both are high-pressure processes, with pressures ranging from 15,000 to 50,000 psi (Battelle 1976). The energy consumption of each process is essentially the same.

Tubular reactors have tubes with an inner diameter of about 1 inch and may be up to 2000 feet long. The material residence time in the reactor may be up to 45 seconds at a production rate of 20 to 40 million lb/yr (Gaines 1980). Large autoclave reactors may have internal diameters up to 2 feet with an outer diameter three or four times as large. The length-to-diameter ratio may vary from 2:1 to 20:1. Reactors can produce from 5 to 15 million lbs/yr (Gaines 1980). Plants range in size from 100 tons/day to 1000 tons/day with the average plant at about 500 tons/day (Palmer 1980). Figure A.8 shows the basic steps in LDPE production.

Feed materials (ethylene, an initiating agent and a chain transfer agent) are compressed in stages and mixed with recycled ethylene. The compressed feed

FIGURE A.8 Low-Density Polyethylene - Generalized Process
(Battelle 1976)

enters the reactor at pressures of from 15,000 to 50,000 psi. In the reactor, the materials are heated to 230 to 340°F to initiate polymerization. The normal conversion of ethylene to LDPE is about 22-30% per pass for tubular

reactors and 10 to 20% per pass for autoclave reactors (UTC 1980). The polyethylene is then separated from the unpolymerized ethylene in a series of heated separators. About 95% of the unreacted ethylene is removed in the high-pressure separator and the remainder is removed in the low-pressure separator (Battelle 1976). The ethylene from the separators is cooled, dewaxed and recycled. The molten polymer from the low-pressure separator is extruded and pelletized, then cooled, dried and stored.

High-Density Polyethylene

High-density polyethylene is manufactured by one of several low-pressure processes that are completely different than the high-pressure processes discussed earlier. Pressures in these processes range from about 15 to 3000 psi (UTC 1980). Nearly complete polymerization occurs in a single pass in these processes. Three commercial processes are employed: (1) the slurry process, (2) the solution process, and (3) the gas-phase process. In the solution process both the quantity of the hydrocarbon solvent and the process temperature are maintained at a sufficiently high level to keep the polymer in solution. The slurry processes use a smaller amount of solvent and lower temperatures, and the polymer is formed as a dispersed solid in a slurry. Gas-phase processes have been developed in which no solvent is required; however, little HDPE is produced by the gas-phase methods.

Figure A.9 outlines the basic steps in the solution process. In the solution process, the solid catalyst in a hydrocarbon diluent is introduced into an autoclave reactor containing ethylene and the diluent. Reactor conditions range from 250 to 350°F at 300 to 500 psia (UTC 1980). The polymer and diluent are separated by steam stripping the diluent, leaving a solid polyethylene and water mixture. The diluent and the unpolymerized ethylene are recycled to the reactor. The solid polyethylene is separated from the water and then dried and extruded to form pellets.

In the slurry process (shown in Figure A.10), high-purity ethylene, a highly active catalyst, and a diluent are fed to the reactor. Reactor conditions range from 68 to 212°F at 100 to 500 psia. Flow velocities vary

sent to auger dryers to remove remaining solvent and the product is sold in bulk, granular or pelletized form.

Polyvinyl Chloride

PVC is manufactured by one of four processes: (1) suspension, (2) bulk, (3) solution, and (4) emulsion. Suspension polymerization is used to produce an estimated 85 to 86% of the total PVC (Battelle 1976, UTC 1980). This process is shown schematically in Figure A.11.

The vinyl chloride monomer, finely dispersed in deionized water, is charged to the reactor which is agitated and heated to between 113 and 131⁰F (UTC 1980). When 90% polymerization is achieved, the mixture is transferred to a dump tank and the unreacted monomer is stripped and recovered for recycle. Most of the water is removed by centrifugation and the resin is dried in a rotary dryer with hot air. A cyclone separator is used to remove the product from the hot air stream exiting the dryer. Stabilizers and plasticizers are added in the blender by tumbling. Some of the PVC is further processed by melting, pelletizing and drying.

Polystyrene

Continuous bulk polymerization is the most common process for producing polystyrene. Figure A.12 shows the major steps in the bulk polymerization process. Styrene monomer is sent to a prepolymerizer where it is heated, forming a viscous solution of polymer in styrene. Prepolymerization, which may take place in a stirred reactor, tower or autoclave reactor, may achieve as little as 11% conversion or as much as 85% depending on the process. The viscous solution is pumped to the top of a tower and passes down through increasing temperature zones. The reaction is completed at the bottom of the tower at a temperature of about 390⁰F (Gaines 1980).

The molten polystyrene is pumped from the bottom of the tower through dies to form strands. Unreacted styrene is vacuum-flashed and recovered for recycle. The strands are cooled and chopped.

FIGURE A.11. Polyvinyl Chloride - Suspension Process

FIGURE A.12. Polystyrene - Bulk Polymerization Process (Battelle 1976)

Heat-Transfer Operations

The major heat-transfer operations for each of the processes described above are discussed below.

Low-Density Polyethylene

The major heat-transfer operations in LDPE production are listed in Table A.10 along with the medium used for heating or cooling. Ethylene compressors are water cooled to prevent premature polymerization. Ethylene is initially preheated to a temperature of 230 to 340°F via a heat transfer fluid such as Dowtherm® in the reactor jacket. As the reaction proceeds, cooling must be provided to the jacket to prevent explosive decomposition. As an alternative to jacketed cooling, multiple feed points may be provided in a tubular reactor and the new feed is heated by the excess heat of polymerization.

Heat must be added to the separators to maintain polyethylene in its molten state and to decrease the solubility of the gaseous ethylene in the product. Steam-jacketed separators are typically used to avoid excessive product heat loss. The off-gas from the primary separators are cooled to between 50 and 100°F and are passed through the secondary separators. The ethylene removed from the separators is air or water cooled.

Initially heat is added to the extruder to maintain polymer fluidity; however, heat generated by the extrusion process itself must subsequently be removed by direct-contact water cooling. Following cooling, the wet pellets are dried in a hot air dryer. The hot air is steam heated.

TABLE A.10. Heat-Transfer Operations in LDPE Production

<u>Operation</u>	<u>Heating/Cooling Medium</u>
Compressor Cooling	water
Ethylene Preheating	steam or Dowtherm®
Reactor Cooling	coolant
Separator Heating	steam
Separator Off-Gas Cooling	water or air
Extrusion	steam
Extruded LDPE Cooling	water
Extruded LDPE Drying	steam

®Trademark of the Dow Chemical Company, Midland, Michigan.

High-Density Polyethylene

The major heat-transfer operations in HDPE production by the slurry process are listed in Table A.11 and those in the solution process are shown in Table A.12.

All the process heat added in the slurry process is in the form of steam. It is estimated that about 1650 pounds of low-pressure steam and 600 pounds of medium-pressure steam are required to produce one short ton of HDPE (Battelle 1976). In the reactor, steam is initially used to promote polymerization. Then, cooling water must be used to maintain the reactor conditions at about 185°F and 130 psi (Battelle 1976). The remaining process equipment is maintained at the temperature levels listed in Table A.13.

TABLE A.11. Major Heat-Transfer Operations in HDPE Production by the Slurry Process (Battelle 1976)

<u>Operation</u>	<u>Heating/Cooling Medium</u>	<u>Quantity</u>
Ethylene Preheating	Steam	550 lb/ton HDPE (60 psi, 295°F)
Reactor Cooling	Water	--
Centrifuge Cooling	Water	--
Steam Stripping	Steam	700 lb/ton HDPE (60 psi, 295°F)
Diluent Distillation		
● Heating	Steam	100 lb/ton HDPE (60 psi, 295°F)
● Cooling	Water	--
Phase Separation	Water	--
Drying	Air (Steam Heated)	500 lb/ton HDPE (175 psi, 370°F)
Extrusion		
● Heating	Steam	300 lb/ton HDPE (60 psi, 295°F)
● Cooling	Water	--
Drying	Air (Steam Heated)	100 lb/ton HDPE (175 psi, 370°F)

TABLE A.12. Heat-Transfer Operations in HDPE Production
by the Solution Process (Battelle 1976)

<u>Operation</u>	<u>Heating/Cooling Medium</u>	<u>Quantity</u>
Reactor Cooling	Water	--
Flash Separator	Steam	1900 lb/ton HDPE (310 psi, 420°F)
Extruder		
● Heating	Steam	300 lb/ton HDPE (60 psi, 295°F)
● Cooling	Water	--
Dryer	Steam	100 lb/ton HDPE (175 psi, 370°F)

TABLE A.13. Unit Operation Temperature Levels
(Battelle 1976)

<u>Equipment</u>	<u>Temperature (°F)</u>
Centrifuge	77
Steam Stripper	212
Distillation	176
Dryers	265
Extrusion	300-570

Polyvinyl Chloride

All process heat in the suspension process is added in the form of low- or medium-pressure steam. Since the polymerization reaction is exothermic, heat must be removed from the reactor by cooling water. The heat-transfer operations, heat-transfer media and quantities of steam used per ton of product produced are listed in Table A.14.

Polystyrene

Although there are several places in the production process where process heat is required, much of the heat is provided by the exothermic polymerization process. This heat is transferred to the operations which use heat through a

TABLE A.14. Heat-Transfer Operations in the Production of Polyvinyl Chloride by the Suspension Process (Battelle 1976)

<u>Operation</u>	<u>Heating/Cooling</u>	<u>Quantity</u>
Reactor		
● Initiation	Steam	450 lb/ton PVC (30 psi, 250°F)
● Cooling	Water	
Vinyl Chloride Stripping/ Distillation	Steam	7 lb/ton PVC (30 psi, 250°F)
Rotary Drying	Air (Steam Heated)	500 lb/ton PVC (175 psi, 370°F)

Dowtherm® distribution system. Some additional heat in the form of steam is required beyond that provided by the heat of the polymerization reaction. The major heat-transfer operations in the production of polystyrene by the bulk process are listed in Table A.15.

Waste Heat Streams

Most of the waste heat in the production of plastics is in the form of cooling water and process water since the polymerization reactions are

TABLE A.15. Heat-Transfer Operations in the Production of Polystyrene by the Bulk Process (Battelle 1976)

<u>Operation</u>	<u>Heating/Cooling</u>	<u>Quantity</u>
Reactor Cooling	Water	--
Heating Dowtherm®	Steam	560 lb/ton (482 psi, 575°F)
Blending	Steam	100 lb/ton (30 psi, 250°F)
Extruding/Pelletizing	Water	
Drying	Steam	100 lb/ton (175 psi, 370°F)

exothermic and require little heat input. The LDPE, HDPE and PVC processes do not appear to recover the heat of reaction for use in other parts of the plant. The production of polystyrene makes extensive use of the heat of polymerization to provide heat elsewhere in the process.

Low-Density Polyethylene

One source estimates that about 6×10^6 lb/hr of cooling water is rejected at temperatures between 100 and 120°F for a 1000 ton/day LDPE plant (Palmer 1980). The sources of this cooling water are the reactors and the compressors. It is estimated that between 35,000 and 44,000 gallons of cooling water are required per ton of LDPE produced (UTC 1980). Another source states that the reactor coolant is at a temperature of 380°F and that the heat of reaction is 3.3×10^6 Btu per ton of LDPE (Sittig 1977).

High-Density Polyethylene

In the production of HDPE, process temperatures are much lower than those in LDPE production, thus the cooling water from this process has little availability and waste heat recovery would not be feasible (Sittig 1977). It is estimated that between 50,000 and 59,000 gallons of cooling water are required per ton of HDPE produced (UTC 1980).

Polyvinyl Chloride

As with HDPE production, process temperatures are typically low in the manufacture of PVC. It is estimated that about 17,000 gallons of cooling water are required per ton of PVC produced (UTC 1980).

Polystyrene

Much of the heat generated in the reactors is recovered and reused in other process operations. No estimates on the volume or the temperature of the cooling water were available.

ORGANIC FIBERS - SIC 2824

This SIC code contains non-cellulosic synthetic organic fibers, including polyester, nylon, and acrylic fibers. Table A.16 shows the 1972 production and energy consumption for selected SIC 2824 synthetic organic fibers.

TABLE A.16. 1972 Production and Energy Consumption for Selected
SIC 2824 Synthetic Organic Fibers (Battelle 1976)

<u>Fiber</u>	<u>Production</u> (10 ⁹ lb)	<u>Energy Consumption</u>	
		(10 ¹² Btu)	(Btu/lb)
Polyester	2327	46.2	19,900
Nylon	1974	49.4	25,500
Acrylic	626	29.5	47,100
Polyolefin	347	8.5	24,600
Other	<u>82</u>	<u>2.1</u>	25,000
Total	5356	135.7	

The following sections describe the processes, heat-transfer operations, and waste heat streams associated with the production of polyester, nylon, and acrylic fibers.

Process Description

In general, fibers are made by reacting simple molecules (monomers) with identical or similar molecules to form long chains of repeating units (polymers). The polymers are spun into fibers, drawn, and wound. The following sections describe the processes used to produce polyester, nylon, and acrylic fibers.

Polyester Fiber Production

Polyester fiber is made from dimethyl terephthalate or terephthalic acid and ethylene glycol. The polymerization reaction occurs at 260-300°C in a vacuum (Shreve and Brink 1977). The reaction products are methanol, ethylene glycol, and a long polymer chain. After melting, the polymer is spun and stretched into polyester fiber. The production process is shown in Figure A.13.

FIGURE A.13. Polyester Fiber Production (Battelle Columbus Laboratories 1976)

Nylon Fiber Production

There are two types of nylon produced in the United States: nylon 66 and nylon 6. In 1974, 70% of the U.S. nylon production was nylon 66 and 30% was nylon 6 (Shreve and Brink 1977).

Nylon 66 is produced by reacting hexamethylenediamine and adipic acid to form "nylon salt." After water removal, the nylon salt is polymerized, solidified, and dried to form nylon chips. The chips are later melted, extruded, spun, and drawn into nylon fiber.

Nylon 6 is produced by the water-catalyzed polymerization of caprolactam (Figure A.14). The caprolactam and water are mixed and heated in a reactor to 500°F. Heat from the exothermic reaction is removed by a heat-transfer fluid such as Dowtherm (a trademark of the Dow Chemical Company). Unreacted monomer is removed and the polymer is cooled and dried, then later melted and spun into nylon fiber.

FIGURE A.14. Nylon 6 Fiber Production
(Battelle Columbus
Laboratories 1976)

Acrylic Fiber Production

Acrylic fiber is produced by the polymerization of acrylonitrile in an aqueous system. Unreacted monomer is removed by water washing. The polymer is then dried and ground. Since it decomposes at its melting point, the polymer is dissolved in dimethylformamide and either dry spun or wet spun into acrylic fiber. This production process is shown in Figure A.15.

Heat-Transfer Operations

Polymerization reactions are exothermic, but may require high temperatures to initiate. Therefore, both heating and cooling of reactors is necessary. This is usually accomplished with a fluid such as Dowtherm (a trademark of the Dow Chemical Company), which is preheated with fuel.

Steam is used for melting, evaporation, distillation, and various other unit operations. Cooling water and air are also used. Large amounts of electricity are required for the spinning processes.

FIGURE A.15. Acrylic Fiber Production (Battelle Columbus Laboratories 1976)

Table A.17 shows the 1971 and 1973 average energy consumption for the production of six synthetic fibers: rayon, acetate, polyester, nylon, acrylic-modacrylic, and olefin. The energy consumption figures differ by a factor of three between the most-energy-intensive fiber (acetate) and the least-energy-intensive fiber (polyester) (Sittig 1977).

TABLE A.17. Energy Consumption in Synthetic Fiber Production (Federal Energy Administration 1974)

Fiber	Energy Consumption (10 ³ Btu/lb)	
	1971	1973
Rayon	61.9	50.4
Acetate	67.2	63.0
Polyester	19.9	17.3
Nylon	25.0	20.6
Acrylic-modacrylic	47.1	43.4
Olefin	24.6	19.0

Table A.18 shows the 1975 energy consumption by energy source for SIC 2824. Fuel oil represented 42 percent of the total consumption of purchased fuel, coal represented 35 percent, and natural gas represented 19 percent.

TABLE A.18. 1975 Energy Consumption for SIC 2824
(U.S. Department of Commerce 1975)

<u>Energy Source</u>	<u>Consumption (10¹² Btu)</u>
Fuel Oil	43.15
Coal	35.91
Natural Gas	19.76
Other ^(a)	<u>4.59</u>
Purchased Fuel (Total)	103.41
Purchased Electricity ^(b)	<u>21.16</u>
Purchased Fuel and Electric Energy (Grand Total)	124.57

(a) "Other" includes "fuels not specified by kind.

(b) Purchased electricity converted at 3413 Btu/kWh; self-generated electricity is already included in the individual fuel consumptions above to avoid double counting.

Heat Transfer in Polyester Fiber Production

Electricity accounts for 55 percent of the energy required for polyester fiber production (Palmer et al. 1980). Most of the electricity is used in the fiber-spinning operation and the air conditioning required to solidify the fiber.

Steam is used for melting and for distillation. The polymerization reactors are usually heated with Dowtherm.® Cooling water and air are used to remove excess heat.

Heat Transfer in Nylon Fiber Production

Electricity is also the major energy input to the nylon fiber production process. It is used to run the motors in the extrusion and spinning/winding operations and also for air conditioning (Palmer et al. 1980).

Steam is used in the evaporation and concentration of the nylon salt. The polymerization reactor is heated with Dowtherm®. Since the melting point of nylon-6,6 is above 500°F, high temperatures are required in the process (Palmer et al. 1980). The required temperature range for nylon 66 is 290-295°C; for nylon 6 it is 280-285°C. The Dowtherm® is heated in a boiler using natural gas for fuel (United Technologies Corporation 1980).

Waste Heat Streams

The only major waste heat streams from polyester fiber production are cooling water and air. The only major waste heat stream from nylon 66 fiber production is cooling water (Palmer et al. 1980). Cooling water waste heat streams for two typical synthetic plants are shown in Table A.19. Cooling air for fiber-spinning operations is shown for polyester production.

TABLE A.19. Waste Heat Streams from Synthetic Fiber Plants
(Palmer et al. 1980)

<u>Plant Type</u>	<u>Plant Size (tons/day)</u>	<u>Waste Stream Type</u>	<u>Temperature (°F)</u>	<u>Flow Rate (lb/hr)</u>
Polyester	250	Cooling water	100 to 120	10×10^6
		Cooling air	90 to 110	750×10^3
Nylon 66	150	Cooling water	100 to 120	2.5×10^6

CYCLIC CRUDES AND INTERMEDIATES - SIC 2865

This SIC code contains cyclic (coal tar) crudes and cyclic intermediates, dyes, and organic pigments. Of the 50 chemicals with the largest 1975 sales volumes in the U.S., the following 10 are included in SIC 2865 (Sittig 1977):

Benzene	Terephthalic Acid (and Dimethyl
Toluene	Terephthalate)
Xylene	p-Xylene
Ethylbenzene	Cumene
Styrene	Cyclohexane
	Phenols

Some of these chemicals are classified under more than one SIC code, depending upon the feedstock used in the production process. For example, 90 percent of the U.S. production of benzene is classified under SIC 2911 (petroleum refining), and only 10 percent is included in SIC 2865 (Bodine and Vitullo 1980).

Thousands of chemicals are included in SIC 2865. Many of them are produced by two or more processes with different feedstocks and energy requirements. In 1972 the total production of SIC 2865 chemicals was 61 billion pounds; the total energy consumption for 1972 was 192 trillion Btu (Battelle 1976).

Table A.20 shows the 1972 production levels of the top ten cyclic intermediates. In 1972 the U.S. produced almost 35 billion pounds of cyclic

TABLE A.20. 1972 Production of Important Cyclic Intermediates (U.S. Tariff Commission 1975)

<u>Chemical</u>	<u>10³ Pounds</u>
Styrene	5,940,729
Ethylbenzene	5,675,900
Cyclohexane	2,298,394
Cumene	2,292,949
p-Xylene	2,207,556
Phenol	2,096,125
Phthalic Anhydride	952,978
o-Xylene	831,782
Nitrobenzene	551,169
Dodecylbenzenes ^(a)	524,009

(a) Includes branched- and straight-chain dodecylbenzene and tridecylbenzene.

intermediates (Shreve and Brink 1977), which accounts for 57 percent of the total production of SIC 2865 chemicals.

The following sections describe the processes, heat-transfer operations, and waste heat streams associated with the production of two representative SIC 2865 chemicals: styrene and phenol.

Process Description

The cyclic intermediates are the raw materials used to produce dyes, medicinals, plastics, rubbers, and synthetic fibers. The main types of chemical conversions used to produce cyclic intermediates are nitration, amination by reduction, amination by ammonolysis, halogenation, sulfonation, hydrolysis, oxidation, and condensation and addition reactions (Friedel-Crafts) (Shreve and Brink 1977). The following sections describe the processes used to produce styrene and phenol.

Styrene Production

Styrene is produced by the catalytic dehydrogenation of ethylbenzene. The ethylbenzene is produced by the catalytic alkylation of benzene with ethylene. It is common practice in the literature to discuss these two processes together.

Ethylbenzene can be produced by two different processes: one uses an aluminum chloride catalyst and the other uses a boron trifluoride catalyst. Most ethylbenzene is produced using the aluminum chloride catalyst. The alkylation reaction conditions are 200-205°F and 5 psig (United Technologies Corporation 1980). The reactor effluent contains ethylbenzene, catalyst, unconverted benzene, and by-product diethylbenzene. The ethylbenzene product is purified in a series of three distillation columns.

Styrene production requires an iron oxide catalyst and a large quantity of steam. The dehydrogenation of ethylbenzene occurs at a temperature of 1050-1100°F and a pressure of 10 psig or less (United Technologies Corporation 1980). The reactor effluent contains styrene, unconverted ethylbenzene, and small quantities of by-products. The styrene product is purified in a series of distillation columns.

Phenol Production

Phenol can be produced by four different processes: oxidation of cumene, the Raschig process, sulfonation of benzene, and oxidation of toluene. The cumene oxidation process was used to produce 87 percent of the 1973 phenol output. The toluene oxidation process is seldom used (Bodine and Vitullo 1980).

In the cumene oxidation process, cumene is oxidized with air to produce phenol and by-product acetone. The major unit operations employed in the process are catalytic reaction, distillation, vacuum evaporation, gas compression, and pumping. The major energy consumption occurs in the distillation column reboilers. All process heat requirements are provided by steam (Palmer et al. 1980).

Heat-Transfer Operations

Table A.21 shows the 1972 conversion energy requirements for manufacturing selected SIC 2865 chemicals. The energy requirements in this table are categorized as lb steam per pound of product, kWh electricity per pound of product, and Btu other energy sources per pound of product. Table A.22 summarizes the 1972 total conversion energy requirements for manufacturing the same SIC 2865 chemicals.

Table A.23 shows the 1975 energy consumption by energy source for SIC 2865. Natural gas represented 60 percent of the total energy consumption, fuel oil represented 22 percent, purchased electricity represented 10 percent, and coal represented 8 percent.

Heat Transfer in Styrene Production

Large amounts of steam are required for the styrene production reaction and for the ethylbenzene and styrene distillation columns. Either natural gas or fuel oil is used as a boiler fuel. Steam and fuel requirements for ethylbenzene and styrene production plants are shown in Table A.24. In addition to the oil and gas fuels, over 200×10^6 Btu/hr of by-product hydrogen and waste oils are produced and consumed as fuel in a styrene production plant (Palmer et al. 1980).

TABLE A.21. 1972 Conversion Energy Requirements for Manufacturing Selected
SIC 2865 Chemicals (Battelle 1976)

Chemical	Process	Conversion Energy (per pound of product)			Total (Btu/lb)	
		Steam (lb)	Electricity (kWh)	Other (Btu)	Net ^(a)	Gross ^(b)
Benzene	Shell sulfolane	--	--	--	620	680
Benzene	Detol	0.044 ^(c)	0.0245	(3870)	(3740)	(3560)
Benzene	Pyrotol	0.065 ^(c)	0.0236	(10900)	(10740)	(10570)
Benzene	Litol	0.387 ^(c)	0.0205	(770)	(236)	(90)
Bisphenol A	Union Carbide	5.3 ^(d)	0.23	--	7810	9410
Cyclohexane	hydrogenation of benzene-ARCO	nil	nil	nil	nil	nil
Dimethyl Terephthalate (fiber grade)	Dynamit Nobel from p-xylene	1.2 ^(d)	0.23	1800	4170	5780
Terephthalic Acid (+ acetic acid)	Eastman Kodak Co.	--	0.018	1475	1540	1660
Dimethyl Terephthalate (fiber grade)	Eastman Kodak Co., from terephthalic acid	--	0.1	5910	6250	6950
Phenol	cumene	3.28 ^(e) 0.5 ^(c)	0.071	117	5860	6355
Styrene	Monsanto	1.35 ^(c) 2.4 ^(d)	0.038	2160	7020	7290
P-xylene	Toray Ind.-UOP	1.04 ^(c)	0.14	--	1670	2650

(a) Electricity equivalence: 3,413 Btu/kWh.

(b) Electricity equivalence: 10,400 Btu/kWh.

(c) Low-pressure steam: 1,150 Btu/lb.

(d) Medium-pressure steam: 1,325 Btu/lb.

(e) High-pressure steam: 1,500 Btu/lb.

TABLE A.22. 1972 Total Conversion Energy Requirements for Manufacturing Selected
SIC 2865 Chemicals (Battelle 1976)

Chemical	Process	SEC ^(a) (Btu/lb)		Production ^(b) (million lb)	Total Conversion Energy (billion Btu)	
		Net	Gross		Net	Gross
Benzene	Shell sulfolane	620	680	8654	5365	5885
Bisphenol A	Union Carbide	7810	9410	255.2	1993	2401
Cyclohexane	hydrogenation of benzene	nil	nil	2298	nil	nil
Dimethyl Terephthalate	Dynamit Nobel	4170	5780	2167	9036	12525
Phenol	cumene	5860	6355	2052	12025	13040
Styrene	Monsanto	7020	7290	5940	41699	43303
P-xylene	Toray Ind.-UOP	<u>1670</u>	<u>2650</u>	<u>2208</u>	<u>3687</u>	<u>5851</u>
Total		--	--	23574	73805	83005
Average Values		3131	3521	--	--	--

(a) SEC: Specific Energy Consumption.

(b) Production statistics from "Synthetic Organic Chemicals, United States Production and Sales, 1972," United States Tariff Commission, Washington, D.C., 1974.

TABLE A.23. 1975 Energy Consumption for SIC 2865
(U.S. Department of Commerce 1975)

<u>Energy Source</u>	<u>Consumption</u>
Fuel Oil	35.99×10^{12} Btu
Coal	12.59×10^{12} Btu
Natural Gas	96.25×10^{12} Btu
Purchased Electricity	4.5×10^9 kWh

TABLE A.24. Steam and Fuel Requirements for Ethylbenzene and Styrene Plants (Palmer et al. 1980)

<u>Plant Type</u>	<u>Plant Size (tons/day)</u>	<u>Steam Pressure (psig)</u>	<u>Steam Flow Rate (lb/hr)</u>	<u>Oil/Gas Consumption (10^6 Btu/hr)</u>
Ethylbenzene	1700	600	220,000	140
Styrene	1500	75	320,000	16
Styrene	1500	30	190,000	-

In ethylbenzene production, distillation accounts for about 15 percent of the total energy requirements. In styrene production, heating the reactants and the steam and distilling the reactor effluent account for over 90 percent of the total energy requirements (Latour et al. 1981).

The production of styrene is thermal-energy-intensive, with most of the energy supplied by steam. Natural gas is used to superheat the steam for the endothermic ethylbenzene dehydrogenation reaction. About 73 percent of the steam required for styrene production is used in the dehydrogenation reaction; the other 27 percent is used in distillation. About 94 percent of the steam required for ethylbenzene production is used in distillation (United Technologies Corporation 1980).

Table A.25 shows the cooling water requirements for ethylbenzene styrene production. About 67 percent of the cooling water is required for desuperheating and cooling the ethylbenzene dehydrogenation reactor product stream.

TABLE A.25. Cooling Water Requirements for Ethylbenzene/Styrene Production (adapted from Latour et al. 1982)

Source	Rate (gallons H ₂ O/ ton styrene)
Desuperheating and cooling ethylbenzene dehydrogenation reactor product stream	79,000
Condensing styrene distillation column overhead	19,400
Condensing ethylbenzene distillation column reflux	14,400
Cooling and scrubbing gaseous ethylbenzene alkylation reactor product stream	3,600
Cooling and decanting ethylbenzene alkylation reaction products	<u>1,350</u>
Total	117,750

About 16 percent is used to condense the styrene distillation column overhead, and about 12 percent is used to condense the ethylbenzene distillation column reflux.

Heat Transfer in Phenol Production

Large quantities of steam are required in the production of phenol by the cumene oxidation process, mostly to supply heat to the distillation column reboilers. For a typical 600-tons-per-day phenol plant, about 270,000 lb/hr of 200-psig steam and about 30,000 lb/hr of 600-psig steam are required (Palmer et al. 1980).

The cumene oxidation reaction is exothermic and careful control of the reactor temperature is mandatory. Cooling water is used to remove the excess heat of reaction.

Waste Heat Streams

In 1977 only about 5.5 percent of SIC 2865 purchased fuels and electricity was discharged as flue gas waste heat. Almost half of this energy was available at temperatures above 350°F (Latour et al. 1980).

The following sections describe the sources and temperatures of waste heat streams associated with styrene and phenol production.

Waste Heat in Styrene Production

One reference states that styrene production results in about 88,000 cubic feet of flue gas at 400°F for each ton of styrene produced, which amounts to 620,000 Btu of waste heat per ton of styrene. The total waste heat discharged to cooling water and process water streams is 28.98 million Btu per ton of styrene (Latour et al. 1981). Thus, almost 50 times more waste heat is contained in the water streams than is contained in the flue gas.

Another reference states that the natural-gas-fired steam superheater in a styrene plant emits 500°F flue gas, representing 720,000 Btu of waste heat per ton of styrene produced (United Technologies Corporation 1980).

Table A.26 shows typical waste heat streams discharged from ethylbenzene and styrene plants, according to a third reference.

TABLE A.26. Typical Waste Heat Streams in Ethylbenzene/Styrene Plants (Palmer et al. 1980)

<u>Plant Type</u>	<u>Plant Size (tons/day)</u>	<u>Type</u>	<u>Waste Stream</u>	
			<u>Flow (lb/hr)</u>	<u>Temp. (°F)</u>
Ethylbenzene	1700	Heat Recovery Steam	198,000	240
Ethylbenzene	1700	Heat Recovery Steam	124,000	360
Ethylbenzene	1700	Cooling Water	245,000	100-120
Ethylbenzene	1700	Flue Gas	177,000	450
Styrene	1500	Cooling Water	8,000,000	100-120
Styrene	1500	Flue Gas	300,000	400
Styrene	1500	Air	660,000	150-240

Waste Heat in Phenol Production

The only major source of waste heat from a phenol production plant is cooling water. A 600-tons-per-day phenol plant would discharge 17,000,000 lb/hr of 100-120°F cooling water (Palmer et al. 1980).

ALIPHATIC ORGANIC CHEMICALS - SIC 2869

This SIC code contains thousands of miscellaneous industrial organic chemicals that are not classified elsewhere. All but about 100 of these are produced in relatively small quantities. Many are produced by more than one process using different feedstocks and having different energy requirements. Of the 50 chemicals with the largest 1975 sales volumes in the U.S., the following 18 are included in SIC 2869 (Sittig 1977):

Ethylene	Acetic acid
Propylene	Acetone
Ethylene dichloride	Isopropyl alcohol
Methanol	Propylene oxide
Formaldehyde	Acetic anhydride
Vinyl chloride	Adipic acid
Ethylene oxide	Ethanol
Ethylene glycol	Acrylonitrile
Butadiene	Vinyl acetate

Table A.27 shows the 1973 production and energy use statistics for selected SIC 2869 chemicals. Ethylene accounted for 29 percent of the production and 80 percent of the energy use. Ethylene is used exclusively as a building block and is the primary feedstock for over 40 percent of all petrochemical products (Tarrillion 1982). The following sections describe the process, heat-transfer operations, and waste heat streams associated with ethylene production.

TABLE A.27. 1973 Production and Energy Use Statistics for Selected SIC 2869 Chemicals (International Research and Technology Corporation 1974)

<u>Chemical</u>	<u>Production (10⁶ tons)</u>	<u>Energy Use (10¹² Btu)</u>
Ethylene	11.0	1,460.26
Ethylene dichloride	3.96	4.17
Propylene	4.0	103.76
Methanol	3.52	124.69
Formaldehyde	3.07	22.83
Ethylene oxide	1.95	29.01
Ethylene glycol	1.83	--
Acetone	0.98	5.70
Acetaldehyde	0.31	6.17
Acetic Anhydride	0.79	12.88
Adipic acid	0.72	19.42
Isopropanol	0.90	11.79
Urea	3.97	16.90
Ethyl alcohol	<u>0.97</u>	<u>11.42</u>
Total	37.97	1,829.00

Process Description

The feedstock for ethylene production can be ethane, propane, or naphtha. Figure A.16 is a flow diagram of the ethylene production process. The feedstock is cracked in a pyrolysis furnace, with steam injection provided to reduce coking (fouling of the furnace by carbon deposits). The hot furnace off gas is quenched with condensate, then compressed and distilled. The distillation products include ethylene, fuel oil, hydrogen, methane, propylene, butane derivatives, and gasoline. Ethane recovered from the distillation column is recycled to the pyrolysis furnace.

Heat-Transfer Operations

The high-temperature cracking reaction and the low-temperature distillation (which requires refrigeration) make this an energy-intensive process. The energy requirement, according to one source, is 20×10^6 Btu per ton of

FIGURE A.16. Ethylene Process Flow Diagram

ethylene produced (Bodine and Vitullo 1980). Another reference states that the energy requirement is 32×10^6 Btu/ton of ethylene (Palmer et al. 1980).

Table A.28 shows the 1971 and 1974 fuel and petroleum feedstock consumption for ethylene production. In each of the two years, natural gas accounted for 90 percent of the fuel consumption. Another reference shows that natural

TABLE A.28. Fuel and Petroleum Feedstock Consumption
for Ethylene Production (International
Research and Technology Corporation 1974)

	<u>1971 Data</u> <u>(10¹² Btu)</u>	<u>1974 Data</u> <u>(10¹² Btu)</u>
Petroleum Feedstock	842.66	1,151.53
Petroleum Fuel	4.40	5.68
Coal	12.19	16.36
Natural Gas	280.55	366.61
Other Fuels	4.74	6.29
Purchased Electricity	<u>10.28</u>	<u>13.38</u>
Total	1,154.82	1,559.85

gas represented about 75 percent of the total 1975 energy consumption for all of SIC 2869 (U.S. Department of Commerce 1978).

The endothermic cracking reaction occurs at 1500-1650°F in the pyrolysis furnace. Quenching the hot furnace off gas with condensate results in the generation of 400-2000 psig steam (Bodine and Vitullo 1980).

The pyrolysis furnace has a thermal efficiency greater than 85 percent. Using the fuel oil and gaseous by-products of the cracking reaction as fuels, the furnace heats the feedstock/steam mixture to the cracking temperature, superheats the steam, and heats the boiler feedwater (Palmer et al. 1980).

Waste-heat boilers are used to recover heat from the hot reaction products. Steam produced in the waste-heat boilers is injected into the pyrolysis furnace and is also used to provide process heat to the distillation column reboilers (Palmer et al. 1980). About two-thirds of the total plant steam requirement is generated in waste-heat boilers (United Technologies Corporation 1980).

Large amounts of cooling water are used to cool reaction products between compression stages. Cooling water is also used in the quench tower and to cool

final product streams. As much as 38×10^6 lb/hr of cooling water at temperatures of 100 to 120°F may be discharged from a plant producing 1510 tons ethylene per day (Palmer et al. 1980). Most of the cooling water is used for between-stage compression.

Waste Heat Streams

Table A.29 shows the sources, temperatures, and quantities of waste heat from the ethylene production process. Stack gases from the pyrolysis unit, which contain 930 Btu/lb, are available at 400°F.

Table A.30 shows the sources, temperatures, and flow rates of waste heat identified by another literature reference (Palmer et al. 1980). This table shows 44,000 lb/hr of 35-psig steam being available, as well as 2.5×10^6 lb/hr of flue gas at 350°F. There is a large amount of cooling water, but it contains very low-grade heat that is not usable.

TABLE A.29. Sources, Temperatures, and Quantities of Waste Heat from Ethylene Production (Reding and Shepherd 1975)

Source	Temperature (°F)	Quantity (Btu/lb)
Radiation and Convection from Pyrolysis Furnace	--	150
Stack Gases from Pyrolysis Furnace	400	930
Water from Quenching, Scrubbing, and Cooling Hot Reaction Products from Pyrolysis Furnace	150	100
Radiation and Convection from Compression of Cool Reaction Products	--	20
Condensate from Compression of Cool Reaction Products	220	1400
Compressed Reaction Products	220	750
Radiation and Convection from Refrigerant Compression	--	10
Condensate from Refrigerant Compression	220	1500
Refrigerant	150	1000
Conduction from Distillation Columns	--	250

TABLE A.30. Sources, Temperatures, and Flow Rates of Waste Heat from Ethylene Production (Palmer et al. 1980)

<u>Source</u>	<u>Temperature (°F)</u>	<u>Flow Rate (lb/hr)</u>
35 psig Steam from Waste-Heat Boilers	260	44,000
Flue Gas	350	2,500,000
Cooling Water	100-120	38,000,000

Table A.31 shows the sources and quantities of waste heat from a third reference (Latour and Menningmann 1981). The only major gas waste heat stream is the 400°F pyrolysis furnace stack gas. The total heat rejected by process waste water and non-contact cooling water amounts to 9.5×10^6 Btu/ton of ethylene produced.

Ethylene production is a relatively clean process if ethane or propane is used as the feedstock. Both the feedstock and the primary fuel (natural gas) are very low in sulfur. The process has no major uncontrollable air, water, or solid waste emissions (Arthur D. Little, Inc. 1976).

TABLE A.31. Sources and Quantities of Waste Heat from Ethylene Production (Latour and Menningmann 1981)

<u>Source</u>	<u>Quantity/Ton Ethylene</u>	<u>Temperature (°F)</u>	<u>Btu/Ton Ethylene</u>
<u>Gas</u>			
Pyrolysis Furnace Stack Gas	233,000 ft ³	400	1,860,000
<u>Water</u>			
Compressor Blowdown	5,200 gal	--	5,800,000
Refrigerant Cooling Water	3,500 gal	--	2,000,000
Pyrolysis Gas Cooling Water	1,340 gal	--	1,500,000
Quench Water Blowdown	350 gal	--	200,000

NITROGENOUS FERTILIZERS - SIC 2873

The nitrogenous fertilizer industry encompasses the manufacture of synthetic ammonia, nitric acid, ammonium compounds and urea. This product category is of particular interest because it is one of the top producers in terms of annual tonnage in the chemical industry and it is one of the major users of natural gas as a feedstock material. Ammonia dominates the production of industrial fertilizers. Ammonia is the basic raw material for most nitrogenous fertilizers, including urea, ammonium nitrate, and ammonium phosphate. The manufacturing process, major heat-transfer operations, and waste heat streams associated with the production of ammonia are described below.

Process Description

Ammonia is made primarily by the steam reforming of natural gas, although other sources of hydrogen such as LPG, naphtha, heavy fuel oil, coal, electrolytic hydrogen, or by-product hydrogen could be used (Arthur D. Little, Inc. 1976). Atmospheric air is used as the source of nitrogen.

Figure A.17 shows the major steps in ammonia manufacture. The process consists of four basic steps: 1) fuel reforming, 2) shift conversion of carbon monoxide, 3) gas purification, and 4) ammonia synthesis.

Fuel reforming converts the fuel and steam to carbon monoxide and hydrogen as follows:

The desulfurized natural gas and steam are fed to the primary reforming furnace. Natural gas is converted to hydrogen and carbon monoxide in the presence of a nickel catalyst inside of externally heated tubes. The product stream exits the primary reformer at about 1500°F and 460 psia (Sittig 1977). Stoichiometric quantities of compressed air are fed to the secondary reformer along with the product stream from the primary reformer. The residual methane in the product steam is converted as the gases pass over a nickel catalyst in a packed bed. The product gases exit the secondary reformer at about 1800°F (Sittig 1977).

FIGURE A.17. Ammonia Production Process (Battelle 1976)

The next step is a shift conversion that converts carbon monoxide and water to carbon dioxide and hydrogen as follows:

This occurs in a converter containing a catalyst.

Next, the gases are purified by removing the carbon dioxide, residual carbon monoxide, and the catalyst poisons. The carbon dioxide is removed by

stripping with one of various types of solvents. Carbon monoxide is typically removed using methanation, whereby the residual carbon monoxide is converted to methane according to the following reaction:

Ammonia synthesis takes place in the presence of a catalyst at elevated pressure and temperature in a packed bed. A multipass arrangement is used to achieve complete conversion. The synthesis reaction is as follows:

Ammonia plants range in size from 50 to 2000 tons/day, with the average plant producing about 220 tons/day (Palmer 1980).

Heat-Transfer Operations

The major heat-transfer operations in ammonia manufacture are listed in Table A.32.

The major energy users in an ammonia plant are the reforming furnaces and the compressors. A typical plant uses 155,000 Btu of electricity and 33×10^6 Btu of natural gas or fuel oil per ton of ammonia produced. Of the fuel used, 62% (20.5×10^6 Btu/ton) is feedstock (Latour 1981). Ammonia plants are designed such that the entire fuel input to the process is to the primary reforming furnace. Fuel burned in the primary reformer averages 12.5 million Btu per ton of ammonia produced (Palmer 1980). About 3.5×10^6 Btu of purge

TABLE A.32. Major Heat-Transfer Operations in Ammonia Manufacture

<u>Operation</u>	<u>Description</u>
Reforming	Fired-heater with combustion gases on shell side and natural gas, steam and the catalyst on the tube side.
Waste Heat Recovery	Waste-heat boilers are used to generate steam from reforming furnace exhausts.
Compression	The steam generated by the waste-heat boilers is used primarily for operating the compressors prior to the synthesis reaction.
Compressor Cooling	Compressors are water cooled.

gas from the synthesizer is recycled and burned in the primary reformer (Latour 1981). Waste heat is then recovered from the flue gases from the primary reforming furnace and from the product gases from the secondary reformer to generate steam in a waste-heat boiler. Plants that have package boilers generally use them only during plant startup unless steam is needed for the manufacture of derivatives of ammonia (Arthur D. Little, Inc. 1976). Little or no steam beyond that produced in the waste-heat boilers is needed at steady-state conditions.

Waste Heat Streams

Sources of waste heat in ammonia production include flue gases from the primary and secondary reformers, dryers and coolers, and combustion equipment; non-contact cooling water; and process waters from strippers. Cooling water in ammonia plants is used to cool the product stream: 1) after secondary reforming, 2) between high- and low-temperature shift conversion, 3) in compressors, and 4) in the ammonia synthesis step. Table A.33 lists the waste heat discharged in liquid streams. Table A.34 shows the waste heat sources and quantities estimated for a 1200 ton/day ammonia plant.

TABLE A.33. Heat Rejected in Wastewater Effluents from Ammonia Plants (Latour 1981)

<u>Source</u>	<u>Temperature^(a) (°F)</u>	<u>Quantity^(b) (Btu/ton)</u>
Boiler Blowdown	220	27,000
Cooling Tower Blowdown	20	175,000
Stripped Process Condensate	70	175,000

(a) Temperature above ambient.

(b) Waste heat discharge per ton of product.

TABLE A.34. Waste Heat Sources and Quantities in Ammonia Production--1200 Ton/Day Plant (Palmer 1980)

<u>Source</u>	<u>Temperature (°F)</u>	<u>Quantity (lb/hr)</u>
Reformer Flue Gas	400	500,000
Compressor Cooling	100-120	24 x 10 ⁶

APPENDIX B

PETROLEUM REFINING AND RELATED INDUSTRIES - SIC 29

APPENDIX B
PETROLEUM REFINING AND RELATED INDUSTRIES - SIC 29

This industry classification includes establishments that are primarily engaged in petroleum refining, manufacturing paving and roofing materials, and compounding lubricating oils and greases from purchased materials. Table B.1 shows the 4-digit industrial groups in SIC 29. Since petroleum refining accounts for about 95 percent of the total energy consumption of SIC 29, it is the only 4-digit industrial group that will be discussed in the following sections.

The petroleum refining industry ranks second in terms of industrial energy use. It consumes about 24 percent of the total energy used by the industrial manufacturing sector. The petroleum refining industry is characterized by year-around, 24-hour-per-day operations, 7 days per week, except for planned and emergency shutdowns.

The petroleum refining industry is extremely energy-intensive. However, as the first supplier of refined fuels to the rest of the country, it has access to by-product fuels not available elsewhere, such as refinery gas and petroleum coke. Only about half of the energy consumed in an oil refinery is supplied by purchased fuels; the other half is supplied by these in-house by-product fuels. Table B.2 shows the petroleum refining industry's 1978 fuel use by energy source.

TABLE B.1. Industrial Groups in SIC 29

<u>SIC</u>	<u>Industry</u>
2911	Petroleum Refining
2951	Paving Mixtures and Blocks
2952	Asphalt Felts and Coatings
2992	Lubricating Oils and Greases
2999	Products of Petroleum and Coal, Not Elsewhere Classified

TABLE B.2. Petroleum Refining Industry Fuel Use - 1978
(General Accounting Office 1980)

<u>Energy Source</u>	<u>10¹² Btu</u>	<u>%</u>
Refinery Gas	1291.7	42.2
Natural Gas	820.6	26.8
Petroleum Coke	394.8	12.9
Residual Fuel Oil	314.6	10.3
Purchased Electricity	94.8	3.1
Liquid Petroleum Gas	57.1	1.9
Distillate Fuel Oil	51.7	1.7
Purchased Steam	32.9	1.0
Coal	3.2	0.1
Crude Oil	2.6	0.0
	<u>3064.0</u>	<u>100.0</u>

High-temperature thermal energy requirements are met with fired heaters, and lower-temperature requirements are met with process steam. Although considerable steam is used throughout the refining process, the ratio of direct heat use to steam use is approximately 4 to 1. Steam pressures range from 200 to 600 psig, with the moderate-to-high-pressure steam being used to supply shaft power, while the lower-pressure steam is used for steam stripping, vacuum condensation, small pumps, and heat exchangers. Steam is generated in both direct-fired boilers and waste-heat boilers. A small amount of high-pressure steam in the 700-1400 psig range is also produced for electrical power generation and shaft power (United Technologies Corporation 1980). High-pressure steam is usually used in extraction turbines, with exhausts used for process heat. Only a small amount of hot water is needed for salt stripping of certain crudes. Steam demand is relatively constant throughout the year (except for space heating requirements).

The following sections describe the major processes, heat-transfer operations, and waste heat streams associated with petroleum refining.

PETROLEUM REFINING

The petroleum refining industry (SIC 2911), as defined by the U.S. Department of Commerce, includes establishments that are primarily engaged in producing gasoline, kerosene, distillate fuel oils, residual fuel oils, lubricants, and other products from crude petroleum and its fractionation products, through straight distillation of crude oil, redistillation of unfinished petroleum derivatives, cracking, or other processes. Establishments that are primarily engaged in producing natural gasoline from natural gas are classified as mining industries. Those that manufacture lubricating oils and greases by blending and compounding purchased materials are included in SIC 2992. Establishments that primarily re-refine used lubricating oils are also included in SIC 2992.

As of January 1, 1982 there were 274 operating petroleum refineries in the United States ("Annual Refining Survey" 1982). Table B.3 shows that these refineries range in size from only 600 barrels per stream-day (B/D) to over 500,000 B/D. The total U.S. refining capacity as of January 1, 1982, was about 18,625,700 B/D. The states with the largest petroleum refining capacities are Texas, Louisiana, California, Illinois, Pennsylvania, New Jersey, Oklahoma, Ohio, Indiana, and Kansas. Although each refinery is characterized by a unique capacity, processing configuration, and product distribution, there are some generic similarities among refineries in a given geographic region, primarily due to the characteristics of the crude oil processed and the products distributed.

Figure B.1 provides a generalized process flow diagram for a large integrated refinery (Hamel and Brown, 1979). Table B.4 provides a summary of energy requirements by major process for the representative refinery depicted in Figure B.1. Values given are based on industry-wide averages for the specific processes involved. It should be re-emphasized that both the processes depicted and the values shown will vary from refinery to refinery.

TABLE B.3 Size Distribution of Operating U.S. Petroleum Refineries
(as of January 1, 1982)

<u>Refinery Size (10³ B/D)^a</u>	<u>Number of Refineries</u>	<u>% of Total Refineries</u>	<u>Cumulative Total (%)</u>	<u>Total Capacity (B/D)</u>	<u>% of Total Capacity</u>	<u>Cumulative Total (%)</u>
0-1	1	0.4	0.4	600	0.0	0.0
1-2	3	1.1	1.5	3,800	0.0	0.0
2-5	16	5.8	7.3	68,900	0.4	0.4
5-10	37	13.5	20.8	283,500	1.5	1.9
10-20	45	16.4	37.2	660,700	3.5	5.4
20-30	32	11.7	48.9	808,500	4.3	9.7
30-50	42	15.3	64.2	1,768,000	9.5	19.2
50-75	29	10.6	74.8	1,792,600	9.6	28.8
75-100	13	4.7	79.5	1,127,200	6.1	34.9
100-125	12	4.4	83.9	1,335,700	7.2	42.1
125-175	14	5.1	89.0	1,964,800	10.5	52.6
175-225	12	4.4	93.4	2,284,800	12.3	64.9
225-300	7	2.6	96.0	1,929,700	10.4	75.3
300-400	5	1.8	97.8	1,720,600	9.2	84.5
400-500	4	1.5	99.3	1,688,300	9.1	93.6
500+	2	0.7	100.0	1,188,000	6.4	100.0
Total	274	100.0		18,625,700	100.0	

a. B/D = Barrels per stream-day. This represents the amount of crude oil that a refinery can process when running at full capacity.

Source: "Annual Refining Survey", Oil & Gas Journal, March 22, 1982.

Process Description

In general, petroleum refineries convert crude oil into finished products by employing three fundamental operations: (1) physical separation (distillation, absorption, stripping, and extraction), (2) chemical conversion (changing molecular structure), and (3) treating. Crude oil, as it comes from the ground, is a mixture of thousands of different hydrocarbons. In addition,

Source: Hamel and Brown, 1979

FIGURE B.1 Process Flow Diagram for Representative Refinery

TABLE B.4. Total Daily Energy Requirements for Representative Refinery

No.	Process	Mass Factor (a)	Charge B/D x 10 ³	Steam (b)		Direct Heat		Electricity	
				LB/BBL Charge	Total LB x 10 ⁶	BTU/BBL x 10 ³	Total BTU x 10 ⁶	KWH/BBL	Total KWH x 10 ³
1	Atmospheric Distillation	1.000	250.00	25 ^(c)	6.25	159 ^(c)	39,750	0.94 ^(c)	235.0
2	Vacuum Distillation	0.462	115.50	28 ^(c)	3.23	103 ^(c)	11,897	0.85 ^(c)	98.2
3	Delayed Coking	0.030	7.50	19 ^(c)	0.14	455 ^(c)	3,413	1.70 ^(c)	12.8
4	Catalytic Cracking	0.407	101.75	116 ^(c)	11.80	235 ^(c)	23,911	6.05 ^(c)	615.6
5	Distillate Hydroforming	0.181	45.25	(8) ^(d)	(0.36)	10 ^(d)	453	2.30 ^(d)	104.1
6	Lube Oil Processing	0.080	20.00	14 ^(d)	0.28	137 ^(d)	2,740	8.93 ^(d)	178.6
7	Asphalt Processing	0.020	5.00	50 ^(e)	0.25	208 ^(e)	1,040	2.55 ^(e)	12.8
8	Visbreaking	0.045	11.25	42 ^(c)	0.47	244 ^(c)	2,745	1.05 ^(c)	11.8
9	Naphtha Hydrotreating	0.198	49.50	11 ^(f)	0.54	53 ^(f)	2,624	1.00 ^(f)	49.5
10	Catalytic Reforming	0.194	48.50	61 ^(c)	2.96	450 ^(c)	21,825	3.15 ^(c)	152.8
11	Isomerization	0.029	7.25	322 ^(c)	2.33	270 ^(c)	1,958	3.05 ^(c)	22.1
12	Alkylation	0.029	7.25	500 ^(c)	3.63	720 ^(c)	5,220	5.75 ^(c)	41.7
13	Gas Recovery	0.083	20.75	None ^(g)	None	62 ^(g)	1,287	0.53 ^(g)	11.0
14	Kerosene Hydrotreating	0.055	13.75	25 ^(f)	0.34	66 ^(f)	908	1.70 ^(f)	23.4
TOTALS					31.86		119,771		1,569.4

- NOTES: (a) Hamel and Brown, 1979.
 (b) Assume 10% of total steam used for mechanical drives.
 (c) United Technologies Corporation, 1980.
 (d) "1982 Refining Process Handbook", 1982.
 (e) Battelle, Columbus Laboratories and Battelle, Pacific Northwest Laboratories, 1976.
 (f) Palmer, et al., 1980.
 (g) Haynes, 1976.

there may be large amounts of paraffin wax, asphaltic matter, sulfur, salts, and other impurities. It is necessary to separate the complex mixture into various cuts of different boiling ranges before any chemical rearrangements are attempted.

Physical Separation

Fractional distillation is based upon the fact that compounds with greater molecular weights have higher boiling points than compounds with lower molecular weights. The crude oil is partially vaporized in the tubes of a furnace and the two-phase mixture then enters the crude unit (distillation column). As the vapors rise, they cool and condense at various levels of the column depending upon their relative volatilities. Light hydrocarbons (C_4^-)^(a) rise to the top of the column where they are liquified in a condenser and recovered in a reflux drum. In between the condenser at the top and the reboiler at the bottom of the column, various sidecuts are drawn off, depending upon the particular product slate of the refinery. The heaviest fractions of the crude oil drop to the bottom of the column and are withdrawn.

Hydrocarbons with roughly fourteen or more carbon atoms cannot be boiled at atmospheric pressure without decomposing. Thus, the heavier crude fractions must be distilled under a vacuum. Because vacuum distillation equipment is more expensive than atmospheric distillation equipment, most crude units consist of two columns. The bottoms from the atmospheric column are pumped to the vacuum column, where the heavy fractions are split into several boiling ranges. The vacuum column bottoms are used in the manufacture of asphalt.

Chemical Conversion

Once the crude oil has been separated, the various fractions are piped to different plants in the refinery. In general, the next step is some type of chemical conversion process, where the hydrocarbon molecules are rearranged to form desired petroleum products such as gasoline. The importance of chemical conversion was realized at the beginning of the 20th century with the advent of

(a) C_4^- refers to all compounds that have boiling points less than or equal to the boiling point of normal butane.

the automobile. In 1920, the gasoline yield from each barrel^(a) of crude was only 11 gallons. Today refineries are able to produce an average of 19 gallons of gasoline per barrel of crude. The major processes which enable refineries to produce gasoline from hydrocarbons that are not in the gasoline boiling range^(b) are thermal cracking, catalytic cracking, hydrocracking, reforming, alkylation, polymerization, and isomerization.

Thermal cracking was the first conversion process introduced in oil refineries. In this process, heavy fractions of the crude are subjected to high temperatures and pressures, resulting in the breaking of molecular bonds. Thus, large complex molecules are cracked into smaller molecules. Cracking produces gasoline which is superior in antiknock characteristics to the gasoline obtained by simple fractionation of the crude. Although thermal cracking gives a low rate of conversion and is not used to a great extent anymore, it is quite important from an historical standpoint. After the first successful thermal cracker was put into operation in 1913, the refiners began to realize the extent of their capability to alter the petroleum molecules in a useful way.

The second major conversion process, brought to light in 1937, was catalytic cracking. This process accomplishes the same objective as thermal cracking, but the use of a selective catalyst enables cracking to occur at moderate pressures. Also, the gasoline produced has an even higher octane rating than that made in a thermal cracker. Catalysts used in various catalytic cracking processes range from aluminum and platinum to acids and processed clay.

The most modern and most complex of the cracking processes is called hydrocracking. It is also the most efficient conversion process in terms of extending the usefulness of a barrel of crude oil. The first hydrocracker was put into service in 1959, and the process was described as "a method of cracking in the presence of hydrogen and a catalyst to convert low-value, high-boiling

(a) A barrel, as used in the petroleum industry, is equal to 42 U.S. gallons.

(b) The gasoline boiling range is 100-400°F.

distillates to lower-boiling higher-value liquid products with essentially no waste gas produced" (Unzelman and Gerber 1965). In a hydrocracker, hydrocarbons are heated under pressure in the presence of hydrogen and a catalyst. The hydrocracking catalyst has two functions: (1) to crack the molecules, and (2) to hydrogenate the unsaturated products. Most of the products formed are isoparaffins, which make good gasoline.

Secondary reactions also occur in the hydrocracking process. The desulfurization reaction produces H_2S , and the denitrification reaction produces NH_3 . Water is injected into the reactor effluent stream to force the H_2S and NH_3 into an aqueous phase. The stream then goes to a separator which removes the aqueous phase from the organic phase and sends it to a waste water treating plant.

The quality of a motor gasoline blend is a function of its volatility and its knock characteristics. The tendency of a fuel to knock in an engine is classified numerically as the fuel's octane number. The higher a gasoline's octane number, the less the tendency to knock and the better the performance expected in an engine. The reference points for octane rating are iso-octane at 100, and normal-heptane at 0. The octane number of "straight-run" gasoline from the crude unit and "cracked" gasoline from the cracking units is raised by feeding these stocks to a catalytic reformer.

The catalytic reformer's main functions are to produce aromatics and to reform normal paraffins into isoparaffins, which causes an increase in octane number. The reforming reactions occur at elevated temperatures and pressures in the presence of hydrogen and a platinum catalyst. Reforming results in molecular rearrangement; the total number of carbon atoms in the rearranged molecule is not altered, and large quantities of hydrogen are produced as a by-product.

Since large volumes of light hydrocarbon gases are produced in a typical refinery, it is common to see alkylation, polymerization, and/or isomerization units present. The first two of these processes are methods of combining small molecules to make larger ones. Isomerization is a molecular rearrangement process which produces feedstock for alkylation units or high-octane isoparaffins

for gasoline blending. Prior to the 1930s, the light gas streams were burned as fuel. Now alkylation, polymerization, and isomerization have increased the gasoline yield from a barrel of crude and eliminated the wasteful burning of useful refinery byproducts.

Treating

The main purpose of treating processes is to remove the odorous and corrosive sulfur compounds from refinery products. The crude oil may be desulfurized before conversion, or the products may be desulfurized individually, depending upon the economics of the situation. Due to strict EPA regulations limiting emission of sulfur compounds into the atmosphere, many refineries are now installing desulfurizers capable of handling all boiling ranges of crude oil. These units are similar to hydrocrackers except that the catalyst performs desulfurization and denitrification without causing cracking.

In addition to sulfur removal, gasoline must also undergo other various blending and treating processes in order to meet strict product specifications. Finished gasoline is a blend of straight-run gasoline, cracked gasoline, reformed gasoline, and polymerized gasoline. To this blend, refiners add a variety of additives to improve the quality of the fuel. Among these additives are anti-knock compounds, antirust compounds, anti-icing compounds, and detergents.

Heat-Transfer Operations

Refinery energy consumption varies between 0.3 and 1.0 million Btu per barrel of crude oil input (Nydick, et al., 1976). This variability is largely due to the type of crude oil being refined and the specific process units that are employed.

Most of the heat-transfer operations that take place in petroleum refineries involve heat exchangers, fired heaters, boilers, or condensers. Heat exchangers that transfer heat from a hot product stream to a cold feed stream are assumed to be completely efficient. That is, the heat lost by the hot stream is equal to the heat gained by the cold stream. This type of heat-transfer operation will not be discussed further since there is no waste heat

to be recovered. The following sections describe the heat-transfer operations that occur in fired heaters, boilers, and condensers.

Fired Heaters

As mentioned earlier, most of the thermal energy requirements of a petroleum refinery are met with fired heaters. Basically, fired heaters consist of combustion chambers surrounded by tubes through which the process fluids flow to absorb heat. Tubes in the radiant section receive heat directly from the flame, while tubes in the convection section receive heat from the hot combustion gases. Nelson (1969) has identified eleven basic types of fired heaters that cover a range of capacities and temperature requirements.

Before 1970 fired heaters operated at a net efficiency of about 75 percent. Modern fired heaters with duties of over 20×10^6 Btu/hr can achieve a net efficiency of 90-92 percent (Sittig 1977).

Table B.5 shows the direct heat demands of the processes depicted in the representative refinery (Figure B.1). It also shows the ranges of process temperatures reported in the literature for these processes.

Table B.6 shows 1979 energy consumption for direct-heat applications in the petroleum refining industry. Refinery gas and natural gas are the preferred fuels because they burn much cleaner than fuel oil. However, many fired heaters in petroleum refineries have dual-fuel capability and can easily switch from refinery gas to fuel oil as fuel prices change.

Refinery gas is composed of methane, ethane, propane, butane, ethylene, propylene, and butylene. These low-boiling refinery products serve as petrochemical feedstocks as well as refinery fuels.

Refinery fuel oil is the residue from crude oil distillation. It is composed of high-molecular-weight compounds and has more sulfur per pound than other fuels. Typical residual fuel oils include No. 5 and No. 6 heating oils. The ash content of residual fuel oil rarely exceeds 0.2 weight percent (Babcock and Wilcox 1975).

TABLE B.5 Direct Heat Demand for Representative Refinery

No.	User Process Description	Medium	Heat Flow (10 ⁶ Btu/Hr)	Process Temperature (°F)	Outlet Conditions
1	Atmospheric Distillation	Fuel	1656.3	600-700 ^(a)	Stack Gas
2	Vacuum Distillation	Fuel	495.7	725-775 ^(a)	Stack Gas
3	Delayed Coking	Fuel	142.2	890-960 ^(a)	Stack Gas
4	Catalytic Cracking	Fuel	996.3	860-950 ^(a)	Stack Gas
5	Distillate Hydroforming	Fuel	18.9	300-700 ^(b)	Stack Gas
6	Lube Oil Processing	Fuel	114.2	390-790 ^(b)	Stack Gas
7	Asphalt Processing	Fuel	43.3	500 ^(d)	Stack Gas
8	Visbreaking	Fuel	114.4	860-890 ^(a)	Stack Gas
9	Naphtha Hydrotreating	Fuel	109.3	500-800 ^(c)	Stack Gas
10	Catalytic Reforming	Fuel	909.4	850-970 ^(a)	Stack Gas
11	Isomerization	Fuel	81.6	100-210 ^(a)	Stack Gas
12	Alkylation	Fuel	217.5	70-115 ^(a)	Stack Gas
13	Gas Recovery	Fuel	53.6	250-350 ^(e)	Stack Gas
14	Kerosene Hydrotreating	Fuel	37.8	500-800 ^(c)	Stack Gas
	TOTAL		4,990.5		

(a) United Technologies Corporation, 1980.

(b) "1982 Refining Process Handbook", 1982.

(c) Palmer, et al., 1980.

(d) Battelle, Columbus Laboratories and Battelle, Pacific Northwest Laboratories, 1976.

(e) Haynes, 1976.

Boilers

Steam is generated in a petroleum refinery in fired boilers and waste-heat boilers. About 75 percent of a refinery's total steam requirements is generated in fired boilers, and 25 percent is generated in waste-heat boilers (Nydick et al. 1976).

TABLE B.6. 1979 Energy Consumption in Direct-Heat Applications in the Petroleum Industry (Energy and Environmental Analysis, Inc., 1983)

<u>Fuel Type</u>	12	<u>%</u>
	<u>10 Btu</u>	
Refinery Gas	910	55
Natural Gas	551	33
Distillate Fuel Oil	16	1
Residual Fuel Oil	168	10
Liquefied Petroleum Gas	<u>25</u>	<u>1</u>
Total	1,670	100

Package boilers are available in sizes up to 80,000 lb/hr for pressures up to 600 psig. Built-in-place boilers are available in a full range of sizes and pressure ratings (Bland and Davidson 1967). Table B.7 shows the steam demands of the processes depicted in Figure B.1.

Fired Boilers

As shown earlier in Table B.2, refinery gas and natural gas represented almost 70 percent of the fuels used by the petroleum refining industry in 1978. Petroleum coke represented about 13 percent of the fuel usage, and residual fuel oil represented about 10 percent. Many refinery boilers have dual-fuel capability and can easily switch from refinery gas to fuel oil as fuel prices change. Refinery gas and natural gas are the preferred boiler fuels because they burn much cleaner than fuel oil or coke.

Petroleum coke is the product of delayed coking. The ash content of the coke can vary from 0.1 to 2.8 weight percent, and the sulfur content can vary from 0.5 to 7.0 weight percent, depending upon the specific coking process employed (Gaines et al. 1981).

Almost no salable petroleum coke is burned in petroleum refineries. The fuels used to generate steam include distillate fuel oil, residual fuel oil, natural gas, liquefied petroleum gas (LPG), and refinery gas. The natural gas,

TABLE B.7. Steam Demand for Representative Refinery

No.	User Process Description	Medium	Pressure (psig)	Temp. (°F)	Heat Content (Btu/lb)	Mass Flow (10 ³ lb/hr)	Heat Flow (10 ⁶ Btu/hr)	Outlet Conditions
1	Atmospheric Distillation	Steam	385	500	1245	234.4	259.5	45% Cond. @ 170°F (138 Btu/lb)
2	Vacuum Distillation	Steam	385	500	1245	121.1	134.1	45% Cond. @ 170°F (138 Btu/lb)
3	Delayed Coking	Steam	385	500	1245	5.3	5.9	45% Cond. @ 170°F (138 Btu/lb)
4	Catalytic Cracking	Steam	385	500	1245	442.5	489.8	45% Cond. @ 170°F (138 Btu/lb)
5	Distillate Hydroforming	Steam	385	500	1245	(13.5)	(14.9)	45% Cond. @ 170°F (138 Btu/lb)
6	Lube Oil Processing	Steam	385	500	1245	10.5	11.6	45% Cond. @ 170°F (138 Btu/lb)
7	Asphalt Processing	Steam	385	500	1245	9.4	10.4	45% Cond. @ 170°F (138 Btu/lb)
8	Visbreaking	Steam	385	500	1245	17.6	19.5	45% Cond. @ 170°F (138 Btu/lb)
9	Naphtha Hydrotreating	Steam	385	500	1245	20.3	22.5	45% Cond. @ 170°F (138 Btu/lb)
10	Catalytic Reforming	Steam	385	500	1245	111.0	122.9	45% Cond. @ 170°F (138 Btu/lb)
11	Isomerization	Steam	385	500	1245	87.4	96.8	45% Cond. @ 170°F (138 Btu/lb)
12	Alkylation	Steam	385	500	1245	136.1	150.7	45% Cond. @ 170°F (138 Btu/lb)
14	Kerosene Hydrotreating	Steam	385	500	1245	12.8	14.2	45% Cond. @ 170°F (138 Btu/lb)
TOTALS						1,194.9	1,323.0	
Mechanical (Total for All Processes)								
	Shaft Power	Steam	705	760	1379	132.9	164.9	Cond. @ 170°F (138 Btu/lb)
	Elec. Gen. @ 60% Turb. Eff.	Steam	705	760	1379	229.7	371.9	Cond. @ 170°F (138 Btu/lb)
TOTALS						432.6	536.8	

LPG, and refinery gas are sometimes fired as a mixture. Oil is probably used more often as a boiler fuel than as a fuel for fired heaters (Nydick et al. 1976).

Even though the ash content of residual fuel oil rarely exceeds 0.2 weight percent, it can still cause significant fireside fouling and corrosion problems in boilers. Compounds of vanadium, sodium, and sulfur have been found in almost every deposit in boilers fired by residual fuel oil. The fouling rates and the thickness of the deposits have been correlated with the sodium-vanadium ratio in the fuel oil, as well as with the velocity and temperature of the flue gases and the tubewall temperatures (Babcock and Wilcox 1975).

Waste-Heat Boilers

Waste-heat boilers in petroleum refineries recover waste heat from process streams or from stack gases leaving a fired heater or catalyst regenerator. Frequently, CO (carbon monoxide) boilers are installed in the regeneration section of fluid catalytic cracking units (FCC). When coke is burned from the FCC catalyst in the regeneration operation, the catalyst reaches a temperature of 1100-1200°F. The hot offgas from this combustion contains about 8-10 percent carbon monoxide. This gas is burned with about 10 percent supplemental fuel in a waste-heat boiler (Nydick et al. 1976). Catalyst fines suspended in the flue gas from a fluid catalytic cracker foul the tube walls of the CO boiler, hindering heat transfer and necessitating shutdown every five months for cleaning (Farrar Undated).

Waste-heat boilers are sometimes employed to generate steam from the following sources of waste heat: fluid coking plants, sulfur recovery plants, hydrogen manufacturing plants (steam-methane or steam-naphtha reformers), the exhaust from gas turbines, recirculating sidecuts from distillation columns, and high-temperature product streams (Nydick et al. 1976).

Condensers

A petroleum refinery uses large volumes of cooling water. It has been estimated that 80 to 85% of the total water required by a refinery is for cooling if cooling towers are used for water conservation. Most refineries use

open circulating cooling systems. Once-through cooling is rare; it is only used at a few coastal refineries that were designed to use seawater (Kemmer 1979).

The separation and conversion processes described earlier require large amounts of heat. In the interest of energy conservation, the hot product streams are often used to preheat the cold feed streams in feed-effluent exchangers. If additional cooling of the hot product streams is required for either process-related or safety-related reasons, it is provided by cooling water.

Cooling water is used extensively to condense the overhead vapors from distillation columns. Barometric condensers are used on some vacuum distillation columns, resulting in intimate mixing of hydrocarbons, steam, and cooling water. Newer refineries use surface condensers (shell-and-tube exchangers) in which the cooling water and the condensate are not in direct contact (Kemmer 1979).

Most condensers and coolers used in petroleum refineries are shell-and-tube exchangers. The cooling water is normally on the tube side and the vapor stream is on the shell side. Thus, any scale or other deposits will occur in the tubes, where cleaning is easier. Also, the vapor will pass through the shell without excessive pressure drop (Bland and Davidson 1967).

Water-side deposits in overhead and side-product condensers and coolers may contain dead algae from the cooling tower, iron oxide, oil from contamination, carbonates, silica or silicates, and phosphates from cooling-water-treatment chemicals. Just about any combination of these can be expected on the water side (Bland and Davidson 1967).

Waste Heat Streams

According to a 1976 Thermo Electron study (Nydick et al. 1976), there are only two significant potential sources of waste heat in a petroleum refinery: (1) hot flue gases from fired heaters, and (2) hot liquid product streams that are currently cooled to safe storage temperatures by water or air. Other studies have come to the same conclusion, as discussed below.

Types and Quantities of Waste Heat

In 1979 Gulf Research and Development Company published a User's Guide that contains a step-by-step procedure for preparing an energy profile at any petroleum refinery (Maier et al. 1979). It explains how to perform a detailed refinery energy balance showing all inputs and losses for the total refinery and for the individual processes. Gulf conducted actual studies on the operating equipment in its Alliance refinery. Table B.8 shows the Alliance refinery energy profile. At the time that the data were taken, about 74 percent of the energy losses at this refinery were from heater and boiler stacks and from air

TABLE B.8. Alliance Refinery Energy Profile
(Maier et al. 1979)

<u>Energy Input to Plant</u>			<u>Energy Output as Losses</u>		
	<u>10³ Btu/ of Oil Charge</u>	<u>%</u>		<u>10³ Btu/ of Oil Charge</u>	<u>%</u>
Natural Gas	102	18	Heater and Boiler Stacks	105	19
Refinery Gas	270	48	Air Coolers	174	31
Electricity	12	2	Water Coolers	137	24
Petroleum Coke	117	21	Steam System	18	3
Feed Streams	12	2	Electrical System	5	1
Exothermic Reactions	14	3	Radiation and Convection	21	4
Oil Charge Loss	<u>32</u>	<u>6</u>	Products and Wastes	10	2
	559	100	Endothermic Reactions	38	7
			Oil and Gas Losses	36	6
			Imbalance	<u>15</u>	<u>3</u>
			Total	559	100

and water coolers. Of course, only part of this energy could be recovered with existing technology. A large part of it is low-level heat that would require the development of advanced waste-heat-recovery techniques.

Latour and Menningman (1981) assessed the potential for waste heat recovery in the petroleum refining industry for the U.S. Environmental Protection Agency. They found that the major sources of waste heat in petroleum refineries are as follows:

- (1) cooling and condensing waters used for heater wall cooling and process stream condensing
- (2) flue gases from fired heaters
- (3) air cooling of recycle and product streams
- (4) process wastewaters.

Through a combination of industry correspondence and literature review, they obtained quantitative and qualitative data on these waste streams. Their data show that petroleum refineries discharge about 66.3 percent of their total energy consumption as waste heat. About 53 percent of this waste heat is in non-contact cooling water, 37 percent is in flue gases, and 10 percent is discharged by air cooling of process streams.

Using Latour and Menningman's figures, we can conclude that of its 3 quads/year total energy consumption, the petroleum refining industry rejects about 2 quads of waste heat per year. About 1.1 quad per year of this waste heat is in non-contact cooling water, about 0.7 quad is in flue gases, and about 0.2 quad is discharged by air cooling of process streams.

Another reference (Sittig 1977) states that up to 80 percent of the energy consumption of a petroleum refinery is for fired heater and boiler fuels. Stack gases leave the furnaces at temperatures ranging from 400⁰F to above 1000⁰F, representing the major energy losses from the heaters and boilers. Radiation and convection from the fireboxes account for losses of only about 3 percent.

Temperature Ranges of Waste Heat

Table B.9 shows the temperature ranges reported in the literature for various petroleum refining waste heat streams. The flue gas streams contain high-temperature waste heat that is probably worth recovering. However, the cooling water, air, and process wastewater streams contain low-temperature waste heat that is probably not worth recovering. The following section presents data on the compositions of various refinery flue gas streams.

Flue Gas Compositions

In 1955 a study was undertaken to determine the quantity and composition of atmospheric emissions from oil refineries in Los Angeles County (U.S. Department of Health, Education, and Welfare 1960). At that time there were 18 refineries in the county with a total combined capacity of over 700,000 barrels of crude oil per day. Table B.10 shows the emissions from 14 fired heaters

TABLE B.9. Petroleum Refining Waste Heat Streams

<u>Source</u>	<u>Temperature</u>
Flue Gases ^(a)	
Crude Distillation	700-900°F
Catalytic Reforming	700-950°F
Coking	800-1000°F
Hydrocracking	700-900°F
Hydrogen Production	600-1000°F
Others	300-1000°F
Cooling Water ^(b)	150-250°F
Air Cooling of Process ^(b)	
Streams to Storage	250-350°F
Process Wastewater ^(c)	95-125°F

(a) Nydick et al. 1976.

(b) Haynes 1976.

(c) Latour and Menningman 1981.

TABLE B.10. Emissions from Boilers and Process Heaters
in Los Angeles County Refineries (U.S.
Department of Health, Education and Welfare
1960)

	<u>Fuel Gas</u> <u>(Lb/10³ Ft³)</u>	<u>Fuel Oil</u> <u>(Lb/Gal)</u>
Oxides of Nitrogen (As NO ₂)	0.23	0.068
Aldehydes (as HCHO)	0.0031	0.0006
Hydrocarbons (as Hexane)	0.026	0.0034
Organic Acids (as Acetic Acid)	0.014	0.011
Particulate Matter	0.021	0.020

Sulfur Dioxide	72 tons/day total for LA County
Sulfur Trioxide	2 tons/day total for LA County

and 10 boilers in the Los Angeles County refineries. Table B.11 summaries the emissions from catalytic cracking unit regenerator stacks in Los Angeles County refineries.

TABLE B.11. Emissions from Catalytic Cracking Unit Regenerator
Stacks in Los Angeles County Refineries (U.S.
Department of Health, Education, and Welfare 1960)

Hydrocarbons	87 - 1655 PPM
Sulfur Dioxide	65 - 2190 PPM
Ammonia	29 - 675 PPM
Aldehydes	3 - 177 PPM
NOX	7 - 394 PPM
Cyanides	0.07 - 0.94 PPM
Carbon Monoxide	0 - 7.8 Vol. %
Sulfur Trioxide	2.7 tons/day total for LA County
Total Particulate Matter	5.4 tons/day total for LA County

In 1976 Arthur D. Little, Inc. did a study of the environmental impacts of potential new process technology in energy-intensive industries for the EPA's Industrial Environmental Research Lab (Arthur D. Little, Inc. 1976). To simulate existing U.S. petroleum refineries, this study developed three cluster models to represent regional characteristics and processing configurations for the East Coast, Gulf Coast, and West Coast. Quantitative data on the sources and composition of airborne emissions from these three model refineries are presented in Tables B.12, B.13, and B.14.

TABLE B.12. Major Airborne Emissions from East Coast Model Refinery

<u>Process/Pollutants</u>	<u>Particulates (lb/day)</u>	<u>SO_x (lb/day)</u>	<u>Hydrocarbons (lb/day)</u>	<u>NO_x (lb/day)</u>	<u>Aldehydes (lb/day)</u>	<u>Ammonia (lb/day)</u>
• Combustion (heaters and boilers)	8,979	45,200	2,671	38,085	373	Negligible
- Gas-fired	881	----	1,321	10,129	132	Negligible
- Oil-fired	8,098	----	1,350	27,956	241	Negligible
• Fluid catalytic cracking	2,780	52,800	13,684	4,416	1,182	3,359
• Vacuum distillation	Negligible	Negligible	8,931	Negligible	Negligible	Negligible
• Claus plant	----	2,280	----	----	----	----
Total emissions	11,759	100,280	25,286	42,501	1,555	3,359

Source: Arthur D. Little, Inc., 1976.

TABLE B.13. Major Airborne Emissions from Gulf Coast Model Refinery

<u>Process/Pollutants</u>	<u>Particulates (lb/day)</u>	<u>SO_x (lb/day)</u>	<u>Hydrocarbons (lb/day)</u>	<u>NO_x (lb/day)</u>	<u>Aldehydes (lb/day)</u>	<u>Ammonia (lb/day)</u>
• Combustion (heaters and boilers)	9,855	27,600	2,798	40,999	398	Negligible
- Gas-fired	867	----	1,300	9,969	130	Negligible
- Oil-fired	8,988	----	1,498	31,030	268	Negligible
• Fluid catalytic cracking	3,585	8,400	17,644	5,694	1,524	4,331
• Vacuum distillation	Negligible	Negligible	9,854	Negligible	Negligible	Negligible
• Claus plant	----	680	----	----	----	----
Total Emissions	13,440	36,680	30,296	46,693	1,922	4,331

Source: Arthur D. Little, Inc., 1976.

TABLE B.14. Major Airborne Emissions from West Coast Model Refinery

Process Pollutants	Particulates (lb/day)	SO _x (lb/day)	Hydrocarbons (lb/day)	NO _x (lb/day)	Aldehydes (lb/day)	Ammonia (lb/day)
• Combustion (heaters and boilers	10,765	58,800	3,055	44,769	434	Negligible
- Gas-fired	945	----	1,418	10,868	142	Negligible
- Oil-fired	9,820	----	1,637	33,901	292	Negligible
• Fluid catalytic cracking	1,708	7,600	8,404	2,712	726	2,063
• Vacuum distillation	Negligible	Negligible	10,309	Negligible	Negligible	Negligible
• Claus plant	----	3,680	----	----	----	----
Total emissions	12,473	70,080	21,763	47,481	1,160	2,063

Source: Arthur D. Little, Inc., 1976.

APPENDIX C
PRIMARY METAL INDUSTRIES - SIC 33

APPENDIX C
PRIMARY METAL INDUSTRIES - SIC 33

The production of primary metal products entails some of the most energy intensive unit operations in the manufacturing sector. SIC 33 accounts for about 20% of the energy consumed in the manufacturing sector and ranks second in energy consumption at the two-digit SIC level. The principal industries within this classification, and the ones that will be discussed in more detail below, are blast furnaces and steel mills (SIC 3312), gray iron foundries (SIC 3321), primary copper (SIC 3331), and primary aluminum (SIC 3334). These industries are ranked according to their purchases of fuels and electricity in Table C.1. The primary metal industries are characterized by a large number of high-temperature, directly heated unit operations. Each industry typically has several unit operations operating in excess of 1000°F. Operating temperatures in the range of 2500°F are quite common. Waste energy streams are typically either high-temperature stack gases or low-temperature cooling or process waters. Various types of furnaces are the most common sources of both high- and low-temperature waste energy streams. Combustion product stack gases exit the furnace after heating a charge. Cooling water is usually employed to cool furnace walls and other equipment subject to extremely high temperatures.

A more specific description of the manufacturing processes, the major heat transfer operations, and the waste energy streams is provided in the following subsections.

TABLE C.1 Ranking of Primary Metal Industries by Energy Purchases
(Bureau of Census 1980)

<u>SIC</u>	<u>Name</u>	<u>Energy Purchased (10¹² Btu)</u>	<u>Percent of SIC 33 Energy Purchases</u>
3312	Blast furnaces & steel mills	1282	56.3
3334	Primary aluminum	360	15.8
3321	Gray iron foundries	111	4.9
3331	Primary copper	53	2.3

BLAST FURNACES AND STEEL MILLS - SIC 3312

According to the 1977 Census of Manufactures (U.S. Department of Commerce 1981), there were 504 establishments involved in some phase of the production of iron and steel at that time. The annual shipments for 1977 amounted to 91 million tons, half of which were produced by 35 fully integrated steel mills. In recent years, annual production has fluctuated around 100 million tons per year; currently, the annual production rate is about 85 million tons of steel (Wall Street Journal, Sept 7, 1983). The relative magnitude of energy consumption and potential for waste heat recovery in the iron and steel industry cannot be overemphasized. Blast furnaces and steel mills consume over 50% of the fuels and electricity purchased by the primary metal industries, but this figure does not include fuels produced and consumed at the same establishment, fuels used as raw materials, or fuel converted into other fuel types such as coal converted to coke. Inclusion of these additional energy consumption components more than doubles the total amount of energy consumed in SIC 3312 to 2.7 quads (Bureau of Census 1980).

Process Description

An integrated steel mill is a rather complex combination of unit operations that transform iron ore and other raw materials into finished steel products. The major steel mill operations are materials preparation (sintering and pelletizing), coking, blast (reduction) furnace, steel making furnaces (open hearth, electric, basic oxygen), casting (continuous or ingot casting coupled with a roughing mill), rolling and finishing. These operational steps are shown in Figure C.1.

Sintering and pelletizing serves to improve iron ore permeability and gas-solid content in the blast furnace. Iron ore fines, limestone fines and coke are sintered on a traveling grate to produce lumps about the size of golf balls. Similarly sized pellets are produced in a balling drum from iron ore and bentonite. The pellets are then coated with pulverized coal and ignited on a traveling grate furnace. Coke is prepared for the blast furnace by the destructive distillation of coal in the coke ovens. The coal is heated externally by coke oven gas produced from previous batches. Iron ore, sinter

FIGURE C.1 Major Steel Mill Operations

pellets, coke and fluxing agents are charged to the blast furnace where iron oxides are reduced to pig iron. Coke is both the reducing agent and the major supplier of heat to melt the iron. The object of steel making is to oxidize

excessive amounts of carbon, silicon, manganese, phosphorus, and other impurities from pig iron and scrap charges. Over the years, the efficiency of the basic oxygen furnace caused the demise of the open hearth furnace as the principal steelmaking operation. Electric furnaces are used principally for recycling steel scrap.

Molten steel from the steelmaking furnaces would be cast into ingots and subsequently rolled into blooms, billets, and slabs in a conventionally operated mill. The energy costs associated with ingot soaking have pushed mill operators toward continuous casting in recent years. In the final steps of an integrated steel mill, blooms, billets, and slabs are distributed to separate rolling and finishing lines to produce plates, sheets, pipes and other structural steel products.

Heat Transfer Operations

An integrated steel mill is one of the largest energy-consuming industrial processes. The significant unit operations from a heat transfer standpoint are coking, agglomeration, blast furnace, open hearth furnace, soaking, reheating, and annealing. Each of these unit operations operate through direct-contact heat exchange, except for coking. Process details are discussed in the following paragraphs.

Coking

Coke is required in the blast furnace for the reduction of iron bearing material to pig iron. Coke is produced from coal via the by-product or retort method. A coking oven is a long, narrow, refractory lined chamber, typically 30 to 40 feet long, 10 to 20 feet high, and 15 to 20 inches wide. A coking plant will usually have 50 to 60 ovens operating together in what is known as a battery. Pulverized coal is charged to the coking ovens, which are then sealed. Previously generated coke oven gas is burned to externally heat the chamber. The by-products (coke oven gas, tars, oils) are recovered separately for their energy content. After about 18 hours, the coal has fused into coke; the doors of the oven are opened; and a ram pushes the coke into a quenching car. The coke is quenched with water and allowed to cool before being charged to the blast furnace. A drawing of a coke oven is shown in Figure C.2.

FIGURE C.2 Coke Oven (Reding et al. 1975)

An average-sized coke oven has a capacity on the order of 500 ft³ of coal. With 50 or 60 ovens per battery, the throughput per battery would be in the range of 1200 tons per day. Energy consumption varies from 850 to 1050 Btu/pound of finished steel. This works out to approximately 1 Mwt per oven. The thermal efficiency of coke ovens is close to 96%, according to a report by Darby and Arons (1979).

Agglomeration

Agglomeration is the process of preparing iron-bearing materials for the blast furnace. The object is to form the iron bearing material into shapes and sizes that will be permeable to gas flow and yet not be blown out of the furnaces. Two processes are used for agglomerating, depending on the type of feedstock. Sintering occurs on a traveling grate in which iron ore fines have

been mixed with coke breeze and limestone fines. The mixture is ignited at the front end of the grate and as it moves down the pathway, air is drawn past the grate to keep the coke burning. The heat from the burning sinters the mixtures into lumps that are more-or-less golf ball sized. The pelletizing operation is principally the same, except that pellets are first manufactured in a balling drum and coated with coal prior to being sent to the traveling grate. Sintering and pelletizing operations are depicted in Figures C.3 and C.4.

Larger sintering plants have capacities ranging up to 350 tons per hour; pelletizing plants are somewhat smaller. Energy consumption for these two operations runs between 600 and 700 Btu/pound of finished steel.

Blast Furnace

The blast furnace is the central piece of equipment in an integrated steel mill. In this operation, iron oxides are reduced to iron in the form of pig

FIGURE C.3 Sintering Machine (Reding et al. 1975)

FIGURE C.4 Pelletizing Machine (Reding et al. 1975)

iron, which contains 4 to 5% carbon and other impurities. Iron ore, sinter, and pellets are charged to the top of a blast furnace along with coke, limestone, and smaller quantities of other fluxes. Hot air, which may often be enriched with oxygen, is injected near the bottom of the furnace through holes called tuyeres. The hottest portion of the furnace is at the bottom combustion zone where temperatures may reach 3000°F. Hot combustion gases rise through the furnace to preheat recent charges near the top of the furnace. The temperature differential from top to bottom divides the furnace into several zones. As the preheated charge descends, it begins partial reduction when temperatures exceed 1000°F. Direct reduction occurs when the temperature exceeds 2000°F. As the charges descend to the bottom, where temperatures are near 3000°F, the final reduction and slag-forming reactions occur. Molten iron and slag are then periodically tapped from the hearth.

The blast furnace is a relatively large piece of equipment with a height ranging up to 100 feet and a diameter of 15 to 30 feet at the hearth. A drawing of a blast furnace and accompanying equipment is shown in Figure C.5. Modern blast furnaces typically have a production capacity varying around 100 tons of pig iron per hour. Approximately 0.60 tons of coke are consumed per ton of finished steel. Coke is both the reducing agent and the principal

FIGURE C.5 Blast Furnace (Reding et al. 1975)

source of thermal energy. Lesser amounts of other fuels and materials add between 1000 and 3000 Btu/lb of finished steel, depending on the operation and whether the energy content of pellets, sinter, ore, and limestone are included with the relatively small amounts of fuel oil, natural gas, coke oven gas, blast furnace gas, electricity, and steam that are consumed in this unit operation. A blast furnace requires these large quantities of energy to drive the endothermic reduction reaction and to melt the charge. The heat of reaction alone is 3000 Btu/lb of finished steel. The overall thermal efficiency of the blast furnace is reported by Darby and Arons (1979) to be 67%.

Steelmaking

Although the open hearth furnace is declining somewhat in importance as a steelmaking process, it is the most significant in terms of energy consumption. In general, the pig iron produced from the blast furnace is high in carbon content and other impurities. The principal object of the steelmaking process is to remove these impurities and reduce the carbon content from 4 to 5% down to the range of 0.5%, depending on the grade of carbon steel required. Pig iron, steel scrap, and fluxing agents are charged to the bath or hearth of the open hearth furnace and are heated from above by a flame. The fuel, usually either natural gas, fuel oil, or coke oven gas, and air are alternately injected from opposite sides of the furnace. The combustion products exit through a brick checker works that serves to preheat the fuel and air when flow is reversed. Although the impurities in the pig iron are oxidized by excess air or oxygen injections, the open hearth furnace is not designed to be energy self-sustaining. The prospects of lower energy consumption and higher production rates have driven the steel industry toward the basic oxygen furnace. Because the energy source is supplied externally, the open hearth furnace does have more flexibility in the feed mix, however. An open hearth furnace is shown in Figure C.6.

The open hearth furnace is a batch operation. Up to 10 hours are required per heat, depending on the temperature and chemical content of the charge. The typical furnace has a capacity of 200 tons (per batch) and consumes 1700 Btu/lb of finished steel.

FIGURE C.6 Open Hearth Furnace (Reding et al. 1975)

Soaking Pits

Unless continuous casting is used, steel ingots must be heated in a soaking pit prior to being rolled. Liquid steel from the steelmaking furnaces is most commonly poured into ingots and allowed to cool prior to production of semi-finished steel products. Continuous casting involves the direct production of semi-finished steel from liquid steel. This production path is more direct and consumes less energy, but is much more complicated. Steel ingots are heated in the soaking pits to between 2200 and 2500⁰F. Ingots exiting the soaking pit should have achieved a uniform temperature and be soft enough for the rolling operations. A drawing of a soaking pit is shown in Figure C.7.

Soaking is a batch operation in which equipment size and heating rates vary drastically. Hearth areas range from 10 to 300 ft² and heating rates can be anywhere from 2 to 250 lb per ft² per hour according to U.S. Steel

FIGURE C.7 Two-Way-Fired Soaking Pit (Reding et al. 1975)

(1971). A typical soaking pit might process 5 tons of steel per hour. Soaking time can be as high as 8 to 12 hours for cold ingots. If ingots are charged hot, the time will obviously be shortened. Despite the large number of factors affecting soaking pit performance, several sources (BCL 1975; Reding et al.; 1975; Darby and Arons 1979) indicate that energy consumption in the soaking pit is close to 750 Btu/lb of finished steel.

Reheating Furnaces

After leaving the soaking pits, ingots are rolled into semi-finished products called blooms, slabs, and billets. At this point in the steel mill, the semi-finished products are reheated so they can be rolled into finished products such as pipes, plates, sheets, and structural steel. As opposed to the soaking furnaces, reheat furnaces are usually designed for continuous operation and have a much higher throughput per hour. The heating ratio depends on the number of heating zones; 100 lb/hr-ft² of hearth and 150 lb/hr ft² of hearth are common for two- and three-zone furnaces, respectively. Continuous reheating furnaces range in size from 50 to 250 ton/hr. Those reheat furnaces that are batch oriented have capacities in the range of 5 to 25 ton/hr. Energy requirements average between 1400 and 1500 Btu/lb of finished steel product. According to Arons and Darby (1979) reheat furnaces are only 25 to 30%

thermally efficient, despite employing some recuperation. A typical reheat furnace is shown in Figure C.8.

Annealing Furnaces

A portion of the products leaving a steel mill are heat treated in an annealing furnace to relieve stresses within the metal. Annealing furnaces have historically been batch-oriented, but continuous furnaces are occasionally employed. Annealing occurs at temperatures in the range of 1200 to 1500°F as opposed to the higher temperatures associated with soaking and reheating. Batch periods may run as long as 1 to 2 days with the charge varying from 40 to 400 tons. Continuous furnaces operate at production levels of 5 to 15 tons per hour. Reported fuel consumption varies between 300 and 1000 Btu/lb of finished steel. As was the case for reheat furnaces, annealing furnaces are not thermally efficient. A value of 30% is reported in Industrial Heating (1981). Figure C.9 depicts an annealing furnace for coiled strip.

Waste Energy Streams

In an industry that consumes as much energy as the steel industry it is not surprising that enormous quantities of energy are rejected that could

FIGURE C.8 Reheating Furnace (Reding et al. 1975)

FIGURE C.9 Annealing Furnace For Coiled Strip (Reding et al. 1975)

potentially be recovered. A lot of this energy is in the form of flue gases from the various types of furnaces described in the previous section. An equal amount of energy is rejected to cooling water streams that circulate through the high-temperature furnaces. Waste energy streams are described for individual unit operations and the industry as a whole in the following subsections.

Coking

The steel industry does a good job of capturing coke oven gas for consumption at the coking plant or in other plant operations. Only relatively small amounts of coke, coke oven gas, and other by-products are lost or unrecovered. The coke oven flue gas (700⁰F, 300 Btu/lb of finished steel) offers some potential for heat recovery. The greatest potential for waste heat recovery in the coking plant lies with the quenching of coke. Currently, coke is quenched with water after it is discharged from the oven. The energy is dissipated to the environment without an attempt to recover it. Alternatively, the coke could be quenched with a cool, inert gas in a process called dry quenching. Heat recovery from the inert gas could yield 900 to 1000 lbs of high pressure steam per ton of finished steel.

Agglomerating

Additional waste heat recovery from the sintering and pelletizing operations does not appear to be attractive. Although the exhaust gases reject 400 to 500 Btu per pound of steel product, the flue gas temperatures are only in the range of 250 to 300⁰F.

Blast Furnace

Industry currently does a good job of collecting the blast furnace gases produced from this operation, but could potentially do better by capturing the thermal as well as chemical content (100 Btu/scf) of the off-gas. Blast furnace gas and associated dust comes off the top of the blast furnace at temperatures in excess of 500⁰F. The gas is currently cleaned and cooled prior to being distributed for consumption around the plant. Recovery of this thermal energy may be possible if abrasive-resistant equipment can be employed. Another candidate for waste heat recovery at the blast furnace is the molten slag that is periodically tapped from the furnace. This slag has a temperature approaching 3000⁰F with an energy flow rate of 250 Btu/lb of finished steel.

Basic Oxygen Furnace

Many reports identify the basic oxygen furnaces (BOF) off-gases as a candidate for waste heat recovery (A.D. Little 1975; BCL 1975; Palmer et al. 1980; Reding et al. 1975). The gas comes off the BOF at about 2300⁰F and has an energy content of 350 Btu/scf at that point and 200 to 250 Btu/scf after collecting and cooling. Approximately 150 to 250 Btu/lb of finished steel could be recovered. The erosive nature of the particulates contained in the off-gas may inhibit thermal energy recovery. The composition of the particulates in the gas stream is identified in Table C.2.

Soaking, Reheating, and Annealing Furnaces

Waste heat recovery in soaking, reheating, and annealing furnaces has received much attention. The relatively low thermal efficiencies (25 to 30%) identified in the previous section for these operations points out the need for

TABLE C.2 BOF Off-Gas Dust Composition

<u>Component</u>	<u>Weight %</u>
FeO	1.6
Fe ₃ O ₄ , Fe ₂ O ₃	57.4
CaO	2.0
SiO ₂	1.0
Other	38.0

advanced waste heat recovery techniques. Ruskin and Bonner (1979) estimated up to 300 Btu/lb of finished steel could be recuperated from soaking pits through the use of advanced equipment. Darby and Arons (1979) reported that 10% of steel soaking pits had no recuperators. Ceramic materials are expected to enhance the recuperative capabilities in the future.

According to Gerlaugh et al. (1979), the potential for applying advanced energy recovery techniques also applies to reheating furnaces where only one-half of the furnaces had recuperators. Here the energy recovery potential was estimated to be 400 Btu/lb of finished steel. An additional 500 Btu/lb of steel is rejected to the cooling water in the furnace skid pipes.

Waste Heat in Process and Cooling Waters

The waste heat recovery potential in process and cooling water streams is often overlooked because of extremely low energy density. Although the energy density is low, the quantities are immense. Almost all unit operations in a steel mill use water for either processing or cooling. The energy availability for process and cooling water streams is identified in Tables C.3 and C.4.

Estimated Waste Heat Discharges by Integrated Steel Mills

A report by Latour and Menningman (1981) has identified the sources, quality, and quantity of waste heat discharges in the energy-intensive industries. The data presented in their report identify the extremely large quantity of waste heat that is rejected by the iron and steel industry. Equal amounts of

TABLE C.3 Energy Content in Process Waste Water Streams
(Latour and Menningman 1981)

<u>Unit Operation(s)</u>	<u>10⁶ Btu/Ton of Steel</u>
Blast furnace & sintering	0.85
Vacuum degassing	0.17
Continuous casting	0.21

TABLE C.4 Energy Content in Cooling Water Streams
(Latour and Menningman 1981)

<u>Unit Operation</u>	<u>10⁶ Btu/Ton of Steel</u>
Coking	0.53
Blast furnace	0.31
Power plant	0.73
Basic oxygen furnace	0.37
Open hearth furnace	0.42
Rolling & finishing	0.69
Electric furnace	0.33
Vacuum degassing	0.05
Continuous casting	0.15

waste energy in the form of gases and water combine to a total of 1.4 quads on an annual basis. The report also points out that large amounts of waste heat are contained in process and cooling water streams. Most of these water streams have temperatures in the range of 100 to 125⁰F. If heat pumps or some other innovative technology could take advantage of these low energy density sources, the potential for waste heat recovery would be enormous. Table C.5 identifies the quantity of waste heat in the blast furnace and steel mill industry according to several temperature ranges.

TABLE C.5 Quantity and Quality of Waste Heat in the Blast Furnace and Steel Mill Industry (Latour and Menningman 1981)

<u>Temperature Range</u>	<u>10¹² Btu</u>
125	706
125-500	294
500-1000	286
1000-1500	77
1500-2000	47
2000	9

GRAY IRON FOUNDRIES

The gray iron foundry industry is relatively diffuse when compared to other industries within the primary metals sector. As of 1977, 984 establishments were engaged in some activity related to the production of gray iron products (1977 Census of Manufactures). Almost 300 of these had 100 or more employees, which together accounted for approximately 90% of the annual production of 13 million tons. In recent years production has fluctuated between 10 and 15 million tons per year. As is the case for most primary metal industries, a gray iron foundry has several high temperature, energy-consuming operations. This equipment and its energy charges and discharges will be discussed in the following subsections.

Process Description

The central piece of equipment in a gray iron foundry is the furnace, which can either be a cupola, electric induction, or electric arc type. The furnace charge consists of iron scrap, pig iron, flux, and other metallic scrap. Other major operations include casting, mold making, and cleaning and finishing. Some products are heat treated as a final processing step. These steps are shown in Figure C.10.

Purchased scrap iron is the major source of raw material for gray iron foundries; other sources include pig iron, scrap steel, and various ferroalloys (United Technologies Corporation 1980). About 75% of the metal feedstock is

FIGURE C.10 Major Iron Foundry Operations

melted in cupola furnaces, with the balance melted in either the electric induction or electric arc furnaces. Electric furnaces are usually employed where higher quality castings are required because product composition is more easily controlled than in a cupola. Malleable iron castings are almost always melted electrically. Castings are produced by pouring or injecting molten iron into a mold. After the casting has cooled, it is removed from the mold and cleaned by sandblasting, scraping, and other finishing operations. The cast product may then be heat treated prior to shipment. According to Darby and Arons (1979), 10% of the gray iron, 50% of the ductile iron, and all of the malleable iron require heat treating. The molds are manufactured from silica sand, which is bonded together by binding materials such as bentonite or sodium silicates. Mold preparation is a major activity in a foundry.

Heat Transfer Operations

The iron melting furnaces are the dominating heat transfer operations in a gray iron foundry. This is the most energy-intensive unit operation in a

foundry and accounts for about half of the total energy consumption. Approximately 75% of the steel is melted in cupolas and the balance is done in electric furnaces. Both of these directly heating operations are discussed in more detail below.

Cupola Furnace

The cupola is a vertical cylindrical steel furnace lined with refractory. This is the same type of furnace that is used for reducing iron ore to pig iron in the steel industry, only smaller. Pig iron, scrap iron, and other iron alloys are charged with coke, limestone, and other fluxing agents at the top of the furnace. Hot air is blown in at the bottom of the furnace through holes called tuyeres. Combustion of the coke provides the energy for melting the charge. Liquid metal is withdrawn near the bottom of the furnace at temperatures of about 2700°F.

Cupola furnaces in a gray iron foundry typically are sized to melt 10 tons of steel per hour as compared to 100 tons per hour for a blast furnace. Cupola melters range in height up to 50 feet with diameters typically 8 to 12 feet. Coke provides the majority of the energy for melting. Natural gas or fuel oil may also be injected through the tuyeres to provide an additional energy source. The energy consumed for melting is about 4×10^6 Btu/ton. Because about one-half of the castings are scrapped and returned to the furnace, the energy consumed per net product is about 8×10^6 Btu/ton.

Electric Furnaces

Electric furnaces are either the induction or arcing type, with the former being preferred in the gray iron foundry industry. An induction furnace supplies heat to the charge by changing the electrical flux in an induction coil that wraps around the furnace shell. When an alternating current is supplied to the coil, a rapidly changing magnetic field is set up that causes secondary current to form in the metal charge. The resistance of the metal converts the electric current to heat and melts the charge. In an electric arc furnace, heat is generated as current flows through the air gaps between carbon electrodes and the metal.

Electric furnaces are more efficient than cupolas, although they obviously consume a more costly energy source. Energy consumption for an electric furnace is about 2×10^6 Btu/ton melted. Again, this figure would double if the energy basis were per ton of cast product.

Waste Heat Streams

Relatively little is mentioned in the literature regarding waste heat recovery potential in the gray iron foundry industry. The industry could benefit most by reducing the percentage of castings which must be recycled. There appear to be opportunities for better management of flue gases from the melting furnaces and various other operations.

According to Latour and Menningmann (1981), the single largest source of waste heat in a gray iron foundry is the flue gas emanating from the scrap preparation process. Oil must be removed from scrap by heating it. The amount of waste heat from this operation was estimated to be nearly 31×10^{12} Btu per year. This represents 60% of the total flue gas waste heat being discharged.

The waste heat contained in furnace cooling waters and flue gas scrubbing waters was also estimated by Latour and Menningmann (1981). These estimates are summarized in Table C.6. Although cooling waters and other process water streams contain substantial amounts of waste heat, their low temperatures (125°F) make energy recovery difficult. A summary of the total waste heat discharged by gray iron foundries is given in Table C.7.

PRIMARY COPPER

Primary copper is one of the most heavily concentrated industries in the primary metals or any other sector. Only 27 establishments were involved in

TABLE C.6 Water Source Waste Heat in Melting Furnaces

<u>Flow Stream</u>	<u>10^6 Btu/ton Melted</u>
Cupola cooling	.31
Electric furnace cooling	.39
Flue gas scrubbing	.67

TABLE C.7 Quantity and Quality of Waste Heat in
the Gray Iron Foundry Industry

<u>Temperature Range</u>	<u>10¹² Btu</u>
<125	22
125-500	21
500-1000	12
1000-1500	8
1500-2000	7
>2000	1

primary copper production in 1977 according to the Census of Manufactures. Most of these were located in the Southwest. Copper production in a typical year will be approximately 2 million short tons; production in 1981 was 1.7 million tons according to the 1983 Mineral Commodity Summaries and had fallen to 1.3 million tons in recessionary 1982. Copper production is highly concentrated due to strong economies-of-scale in smelter operations. Plant capacities in the range of 100,000 tons per year are typical for the industry. High-temperature, high-energy flux operations are the rule rather than the exception in the primary copper process. These unit operations and their energy streams are discussed in the following subsections.

Process Description

Copper smelting and refining consist of several consecutive unit operations that remove the noncopper impurities from the feedstock as it moves through the plant. Concentrated ore, either wet and/or partially dried in a roaster, is fed to a reverberatory smelting furnace. Copper and ferrous sulfides collect at the bottom of the furnace; slag is removed from the top. Flue gases from the smelting furnace are passed through a waste-heat boiler prior to cleaning. The matte (copper and ferrous sulfides) is transferred next to the converter. Iron and sulfur are oxidized in the converter with a high silica flux and forced air. Slag from this operation is recycled to the smelter. The product from the converter is called blister copper, which is about 98% pure. Flue gases from the converter are cleaned and sent to a sulfuric acid plant.

The final processing steps involve fire refining and/or electrolytic refining to achieve the desired copper purity. These steps are shown in Figure C.11.

Heat Transfer Operations

The smelting furnace is the most important heat-transfer operation in a primary copper plant. Other significant heat-transfer operations to be discussed in the following subsections include the fire refining furnace, electrolytic refining furnace, and cathode melting.

Smelting Furnace

The most energy-intensive unit operation in a primary copper plant is the smelting furnace. Concentrated copper ores are fed to a reverberatory furnace with fluxing agents. The ores may be fed green (wet), dried, or calcined. The fluxing agents combine with the gangue material to form a slag while copper and

FIGURE C.11 Major Copper Smelting and Refining Operations

ferrous sulfides collect at the bottom of the furnace in a form known as matte. A portion of the sulphur content is oxidized to SO_2 and exits with the flue gas. Energy consumption will obviously vary depending on whether the feed has been dried or calcined. Several sources have estimated the energy requirements for this operation to be about 24×10^6 Btu/ton of refined copper (Bodine and Vitullo 1980; A.D. Little 1976; Hamell et al. 1979). Sources reporting lower figures of 14 to 15×10^6 Btu/ton have probably already taken credit for energy recovery from the flue gas.

The smelting furnace operates at temperatures close to 2200°F (Bodine and Vitullo 1980; Gaines et al. 1980; Hamell et al. 1980), although Hall (1974) reports temperatures as high as 3000°F . As was mentioned in the introduction, the copper industry is highly concentrated, with individual smelters having capacities up to 1500 tons/day (Hall 1974). Palmer et al. (1980) reports capacities of 450 tons/day and 200 tons/day for "medium" and "small" sized smelters.

Fire Refining (anode furnace)

The iron and copper sulphides in the matte from the smelting furnace are oxidized in the converter. The product from that operation is called blister copper, which is approximately 98% pure. Further refining occurs in this step in an operation similar to open hearth steelmaking. Impurities within the blister copper are preferentially oxidized when submitted to the 2100°F conditions of the reverberatory fire refining furnace. Reported energy consumption for this operation varies from 3.5 to 3.7×10^6 Btu/ton of refined copper (Bodine and Vitullo 1980; Gaines et al. 1980; Hamell et al. 1980). Furnace capacity ranges from 165 to 330 tons for this batch operation.

Electrolytic Refining and Cathode Melting

Depending on the requirements for end-product consumption, the copper purity resulting from fire refining may be adequate. If not, the copper is further refined by electrolytic means. Electrolytic refining occurs in a solution of copper sulphate and sulphuric acid. Fire refined copper is used as the

anode and pure copper plates out at the cathode. The cathodes are then melted and cast into more useful shapes. Electrolytic refining requires both electric energy and thermal energy for heating the electrolytic solution. Reported energy consumption for these three unit operations vary widely in the literature. Energy consumption estimates are compared in Table C.8.

Waste Heat Streams

Waste heat recovery potential in a primary copper plant is dominated by the smelting furnace. Because the smelter is the largest energy consumer, it has the greatest potential for heat recovery. The flue gas exits the smelter at about 2250°F and carries with it 14.2×10^6 Btu/ton of refined copper (Hammel et al. 1980). The majority of this energy is recovered in waste heat boilers; Bodine and Vitullo (1980) has estimated the energy recovery from flue gases to be 9.35×10^6 Btu/ton of copper. An impediment to waste heat recovery is the sulphur dioxide content of the flue gas. The portion of flue gas thermal energy that is not currently recovered could possibly be used to preheat the concentrated ones. Concentrations (by volume) of 0.5 to 1% SO₂ for calcined charges and 1.5 to 3% SO₂ for green charges are reported by Gaines et al. (1980). Smelter slag is another waste heat source that is currently unrecovered. The energy contained in the slag is estimated by Hammel et

TABLE C.8 Reported Energy Consumption for Electrolytic Refining and Cathode Melting

<u>Operation</u>	<u>Energy Consumption</u>	<u>Source</u>
Refining-electric ^(a)	3.23×10^6 Btu/ton	Bodine and Vitullo 1980
	2.63×10^6 Btu/ton	A.D. Little 1976
	2.93×10^6 Btu/ton	Hammel et al. 1980
Refining-thermal	4.2×10^6 Btu/ton	Bodine and Vitullo 1980
	2.0×10^6 Btu/ton	A.D. Little 1976
	0.3×10^6 Btu/ton	Hammel et al. 1980
Cathode melting	1.95×10^6 Btu/ton	Bodine and Vitullo 1980
	3.0×10^6 Btu/ton	Hammel et al. 1980
	4.0×10^6 Btu/ton	Hall 1974

(a) Based on 10,500 Btu/kWh

al. (1980) to be 3.4×10^6 Btu/ton of copper. Flue gases from fire refining and cathode melting are also potential sources of recoverable energy. The current rejection of flue gases is 3×10^6 Btu/ton of copper, which exit these operations at temperatures of about 2600°F (Hammel et al. 1980).

Primary copper plants are similar to other high-temperature metals processes in that significant amounts of non-contact cooling water are required to cool the high-temperature furnaces. The waste heat contained in contact and non-contact cooling waters have been estimated by Latour and Menningman (1981). These estimates are summarized in Table C.9. Latour and Menningman (1981) also estimated the energy discharged from primary copper plants in the form of flue gases. Their estimates for primary copper waste heat discharges are summarized in Table C.10 according to temperature.

PRIMARY ALUMINUM

The primary aluminum industry, like primary copper, is highly concentrated. According to Bodine (1980), there are 12 primary aluminum producers in

TABLE C.9 Energy Contained in Primary Copper Plant Water Streams (Latour and Menningman 1981)

<u>Unit Operation</u>	<u>Btu/ton of Copper</u>
Smelting	7×10^6
Acid plant	1×10^6
Fire refining	2×10^6
Misc.	1×10^6

TABLE C.10 Quantity and Quality of Waste Heat Discharged in the Primary Copper Industry (Latour and Menningmann 1981)

<u>Temperature Range (°F)</u>	<u>10^{12} Btu</u>
125	21
125-500	34
500-1000	21
1000	--

the U.S. operating 31 reductions plants. Individual plants vary in capacity from 36,000 to 285,000 tons per year. Total production capacity is about 5,000,000 tons/year. Actual production was near this level in 1981 but has dropped off due to the recent (1982) recession. Because aluminum production is extremely energy intensive and requires electricity for the reduction process, the industry is principally located where energy is cheap and/or abundant. The majority of plants are located in the Pacific Northwest, the Gulf Coast, Tennessee and Ohio River Valleys, and the St. Lawrence Seaway.

Process Description

Activity at an aluminum reduction plant centers on the potlines where alumina (Al_2O_3) is electrolytically reduced to aluminum. Alumina is charged to the reduction cell, where it is first dissolved in a solution of molten cryolite. The cryolite solution serves as an electrolyte. A high current passes through the solution from the carbon anode to the cathode, where aluminum is deposited. Oxygen liberated in the process collects at the anode and combines with the carbon surface to form CO_2 .

The carbon anodes are prepared for reduction cells onsite, either by the pre-baked or Soderberg process. High-grade petroleum coke and pitch is ground, calcined, and blended into a paste-like mixture that is sent directly to the reduction cell in Soderberg operations. The molding and baking of the paste occurs in the reduction cell for the Soderberg systems and external to the cell for pre-baked systems.

The casting and cooling of ingots are the final operations at a reduction plant. Some integrated facilities allow for transportation of molten aluminum directly to rolling facilities. The steps described above are shown in Figure C.12.

Heat Transfer Operations

As was noted above in the process description, the electrolytic reduction cell is the dominate heat transfer operation in a primary aluminum plant. Other operations that will also be discussed in this section are anode baking and casting.

FIGURE C.12 Major Aluminum Reduction Plant Operations

Electrolytic Reduction

The electrolytic reduction cells are the center of activity at an aluminum reduction plant. A diagram of a single cell is shown in Figure C.13. A single cell consists of a refractory lined steel pot, with an additional carbon liner that serves as the cathode. A carbon anode is suspended over the center of the pot and hangs down into the electrolytic bath. Alumina is periodically charged to the continuously operated pot and is dissolved in a molten bath of cryolite, fluorspar and aluminum fluoride. Aluminum is reduced via a series of complex reductions and collects at the bottom of the pot on the cathode. The oxygen that is liberated from the alumina reacts with the carbon anode to form CO_2 and CO . The mixture of CO and CO_2 exits the cell with several volatile

FIGURE C.13 Aluminum Reduction Cell (Shen 1980)

fluoride compounds. The electric current provides energy to drive the reduction reaction and to keep the pot mixture molten at a temperature of about 1700°F. Additional thermal energy is supplied by the oxidation of carbon anodes. Thermal losses from the cells are inhibited by a crust of alumina and cryolite, which forms on the surface of the bath.

Electrical energy consumption in the reduction cell varies from 14,000 to 16,000 kWh per ton of aluminum, depending on the efficiency of the cell. The theoretical minimum to drive the reaction is 7380 kWh/ton. In addition to the electrical input, approximately 14×10^6 Btu/ton are added by the oxidation of the anodes. An individual cell has a voltage drop of 4 to 5 volts and operates at a current of about 100,000 amps. Long rows of cells, called potlines, are operated in series. A single potline may consist of 50 to 180 cells (Shen 1980).

Anode Baking and Casting

The carbon anodes consumed in the reduction cells are manufactured from petroleum coke and pitch. Approximately half a ton of coke and 300 lbs of pitch are consumed per ton of aluminum product. Calcined coke and pitch are crushed, mixed, and molded into anode shapes and then baked in a pit-type ring furnace or a tunnel kiln (Alcoa 1983; Kaiser 1983). Petroleum coke is preferred to coal-based coke because of its lower ash content. The baking operation occurs at temperatures between 2000 and 2400⁰F (Palmer et al. 1980). Energy estimates for anode baking vary between 2.3 and 3.6×10^6 Btu/ton of aluminum; the median value is nearly 2.6×10^6 Btu/ton (Bodine and Vitullo 1980).

Casting the molten aluminum is a relatively simple operation, but consumes a significant amount of energy. Bodine and Vitullo (1980) reports energy consumption ranging from 1.5 to 11 Btu/ton, depending on the type of casting. The energy required for the casting of sows was reported as being 1.5×10^6 Btu/ton although the average for this operation was reported to be 5×10^6 Btu/ton (Bodine and Vitullo 1980). Latour and Menningman (1981) estimates the average for casting a mixture of slabs, billets, and sows to be 4×10^6 Btu/ton.

Waste Heat Streams

The waste heat recovery potential in an aluminum reduction plant is large in theory, but the practical applications seem to be limited. The off-gases (mostly CO and CO₂) from the potlines have a temperature of about 1800⁰F and carry away between 6×10^6 and 13×10^6 Btu/ton of aluminum produced according to Reding et al. (1975) and Hamell et al. (1980). However, employees of Alcoa and Kaiser indicated that the off-gases from the reduction cells were typically not recuperated because of relatively low energy density, difficulty in collection, and more concern with pollution control and recovery of valuable fluoride compounds. The energy content in anode baking and ingot melting furnace off-gases (estimated by Reding et al. (1975) and Hamell et al. (1980) to be a combined 5.4×10^6 Btu/ton) were similarly discounted. The energy requirements of the reduction cell are so dominating that industry believes

their time is better spent exploring ways to improve cell efficiency, such as lowering the electrical resistance of anodes, cathodes, and the electrolyte.

In addition to the above information sources, Latour and Menningman (1981) have surveyed the waste heat discharges of the aluminum industry. They found that a total of 53.2×10^{12} Btu were rejected in the form of flue gas and 5.2×10^{12} Btu were rejected via wastewaters on an annual basis. Their results were summarized in Table C.11.

TABLE C.11 Quantity and Quality of Waste Heat Discharged in the Primary Aluminum Industry (Latour and Menningman (1981))

<u>Temperature Range (°F)</u>	<u>10^{12} Btu</u>
125	2
125-500	47
500-1000	3
1000-1500	1
1500	--

APPENDIX D
PAPER AND ALLIED PRODUCTS - SIC 26

APPENDIX D
PAPER AND ALLIED PRODUCTS - SIC 26

The paper and allied products industry includes the production of pulp, paper and paperboard; conversion of paper and paperboard into end products, and the manufacture of building paper and board.

Paper and paperboard are essential commodities. Annual U.S. per capita consumption is over 600 lbs (Hersh 1981). The industry is highly capital intensive and among the largest consumers of purchased fuels and electricity and of fresh water. According to the 1980 Annual Survey of Manufactures, (U.S. Department of Commerce 1982) this industry ranks third at the 2-digit SIC level in energy use and accounts for 10% of industrial energy use. Table D.1 ranks the major processes within this classification according to purchased energy use.

Three milling operations pulp, paper and paperboard, consume 88.7% of the industry's purchased fuels and electricity. Together they reject over 0.3 quads (3.25×10^{14} Btu) of waste heat each year (Latour 1981). Figure D.1 presents an energy flow diagram for a modern integrated mill.

Table D.2 shows what percentages of the heat rejected by this industry can be expected at various temperatures.

TABLE D.1 Ranking by Purchased Energy Use - Paper and Allied Products
 (U.S. Department of Commerce 1982)

<u>SIC</u>	<u>Paper Mills</u>	<u>Percent of SIC 26 Energy Use</u>
2621	Paper mills (excluding building papers)	45.6
2631	Paperboard mills	35.8
2611	Pulpmills	7.3
2653	Corrugated, solid fiber boxes	2.8
2661	Building paper and board mills	2.8

FIGURE D.1 Energy Flows in a Modern Integrated Mill (DOE 1977)

TABLE D.2 Heat Rejection - Paper Industry (SIC 26) (Reding 1975)

Temperature °F	% of Total Heat Rejected
below 212	56.3
212 to 482	30.7
482 to 1472	5.0
(radiation, convection, conduction, other)	8.0

Energy purchased by the pulp and paper industry supplied about 52% of the demand. The remaining 48% of the industry's energy requirements were generated from renewable process wastes, such as spent pulping liquors and wood wastes (Mellon Institute 1983). Table D.3 presents an energy-use pattern for the paper industry.

The following sections discuss manufacturing processes, major heat transfer operations, and waste heat streams.

PULP MILLS

As defined in SIC 2611, pulp mills are primarily concerned with the production of pulp from wood or alternate fiber sources such as wastepaper, cotton, flax, rags, or straw. They produce market pulp for sale and do not manufacture paper, paperboard or converted products.

TABLE D.3 Energy-Use Pattern - Paper Industry
(API Statistics, Source: Mellon Institute 1983)

<u>Purchased Fuels</u>	<u>1980 (%)</u>
Electricity	6.2
Coal	10.5
Residual oil	16.1
Distillate oil	0.4
Natural gas	17.7
Other	<u>1.0</u>
Total purchased	51.9
<u>Self-generated</u>	<u>1980 (%)</u>
Hogged (wood waste)	5.4
Bark	4.7
Spent liquor	37.2
Self-generated hydroelectric	0.4
Other	<u>0.4</u>
Total self-generated	48.1

Process Description

During pulping operations the cellulosic raw materials (of which 80% is wood) are separated into discrete fibers for further processing into paper and textiles (Hersh 1981).

The following are units operations commonly encountered during the production of pulp.

- Raw material acquisition - This operation involves the harvesting, collection and transportation of the raw material from sawmills, lumbering operations, and/or recycling centers.
- Wood preparation - This step involves conversion of the raw material into a form suitable for pulping. Activities may include debarking and chipping of whole trees.
- Pulping - Wood chips or other suitable raw materials undergo conversion into fibers by chemical and/or mechanical means.
- Stock preparation - Pulp may be washed, screened, thickened and bleached as required.
- Chemical recovery - Recovery practices are usually associated with mills producing Kraft pulp.

From a waste heat recovery viewpoint, operations of interest at a pulp mill occur during the pulping, bleaching, and recovery steps.

Several methods are used for pulping wood. In some, the wood is chipped and then cooked with chemicals under controlled conditions of temperature, pressure, time, and pulping liquor composition. Different chemicals, or combinations of them are used by the various processes. In other methods, wood is reduced to a fibrous state by mechanical means or a combination of chemical, thermal and mechanical action. There are four major pulping processes, three of which are chemical pulps (Kraft, semichemical and sulfite) and one mechanical pulping process (groundwood) that account for over 90% of all pulp production (CTAS Vol II, 1980). Of these four processes, Kraft pulping is the dominant method, accounting for 70% of the pulp consumed (Hersh 1981).

Although chemical pulping methods require elevated temperatures to activate chip digestion reactions, it is possible in the Kraft process, and to a lesser extent in the neutral sulfite semichemical (NSSC) process, to recover organic material from the spent pulping liquors that can be burned in a recovery boiler. The steam from the boiler can then be used for process heat or electricity generation. Depleted inorganics from pulping chemicals can be recycled by a chemical recovery system.

In the Kraft (also called sulfate) process, wood chips are heated in batch or continuous digesters at temperatures up to 340°F and 150 psi in solutions of sodium hydroxide and sodium sulfide (Authur D. Little 1976). Spent liquors from this process are evaporated in multiple evaporators to produce strong black liquor. The liquor is burned in recovery furnaces for steam and power generation. From the combustion process a smelt is obtained that contains inorganic material. The smelt is treated to obtain (calcium carbonate) lime mud, and the lime mud is calcined in a lime kiln to recover calcium oxide (CaO). Figure D.2 presents a flow-diagram for Kraft pulping.

Pulp made by the NSSC method requires that the wood chips be processed in a neutral solution of sodium sulfate - sodium bisulfate, and then reduced to a pulp in a disc refiner. Reaction conditions typically are 340°F at 100 psi (Hersh 1981).

Chemical recovery in the sodium-based NSSC process is more difficult than in the Kraft process. Many mills evaporate and burn spent liquor without chemical recovery and some practice "cross recovery," which requires sending the liquor to a nearby Kraft recovery system (Vogt 1974). Figure D.3 illustrates a flow diagram for an NSSC pulp mill that evaporates and burns spent pulping liquors to recover energy.

Sulfite pulp is made by cooking the fiber source under pressure in an acidic aqueous solution of calcium, magnesium/or ammonium bisulfite, and sulfur dioxide. Due to effluent problems, sulfite recovery systems are not currently practical (Mellon Institute 1983).

FIGURE D.2. Bleached Kraft Pulping

FIGURE D.3 Neutral Sulfite Semichemical Pulping

Groundwood pulp is made by using a water-cooled grindstone to abrade whole logs or wood chips (see Figure D.4). The mechanical action tears apart the wood fibers and an aqueous slurry is obtained. The grindstone is immersed in recirculating water that reaches a steady-state temperature of about 140⁰F (Hersh 1981). The major energy input is electricity to drive the grindstones.

After the fiber source has been pulped, it may require bleaching. Bleaching produces whiter papers by removing or converting the colored matter still present in the pulp. Softwoods generally require more bleaching than hardwoods, because softwoods usually contain more lignin. Standard bleaching agents based on chlorine, chlorine compounds, and peroxide are used, usually in

FIGURE D.4 Stone Groundwood Pulping

a variety of sequences designed for the particular pulp being bleached. Energy requirements depend on the type of pulp, fiber source, and degree of brightness desired.

Heat-Transfer Operations

Significant heat-transfer operations occurring at a pulp mill are discussed below.

Digestion

Cooking or digesting of wood chips in the chemical or semimechanical processes can occur in batch or continuous digesters (Figures D.5 and D.6). Table D.4 shows cooking times and temperatures.

FIGURE D.5. Batch Digester (Kocureck 1983)

FIGURE D.6 Downflow Continuous Digester

TABLE D.4 Cooking Statistics
(Kozureck 1983)

<u>Method</u>	<u>Time (hrs)</u>	<u>Temperature Range °F</u>
1. Kraft	2 to 5	338 to 356
2. Bisulfite	3 to 5	302 to 320
3. Acid bisulfite	4 to 15	248 to 284
4. Neutral sulfite semi-chemical	1/4 to 1/2	320 to 374

Batch digesters have a reported steam demand of 8,100 lb/ton pulp and continuous digesters have a demand of 8,700 lbs/ton pulp (Sittig 1977). It is estimated that pulping operations for the Kraft process requires 10.67×10^6 Btu/bone-dry ton pulp as an average heat absorption (steam) (Sittig 1977). The different cooking zones, temperatures and cooking time for an example continuous digester are shown in Figure D.7. Cooking statistics will vary from mill to mill depending upon fiber source and pulping method.

Bleaching

Temperatures of bleaching operations can range from 80 to 290°F (Sittig 1977). The lower temperatures are representative of mechanical bleaching operations. Electric energy and steam required for pulp bleaching is a factor of the extent of bleaching and nature of the pulp.

Groundwood pulp bleaching uses about 24×10^3 Btu of heat absorbed per bone-dry ton (Sittig 1977). Steam usage in Kraft pulp and bleaching is reported as equivalent to 4.1×10^3 Btu (heat absorbed) per bone dry ton pulp (Sittig 1977).

Recovery

Kraft or NSSC spent cooking liquors are concentrated in multiple-effect evaporators. Table D.5 shows process conditions for two single-effect evaporators operating at atmospheric pressure.

FIGURE D.7 Cooking Zones in a Continuous Digester
(Kocureck 1983)

The multiple-effect evaporator (Figure D.8) is usually composed of several units (effects) that are connected in series. Operating temperature in an evaporator is influenced by:

1. temperature of liquor entering an effect
2. latent heat of condensation and vaporization
3. amount of heating surface
4. operating conditions.

TABLE D.5 Process Conditions for Two Single-Effect Evaporators
(ERDA 1977)

Process Conditions	Single-Effect Evaporators	
	1	2
Evaporator feed rate, lb/hr	15,000	15,000
Evaporator capacity, lb/hr	10,000	10,000
Evaporator pressure, psig	0	0
Steam-chest pressure, psig	5	12
Steam rates (approx.), lb/hr	12,000	12,000
Vapor rate to condenser, lb/hr	10,000	10,000

FIGURE D.8 Sources of Energy and Process Flows in the Typical Multieffect Evaporator (ERDA 1977)

Secondary concentration of the black liquor can occur by direct contact evaporation, which uses hot exhaust gases from the recovery boiler.

When the liquor is concentrated to 62% solids it can be burned in a recovery boiler (Jansen 1979). Example operating temperatures are shown in Table D.6. An illustration of a recovery boiler is shown in Figure D.9.

The smelt obtained is dissolved in a dilute basic solution to form "green liquor." Green liquor is treated with calcium oxide (CaO) in causticizers to cause the precipitation of calcium carbonate (also called lime mud). The lime mud is sent to a lime kiln to be converted back to lime at temperatures above 1500°F (Battelle 1976). In a simple form, a rotary lime kiln consists of a refractory-lined, open-end steel cylinder inclined about 12° from feed end to discharge end, and is rotated about the longitudinal axis. Lime kiln sizes range from 6 to 13 feet inside diameter and are 100 to 350 feet long (Mellon Institute 1983). Figure D.10 shows a chemical recovery flow diagram.

Waste Heat Recovery

Direct-contact and non-contact heat recovery techniques are practiced by this industry. Table D.7 lists common pulp mill sources of recoverable waste heat.

Digestion

Waste heat can be recovered from digester blowdown. When the digester is blown during the cooking process, the pressure is reduced and steam is flashed

TABLE D.6 Recovery Boiler Operating Temperatures
(Jansen 1979)

	<u>Temperature °F</u>
1. Liquor heaters	220-235
2. Combustion air	300-400
3. Boiler furnace flue gases	2,200-2,600
4. Superheater section	800-1700
5. Economizer	350-800
6. Molten smelt	1,350-1500

FIGURE D.9 Recovery Boiler (Pierce 1973)

off, resulting in an estimated loss of 2 million Btu/air dry ton of pulp if recovery techniques are not practiced (McDonald 1969).

Two types of recovery systems are commonly used and are classified as 1) the surface condenser, and 2) the jet or direct-contact condenser (McDonald 1969). Table D.8 presents calculations for an example blow down recovery system.

FIGURE D.10. Chemical Recovery Flow Diagram (Battelle 1980)

TABLE D.7 Major Sources of Recoverable Waste Heat
(Gilbreath 1980)

<u>Mill Source</u>	<u>Temp °F</u>	<u>Reported Ranges Heat Available Btu/ADT</u>	<u>Availability</u>
1. Blow heat primary condenser	195-210	1.5-1.8	Intermittent
2. Blow heat secondary cond.	140-150	0.15-0.25	Intermittent
3. Evap. surface condenser	110-120	2.8-3.2	Continuous
4. Turbine condenser	105	0.0-7.5	Variable
5. Steam strippers	130-150	0.4-0.65	Continuous

TABLE D.8 Example Blowdown Recovery System
(McDonald 1969)

<u>Expected Steam Flash</u>	<u>Pulp Prod.</u>	<u>Heat rej. to Sewer (at 110°F)</u>	<u>Average Heat Recovery</u>
2031.3 lb/ ton a.d. pulp	200 ton/day	78 Btu/ lb steam	18,200,000 Btu/hr

The quantity of heat that can be recovered will vary from mill to mill and depends on cooking conditions used.

Recovery Operations

Economizers use waste heat from recovery boiler flue gases to preheat boiler feedwater. Recovery boiler flue gases can also be used by direct contact evaporators to concentrate spent pulping liquors. Basically an economizer consists of enclosed finned heat transfer tubes. The shape and size of a unit depends on the shape of the stack, stream temperature and exhaust flow rate.

Heat recovered through installation of an economizer in the main exhaust stack was reported by one mill as equivalent to 5×10^{16} Btu/hr (Minnesota Energy Agency 1979).

Hoods can be installed over the hot end of lime kilns to recover heat. These hoods, which can be 100 ft long, contain an air collection pipe the

length of the hood. One mill uses this system to preheat combustion air and reports heating values of 100⁰F over ambient (Lane 1979).

Another kiln had a heat exchanger added to the exhaust duct system. Combustion air was preheated to 650⁰F and exhaust stack temperatures were reduced from 1250⁰F to 800⁰F (Hogeland 1983).

Waste Streams

Waste waters and saturated vapors at temperatures less than 350⁰F are the most significant waste heat discharge from pulp mills (Latour 1981). Groundwood pulping has one significant waste heat stream. Waste water from bleaching operations has a waste heat discharge equivalent to 1.10×10^6 Btu/BDT (Latour 1981).

Total useful energy delivered from Kraft pulping operations has been estimated at 42.6×10^6 Btu/ton (Streb 1977). Steam flashed during digester blow-down accounts for approximately 2.8×10^6 Btu/BDT of the pulping operation waste heat (Latour 1981).

In a five stage Kraft pulp bleaching operation, the waste heat content is estimated at 0.4×10^6 Btu/BDT. A three-stage bleaching operation has a discharge of 1.2×10^6 Btu/BDT (Latour 1981). Since most bleaching effluents are sent to the sewer at approximately 100⁰F, it is not considered practical to recover the heat (Palmer 1980).

There are two significant rejected heat streams from multiple effect evaporators: 1) saturated steam with an estimated heat content of 3.3×10^6 Btu/BDT, and 2) foul condensate with 1.9×10^6 Btu/BDT waste heat (Latour 1981).

The gases that leave recovery boilers at approximately 300⁰F are estimated to have a waste heat discharge of 5.4×10^6 Btu/BDT (Latour 1981).

Off-gases are produced during lime kiln operation. At a temperature of 400⁰F a waste heat discharge of 8.20×10^5 Btu/BDT can be expected (Latour 1981). The lime kiln dryer is estimated to have a waste heat stream of 219×10^{12} Btu/yr (Grogan 1981). Exhaust from kiln operations have recoverable

heat down to 160°F (CTAS 1980). Table D.9 shows waste heat streams and theoretical energy content.

PAPER AND PAPERBOARD MILLS

Paper and paperboard mills are establishments primarily engaged in the manufacture of paper and paperboard (paper thicker than 0.012 in.). They may also manufacture converted paper and paperboard products.

Some mills may be integrated, meaning they combine pulping and papermaking at the same site. Because many mills are integrated, energy consumption figures for SIC 2621 and SIC 2631 will reflect energy requirements necessary for pulping operations in addition to the papermaking process. Non-integrated mills buy market pulp to process into paper.

Process Description

Paper is made by depositing, from a dilute water suspension of pulp, a layer of fiber on a moving wire screen or filament mesh that allows the water to drain and forms a fiber layer. This fiber layer or web is pressed and dried to remove the remaining water. Paper usually leaves the drier section with a 5 to 10% moisture content (Hersh 1981).

TABLE D.9 Waste Heat Streams - Pulp Mills
(Latour 1981; CTAS 1980; Palmer 1980)

<u>Source</u>	<u>Medium</u>	<u>Reported Theoretical Heat Content (10⁶ Btu/BDT)</u>
1. Ground wood bleaching	Bleaching effluent	1.1
2. Digestor blowdown	Steam	2.8
3. Kraft bleaching	Bleach effluent	0.4 - 1.2
4. Multiple effect evaporators	Steam Foul condensate	3.3 1.9
5. Recovery boilers	Flue gases	5.4
6. Kiln	Off gases	0.82

It is usual for paper to be made on a fourdrinier machine and board or heavy, multilayer papers on cylinder machines. The basic difference between these two machines is in the web formation (Figures D.11 and D.12). A cylinder

FIGURE D.11 Fourdrinier Paper Machine (TAPPI Press, 1976)

FIGURE D.12 Cylinder Machine Wet End (TAPPI Press, 1976)

machine has a series of wire-covered cylinder molds that rotate while supporting and draining the moving fiber web. A fourdrinier machine has a flat sheet-forming surface. A flow sheet of the fourdrinier operation is presented in Figure D.13.

Heat-Transfer Operations

The major heat transfer operations in the production of paper and paperboard occur during the drying of the paper web.

Drying

Drying is the most energy-intensive unit operation in the production of paper. About two-thirds of the energy used by the forming, pressing and drying section goes into drying the paper (Mellon Institute 1983).

The dryer section is comprised of many rotating heated drying cylinders. The cylinders are usually steam heated and the entire section is often enclosed or hooded. An enclosed hood drying system requires about 10 lbs of air to remove one pound of moisture while open hoods require 25 lbs of air per pound of moisture (Midland-Ross 1983). Air temperatures range from 300 to 800⁰F in the dryer section (McDonald 1960). Electrical energy required in the drier section is usually associated with machine drives.

Waste Heat Recovery

The most common type of heat recovery from the dryer section is the indirect heating of air using cross-flow heat exchange (Midland-Ross 1983).

Using an air-to-air economizer to heat the air, a 50 to 100⁰F temperature rise could be expected in a single pass and from 100 to 300⁰F rise with multiple passes (Midland-Ross 1983). The single-pass would be used for makeup air to the paper machine and multiple passes for makeup to a dryer section.

Heating of water can be accomplished directly or indirectly. The direct heating method requires that water be sprayed directly on the hot exhaust surface or into the hot air stream. This results in dirty hot water that must be filtered. Finned-tube coil heat exchanger systems allow indirect heating of water.

FIGURE D.13 Fourdrinier Paper Machine Process (Hersh 1981)

Waste Streams

Waste heat discharged by paper and paperboard mills accounts for about 19 to 40% of their purchased fuels and electricity. There are two important waste streams: 1) hot moist air with about 3.1×10^6 Btu/BDT of waste heat, and 2) hot water containing about 690,000 Btu/BDT at a temperature of 250°F (Latour 1981). Table D.10 shows different heat contents of exhaust from paper machine hood sections. These are typical values and vary from mill to mill and from wet end to dry end of the hood.

CORRUGATED AND SOLID FIBER BOXES AND BUILDING PAPER AND BOARD MILLS - SIC 2653, SIC 2661

Corrugated and solid fiber box plants manufacture products from purchased paperboard, whereas building paper and board mills either purchase market pulp or operate integrated facilities.

In 1979, the construction paper and board production was reported at 5,516 thousand short tons (Post Pulp and Paper Directory 1982). A flowsheet for a typical boxboard operation is shown in Figure D.14.

Unit operations encountered are similar to those discussed in previous sections.

TABLE D.10 Hood Exhaust Heat Contents
(Midland-Ross 1983)

<u>Type of Hood</u>	<u>Temp. Dry Bulb (°F)</u>	<u>Dew Point (°F)</u>	<u>Heat Content Btu/lb</u>
Open canopy, uninsulated	130	109	111
Insulated totally enclosed	165	131	170
Pulp dryer enclosure	275	155	345
Gas-fired Yankee dryer	550	164	570

FIGURE D.14 Folding Boxboard Flow Diagram (Sittig 1977)

APPENDIX E

STONE, CLAY AND GLASS - SIC 32

APPENDIX E
STONE, CLAY and GLASS - SIC 32

The major products included in this industry classification are cement, glass (flat, container, pressed and blown), gypsum, brick and structural clay, mineral wool and ready-mix concrete. The production processes for each of these products, with the exception of ready-mix concrete, are characterized by their use of high-temperature, direct-heat operations.

The stone, clay and glass industry ranks fifth in terms of energy use at the two-digit SIC level, accounting for about six percent of the energy used by the manufacturing sector (Radian 1980). Table 5.1 ranks the major processes within this classification according to energy use.

TABLE E.1. Ranking of Stone, Clay and Glass Processes
by Energy Use (Bureau of Census 1980)

<u>SIC</u>	<u>Name</u>	<u>Percent of SIC 32 Energy Use</u>
3241	Cement	34.8
3221	Glass Containers	11.8
3274	Lime	7.6
3229	Pressed and Blown Glass	5.9
3251	Brick and Structural Clay	5.1
3296	Mineral Wool	4.8
3211	Flat Glass	4.5
3275	Gypsum	3.8

Three manufacturing processes, cement, lime, and glass (including flat glass, container glass, pressed and blown glass, and mineral wool), consume 70% of the energy used by this industry grouping. These industries reject almost 0.4 quads (393×10^{12} Btu) of waste heat each year in kiln and furnace exhausts (Latour 1981). A description of the manufacturing processes, the major heat transfer operations, and the waste heat streams is provided below for each of the industries.

CEMENT

At the end of 1980, there were 142 plants producing Portland cement clinker, operated by 44 separate companies (PCA 1980). The plants encompass a wide range of raw materials and product specifications, making it difficult to generalize cement plant design. The following discussion of cement-making processes, heat-transfer operations, and waste-heat streams provides ranges for

the various parameters. These ranges are indicative of the variation in operating parameters encountered in the industry.

Process Description

Two types of processes are used to manufacture cement: the wet process and the dry process. The basic processing steps (shown in Figure E.1) are the same in both cases, with the exception that in the wet process, raw materials enter the kiln as a slurry rather than as a powder as in the dry process. Currently, about half of the cement produced in the United States is by the wet process (PCA 1980).

Feed preparation involves crushing the limestone rock to mill size, proportioning the feed materials, and, in the dry process, feed drying. The

FIGURE E.1. Cement Process

grinding step further pulverizes feed materials to a fine powder. In the wet process, water is added during the grinding step to produce a slurry containing about 65% solids (BuMines 1980).

Calcining or burning involves heating the feed as high as 2900°F in a rotary kiln. In the kiln, moisture is driven off, calcium carbonate (CaCO_3) is converted to calcium oxide (CaO), alkalies are vaporized and any organic material is burned. After calcining, the hot clinker is air-quenched and then fine ground with gypsum to produce cement.

Fossil fuels used to supply direct heat to the kiln account for about 80% of the energy used in cement manufacture (Sapp 1981). The remaining 20% is electricity for crushing, grinding, fan power and materials handling. In 1980, 87% of the cement plants in the United States used coal, 10% used natural gas, and 1% used fuel oil (PCA 1980). The trend toward converting to coal is expected to continue, along with an interest in burning waste materials, such as wood chips or waste oils.

Heat-Transfer Operations

The major heat-transfer operations in the production of cement are burning and clinker cooling. Both are direct-contact operations. Other heat-transfer operations may occur if waste heat recovery is practiced.

Burning

Burning is the most energy-intensive step in manufacturing cement. Fossil fuels are burned and the hot combustion gases directly contact the feed materials as the two streams move countercurrently through the kiln. Table E.2 shows the events that occur at each temperature zone in the kiln. In the wet

TABLE E.2. Clinker Production-Temperature Zones and Sequential Events

<u>Process Temperature (°F)</u>	<u>Sequential Events</u>
100 - 300	evaporation of water
300 - 2000	<ul style="list-style-type: none"> ● vaporize alkalies ● combust organics ● convert CaCO_3 to CaO
2000 - 2900	clinker formation

process, the water in the slurry is evaporated in the first section of the kiln. The remaining temperature zones are the same in both the wet and the dry process.

Four basic kiln configurations are used to produce clinker: (1) wet kiln, (2) dry kiln, (3) dry kiln with preheater, and (4) dry kiln with precalciner. In each case, the kiln is a rotary kiln which consists of a refractory-lined, cylindrical, steel shell that rotates around an inclined axis. Feed materials enter the top of the kiln and are conveyed by gravity to the lower end where the combustion occurs.

Kiln sizes range from 6 feet in diameter and 120 feet long to 25 feet in diameter and 760 feet long, and rotate at 50 to 90 revolutions per hour (BuMines 1980). In general, the wet process requires the longest kilns since the water must be evaporated. As much as one-fourth the length of the wet kiln contains hanging chains to facilitate heat transfer in the evaporation zone (BuMines 1980). Precalciner and preheater systems allow the use of shorter kilns since much of the preheating and calcining occurs in this equipment before the feed enters the kiln.

Suspension preheaters (see Figure E.2) are used with dry kilns to provide for preheating the incoming kiln feed by direct contact with the kiln exit gases. Between 40 and 50% of the feed is calcined in the preheater, reducing energy requirements to about 3.0×10^6 Btu/ton of clinker (Garrett 1980). If auxiliary fuel burning is introduced in the last stage of the preheater, up to 90% of the calcining occurs before the feed enters the kiln (UTC 1980). The latter configuration is referred to as a precalciner.

The theoretical enthalpy requirement for clinker manufacture is 1.5×10^6 Btu/short ton (Gartner 1982). Table E.3 summarizes the average kiln energy use for each process.

TABLE E.3. Average Kiln Energy Use by Process
(Garrett 1980)

<u>Process</u>	<u>Average Fuel Use (10^6 Btu/Ton Clinker)</u>
Wet	5.15
Dry	4.2
Dry with Preheater	3.0

FIGURE E.2 Suspension Preheater

The fuel efficiency of the precalciner is reportedly 3 to 6% better than a four-stage preheater (Howlett 1981). Despite their increased fuel efficiency, adoption of preheaters and precalciners in the United States has been slow. Fouling problems have acted as a barrier to their adoption (Marner 1982). Currently about 48 of the long-dry kilns in the United States use suspension preheaters, eleven of which are precalciners (Gartner 1982). Table E.4 summarizes the U.S. clinker capacity and number of kilns by type of process.

TABLE E.4. Number of Kilns and Capacity by Type of Process
(PCA 1980)

<u>Process</u>	<u>Number of Kilns</u>	<u>Capacity (10⁶ Short Tons/Year)</u>
Wet	175	45.6
Dry	104	23.6
Preheater ^(a)	<u>48</u>	<u>20.2</u>
Total	327	89.4

(a) 11 are precalciners

The average capacity of a single kiln ranges from 170,000 tons/year to 2,322,000 tons/year with a current average of about 264,000 tons/year (PCA 1980). Table E.5 lists average capacity figures for each type of process. The preheater and precalciner systems have the highest capacity capability and the wet process systems have the lowest.

TABLE E.5. Typical Kiln Capacities (PCA 1980)

	<u>Tons/Year</u>
Wet Kiln	250,000
Dry Kiln	300,000
Preheater or Precalciner	600,000 - 1,400,000

Clinker Cooling

Clinker cooling involves air-quenching the hot clinker as it is discharged from the kiln. In the U.S., most clinker is air cooled in a traveling grate or reciprocating grate cooler in which air is passed up through a moving bed (BuMines 1980). The clinker is cooled from about 2500°F to about 150°F (Marner 1982). The heated air from the cooler is often routed back to the kiln to serve as combustion air.

Waste Heat Recovery

Both direct-contact and non-contact heat recovery techniques are used to recover waste heat from cement manufacturing operations, although waste-heat recovery is not practiced extensively. Table E.6 summarizes the types of heat recovery currently practiced.

TABLE E.6. Current Waste-Heat-Recovery Practices

<u>Waste Heat Source</u>	<u>Temperature (°F)</u>	<u>Use</u>
Clinker Cooler Excess Air	Above 700	Combustion Air
Clinker Cooler Vent Air	Below 700	Coal Drying or Raw Feed Drying
Kiln Exhaust (dry process)	700 - 1800	Preheating Feed or Power Generation

The high-temperature air from clinker cooling operations is routed to the kiln to serve as combustion air. The low-temperature vent air may be used to dry coal or raw feed materials. In some cases, the vent air is passed through an air-to-air exchanger to cool the exhaust to: (1) 150°F for recirculation, or (2) to about 400°F before routing to a baghouse (Marner 1982).

About 15% of the kilns in the U.S. utilize kiln exhaust gases to preheat feed materials in suspension preheater systems. This is a direct-contact operation. Currently, only four plants recover kiln exhausts to operate waste-heat boilers for power production. These are listed in Table E.7 (Marner 1982).

TABLE E.7. Waste-Heat Boiler Installations

	<u>Type of Fuel</u>
National Gypsum Co. Alpena, Michigan	Coal
Gifford-Hill Co. Oro Grande, California	Coal
Medusa Cement Company Sylvania, Ohio	Coal
Lehigh Portland Cement Co. Independence, Kansas	Natural Gas

Exhaust gases from kilns and preheaters and preheater by-pass gases are generally cooled to less than about 500°F in air-to-air exchangers before entering the baghouse (Marner 1982).

Waste Heat Streams

The theoretical enthalpy requirement for clinker production is about 1.5×10^6 Btu/ton (Gartner 1982). In 1980, the average fossil fuel requirement for clinker production was about 5.4×10^6 Btu/ton, suggesting that about 3.9×10^6 Btu/ton of heat is lost during cement manufacture (Gartner 1982). This amounts to about 266×10^{12} Btu of lost heat in 1980 from clinker production. Table E.8 provides an estimated heat balance for an average kiln.

TABLE E.8. Kiln Heat Balance

	<u>Btu/Short Ton</u>	<u>%</u>
Theoretical Heat Requirement	1.5×10^6	28
Kiln Exit Gases	2.4×10^6	44
Shell Losses	0.9×10^6	17
Clinker Cooling Air	0.54×10^6	10
Cooling Water	0.05×10^6	1
Total	5.4×10^6	100

Reducing shell radiative and convective losses may be possible through better insulation practices or improved insulating materials. However, this source of waste heat is barred from recovery due to practical considerations. Thus, only the exhaust gases and the cooling water will be considered further.

Waste streams and waste stream temperatures are summarized in Table E.9. Non-contact waste cooling water is from two sources. One source is equipment cooling, including kiln bearings, grinding equipment, air compressors and burner pipes. The other source is cement cooling. Cement cooling removes the heat generated by finish grinding prior to storage or shipment. The average waste heat rejected in this cooling water has been estimated as shown in Table E.10.

TABLE E.9. Cement Industry Waste Streams and Temperatures

<u>Type</u>	<u>Source</u>	<u>Temperature (°F)</u>
Non-Contact Cooling Water	1) Equipment Cooling	5(a)
	2) Cement Cooling	25(a)
Exhaust Gas	1) Kiln - wet	150
	dry	700
	preheater	500-700
	preheater bypass	1700-2000
	2) Clinker Cooler - wet	150-250
	dry	300-450
	preheater	300-450
	3) Finishing Mill	160

a) temperature above ambient

TABLE E.10. Heat Rejected in Non-Contact Cooling Water
(Latour 1981)

	<u>Volume (gal/ton cement)</u>	<u>Waste Heat (Btu/ton cement)</u>
Equipment Cooling	400	16,690
Cement Cooling	200	41,725

The temperature of kiln exhaust gases varies depending on whether the process is wet or dry, and, if dry, whether a preheater is used. The exhaust gases from efficient, well maintained wet process kilns are too low in temperature and too high in moisture content for practical heat recovery using currently available techniques (Garrett 1974).

Both the quantity and temperature of the exhausts from long dry kilns is greater than those of preheater kilns. However, several drawbacks have limited the use of waste heat from the long dry kilns (Garrett 1974):

- exhaust gases are above the inlet temperature limits for roller mills
- the high volumetric flowrate would require large-diameter shells for rotary dryers to keep dryer gas velocity low to prevent excessive dust entrainment.

Table E.11 provides estimates of the volume of kiln exit gases for the three types of systems from two sources.

TABLE E.11. Volume of Kiln Exit Gas per Ton of Clinker

<u>Type of Kiln</u>	(Garrett) <u>ft³/ton</u>	(Marner) <u>ft³/ton</u>
wet kilns	100,000	140,000
dry kilns	70,000	64,000
preheater kilns	50,000	44,000

In the cement industry, the primary heating and cooling operations are direct contact. Therefore, exhaust gases from heating operations contain constituents from the product stream as well as from the fuel. Cooling air that directly contacts the product also carries entrained particles from the product. These waste streams are dusty and highly abrasive. Wet kiln exhausts are estimated to contain between 3 and 18 percent dust and dry kiln exhausts are estimated to contain between 25 and 35 percent dust (Sapp 1981).

Table E.12 provides chemical analyses of various kiln dusts. These constituents are responsible for buildups in the kilns, preheaters and waste-

heat boilers as well as on the surfaces of induced-draft fan blades. Tables E.13 and E.14 provide chemical analyses of the buildups that occur in waste-heat boilers.

TABLE E.12. Chemical Analyses of Kiln Dusts (Bhatty 1981)

Item	(weight %)			
	A(a)	B(b)	C(c)	D(d)
SiO ₂	14.6	13.4	11.4	16.4
Al ₂ O ₃	4.0	2.66	3.48	2.89
Fe ₂ O ₃	2.2	1.25	1.16	2.33
CaO	43.5	37.0	43.2	56.68
MgO	1.23	1.3	1.35	0.85
SO ₃	16.9	2.01	0.73	4.36
Na ₂ O	0.39	0.44	0.08	0.07
K ₂ O	5.57	10.31	2.22	0.82
P ₂ O ₅	0.07	0.19	0.05	0.17
TiO ₂	0.19	0.15	0.16	0.17
L.O.I.	10.20	24.04	35.24	17.86
F ⁻	0.21	0.11	0.02	0.1
Cl ⁻	0.45	6.24	0.52	0.03

-
- a) high sulfate
 - b) high chloride
 - c) low chloride - low sulfate
 - d) moderate sulfate

TABLE E.13. Typical Chemical Analysis of Waste-Heat Boiler Build-Ups (Bhatty 1983)

<u>Component (wt. %)</u>	<u>Sample A</u>	<u>Sample B</u>
SiO ₂	14.26	12.12
Al ₂ O ₃	4.38	4.00
Fe ₂ O ₃	2.64	2.24
CaO	44.16	32.40
MgO	1.31	0.95
SO ₃	23.25	30.64
Na ₂ O	0.80	1.12
K ₂ O	9.44	14.20

TABLE E.14. Compounds in Waste-Heat Boiler Buildups^(a) (Bhatty 1983)

<u>First Batch</u>			<u>Second Batch</u>	
1	2	3	1	2
Calcite	Calcite	Anhydrite	Calcium langbeinite	Anhydrite
Calcium langbeinite	Calcium langbeinite	Calcium langbeinite	Calcium oxide	Calcium langbeinite
Anhydrite	Anhydrite	Calcite	Dicalcium silicate	Calcite
Quartz	Calcium oxide	Quartz	Aphthitalite	Quartz
Calcium oxide	Quartz	Calcium oxide	Syngenite	Calcium oxide

(a) Relative amounts in decreasing order of X-ray diffraction intensity

GLASS INDUSTRY - SIC 3211, 3221, 3229 and 3296

Although the end products differ, the major heat-transfer operation (melting) is the same for each of the product categories listed below:

SIC 3211 Flat Glass

SIC 3221 Glass Containers

SIC 3229 Pressed and Blown Glass

SIC 3296 Mineral Wool

Glass container manufacturing accounts for about 70% of glass production, flat glass 15%, pressed and blown glass 12%, and fibers 3% (EPRI 1982).

The following discussion applies generally to the glass industry. Where significant differences occur among product categories, they will be highlighted.

Process Description

Glass-making operations are typically grouped into the five basic operations shown in Figure E.3: (1) batch handling, (2) melting and fining, (3) forming, (4) post forming, and (5) product handling.

Batch handling involves preparing and transferring the feed to the melting furnace. The feed is primarily composed of sand, soda ash, limestone, and feldspar. In addition, the feed may contain significant amounts of cullet, which is scrap glass. Cullet is used as a batch material to reduce the melting energy requirement and to reduce the amount of dust and particulate matter in the exhaust gases. Some forming operations generate as much as 70% waste glass which must be recycled as cullet (Kirk-Othmer undated). More efficient operations may require purchasing cullet from flat-glass companies or recycling centers.

Melting and fining occurs in refractory-lined furnaces at temperatures up to about 2800°F. The temperature of the batch is raised as quickly as possible to the melting temperature where various dissolution, volatilization and redox reactions occur. These reactions are as follows (Kirk-Othmer):

1020°F	$\text{Na}_2\text{CO}_3 + \text{SiO}_2$	$\text{Na}_2\text{SiO}_3 + \text{CO}_2$
1290°F	$\text{Na}_2\text{SiO}_3 + \text{SiO}_2$	$\text{Na}_2\text{Si}_2\text{O}_5$
1435°F	$3\text{Na}_2\text{Si}_2\text{O}_5 + \text{SiO}_2$	forms a mixture approaching eutectic

Fining involves holding the glass in the furnace to allow entrapped gas bubbles to escape. The glass must be raised to nearly 2730°F to eliminate seeds of entrained air (Berg 1982). Current melting practices of raising glass temperatures to about 2500°F represents a trade-off between product quality and energy costs (Berg 1982).

FIGURE E.3. Glass Production Process

Forming converts the molten glass to an intermediate shape by pressing, blowing, drawing, or casting. A major post-forming operation through which most glass products (except glass fibers) pass is annealing, in which internal stresses are removed. Annealing involves heating the glass to about 1100-1200°F, followed by controlled cooling.

Natural gas is preferred over other fuels for glass melting because it has been relatively cheap and it is an exceptionally pure fuel. Natural gas accounts for about 80 percent of the energy used by the glass industry (Webb 1982). The remaining melters use fuel oil or are electric.

Heat-Transfer Operations

The major heat-transfer operations in the glass industry are melting, heat recovery from melter exhausts, and annealing.

Glass Melting

Melting is the most energy-intensive step in glass manufacture. Typically, the heat transfer occurs through direct contact with hot combustion gases. However, a larger number of glass manufacturers now use resistive electric melting. Current estimates indicate that about 5% of the energy used for melting is electricity (Berg 1982).

Two basic melter configurations are used to produce glass: (1) pot furnaces and (2) tank furnaces. Pot furnaces are used for melting smaller quantities of glass, particularly special glasses where the melting batch must be protected from the products of combustion. These furnaces are generally inefficient and have poor temperature-control capability.

In tank furnaces, batch materials are charged to one end of the tank and fined glass is pulled from the opposite end in a continuous operation. Small, continuous tanks are used to produce high-quality glasses in low volumes. Tank capacity is about 7 tons/day. Some of the tanks operate as cold-crown units with the unmelted batch covering the molten glass in the premelt zone. Pollution from glass melting is substantially reduced by using cold-crown units. These are electrically heated from the bottom or the sides.

The largest furnaces are continuous regenerative furnaces that recover waste heat from the melter off-gases. These furnaces may be cross-fired or end-

fired. End-port furnaces fire and exhaust from the back wall forming a U-shaped flame over the glass surface (Kirk-Othmer). Cross-firing allows more even heating across a larger surface. Production capacities range from less than 150 tons/day to over 700 tons/day.

Energy consumption is a function of furnace type and size, and of the type of glass. All flat glass is produced in side-port regenerative furnaces. The capacity and energy use varies considerably, as shown in Table E.15. A number of different types of furnaces are used for container glass. More than half of the container glass is produced in side-port regenerative furnaces. The number of ports on a side varies from 3 to 7 depending on furnace size. Table E.16 shows the types of furnaces used to produce container glass and their energy consumption. Furnaces now used in the container glass industry range in capacity from about 75 to 480 tons/day, with an average capacity of 180 tons/day (Berg 1982). Because of the wide variety of products produced, a variety of furnaces are used to produce pressed and blown glass. These are listed in Table E.17 along with their capacity ranges and energy use.

TABLE E.15. Flat Glass Furnace Capacity and Energy Use (Schoor 1975)

	<u>Capacity (Tons/Day)</u>	<u>Energy Use (10⁶ Btu/Ton)</u>
Sheet	100 - 250	12 - 20
Plate	100 - 300	10 - 20
Float	300 - 750	6 - 11

TABLE E.16. Container Glass Furnace Energy Use (Schoor 1975)

<u>Furnace Type</u>	<u>Energy Use (10⁶ Btu/Ton)</u>
Side-Port Regenerative	5 - 9
End-Port Regenerative	5 - 14
Electric	3 - 5
Electrically Boosted Regenerative	4.5 - 7.5

TABLE E.17. Pressed and Blown Glass Furnace Capacities and Energy Use

<u>Furnace Type</u>	<u>Capacity (Tons/Day)</u>	<u>Energy Use (10⁶ Btu/Ton)</u>
Side-Port Regenerative	100 - 300	5 - 20
End-Port Regenerative	60 - 150	5 - 25
Unit Melters	<100	12 - 35
Electric		3 - 5
Electrically Boosted Regenerative	--	4.5 - 7.5
Day Tanks	1-4	12 - 50
Pot Furnaces	2	--

Waste Heat Recovery

It is common practice in the glass industry to recover heat from melter exhausts to preheat combustion air. Brick regenerators (checkers) are the predominant heat-recovery device. In the glass industry, approximately 90% of all glass is melted in regenerative furnaces (A. D. Little 1976). The remaining 10% is melted in recuperated glass furnaces.

The regenerators are constructed of refractory bricks in an open matrix arrangement (see Figure E.4). Combustion gases are directed across the batch surface and are routed downward through one of the checkers, through the reversing valve and finally to the stack. The hot gases transfer a significant amount of heat to the checker bricks. Combustion air is preheated as it is drawn up through the opposing checker. The reversing valve is alternated at 20 to 30 minute intervals, thus directing the exhaust gas and combustion air to the opposing checkers (Wei 1981).

Checker size averages about 46 ft³ per ton of glass melted. Typical gas passage dimensions within the checker range from 4" x 4" to 6" x 9" (Webb 1982). Smaller openings have been found to become plugged quickly by constituents in the melter exhaust.

FIGURE E.4. Regenerative Glass Furnace

Chrome-magnesite bricks are typically used in the upper regenerator chamber which must have high-temperature capability to resist slagging and creep due to batch carryover. High-magnesium oxide bricks are used in the upper part of the checker, whereas chrome-magnesite bricks are used in the middle and lower levels of the checkers, because magnesium oxide reacts with SO_3 to form magnesium sulfate at temperatures below 2055°F (Wei 1981). Direct-bonded chrome-magnesite or super duty fireclay bricks are used for the rider arches which must bear the load of the entire checker. Lower walls are typically constructed of fireclay bricks.

Exhausts enter the regenerator at temperatures from 2300°F to 2600°F. Air preheat temperatures range from as low as 800°F for inefficient, one-pass designs to about 1600°F for more efficient one-pass designs or two- and four-pass designs (Webb 1982). Using secondary checkers, air preheat temperatures as high as 1100°F can be achieved.

Metallic recuperators are used on small, continuous melting furnaces (generally less than 100 tons/day) and on day tanks. They are not generally used on larger furnaces because the size required would be prohibitively expensive. There are two basic recuperator designs. One is an annular type, with hot gases flowing in the inner cylinder. The second design has a group of tubes arranged around the circumference of the flue, parallel to the waste gas flow (Webb 1982).

Metallic recuperators provide lower air preheat temperatures of about 1000 to 1400°F. Their thermal effectiveness ranges from about 35% to 50% (Webb 1982). Expensive alloys, such as stainless steel and Inconel are required to withstand the high-temperature, corrosive waste gases.

Annealing

Annealing involves heating the glass after it has been formed to 1000-1200°F to reduce internal stresses, followed by controlled cooling to ambient temperatures. Annealing takes place in gas-fired lehrs. The lehr is a heated chamber in which the rate of cooling can be controlled. Annealing may consume as much as 10 percent of the total plant process heat. In flat glass manufacture, 500 to 1000 Btu/ft² are required for annealing (Battelle 1976).

Waste Heat Streams

Waste heat streams from glass manufacturing operations include exhaust gases from melting and annealing operations and contact and non-contact cooling water.

The theoretical enthalpy requirement for glass melting is 2.24×10^6 Btu/ton. Actual melting energy averages about 7×10^6 Btu/ton (A. D. Little 1976). This suggests that about 4.4×10^6 Btu/ton is lost during glass melting. Based on an estimated 1980 production of 23×10^6 tons of glass, the annual waste heat from glass melting would be 101.2×10^{12} Btu/year. Table E.18 provides an estimated heat balance for a typical melter.

TABLE E.18. Melter Heat Balance

	<u>Btu/Short Ton</u>	<u>%</u>
Theoretical Heat Requirement	2.24×10^6	32
Melter Exit Gases	1.40×10^6	20
Radiation Losses	<u>3.40×10^6</u>	<u>48</u>
Total	7.04×10^6	100

Radiation losses are barred from recovery due to practical considerations. These losses, however, can be reduced through better insulation practices or improved insulating materials.

The sources and temperatures of waste gases are listed in Table E.19. The average flow rate of gases from checker regenerators was found to be about 100,000 scf/ton (AiResearch 1982).

Waste heat recovery from kiln exhausts is impeded by the fouling and corrosion potential of the waste streams. Potential foulants in glass melter exhausts include constituents from fuel combustion and from the batch, as well as degradation products from the refractory-lined furnaces and from the checkers.

TABLE E.19. Exhaust Gas Sources and Temperatures

<u>Source</u>	<u>Exit Temperature (°F)</u>
Melting Furnace	2000 - 2800
Primary Regenerator	1200 - 1500
Secondary Regenerator	800 - 1000
Metallic Recuperator	1600 - 1800
Annealing Lehrs	1000 - 1200

Because of the direct contact between the combustion gases and the glass batch in fuel-fired furnaces, the furnace exhausts are laden with particles and

volatilized species from the glass. Gases bubble up through the melted glass and propel particles from the batch (Sittig 1977). These become entrained in the combustion gases which are flowing across the surface of the batch. The particulates consist primarily of sodium sulfate (Na_2SO_4) from the salt cake added to the feed. Particulates also include Na_2O , SiO_2 , CaO and cullet dust. The primary liquid component is sodium sulfate and SO_3 (AiResearch 1980). The gas phase constituents are primarily NO_x and SO_2 (Sittig 1977; AiResearch, 1982).

Particulates collect in the regenerator and in the off-gas passages following the regenerator. The ultimate results of particulate deposition may include: (1) loss of regenerator effectiveness, (2) complete plugging of regenerator passages, or (3) destruction of regenerator brick. Particles collect within the checkers by impingement and settling, with impingement as the dominant mechanism (Sittig 1977). Dust and condensate collect on the surface of the bricks in the upper part of the checkers and form a slag that drips down into the lower zones. Here, because of the lower temperature, the slag solidifies and blocks the passages. Slag may also stay in the upper zones, causing plugging (Sittig 1977). The loss of effectiveness occurs as the pressure drop increases across the regenerator through constriction of the flow passages.

In the top zone of the regenerator, the following mechanisms are reported to contribute to erosion and corrosion of the brick (Kulkarni 1982):

- High-temperature flow of gases erode brick.
- MgO in magnesite brick reacts with SiO_2 in the exhaust to form forsterite (Mg_2SiO_4). This leads to volume expansion and subsequent crumbling of the brick.
- MgO and CaO combine with SO_3 to form sulfates. The melting temperature of the bricks is lowered, leading to subsequent crumbling. This process is accelerated by the presence of vanadium oxide and sodium sulfate.

In the bottom zone of the regenerator, the following mechanisms are reported to lead to fouling and corrosion problems (Kulkarni 1982). Na_2O

and SO_x combine to form sodium sulfate which condenses on the brick surface. The liquid sodium sulfate dissolves SO_3 from the exhaust and it is transferred through the liquid to the refractory surface. The SO_3 attacks the magnesium oxide (MgO) in the magnesite bricks and the calcium oxide (CaO) in the silicate bond to form magnesium sulfate (MgSO_4) and calcium sulfate (CaSO_4), respectively. Both reactions weaken the brick. These compounds form a eutectic mixture with the sodium sulfate, which drips down the bricks. When the gas flow is reversed, the eutectic is thought to form a white slag upon cooling. The sodium sulfate, still in the vapor phase, condenses when the gas flow is reversed to form a light powder.

Currently glass manufacturers do not employ secondary heat recovery equipment downstream from the checker regenerator. Potential fouling problems are the barrier to the adoption of secondary heat recovery equipment. Although much of the particulate carried over from the glass furnace collects in the regenerator, the exhausts leaving the regenerator still contain a high concentration of particulate. The composition of the particulates and the vapor contaminants leaving the regenerator are listed in Table E.20 for soda-lime glass.

TABLE E.20. Constituents in Regenerator Exhausts (Webb 1982)

<u>Particulate Composition</u>		<u>(ppm)</u>
Na_2SO_4		90
K_2SO_4		3
CaSO_4		4
SiO_2 , Al_2O_3 , others		3
<u>Vapor Composition</u>	<u>Gas-Fired (ppm)</u>	<u>Oil-Fired (ppm)</u>
SO_2	10 - 80	up to 270
SO_3	0 - 2	2-10
NO_x	433	433
HCl	13.7	13.7
HF	0.1	0.1

The following potential fouling problems in heat exchangers for secondary recovery have been reported for the hot end and the cold end of the exchanger (Webb 1982):

- HOT END:
- Corrosion may result from the reaction of SO_3 with K_2SO_4 and Na_2SO_4 , which form corrosive pyrosulfates, $\text{K}_2\text{S}_2\text{O}_7$ and $\text{Na}_2\text{S}_2\text{O}_7$, respectively.
 - The liquid pyrosulfates entrap particulates.
 - The pyrosulfates dry to a hard scale as the surface temperature is lowered. Scales are not removable by air blowing, but are water soluble.
- COLD END:
- If the surface temperature is below the dewpoint temperature, H_2SO_4 condenses. The condensed acid may react with sodium sulfate to form corrosive Na_2SO_7 .
 - If water condenses with the acid, NaHSO_4 may be formed.
 - The $\text{Na}_2\text{S}_2\text{O}_7$ and NaHSO_4 form a sticky surface which traps particulates, forming a sludge.

Non-contact cooling water is used for equipment cooling. Cullet quench water is used to dissipate the heat from the scrap glass from product rejection, breakage or intentional wasting of molten glass during production interruptions. Cooling and process water for cullet quenching vary considerably between the product operations. Table E.21 summarizes the temperature above ambient, average flow rate and heat content of cooling and process waters by product category.

TABLE E.21. Waste Heat Discharged in Cooling and Process Waters
(Latour 1981)

	<u>Flow</u> <u>(Gal/Ton)</u>	<u>T</u> <u>(°F)</u>	<u>Waste Heat</u> <u>(Btu/Ton)</u>
Flat Glass	500-20,000	10-40	2×10^6
Container Glass	1500	11	6×10^4
Pressed and Blown Glass			
• Pressed and Blown	1350	18	2×10^5
• Glass Tubing	2000	8	1×10^5
• T. V. Tubes	3000	25	6×10^5
• Incandescent Lights	1080	14	1×10^5
• Frosting	950	20	1×10^5

LIME - SIC 3274

In 1982, lime producers at 147 plants in the United States sold or used 14.6 million tons of lime. About 23% (3.3 million tons) of this is captive lime (BuMines 1983). Captive lime is produced for consumption within a process rather than for sale.

Process Description

The lime production process is shown in Figure E.5. Basically, limestone is produced by calcining high-calcium or dolomitic limestone. The reactions that occur in the calcination step are given below for each type of limestone:

FIGURE E.5 Lime Production Process

At temperatures between 1700 and 2450°F, dissociation of limestone proceeds gradually from the outer surface of the particle toward the center. In general, larger diameter particles require higher calcining temperatures. Thus, feed crushing and screening have a significant effect on kiln energy use. Temperature control in the kiln must be maintained to obtain a high-quality product. Insufficient temperatures result in incomplete calcination, which tends to dissipate the concentration of lime in the final product. Overheating the lime may reduce the reactivity of the lime through desensification and occlusion of surface micropores and fissures (Kirk-Othmer, 3rd Ed.).

The lime industry is energy-intensive, consuming about 7.1 million Btu/ton of lime productd (BuMines 1983). More than 70% of the fuel used in lime production is coal and about 25% is natural gas. The remaining 5% is fuel oil and other fuels. It is expected that the industry will continue to convert to coal within the limits of kiln fuel use capabilities.

Heat-Transfer Operations

The major heat-transfer operation in lime manufacture is calcining. Calcining accounts for 90 to 95% of the energy used in lime production (Warren 1980). Other heat-transfer operations include air cooling of calcined limestone and non-contact water cooling of equipment.

Calcining

Calcining is a direct-heat operation carried out at 2000°F to 2400°F. A variety of refractory-lined kilns are used to calcine limestone. They vary with respect to capacity, energy use, and product-quality capability.

About 85% of the commercial and 70% of the captive lime is produced in rotary kilns (BuMines 1983). The production capacity of rotary kilns ranges from 50 tons/day to 1000 tons/day (Schwarzkopf 1970). Use of large rotary kilns in the cement industry suggests that it is possible to produce 3000 tons/day lime in a single rotary kiln system (Schwarzkopf 1970). Rotary kilns have three distinct advantages over other kiln systems: (1) they can use any type of fuel, (2) they produce a higher quality product, and (3) they have a larger capacity. Rotary kilns generally have a higher fuel consumption per

unit of product and a higher capital cost than other types of kilns. Using a preheater with a rotary kiln is one means of reducing energy consumption. In the preheater, the exit gases from the kiln are mixed with the incoming feed and some surface calcination occurs.

Vertical kilns are available in capacities from 100 to 680 tons/day. These use less fuel than the rotary kilns per ton of output, but they are restricted to gaseous and liquid fuels. These kilns also produce a lower quality product. Because of their lack of fuel flexibility and lower-quality output, these kilns are being phased out.

Two other types of kilns that have limited application in the United States are the rotary hearth calciner and the fluid bed. Table E.22 summarizes some of the pertinent features of the four types of kilns.

Lime Cooling

Calcined lime from the rotary kiln drops onto a cooler through which cooling air is passed. Coolers may be contact-, rotary- or grate-type coolers. The calcined lime is cooled from about 2000°F to 200°F (Intertechnology 1977). The cooling air is heated from ambient to about 1000°F. The heated air serves as combustion air in the kiln.

TABLE E.22. Comparison of Lime Calcining Systems
(Schwarzkopf 1970; Intertechnology 1977)

	<u>Rotary</u>	<u>Rotary with Preheater</u>	<u>Vertical</u>	<u>Rotary Hearth</u>	<u>Fluid Bed</u>
Capacity (tons/day)	100-1000	150-1000	100-680	100-600	50-300
Type of Fuel	any	any	gas	gas/oil	gas/oil
Fuel Use (10 ⁶ Btu/ton)	6-12	5-6	5	4.7-5	4.5
Power Use (kWh/ton)	24-32	32-36	10-25	28-32	25

Waste Heat Streams

Waste heat streams from lime manufacture include kiln exhausts and non-contact cooling water.

The theoretical enthalpy requirement for lime production is 4.23×10^6 Btu/ton for high-calcium quicklime and 3.85×10^6 Btu/ton for dolomitic quicklime (Kirk-Othmer, 3rd Ed.). Most of the lime produced is high-calcium. Comparison of the theoretical enthalpy requirement with the energy consumption figures presented earlier in Table E.22 shows that in practice a great deal more heat is required because of losses through the kiln shell, in the exhaust gases, and as sensible heat in the product. Table E.23 provides an estimated energy balance for a rotary lime kiln.

TABLE E.23. Estimated Energy Balance for Rotary Lime Kiln

	<u>10^6 Btu/ton</u>	<u>%</u>
Theoretical Heat Requirement	4.23	60
Kiln Exhaust	1.63	23
Product Sensible Heat	1.14	16
Power Use	<u>0.10</u>	<u>1</u>
	7.10	100

Kilns with preheaters recover some of the heat rejected in the kiln exhausts and some of the sensible heat in the product is recovered for combustion air preheat. The temperatures of kiln exhausts range from 1800-2000°F. If a preheater is used, the exit gases from the preheater range from about 450°F to 550°F (Intertechnology 1977).

Kiln exhausts are laden with dust particles. The average dust loading in a rotary kiln is reported to be 10% of the kiln feed or approximately 44 lbs/ton of lime, allowing for about 2 tons limestone/ton lime (Kirk-Othmer, 3rd Ed.). The hot combustion gases from direct-fired combustion blow the dust from the kiln. The dust is hot, dry, and difficult to wet. In addition, the

particles are prone to becoming electrostatically charged (Sittig 1977). The dust varies in composition from raw limestone to calcined lime. It will also contain fly ash and unburned carbon if pulverized coal is the fuel.

Flow rates of water for non-contact equipment cooling are estimated to be 100 to 400 gallons/ton of lime produced. The discharged water ranges from 5°F to 10°F above the inlet, corresponding to between 5000 and 30,000 Btu of heat rejected per ton of lime produced (Latour 1981).

GYPSUM - SIC 3275

The primary uses of gypsum are in cement production and in the manufacture of plaster products used as building materials. Over 60% of the gypsum produced is used for building materials and plaster products (BuMines, 1983). Because of its association with the construction industry, gypsum manufacturing is somewhat seasonal. About 60% of the industry energy requirement is consumed between April and September (Battelle 1976).

Process Description

Figure E.6 shows the processing steps in gypsum manufacture. Gypsum occurs as a relatively pure hydrated calcium sulfate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. The crude gypsum is crushed and ground in roller mills. Typically, drying occurs during grinding. About 40% of the gypsum is withdrawn after this step for sale as Portland cement retarder or agricultural gypsum.

Calcining converts the hydrate to the hemihydrate as follows:

A portion of the calcined gypsum is sold as gypsum building plaster following grinding and packaging.

The majority of calcined limestone is further processed to manufacture prefabricated forms. This involves extruding a layer of wet plaster on a moving sheet of cardboard, followed by covering with another sheet of cardboard. Initial setting and hardening is promoted through the use of additives. After setting, the sheets are cut and sent to the dryers. In the dryers, the moisture content of the plasterboard is reduced from about 50% to between 1 and 2% (Battelle 1976). The dried plasterboard is then cooled and sent to storage.

FIGURE E.6 Gypsum Processing

The breakdown of energy use by the gypsum industry is as follows (BuMines 1980):

Natural Gas	82%
Electricity	7%
Fuel Oil No. 2	5%
Fuel Oil No. 4 & 6	3%
Propane	2%
Coal	1%.

Heat-Transfer Operations

The major heat-transfer operations in gypsum manufacture are calcining and plasterboard drying.

Gypsum Calcining

Most gypsum is calcined in large, direct-fired kettles. A few rotary kilns are used. The steel kettles are 8 to 15 feet in diameter and 6 to 14 feet deep (Battelle 1976). The kettles hold between 10 and 25 tons of gypsum (Shreve 1977). Ports are provided to charge the feed and withdraw the product.

A series of burners located under the kettle provide the heat for calcination. The hot combustion gases flow through the annular space between the kettle and a brick shell. In addition, a number of horizontal flues run through the kettle to enhance heat transfer (Intertechnology 1977). The gypsum is continuously stirred by several sweep arms or blades.

Calcining is a batch operation, requiring from one to two and one-half hours, depending on the batch size and firing rate. The batch is charged to the kettle and it is then fired. The water of hydration begins to be driven off at about 120°F. The temperature then increases and is maintained at 250-260°F until calcination to the hemihydrate is completed. At this point, a rapid temperature rise occurs. When the temperature reaches 320-340°F the batch is withdrawn.

Between 0.8×10^6 and 1.1×10^6 Btu/ton of hemihydrate is used. Excess air ranges from 40 to 100% and overall efficiency is about 50% (Intertechnology 1977).

Wallboard Drying

The moisture in the wallboard is removed by drying. Dryers usually contain several tiers and have two or three zones at different, but constant, temperatures. Typically, the temperature zones are as follows (Intertechnology 1977):

first zone	450°F
second zone	440°F
third zone	150-230°F.

Temperatures of the drying gases generally do not exceed 450°F to avoid warping and possible recalcination of the gypsum (Intertechnology 1977). Each zone is equipped with a fan and a heater for the air. Partial recycling of the air stream helps to reduce heat losses. Heat for the air heaters is most commonly supplied by steam, although the use of heat-transfer liquids is increasing (Battelle 1976).

Waste Heat Streams

The major waste heat streams from gypsum manufacturing are the exhaust gases from calcining and from wallboard drying.

The stack gases from calcining operations range from 700 to 1100°F (Inter-technology 1977). Apparently no heat recovery techniques are commonly employed to recover heat from these exhausts. Dryer exhausts are generally less than about 200°F and are high in moisture.

BRICK AND STRUCTURAL CLAY - SIC 3251

Common brick has historically accounted for most of the value of shipments for this industry. Minor products include ceramic glazed brick and tile and structural tile.

Process Description

Figure E.7 shows the major steps in brick manufacture. Clay from mines or quarries is crushed, ground and classified to obtain uniform particle diameters for feed materials.

There are three forming processes: (1) the soft-mud, (2) the stiff-mud, and (3) the dry-press. The stiff-mud process is now predominant (Shreve 1977). In the soft-mud process, the clay is mixed with water, excess water is

FIGURE E.7. Brick Manufacturing

filtered off (leaving 20 to 30% water), and the mixture is de-aerated to reduce porosity. The batch is then extruded into slugs which are soft and easy to form.

The stiff-mud process involves adding 12 to 15% water to the clay. The moistened clay is passed through a die and into a de-airing chamber in which a vacuum is maintained to remove gases in the clay. Finally, the mass is extruded continuously in columns, which are wire cut to the appropriate length.

In dry pressing, only 3 to 4% moisture is added to the dry clay. A press that delivers about 5 tons/in² is used to mold the brick. This process is not commonly used.

Following forming, bricks are dried and then fired. Fired bricks are slowly cooled to avoid thermal shock. The combined drying and firing steps account for about 90% of the total energy consumed by the process (Battelle, 1976).

Heat-Transfer Operations

The major heat-transfer operations in brick manufacturing are drying and firing.

Drying

Historically, bricks were dried outside at ambient temperatures. However, most brick is now dried in ovens at temperatures between 300°F and 400°F (Intertechnology 1977). These dryers may be direct fired, steam heated, or resistance heated. A significant portion of the dryers use waste heat from kiln exhausts exclusively.

Firing

Most brick is fired in continuous tunnel kilns rather than in the older, less efficient batch kilns. Kiln capacity ranges from about 80 to 1000 tons/day (Intertechnology 1977). The trend toward replacing batch kilns with continuous tunnel kilns is expected to continue.

Kiln firing temperatures range from about 1800 to 2200°F (Warren 1980). Total process heat requirements for a kiln which also supplies all dryer heat requirements is about 3.3×10^6 to 3.4×10^6 Btu/ton of product (Intertechnology 1977).

Waste Heat Streams

The most significant waste heat streams in brick manufacture are the exhaust gases from kilns and drying ovens. Exhaust temperatures from the kiln that are recycled to the dryers are between 300°F and 400°F (Intertechnology 1977).

APPENDIX F
TEXTILES - SIC 22

APPENDIX F
TEXTILES - SIC 22

The textile industry produces a wide variety of products from both natural and synthetic fibers. These products include knit and woven fabrics, rugs and carpets, and thread and yarn. In 1977, there were 7,202 textile mills in the United States (U.S. Department of Commerce 1981). The industry is concentrated in the Southeast, primarily in North and South Carolina and Georgia.

Textile plants range from highly integrated mills that process fibers into finished products to smaller, non-integrated plants that process goods owned by other producers on a contract basis. The industry has been classified according to the Standard Industrial Classification (SIC) as shown in Table F.1. Knitting mills constitute the largest group within the industry with 2,617 plants.

Within the textile industry, textile finishing (SIC 226) is the largest user of purchased fuels and energy. Energy purchases for 1980 are shown in Table F.2 by SIC number. Two-thirds of the energy consumed in the industry is

TABLE F.1. Textile Mill Industry Classification
(U.S. Department of Commerce 1981)

<u>SIC Number</u>	<u>Description</u>	<u>Number of Establishments</u>
22	Textile Mill Products	7,202
2211	Weaving Mills, Cotton	314
2221	Weaving Mills, Manmade Fiber, Silk	449
2231	Weaving and Finishing Mills, Wool	165
2241	Narrow Fabric Mills	335
225	Knitting Mills	2,617
226	Textile Finishing, Except Wool	678
227	Floor Covering Mills	592
228	Yarn and Thread Mills	798
229	Miscellaneous Textile Goods	1,254

TABLE F.2. Textile Industry Energy Use, 1980
(Annual Survey of Manufactures 1980)

<u>SIC Number</u>	<u>Industry Category</u>	<u>Energy Use</u> (10 ¹² Btu)
2211	Weaving Mills, Cotton	35.9
2221	Weaving Mills, Manmade Fiber, Silk	44.9
2231	Weaving and Finishing Mills, Wool	4.9
2241	Narrow Fabric Mills	3.7
225	Knitting Mills	52.8
226	Textile Finishing, Except Wool	65.4
227	Floor Covering Mills	27.9
228	Yarn and Thread Mills	35.5
229	Miscellaneous Textile Goods	<u>23.9</u>
	Total	294.9

used in fabric finishing (Streb 1977). Most of the energy is used to raise steam, which is used for drying, and for heating water for washing or chemical preparation. Between 50 and 70% of the fossil energy consumed by the textile industry is used for steam production (Georgia Institute of Technology 1982). Direct firing of natural gas in dryers and ovens is the second largest use of energy, accounting for 25% of the total energy use.

Textile production consists of two basic operations: (1) the production of undyed, unfinished (greige) fabric, and (2) the production of finished goods from the greige fabric.

PROCESS DESCRIPTION

Figure F.1 shows typical processing steps for knit and woven greige goods production. These front-end operations are essentially dry, with the exception of slashing.

Yarn preparation converts the natural or synthetic fibers to yarn. Yarn which is to be used in knitting operations is treated with an oil or wax

FIGURE F.1 Typical Processing Steps for Knit and Woven Greige Goods Production

emulsion in the finishing process. This treatment helps to increase the speed of the knitting process.

Yarn destined for weaving mills is treated with compounds such as carboxymethylcellulose, polyvinyl alcohol, or starch in the slashing (sizing) process. These compounds protect the thread against abrasion during weaving. The size compounds are applied by passing the yarns through a hot aqueous solution containing the sizing chemicals. The solution is generally heated through direct steam injection. Following sizing, the thread is dried by passing it over steam-heated drying cylinders. The thread is then sent to the weaving looms for production of woven greige fabric.

Finishing operations (dyeing and finishing) transform the greige goods into finished fabric. Figure F.2 shows the typical processing steps in finishing woven and knit greige fabric. Many of the finishing steps are wet operations which use water heated by direct steam injection. Textile mills use a great deal of process water for product washing, air-washing, boiler makeup, cooling of process equipment, and as a diluent for process chemicals. Drying operations use direct-fired natural gas or indirect steam heating of drying cylinders.

FIGURE F.2 Typical Processing Steps in Finishing Woven and Knit Greige Fabric

HEAT-TRANSFER OPERATIONS

The major heat-transfer operations in textile production are listed in Table F.3. An operation is designated as "non-contact" if the heat-transfer fluids do not mix with the media that is being heated and as "contact" if they are in contact.

Steam Generation

Steam process heat demands from plant-to-plant range from 4000 to 40,000 lbs/hr (Battelle 1976). The steam temperature at the boiler is in the range of 250 to 400⁰F (Battelle 1976). Gas and oil-fired boilers have largely been converted back to coal, with standby capability provided by fuel oil or natural gas. Several textile plants now purchase steam from a central source, rather than generate steam on-site (Power 1983). For all greige mills, steam pressures range between 15 psig and 125 psig. Integrated mills generally use steam between 100 and 150 psig (UTC 1980).

Drying (Drying Cylinders)

Steam-heated drying cylinders (drying cans) are used for drying both in woven greige goods production and in fabric finishing. In greige goods production, the treated warp yarns from the sizing operation are passed over the drying cylinders prior to weaving. Drying cans are used for predrying fabric prior to drying in tenter-frame dryers.

TABLE F.3. Textile Mill Heat-Transfer Operations

	<u>Operation</u>	<u>Equipment</u>	<u>Heat-Transfer Medium</u>
NON-CONTACT:	Steam Generation	Boiler	Combustion Gases
	Drying	Drying Cans	Steam
CONTACT:	Singeing	Ovens	Natural Gas Flame
	Drying	Tenter Frames	Combustion Gases
	Water and Chemical Heating	Injection Nozzle	Steam
	Air Tempering	Air Washers and Cooling Towers	Chilled or Hot Water

Heat is transferred to the yarn or the fabric via conduction through the cylinder to the yarn. Steam is used at pressures ranging from 15 to 35 psig and from 75 to 125 psig, with the higher pressures used to increase the production rate (UTC 1980). The steam pressures are sufficient to keep the can surface temperature at about 315⁰F (Cook October 1978). About 2000 Btu are used in steam drying cans per pound of water evaporated (Hendrix 1983). Steam is condensed and returned to the boiler.

Singeing

Singeing is the process by which protruding fibers from yarn or fabric are burned off by passing over an open flame. Some fabrics are singed only on one side and some are singed on both sides.

Natural gas is burned to provide the flame for singeing. It is estimated that about 200 Btu/lb of fabric is used in the singeing process (Cook January 1978).

Drying (Tenter Frames and Ovens)

Convective drying of fabric occurs as it moves through the tenter-frame dryers. Dryers are of two general types that differ in air flow arrangement:

- (1) flow-through dryers -- hot air is forced through the fabric from one side
- (2) impingement dryers - high-velocity air is directed toward both surfaces of the fabric.

Most dryers have several zones with individual burners. Each zone has a separate temperature controller and exhaust duct. Table F.4 provides energy consumption information collected for several different dryers. The average energy use figure from this sample was determined to be about 2100 Btu/lb of fabric. A figure of 3000 Btu has been reported for tenter-frame dryers per pound of water evaporated (Hendrix 1983).

Water or Chemical Heating

Water and textile chemical heating may occur through direct or indirect heat transfer with steam. Examples of unit operations that require steam heating are slashing, dyeing, washing, and mercerizing.

TABLE F.4. Dryer Performance Values (Cook January 1978)

<u>Sample</u>	<u>Fuel</u>	<u>Fabric Weight lbs./yd.</u>	<u>% Moisture Entering</u>	<u>Highest Exhaust Temp. °F</u>	<u>Exhaust Humidity Ratio</u>	<u>Energy Required Btu/lb.</u>
1A	Propane	2.96	129	247	.04	2,690
1B	Propane	2.76	122	210	.04	2,250
2A	Steam	2.12	26	254	.015	1,800
2B	Steam		22	254	.015	1,400
3A	Steam	.534	16 1/2	193	.012	2,880
3B	Steam	2.19	55	220	.03	1,610
4	Propane	.77	30	300	.04	1,075
5						
6	Natural Gas		35	320	.04	1,160
7	Natural Gas	.85	77	380	.03	3,150
8	Natural Gas	.85	29	350	.03	2,460
9	Natural Gas	.64	50	408	NA	1,220
10	Natural Gas	.53	50	400	NA	2,750

Air Tempering

Ambient temperature and humidity control is extremely important in yarn and fabric processing. These variables are controlled by large, air-tempering systems. The textile industry is one of the largest users of air-washing equipment to clean and temper air in the processing areas. Tempering requires adding heat in the winter and removing heat in the summer. Chilled water is used in the air washers in the summer at temperatures of 40 to 50°F (Kemmer 1979). Heat collected in the chilled water is dissipated through evaporative cooling in cooling towers.

In the air tempering system, airborne particles (particularly lint) can build up on heat-transfer surfaces, reducing effectiveness. Lint can enter the cooling water loop through the natural scrubbing effect of the cooling tower, which tends to entrain airborne particulates (Capper 1974). Chiller tube sheets are vulnerable to fouling and corrosion. Dirt, fiber, oil, and micro-biological deposits can form on tube sheet surfaces, impeding heat transfer. Severe pitting can occur under the slimes (Kemmer 1979).

WASTE HEAT STREAMS

Sources and approximate temperatures of waste heat streams from textile operations are summarized in Table F.5. Table F.6 provides flow quantities for a typical interated knit mill and an integrated weaving mill.

Exhaust gases from boilers may contain fly ash, unburned hydrocarbons, and SO₃, which may condense at lower temperatures. The volume and enthalpy of the exhaust depends on the firing rate of the boiler, the amount of excess air, and the efficiency of primary and secondary heat-recovery equipment. It is difficult to generalize because of the variability across the industry.

Exhausts from singeing and drying operations contain lint, and exhausts from heat setting operations contain finishing chemicals as well as lint. Two major barriers to the adoption of heat-recovery equipment for textile dryers and ovens are the buildup of lint and the condensation of finishing chemicals on heat exchanger surfaces (Georgia Institute of Technology 1982). Finishing chemicals include anti-statics, fire retardants, softeners, water repellants,

TABLE F.5. Sources of Waste Heat from Textile Mill Operations

<u>Type</u>	<u>Source</u>	<u>Temperature (°F)</u>
Exhaust Gas	Boilers	400-650
	Singeing Ovens	390-400
	Tenter-Frame Dryers	250-400
Process Water	Slashing, Bleaching, Washing, Mercerizing, Dyeing	100-120
Non-Contact Cooling Water	Product Cooling	140

TABLE F.6. Flow Rate of Waste Heat Streams (A. D. Little 1976)

INTEGRATED KNIT MILL (22,000 lbs/day knit fabric):

<u>Type</u>	<u>Source</u>	<u>Flow Rate</u>
non-contact cooling water	dyeing operations	114,000 gal/day
process water	washing	136,000 gal/day
flue gas	drying	$586 \times 10^6 \text{ ft}^3/\text{day}$
	heat setting	$5.78 \times 10^9 \text{ ft}^3/\text{day}$

INTEGRATED WEAVING MILL (66,000 lbs/day woven fabric):

flue gas	single & heat set	$17.7 \times 10^{12} \text{ ft}^3/\text{day}$
	drying & setting	$18.7 \times 10^{12} \text{ ft}^3/\text{day}$
	heat cure	$17.5 \times 10^{12} \text{ ft}^3/\text{day}$
process water	fabric preparation	$1.11 \times 10^6 \text{ gal/day}$
	fabric dyeing	$1.11 \times 10^6 \text{ gal/day}$

or durable-press resins (Cooper 1978). These chemicals act as adhesives to hold the lint on the surface.

A heat recovery system with glass rather than metal tubes has been developed for use with dryer exhausts. The smooth, nonporous surface is more effective than metal tubes in preventing deposition of finishing chemicals or

lint. In addition, the glass tubes are assembled in modules that can be easily removed for cleaning or replacement. The manufacturer recommends cleaning at six-month intervals. Cleaning takes approximately 12 hours in a heated tank with a circulating pump that is part of the system package (Georgia Institute of Technology 1982).

Another heat-recovery system that may mitigate the lint and finishing-chemical deposit problems consists of two regenerator units that attach to the dryer. The dryer exit gas passes through one regenerator that stores heat from the exhaust while the cool, makeup air is heated as it passes through the opposite regenerator. Flow direction is alternated through the regenerators at set intervals. Deposition problems are minimized because lint builds up at the hot end of the regenerator and the finishing chemicals do not condense until they reach the cold end. The lint can then be easily removed by blowing with air. Weekly air cleaning is recommended (Georgia Institute of Technology 1982).

A large portion of the energy and water used in wet processing operations is used in batch operations. Thus, the waste heat rejected from these operations is not continuously available. Batch operations which reject low temperature waste heat in process water include various types of dyeing. Atmospheric dye becks^(a) reject about all of their input energy as waste heat. A heat balance for a typical atmospheric dye beck is given in Table F.7. The process water from dyeing contains unspent dye chemicals and lint.

(a) A vessel for drying fabric.

TABLE F.7. Heat Balance for Atmospheric Dye Beck
(Cook January 1978)

	<u>Percent</u>
Radiation and Convection	2
Exhaust	49
Process Water	<u>49</u>
Total	100

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