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Technical Memo

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ARGONNE NATIONAL LABORATORY

Energy and Environmental Systems Division

prepared for

U. S. DEPARTMENT OF ENERGY

under Contract W-31-109-Eng-38

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Printed in the United States of America. Available from National Technical Information Service,
U. S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161

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Argonne, Illinois 60439

ANL/CNSV-TM-48

LOW-TEMPERATURE WASTE-HEAT RECOVERY IN THE FOOD AND PAPER INDUSTRIES

by

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Argonne National Laboratory
under Argonne Contract 31-109-38-5235

November 1980

Work sponsored by

U.S. DEPARTMENT OF ENERGY
Assistant Secretary for Conservation and Solar Energy
Office of Industrial Programs

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FOREWORD

Argonne National Laboratory (ANL) is engaged in a program to assist the DOE Office of Industrial Programs in technology evaluation and policy analysis related to industrial conservation. Among the objectives of the DOE program are to (a) assist private sector research, development, and demonstration (RD&D) initiatives in industrial energy conservation, (b) help accelerate the market penetration of industrial energy conservation technologies, (c) ensure the environmental and institutional acceptability of DOE-sponsored RD&D, and (d) evaluate and disseminate RD&D project results. At the present time, DOE is sponsoring a large number of projects intended to improve process energy efficiency in specific industries and to develop waste energy utilization technologies that are applicable across a range of industries. In addition to these RD&D projects, a number of supporting activities, including the ANL program, have been initiated to aid in the definition of programs to identify, develop, evaluate, and help commercialize individual RD&D projects.

The work reported here was completed by Resource Management Associates (RMA) under the direction of ANL staff as part of a larger ANL industrial energy conservation program. This larger program is designed to emphasize market-oriented technology identification and development in the formulation of DOE RD&D policies. The ANL program consists of an analysis of existing but underutilized technologies, part of which is described in this report. Also included in the ANL industrial energy conservation program is the development of industrial marketing techniques and methods for application to new energy conservation technologies, the application of marketing research methodologies to the analysis of generic technologies, the application of marketing research methodologies to chemical industry technology and an analysis of the implementation of industrial energy conservation technology at the state level. Questions or comments on the work reported here or on the ANL program in general can be directed to: Paul J. Grogan, Energy and Environmental Systems Division, Building 12, Argonne National Laboratory, Argonne, Illinois 60439.

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EXECUTIVE SUMMARY

OBJECTIVE

The primary objective of this study is to shed light on the potential of low temperature waste-heat recovery technology in industry, to provide a picture of the barriers which impede it, and to identify Research and Development activities. In late 1979, Argonne National Laboratory commissioned Resource Management Associates (RMA) to conduct a study examining industrial decision procedures and barriers in implementation of low temperature waste-heat recovery. The University of Wisconsin-Madison received a grant from RMA to collaborate on specific aspects of the project.

INDUSTRIAL SETTING

The food industry and the paper and pulp industry in Wisconsin were chosen as the industrial setting for this study because of their large energy consumption and the potential that both may offer for increased utilization of low temperature waste heat.

METHODOLOGY

A case study approach was used. Planning workshops were held with several firms in each of the respective industries. Three firms in each industry agreed to participate in the study. These firms served as primary sources of economic, technical, and institutional information for the study. These data were supplemented during the course of the study by extensive information from the literature and by previous energy analysis of these industries. The project team developed a picture of the recovery potential and the decision procedures in these industries. Additional interviews and workshops with the firms were used to elicit industry reactions and to modify the project's analyses.

MAJOR FINDINGS

Barriers to Use of Heat Recovery Systems for Low Temperature Waste-Heat Recovery

A significant potential exists for recovery of low temperature waste-heat in the food and paper industries. However, our case studies indicate that firms in these industries face significant barriers, either real or perceived, to the implementation of this recovery. These prominent barriers, identified by these firms, include technical, economic, and informational/institutional factors. Prominent among these barriers are lack of accessibility of acceptor streams for heat recovery, lack of information about specific energy flows within a firm's plants, insufficient information about future energy prices, inadequate economic justification for a proposed recovery project, and lack of capital funds.

Substantial parts of these barriers could be removed through the improvement of industry's information and its understanding of the potential heat recovery. However, economic justification and competitiveness for available capital with non-energy projects are pre-eminent factors in influencing implementation of recovery projects.

Waste-Heat Recovery in the Food Industry

The food industry is the second largest industrial energy consumer in Wisconsin. Most of this energy is used for process heat at moderate temperatures (below 270°F).

Significant potential exists to recover and reuse energy from waste streams through the installation of heat exchangers and heat pumps or the direct reuse of waste streams. Important limiting factors are fouling of heat exchangers, product quality control, sanitary regulations, coincidence of waste and acceptor streams, and economic viability.

Calculations were made to assess energy recovery in canning, meat processing, fluid milk, and cheese processing plants under a variety of conditions and assumptions. It is technically feasible to reduce boiler fuel requirements by 8 to 10 percent through installation of liquid-to-liquid heat exchangers and direct use of suitable waste streams as boiler feed water.

Waste Heat Recovery in the Pulp and Paper Industry

The pulp and paper industry is the largest industrial energy consumer in Wisconsin. Most of this energy is used for process heat and drying. Much waste heat available is already recovered especially on drying equipment. The potential for heat recovery depends on such factors as degree of integration, product mix, processes used and physical plant parameters.

Our calculations indicate that heat recovery may reduce total energy consumption by 3 to 8 percent. This takes into account the decreased potential for cogeneration of electric power associated with reduced steam requirements. The analysis considered only one waste stream (evaporator condensate) and two acceptor streams (boiler feed water, water for bleaching). There should be additional opportunities for waste heat recovery using other streams.

Economic Decision Criteria and Models for Waste Heat Recovery

Economic justification is a major barrier to implementation of waste heat recovery projects. Cost savings from conservation projects depend on energy prices and fuel mix. Economic acceptability depends on the method used to evaluate the cost savings. We demonstrated how the payback method, commonly used among firms in our study, favors projects with short lives and large immediate savings over those with longer lives and increasing savings. Energy conservation projects tend to be of the second kind. We therefore conclude that the economic value of conservation projects is more accurately estimated based on life cycle than payback analysis. A general life cycle costing methodology is presented.

Development of a convenient and standardized life cycle evaluation guide for energy conservation projects is desirable. Life cycle analyses also create a greater need for credible energy price and availability forecasts. State and federal government should become more involved in preparing and disseminating such forecasts.

Engineering/Economic Procedures for Selection of Heat Exchangers and Heat Pumps

Even when it is technically feasible to recover heat using a heat exchanger or heat pump, it may not always be cost effective to do so. Life cycle cost analysis is needed to accurately estimate costs and benefits of a specific application.

The maximum economic benefits depend on the choice of recovery equipment. We have developed generalized methods to calculate break-even fuel costs (the fuel price below which no heat exchanger is cost effective) and to determine the optimum size heat exchanger. A simplified version of this method was also developed for heat exchangers. A third procedure was developed to evaluate energy savings and cost effectiveness of heat pumps. Plant and equipment specific data are required as input. In general, heat exchangers yield more savings with larger temperature differentials between waste and acceptor streams. Heat pumps become more cost effective with smaller temperature differences.

Institutional Aspects

Organizational structure strongly influences the adoption of energy conservation projects. We found that larger firms generally employ energy staff personnel at the corporate level. Smaller firms often have no specific energy official or program but handle energy like any other production factor. At the plant level, energy coordinators and/or committees have been commonly appointed. If responsibility for energy conservation rests with the engineering staff, plant improvements seem to be commonly used to reduce energy consumption. If this responsibility resided with the operations' staff, operational improvements tend to be favored.

Many companies have energy reporting systems to facilitate reporting to government and as a management tool. Energy conservation incentives are being provided through the setting of conservation objectives. The lack of detailed energy flow metering hampers evaluation of how well objectives are met and makes it difficult to assess potential project ideas.

Dissemination of information should be encouraged with vehicles such as regional workshops, and newsletters.

Implications of Study Findings for Research and Development in Low Temperature Waste-Heat Recovery Systems

Because heat exchangers and heat pumps are relatively expensive, many heat recovery applications are not cost effective. Initial capital costs play a major role in determining the attractiveness of heat recovery projects. Research and development strategies for advanced heat-recovery technologies must point toward equipment first-costs that are competitive with conventional recovery technologies. High priority should be given to demonstrations and case studies which focus on experiences with industrial implementation of advanced and conventional recovery technologies.

Decision Models for Waste-Heat Recovery Projects

Because of the large number of technical, economic, and institutional factors affecting implementation of waste-heat recovery projects, no single model is applicable for evaluating all aspects of a project's feasibility or for forecasting their implementation in any particular industry. However, we strongly encourage the use of the engineering and economic decision framework presented in this study, including the use of life cycle analysis as a guide for a firm's allocation of its capital resources.

CHAPTER I

INTRODUCTION

PROBLEM BACKGROUND

Of all the sectors of the U.S. economy, energy policy makers have given the least attention to industry. One reason for this is that industry has been able to increase the efficiency of its energy use over the past several years; energy use per unit of industrial output has decreased significantly. A second reason is the general perception that, of all the sectors, industry is best able to make its own plans and adjustments for changes in the energy situation.

There is, however, also a recognition that the recent slowing of industrial energy growth is due largely to an initial housecleaning of the system, motivated by the sudden realization of the increasing price and scarcity of energy. Nevertheless, much potential for additional conservation remains. Some of this potential exists today, unrealized because of a variety of barriers. Other opportunities will evolve as industries consider plant retrofits, plant modifications, and new technologies in their expansion activities.

In recognition of this potential, Argonne National Laboratory (ANL) is engaged in a project to assist the U.S. Department of Energy (DOE) in evaluating and implementing industrial energy conservation technologies. One component of that project is intended to assist DOE in accelerating the adoption of waste-heat recovery technologies. Under contract to Argonne, Resource Management Associates (RMA) has contributed to that study by examining industrial decision procedures for implementing low temperature waste-heat recovery technology. The University of Wisconsin also collaborated in this work within the framework of a research grant from RMA to the Madison campus.

RESEARCH SETTING

Among the areas of potential industrial energy conservation, recovery of low-temperature waste heat appears to be one of the most significant. During the past year, RMA has conducted a study to understand better the industrial decision-making process through which these conservation measures are implemented. This study was also intended to provide a picture of the barriers impeding industry's use of waste-heat recovery and to shed additional light on waste-heat recovery's potential in specific industries.

The food industry and the paper and pulp industry were chosen as the industrial setting for this study because of their large energy consumption and the opportunities both offer for increased utilization of low temperature waste heat. A variety of firm-specific and plant-specific factors affect the implementation of waste-heat recovery technologies within these industries. By focusing on selected case studies, this study provides some of the detailed information required to examine the decision making processes through which the technologies are implemented.

PROJECT APPROACH

Because of their size and importance in the state, the Wisconsin food industry and paper and pulp industry provide excellent sites for the study. These two sectors rank one and two in energy consumption in Wisconsin industry, consuming 40 percent and 16 percent respectively of total industrial energy use in 1976. In previous work (Foell et al.,1980), the University of Wisconsin Energy Systems and Policy Research Program (ESPRP) has analyzed these sectors on a highly aggregated basis in an investigation of future industrial energy demands in Wisconsin. While that study did not treat energy use at the process level, the study described in this report examines specific processes for the recovery of low-grade heat in these sectors. Heat exchangers and industrial heat pumps were used in the analysis as candidate devices for heat recovery; however, the study's analytic methods are applicable in general to other heat recovery devices or sources.

To develop background characterization of the industries, the project began with separate workshops held with participation by several firms and trade organizations. Six of the firms agreed to provide plant-specific energy data for the studies. From these workshops came a specific plan and schedule for the project. The major components were: (1) waste-heat recovery in the food industry, (2) waste-heat recovery in the paper and pulp industry, (3) economic analysis and criteria for energy conservation projects, (4) engineering/economic procedures for examining the potential of heat exchangers and heat pumps for heat recovery, and (5) institutional factors in industrial energy conservation.

Waste-Heat Recovery in the Food Industry

The assessment of potential heat recovery requires a technical characterization of the industry and a generic description of energy use. The study focused on the three main food industries in Wisconsin: canning, meat processing, and dairy processing. Energy consumption patterns were described for these sectors. Representative plant and process descriptions were developed, based upon literature and upon information supplied from the industry case study participants. From these descriptions, potential waste-heat source and acceptor streams were identified and analyzed for the technical feasiblity of waste heat recovery.

Waste-Heat Recovery in the Paper and Pulp Industry

A similar approach was taken for this industry as in the food industry.

Economic Analysis and Criteria for Energy Conservation Projects

An important factor in implementing conservation is the economic criterion used by the firm to assess the merit of a particular project. The six firms were interviewed extensively to determine the methods used in their analyses. The study investigated the return and payback period objectives, and the conventions used for determining future costs, including fuel expenditures. Because either rate of return or payback analysis was used in the six firms interviewed, the study compared their project selection properties under various conditions of cost increases and for different project lives. Since conservation investments will alter prospective cost patterns over a number of years, life cycle costing should be used for project evaluation. Therefore, the study developed a framework for life cycle cost analysis.

Engineering/Economic Procedures for Examining the Potential of Heat Exchangers and Heat Pumps for Heat Recovery

The study's examination of a firm's approach to energy conservation decisions focused in part on the engineering approaches used. It also sought to generalize some of these approaches into a set of aids useful to plant or corporate engineers in evaluating specific conservation investment situations. Life cycle costing was selected to be the appropriate basis for these evaluations and therefore was incorporated into the approach. The procedure was developed for both heat exchangers and heat pumps. Using economic and engineering parameters, the procedure allows the engineer to determine whether to install the heat recovery device, and, if so, to determine what size to install.

Institutional Factors in Industrial Energy Conservation

The initiation and ultimate implementation of corporate energy conservation projects depends upon the nature of the institutional infrastructure. Such factors include, among others, whether a separate energy and conservation division exists in the firm, the relationship of energy managers to plant and production and production managers, the form of energy data collection, and the manner in which production units are evaluated on energy conservation performance. Through the case studies, the RMA project sought to identify and explain how these factors and barriers affect both the range of potential conservation projects and the manner and speed with which they are evaluated and adopted.

ORGANIZATION OF REPORT

The report is organized in chapters corresponding to the above study components. Cahpters IV and VI, on the economic and institutional aspects of heat recovery projects, respectively, provide complementary integrative frameworks for the results of the study. Chapter VII gives a final summary and major concluding observations.

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CHAPTER II

WASTE-HEAT RECOVERY IN THE WISCONSIN FOOD INDUSTRY

This chapter presents a description of energy use and potential waste heat recovery in three important food industries in Wisconsin, namely, canning, meat processing, and dairy processing. The approach used here develops representative plant and process descriptions based on literature and information supplied by industrial participants in the project. From these descriptions, potential waste heat source and acceptor streams were identified and analyzed for the technical feasibility of waste-heat recovery.

OVERVIEW

Several generalities apply to energy utilization within the food industry. First, boilers generally operate in the 80-150 psig range, since most of the process heating is carried out at temperature less than 270°F. This is necessary because of the product quality's sensitivity to higher temperatures. Second, most of the process heat is applied to the product indirectly. That is, generally the product is packaged before heating (as in thermal processing of canned products) or is heated in heat exchangers or vats (as in pasteurization of fluid milk or partial cooking of meat products). The resultant waste stream is therefore usually condensate or hot water not highly contaminated by product, and as such offers some potential for recovery of its waste heat. Finally, because of the heating medium's relatively low temperature, the waste-heat streams are generally high-volume, lower-temperature sources. Waste-heat streams are often comingled to reduce the mass-average temperature to a value acceptable for disposal. Successful application of waste-heat recovery systems would therefore require segregation of waste-heat sources in some operations.

Before describing food process operations in greater detail, one essential criterion must be established: The food industry's primary objective is to produce safe, nutritious, wholesome foods for trusting consumers. Thus, any consideration of waste-heat recovery projects should include a hazard analysis. In this, the potential benefits are weighed against the potential risk of product contamination or impact on consumer safety. For example, if an ammonia leak in a refrigeration system developed as a result of a waste-heat recovery project, it could result in a freezer full of tainted ice cream. The main point is that energy is only one factor used to evaluate food processing systems. Product quality and consumer safety are more important, particularly in on-going systems, and must remain foremost in designs of new systems.

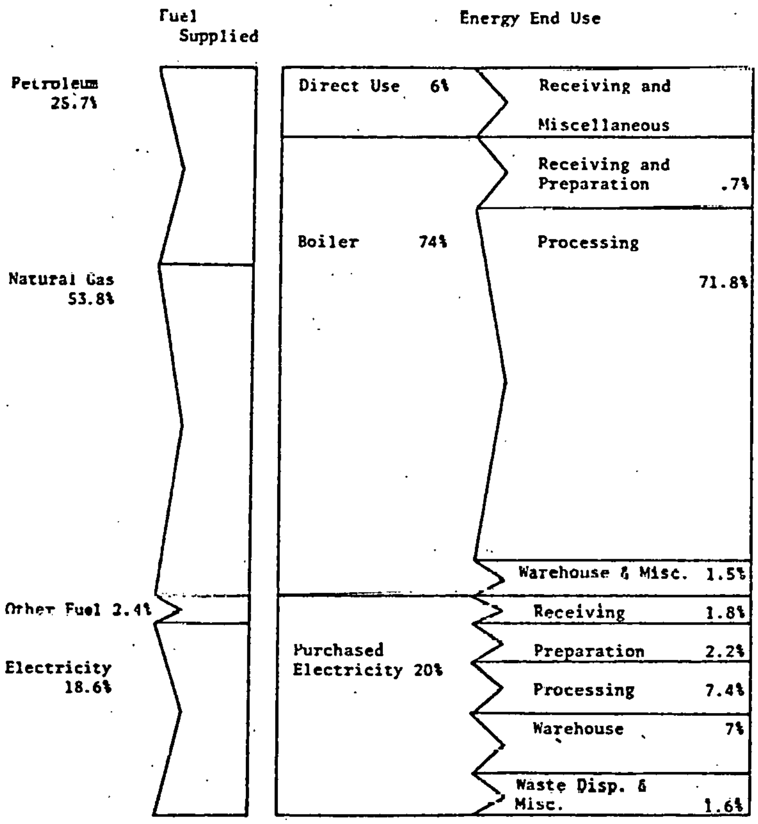
Process Descriptions

Although each food processing facility is unique in layout, the unit operations applied to transform raw agricultural commodities into consumer-acceptable products are fairly standard. Figures 2-1 through 2-11 and Table 2-1 present generalized energy and material flow charts for several of the four-digit SIC 20 (Standard Industrial Classification) industries, (Casper, 1980). From these diagrams and from the industrial cooperators on the project, it is possible to identify the waste heat sources that may be used in heat recovery schemes.

In meat processing (meat packing SIC 2011, poultry processing SIC 2016 and processed meats SIC 2013), waste-heat streams are generated from: (1) hog dehairing, (2) edible and inedible rendering, (3) clean-up, (4) boiler blowdown, (5) condensate from indirect heating, (6) refrigeration condensers and compressors including water from water-cooled condensers, (7) poultry scalding and defeathering, (8) thawing and tempering, and (9) retorting (thermal processing) (Figures 2-5, 2-6, 2-7a, 2-7b, 2-7c). For canning fruits and vegetables (Figure 2-8), the major sources of waste heat are: (1) blanching water, (2) topping water (water added to the can after the produce has been added), (3) retort condensate, (4) can-cooling water, (5) clean-up water, (6) boiler blowdown, and (7) venting of still retorts. Finally in dairy processing, the major waste-heat sources are: (1) pasteurizer condensate or overflow, (2) refrigeration condensers and compressors, (3) whey, (4) clean-up water, (5) vapor from evaporators (referred to as cow water), (6) exhaust from spray driers, and (7) wastewater from membrane processing systems (Figure 2-9 through 2-11).

Figure 2-1

Energy Flow Sheet - Frozen Fruits and Vegetables (SIC 2037)†



Total Fuel - 31.44×10^{12} Btu for 1974

Figure 2-2

Energy Flow Sheet - Canned Fruits and Vegetables SIC: 2033

Total Fuel - 52.64 x 10^{12} Btu
for 1972

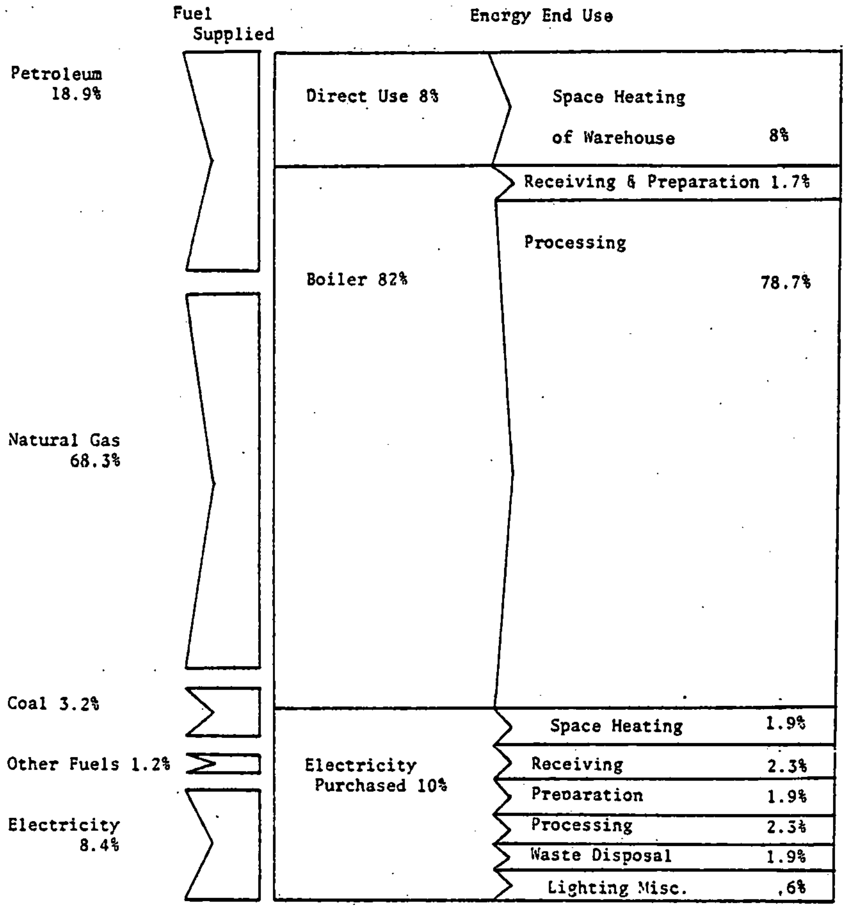


Figure 2-3

Energy Flow Sheet - Dairy Products - Cheese (SIC 2022)

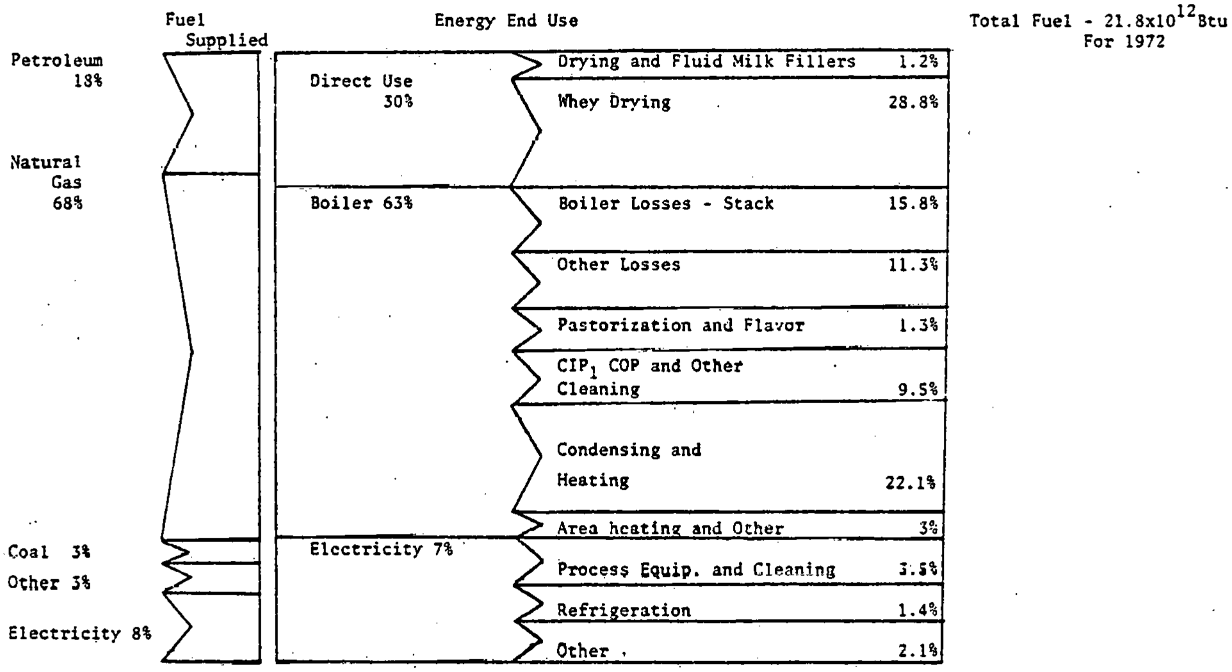


Figure 2-4a

Energy Flow Sheet - Sausages and Prepared Meats SIC: 2013

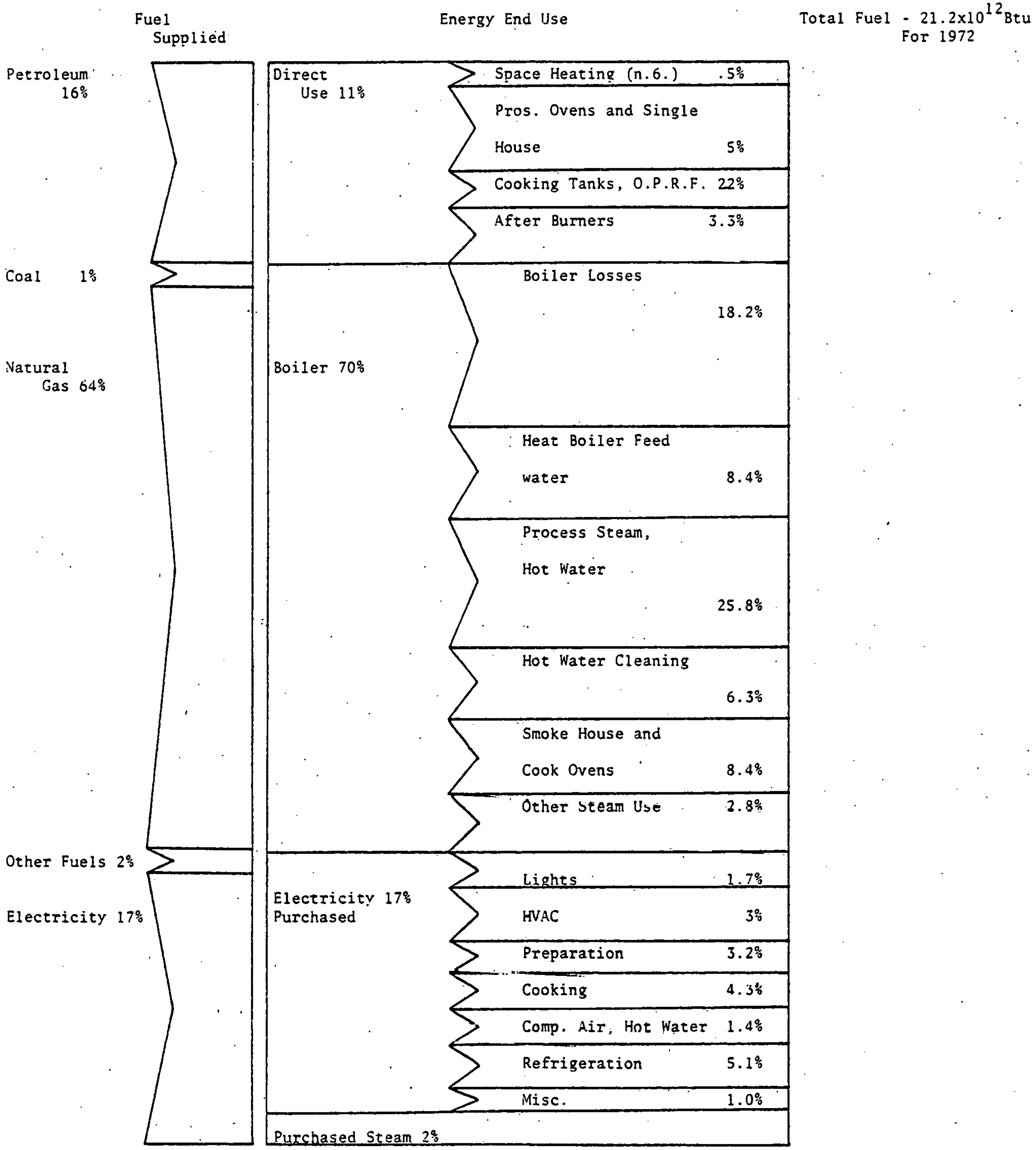


Figure 2-4b

Energy Flow Sheet - Meat Packing Industry

SIC: 2011

Total Fuel - 87.3 x 10^{12} Btu for 1972

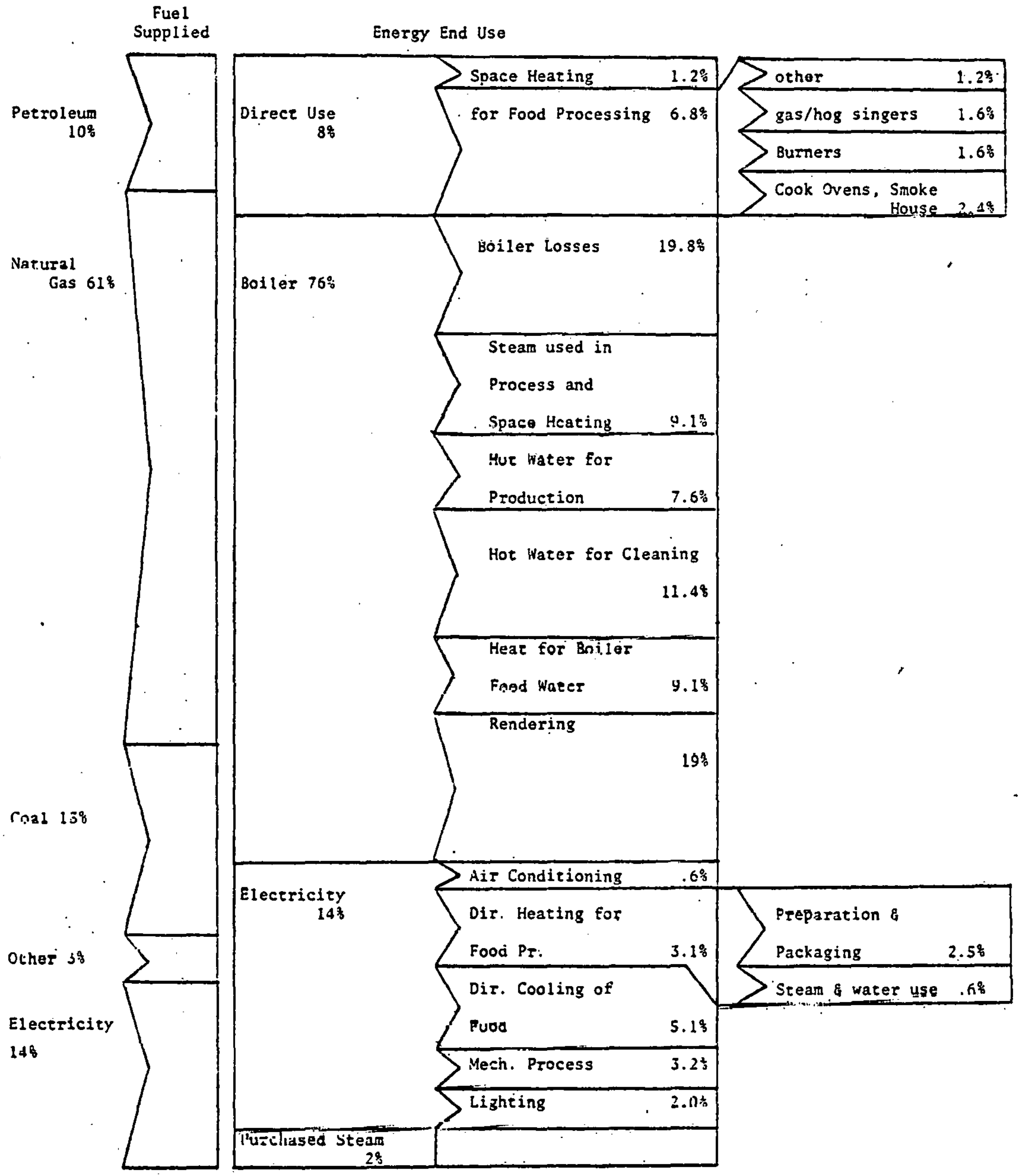
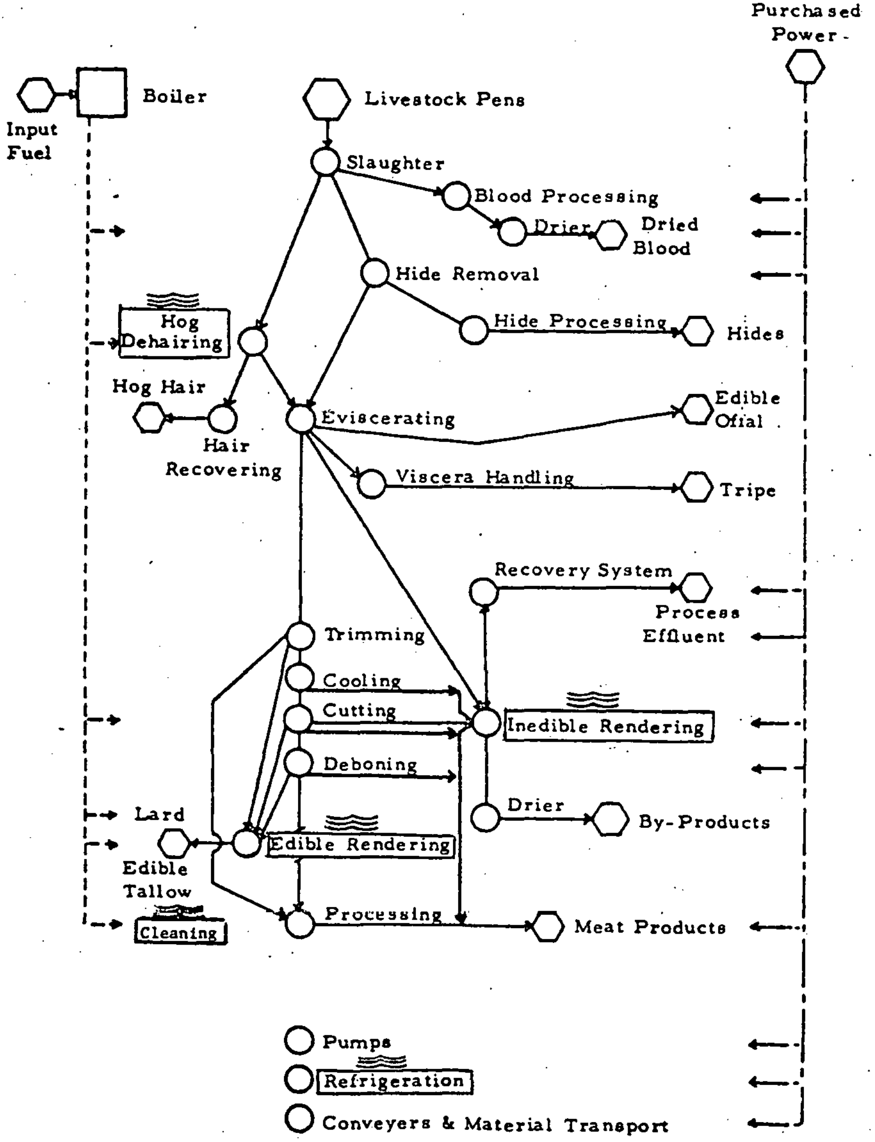


Figure 2-5

Material and Energy Flow for Meat Packing Plant†



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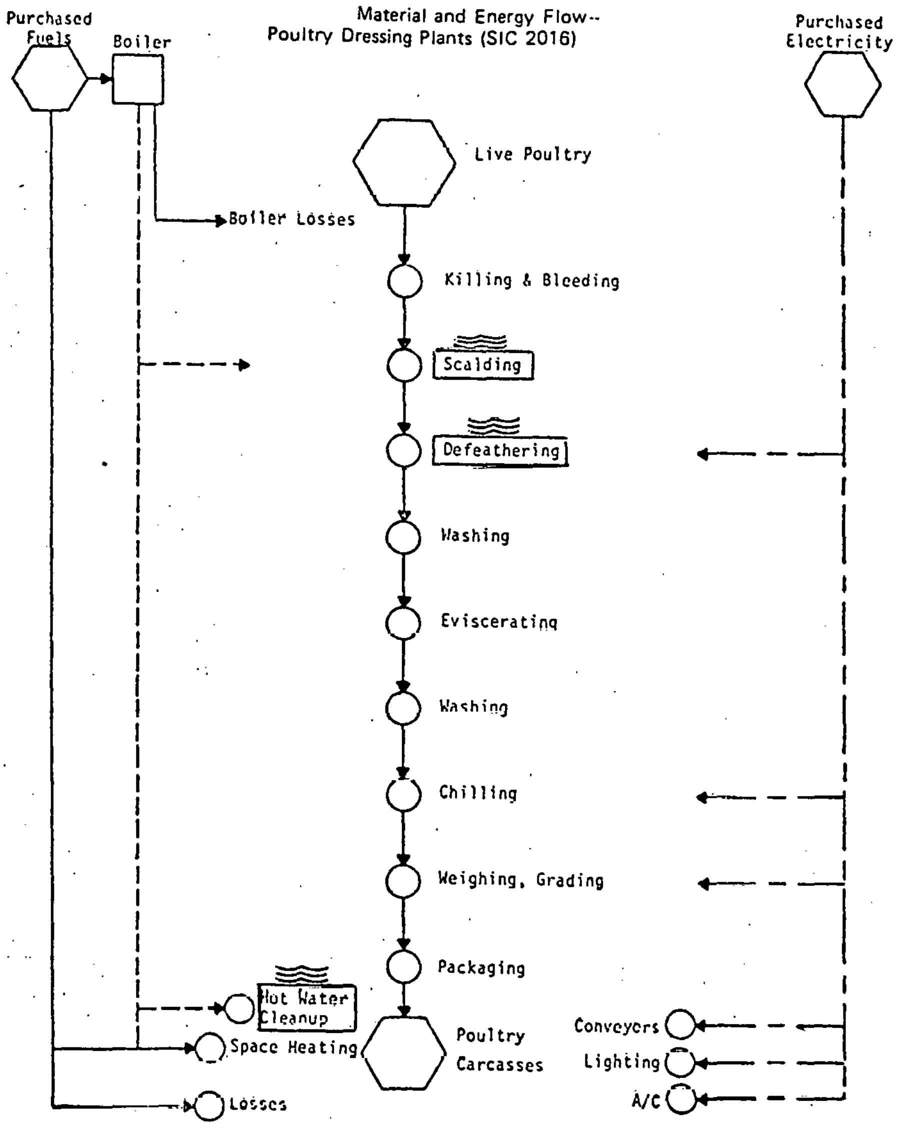
†From Casper, M.E. 1977. Energy Saving Techniques for the Food Industry. Noyes Data Corp., Park Ridge, N.J., p. 99.

▭ = Potential Waste Heat Recovery Stream

Figure 2-6

Material and Energy Flow -- Poultry Dressing Plants (SIC 2016)†



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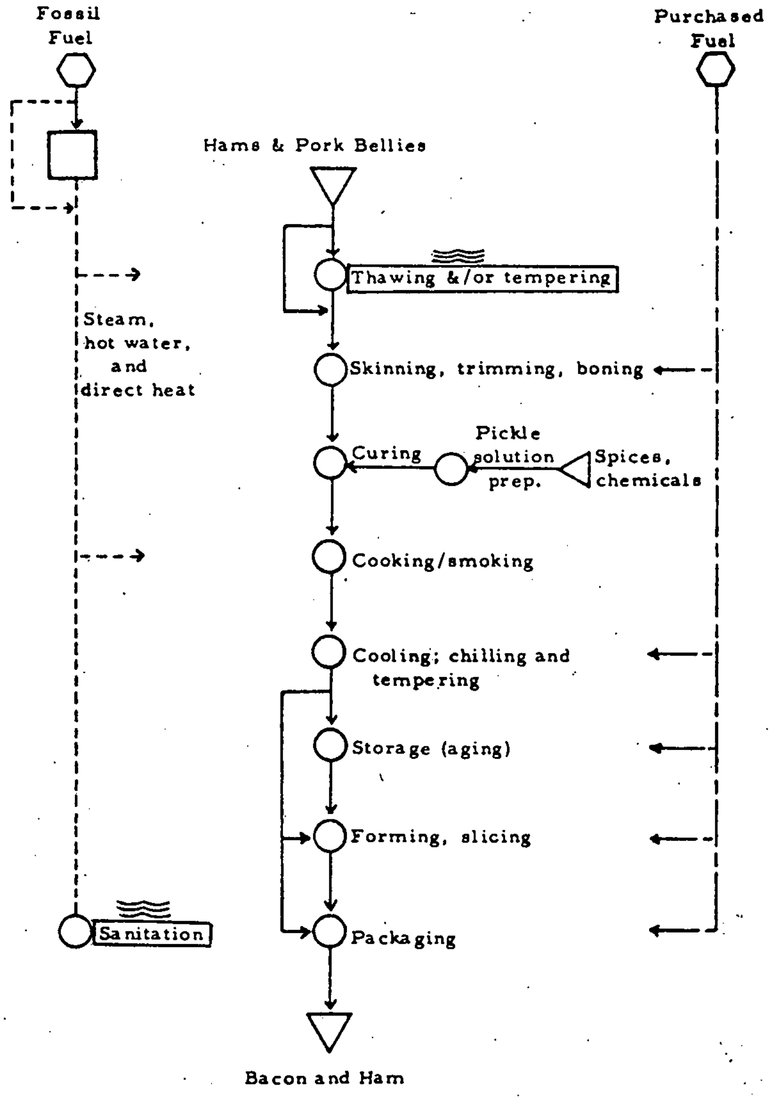
†From Casper, M.E. 1977. Energy Saving Techniques for the Food Industry. Noyes Data Corp., Park Ridge, N.J., p. 320.

≋ = Potential waste heat recovery stream

Figure 2-7a

Material and Energy Flow for Major Processes in SIC 2013[†]

for Processing Ham, Bacon and Picnics



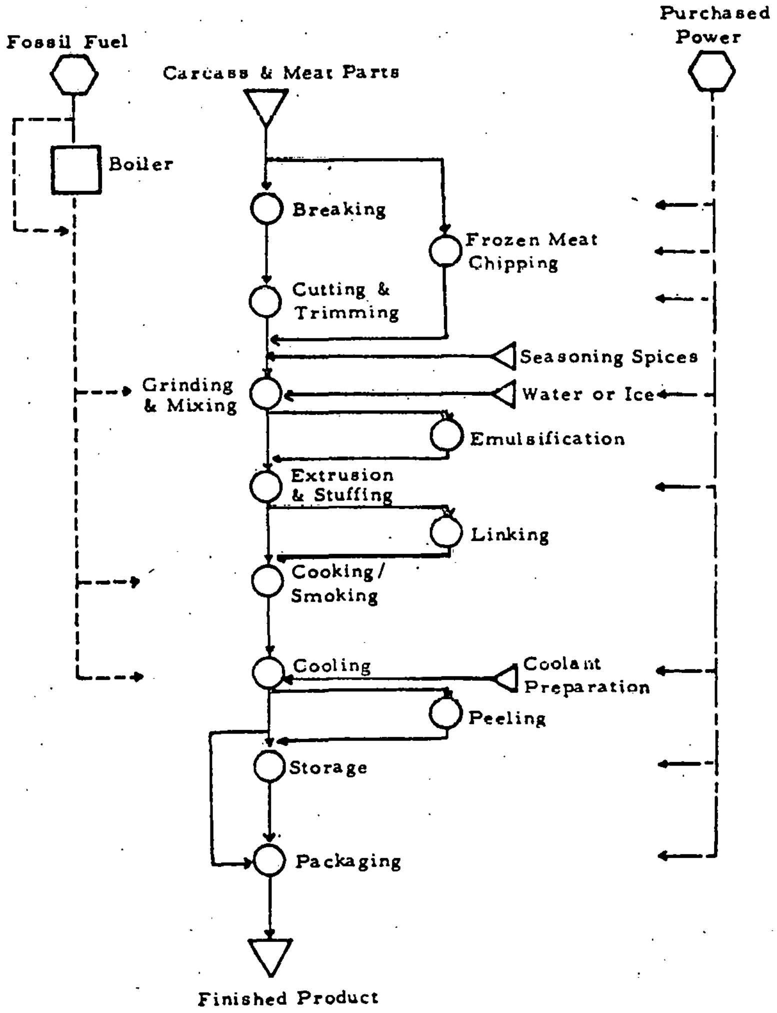
[†]From Casper, M.E. 1977. <u>Energy Saving Techniques for the Food Industry</u>. Noyes Data Corp., Park Ridge, N.J. p. 344.

≋ = Potential waste heat recovery stream

Figure 2-7b

Material and Energy Flow for Major Processes in SIC 2013[†]

for Sausage and Comminuted Meat Products

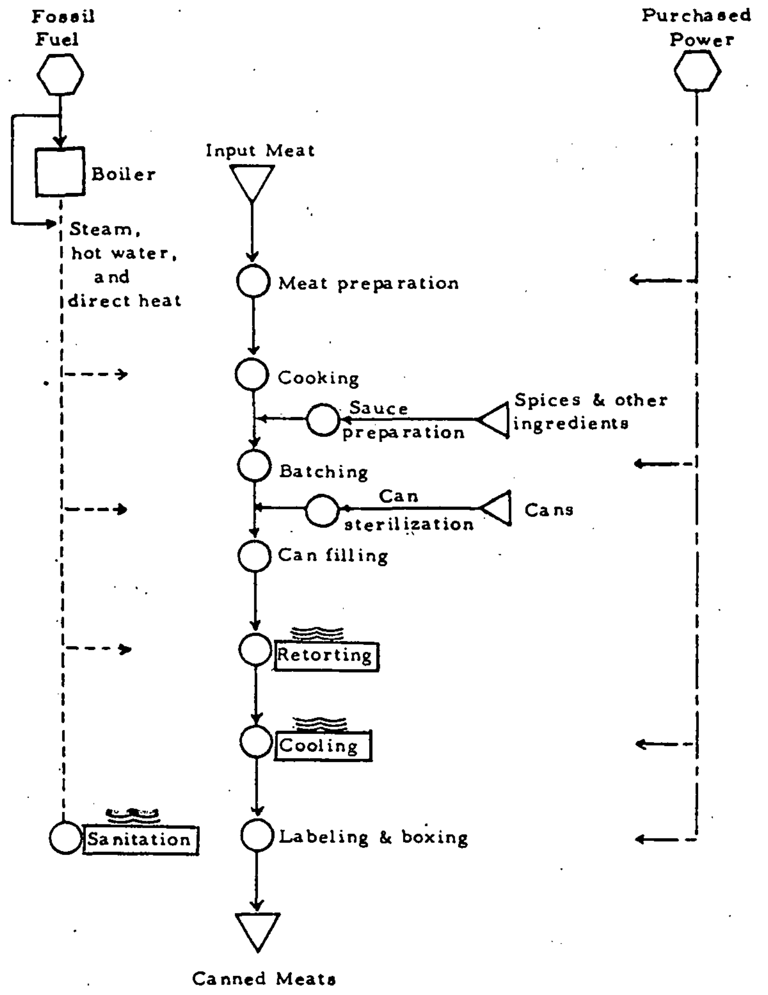


[†] From Casper, M.E. 1977. Energy Saving Techniques for the Food Industry. Noyes Data Corp., Park Ridge, N.J., p. 345.

Figure 2-7c

Material and Energy Flow for Major Processes in SIC 2013†

for Canned Meat Products

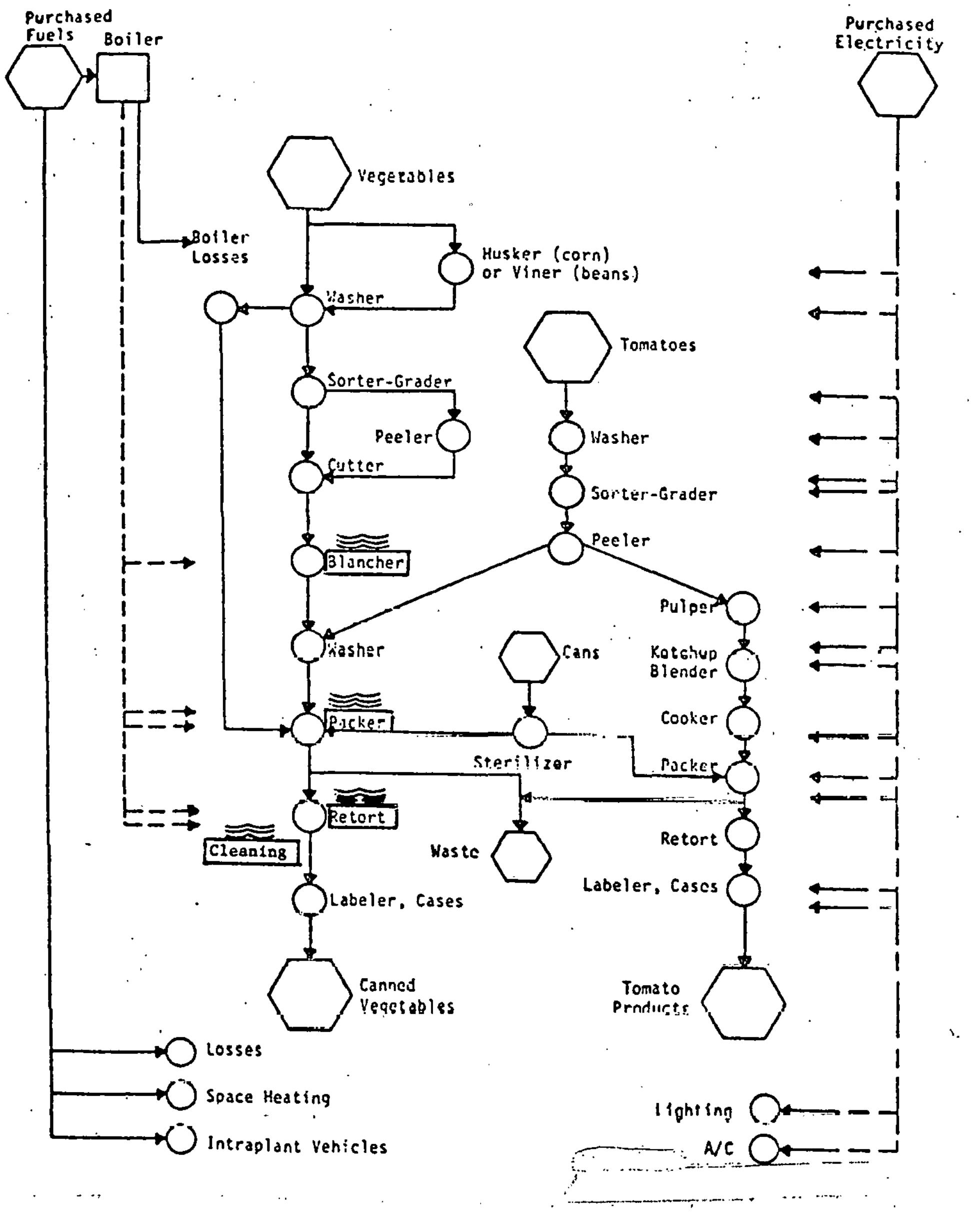


†From Caspter, M.E. 1977. Energy Saving Techniques for the Food Industry. Noyes Data Corp., Park Ridge, N.J., p. 346.

 = Potential waste heat recovery stream

Figure 2-8

Canned Vegetables and Tomato Products Segment of Canned Fruits and Vegetables (SIC 2033)†

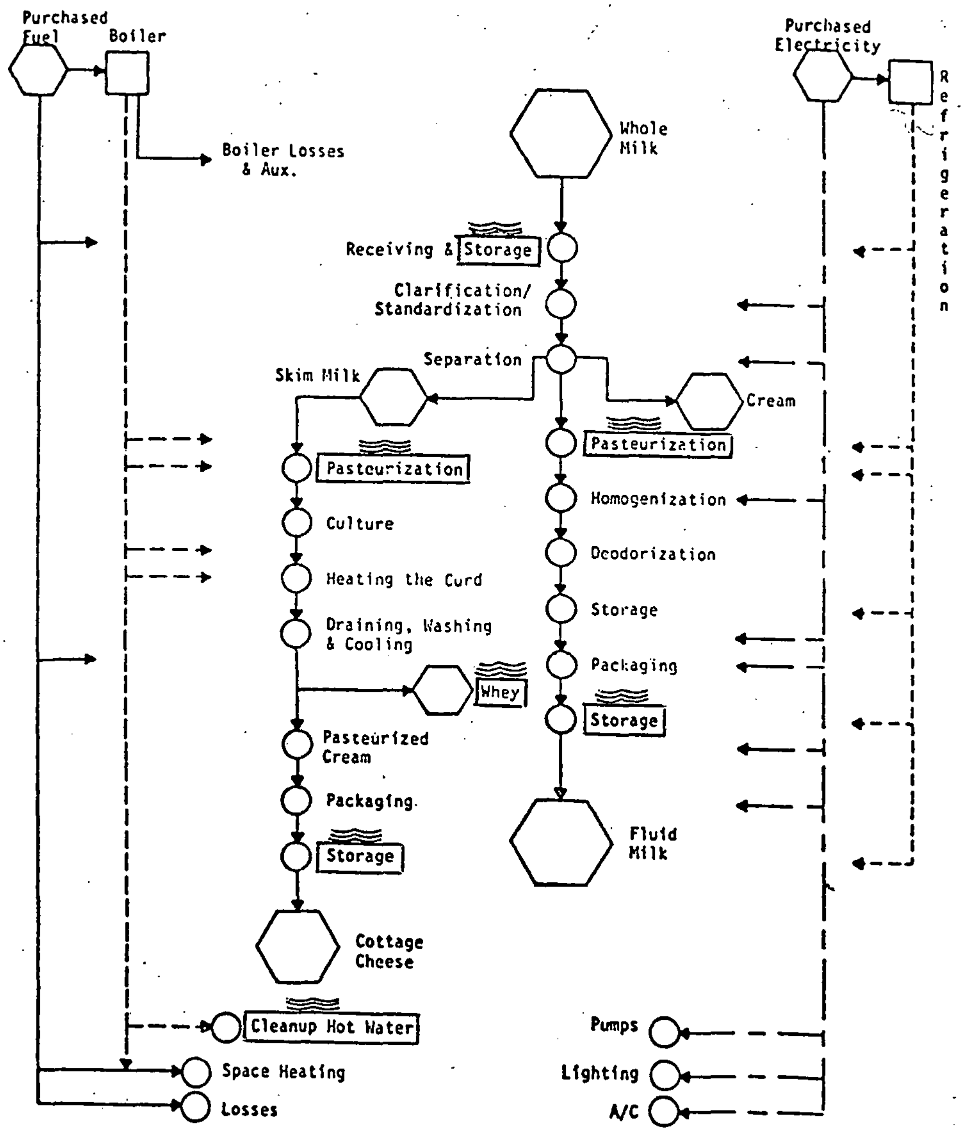


†From Casper, M.E. 1977. Energy Saving Techniques for the Food Industry. Noyes Data Corp., Park Ridge, N.J., p. 131.

▭ = Potential waste heat recovery stream

Figure 2-9

Material and Energy Flow--Fluid Milk (SIC 2026)[†]

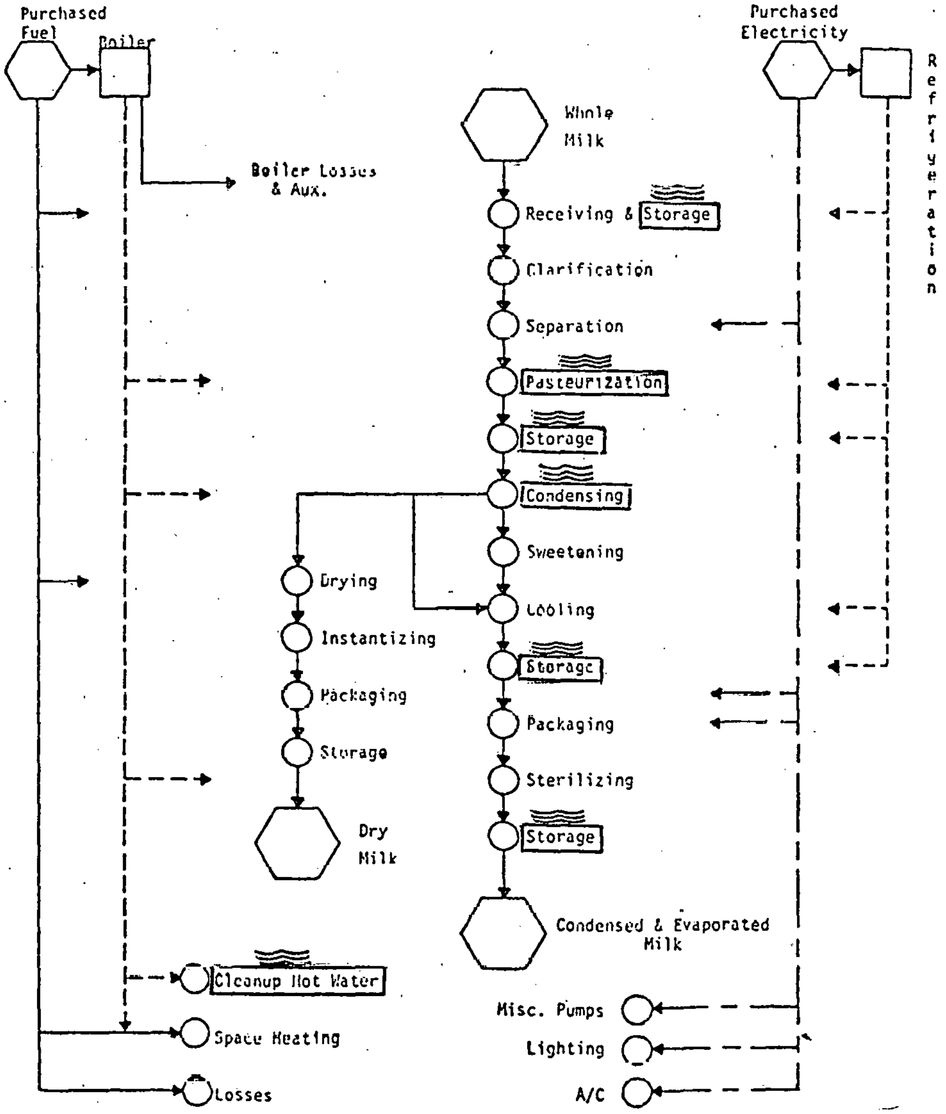


[†] From Casper, M.E. 1977. Energy Saving Techniques for the Food Industry. Noyes Data Corp., Park Ridge, N.J., p. 147.

≋ = Potential waste heat recovery stream

Figure 2-10

Material and Energy Flow--Condensed and Evaporated Milk (SIC 2023)†



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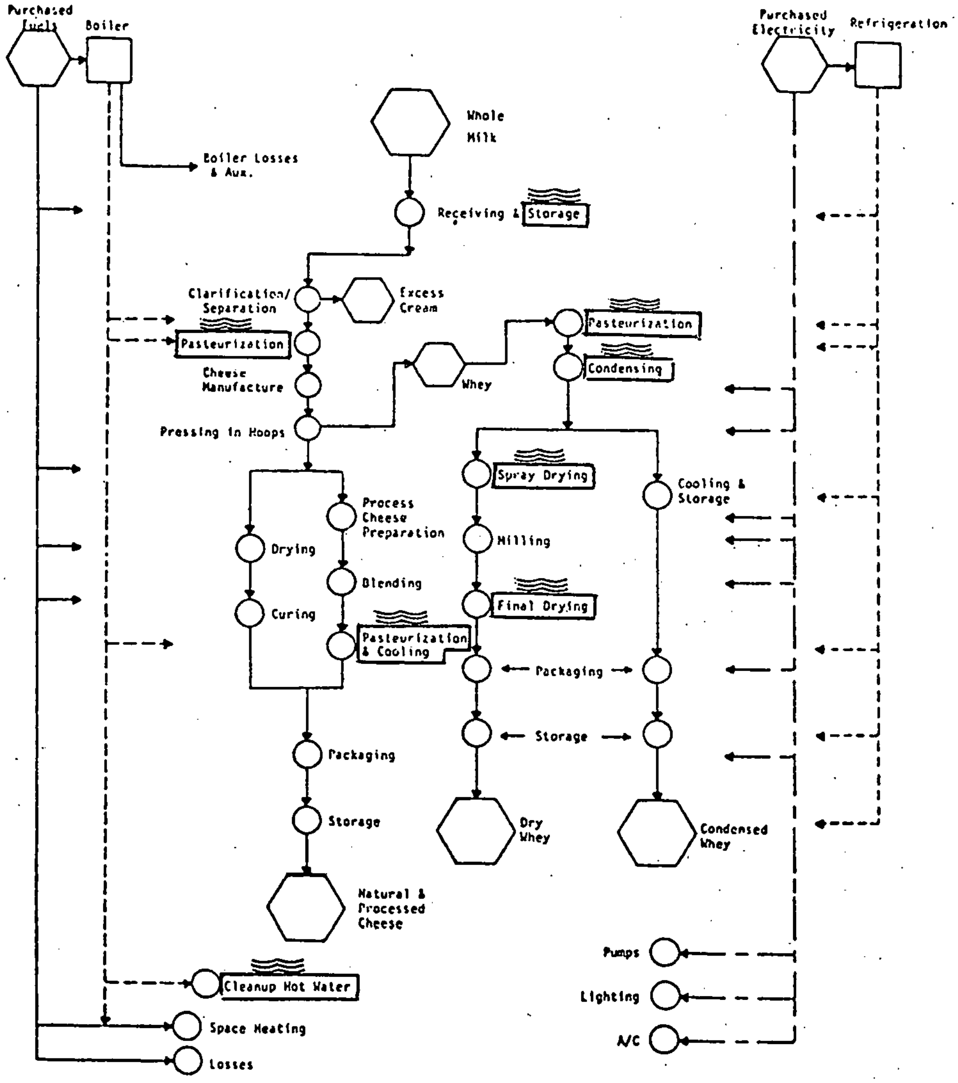
†From Casper, M.E. 1977. Energy Saving Techniques for the Food Industry. Noyes Data Corp., Park Ridge, N.J., p. 282.

▭ = Potential waste heat recovery stream

Figure 2-11

Material and Energy Flow - Cheese (SIC 2022)†



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†From Casper, M.E. 1977. Energy Saving Techniques for the Food Industry. Noyes Data Corp., Park Ridge, N.J. p. 270.

▭ = Potential waste heat recovery stream

Table 2-1

Characteristics of Waste Heat Sources and Accepter Streams in the Canning, Meat Processing and Dairy Industry

Source	Characteristics	Hydraulic Load	Temp. (°F)	Reference
CANNING PROCESS				
Water Blanching				
Snap Beans	BOD = 1.38[a] (lb/ton) SS = .26[b] "	29.8-80.2 gal/ton[c]	190	(Bomben, 1977 Weckel et al. 1968)
Lima Beans	BOD = 1.30 "	197 "	190	"
Peas	BOD = 2.8-6.0 "	57.6-92.2 "	190	"
Steam Blanching				
Snap Beans	BOD = 1.1 " SS = .04 "	30.0-36.0 "	190	"
Lima Beans Lima Beans	BOD = 7.0 "	27.1-57.1 "	190	"
Peas	BOD = 8.6 "	45.8-75.1 "	190	"
Vibratory Spiral Blancher				
Snap Beans	BOD = 1.06 " SS = .17 "	6.48 "	190	"
Lima Beans	BOD = 1.80 " SS = 1.08 "	6.07 "	190	"
Brussel Sprouts	BOD = .86 " SS = .13 "	3.60 "	190	"
Broccoli	BOD = .50 " SS = .18 "	2.62 "	190	"
Cauliflower		.72 "	190	"
Steam Blanching including Water Cooling				
(Steam Blanching)	BOD = 1.84 "	36.0 "	190	"
Snap Beans (Water Cooling)	BOD = 3.2 "	1183.2 "		
Lima Beans	BOD = 2.2 " BOD = 6.8 "	27.1 " 1190.4 "	190	"
Peas	BOD = 3.4 " BOD = 5.8 "	45.8 " 1190.4 "	190	"
Cooker Codensate	---	28-50 "	250	Estimate this study
Cooling Water	---	60-100 "	130	"
Can Topping Water Overflow	dilute salt solution	40-50 "	200	"
Boiler Feed Water	---	380-450 "	60	"

Source	Characteristic	Hydraulic Load	Temp. (°F)	Reference
MEAT PROCESSING Hog Production Process				
Clean-up	---	9.6 gal/hog	140	Davis & Connor 1976
Primary Chicken Processing				
Scalding Water Overflow	Water & Feathers	147-103 gal/ton	140	Dwyer et al. 1976
Defeathering	Water & Feathers	136 "	68	"
Primary Chill	---	226 "	70	"
Slaughter				
Condensate from Heating water	---	16 gal/cwt[d]	210	Estimate this study
Boiler Feed Water	---	6 gal/cwt	60	"
Manufacture				
Condensate from Heating Water	---	40-50	210	"
Boiler Feed Water		15-25 gal/cwt	60	"
Milk Processing				
Cooling Stages	Sweet water-water cooled by ice	1100 gal/ton[e]	42	Knopf, et al. 1978
"	Glycol	660 "	32	"
Cottage Cheese Clean-up	Water	195 "	140	"
Ice Cream Room Clean-up	Water	371 "	140	Estimate this study
Pasteurizer overflow or condensate		3-4 "	160	"
Clean-up	---	50-60 "	150	"
Boiler Feed Water	---	8-10 "	60	"
Cheese Processing				
Whey	Whey	238 gal/ton[e]	100	Lund et al. 1977
Clean-up Water	Water	60-130 "	140	"
Pasteurizer Overflow Water		3.2 "	160	Estimate this study
Condensate Curd/Whey Heating		7 "	200	"
Boiler Feed Water		36 "	60	"

[a] BOD = Biochemical Oxygen Demand (=) lb/ton
[b] SS = Suspended Solids (=) lb/ton
[c] gal/ton = gallons of water per ton raw commodity
[d] gal/ton = gallons of water per 100 pounds live weight
[e] gal/ton = gallons of water or whey per ton of raw milk

To assess the potential for heat recovery from these streams, it is necessary to characterize each stream's composition, temperature, and flow rate. These data for most of these waste streams are summarized in Table 2-1. Some convenient conversion factors are given in Appendix A . The data were obtained from several sources, including the five industrial contacts on this project. Obviously, these data generally apply to specific plants and therefore only indicate order of magnitude estimates for some streams. Like the energy use profile, the waste-heat sources are unique to each plant. Thus, these data are presented only as examples. The data are presented on a per unit-of-production basis because most plants are using that basis in reporting data directly or indirectly to DOE and because that basis facilitates scaling the data to different plant capacities.

Potential for heat exchanger fouling by stream components is an important consideration in heat recovery from waste streams in the food industry. Constituents of these waste streams such as proteins, sugars and other soluble organic compounds, and inverse solubility salts (e.g., calcium and magnesium phosphates and sulfates) readily interact with negatively charged heat exchanger surfaces; this may result in deposition and reduction in heat exchanger efficiency. These deposits are generally tenacious, and their removal require use of chemical cleaning agents. Unfortunately, the fouling characteristics of these streams are not known and there is an insufficient data base to predict their fouling behavior. In some streams, such as clean-up water in meat processing, heat is potentially recoverable but fouling characteristics necessitate using more energy in cleaning the heat recovery system than is recovered by that system. In such cases, a settling tank and skimmer could be used as a pretreatment to reduce the fouling potential.

Despite a risk of oversimplification, some generalities can be made about the fouling potential for waste streams from food processing. First, because waste streams are being cooled, inverse solubility salts should not present fouling problems, and generally the solubility of other mineral salts will not be exceeded through the limited temperature drop waste streams normally experience. Second, waste streams containing sizable quantities of animal fat should probably go through a settling tank with skimmer before indirect recovery to avoid potential problems of crystallizing on the exchanger surface. Third, water from vegetable processing operations, even though relatively high in organic material, should present no difficulty in waste-heat recovery because the stream's temperature is being reduced. Fourth, waste-heat streams resulting from indirect heat exchange with food products should require only the normal precautions necessary for use as boiler feed water (i.e., settling tank, skimmer, deaerator, etc.).

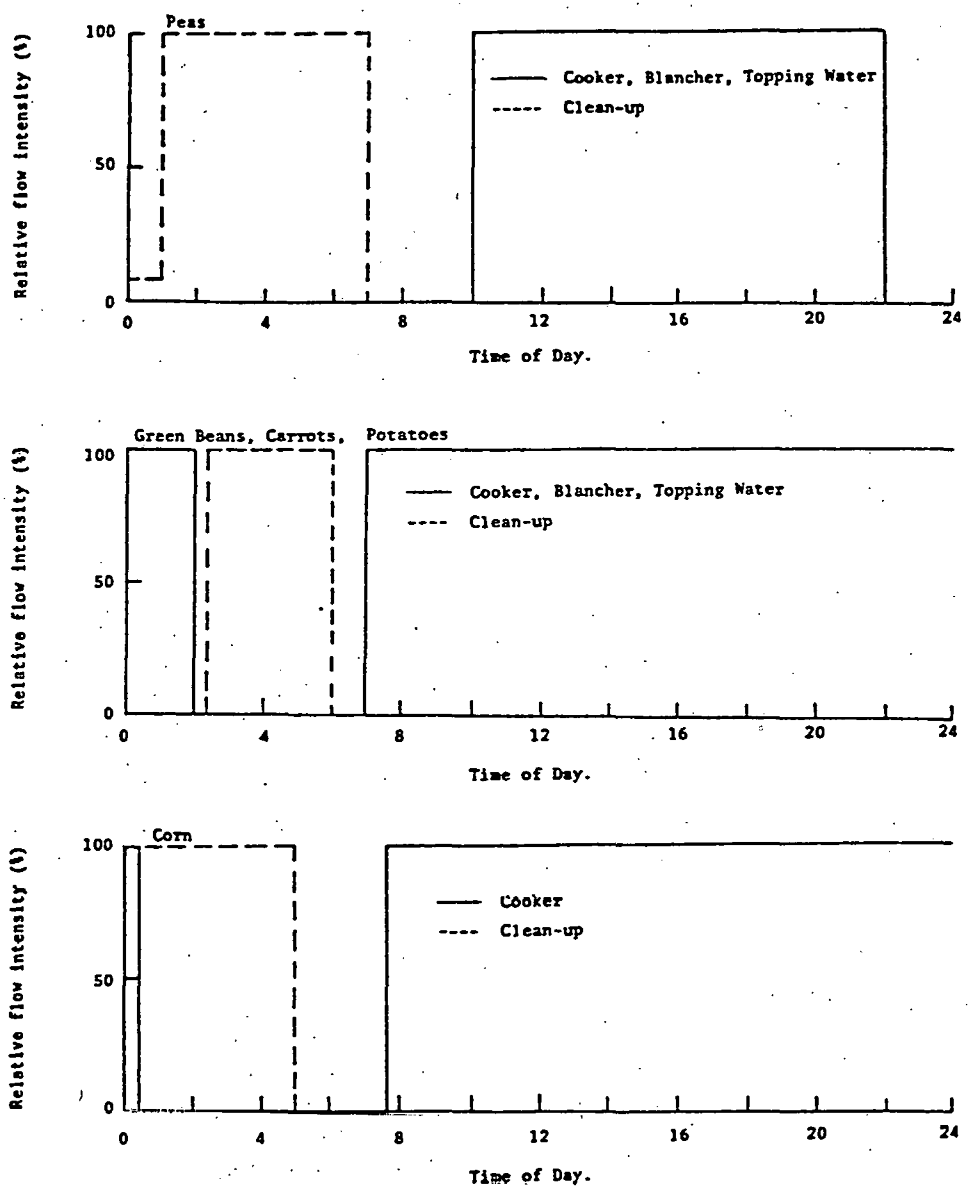
One important characteristic of aqueous streams from food processing is that the temperature of these streams is 100-200°F. A common acceptor stream for indirect heating is boiler feed water which is usually 50-70°F. Other acceptor streams, however, can be identified. In meat processing clean-up, water used in dehairing, and water used for thawing or tempering can serve as acceptor streams. In each case only the make-up water can be preheated, because the unit operation is conducted at temperatures greater than that of the waste-heat source stream. In canning, acceptor streams are boiler feed-water, can topping water, and clean-up water. Blancher feedwater is not considered an acceptor stream because blanching operations can be carried out using direct steam condensate as the sole source of overflow. It is desirable to have some blancher overflow to control the build-up of solids in blanching water. Using direct steam heating appears to generate a desired rate of blancher overflow. In the dairy industry, acceptor streams are boiler feedwater and clean-up water.

Maximum waste-heat recovery occurs when waste stream availability exactly coincides with acceptor stream demands. It is essential, therefore, to determine the time frame for both waste and acceptor streams. Figures 2-12, 2-13 and 2-14 show representative processing schedules for canning plants, a cheese plant with dryer, and a fluid milk plant with cottage cheese production. In canning plants, clean-up water is generally required out-of-phase with waste-heat sources, but boiler feedwater demand is in-phase, making it the primary acceptor stream for waste heat. For peas, green beans, potatoes, and carrots, topping water is also a potential acceptor stream. One striking characteristic of both acceptor and source streams is that they are basically on/off streams. This is a characteristic of most food industry process streams. Raw product is usually accumulated, insofar as possible, so the plant runs at maximum capacity. (Figure 2-12 presents the 24-hour cycle for canning plant operation.) Production is dependent on availability of raw material, which is highly variable. In general, Wisconsin Plants run on an average of 6 days per week. Peas are processed from mid-June through July, green beans from mid-July through September, corn from mid-August through September, and root crops (potatoes, carrots and beets) from October through late November.

In dairy and meat processing, operations are not as strikingly seasonal. Production schedules are shifted from one product to another, but energy demands are fairly constant. Figure 2-13 and 2-14 present the processing energy demands on a 24-hour period in a cheese plant with whey concentration and drying capa-

Figure 2-12

Relative Flow Rates in a 24-Hour Period in Various Canning Operations[†]



$$\text{Relative flow intensity} = \frac{\text{Instantaneous flow rate}}{\text{Maximum flow rate}}$$

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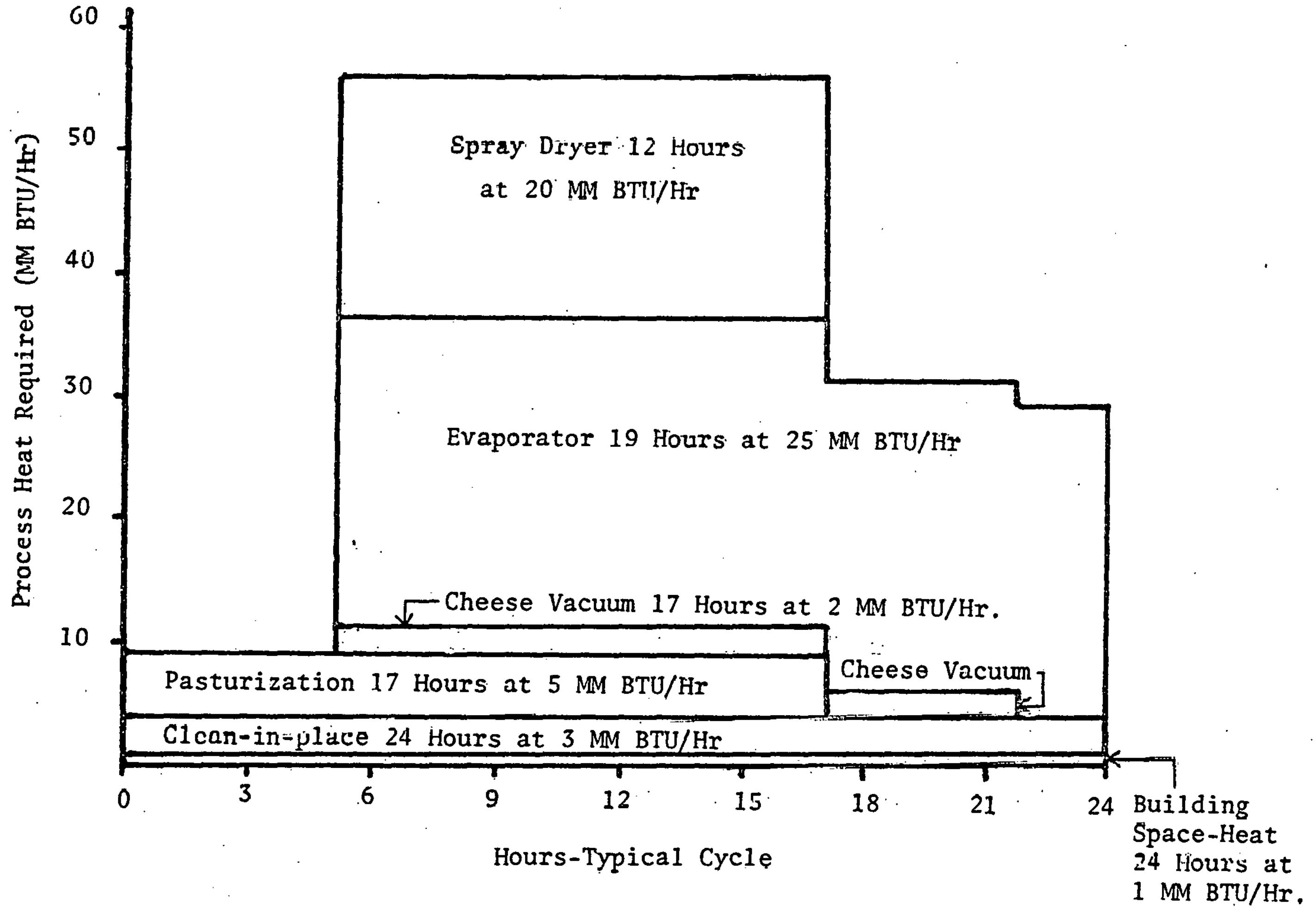
†Source: RMA analysis

Figure 2-13

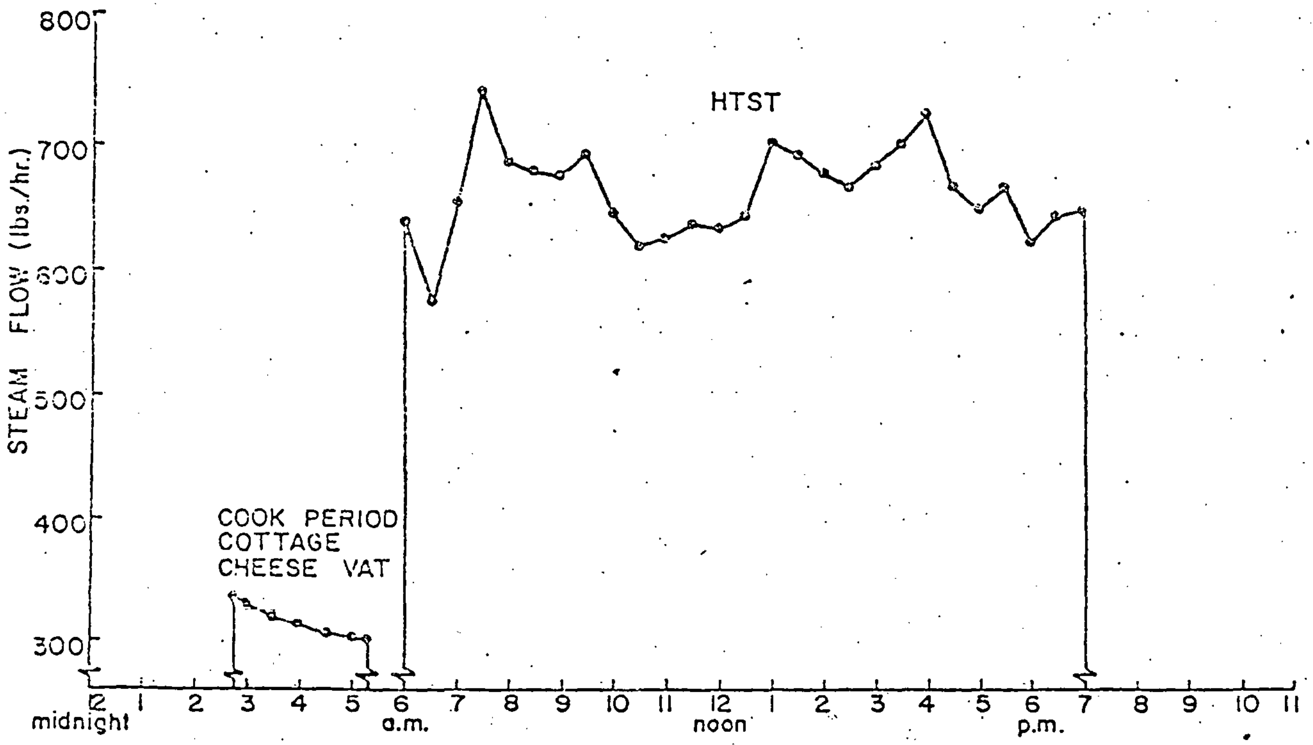
Cheese Plant Load Profile*



*Source: RMA Analysis

Figure 2-14

Daily Steam Demand at a Milk Plant[†]



[†] Knopf et al., 1978.

bility, and a fluid milk plant, respectively. The demands are basically on/off, similar to canning plant demands. Meat processing plants operate on a pattern similar to dairy plants. Production is relatively constant throughout the year and waste-heat streams are generally compatable with acceptor streams, with the exception of plant clean-up. In canning, dairy and meat processing, most plant clean-up hot water is used during non-production hours.

POTENTIAL WASTE-HEAT RECOVERY

Canning Industry

Several waste-heat streams, as previously explained, present some potential for waste-heat recovery in the canning industry. In the thermal process, steam is condensed on the outside of cans to heat the product to temperatures between 240°and 265°F, and after the scheduled process time the heat is extracted from the container and its contents by using cold water as a heat sink. This process generates two large waste-heat streams: (1) condensate from the heating process, which is under pressure and at the corresponding condensing temperature, and (2) cooling water, which is at 100 - 130°F. In both cases, the waste-heat source is relatively clean.

Before investigating the potential for waste-heat recovery from these and other streams, however, several observations made by the industrial cooperators should be noted. First, energy conservation measures may be the primary prerequisite to using waste heat. By reducing the flow rates of the waste-heat streams, more heat could be extracted from them using the same flow rates as the acceptor streams. Conservation measures could also include insulation of retorts, thereby reducing the rate of condensation. Second, blancher overflow may be one of the largest waste-heat streams in a canning plant. As previously mentioned, there is evidence that direct steam heating of blancher water provides sufficient overflow to control solids buildup in the blancher water. Thus there is not need for additional make-up water to the blancher. Third, can topping is currently one of the more inefficient water transfer operations, with as much as one third of the 200°F water lost as waste. Undoubtedly mechanical handling designs exist which would essentially eliminate topping water waste. Finally, venting of still retorts is established by the Food and Drug Administration. Two opportunities for energy conservation exist here. The first involves designing retort steam distributor systems which feed steam to the top of the retort and vent from the bottom (since air is heavier than steam). The second involves designing of vent systems using vented steam as a heat source.

Several waste-heat recovery systems are already being used in the canning industry. Examples include:

1. using cooker (retort) condensate to provide boiler feed water, to preheat topping water, and to defrost freezing tunnels where freezing operations are run parallel to canning operations;
2. using waste heat from refrigeration compressors to preheat water used to defrost freezing tunnels;
3. using boiler blowdown to preheat feedwater to the boiler; and
4. using can cooling water to provide boiler feed water and to preheat can topping water. Currently it is not possible to estimate the extent to which these systems are used in the canning industry.

To estimate the potential for waste-heat recovery, the project team developed three scenarios. Several assumptions were made in setting up the calculations. First, only liquid/liquid heat exchangers were considered for waste-heat recovery. In the canning industry, nearly all waste-heat streams are liquid. For meat processing and dairy operations, this is not necessarily the case. Waste heat from hair singeing in hog processing and in smoke house operations could be recovered; in dairy plants, waste heat from spray drying offers potential for recovery. These were not included, however, because the first line of heat recovery would be from liquid streams, and because generally the economics of heat recovery from gas streams is not favorable. Second, the liquid/liquid heat exchangers operate at 75 percent effectiveness. Effectiveness is defined as:

$$\varepsilon = \frac{[\dot{m}\, C_p\, (T_{in} - T_{out})]_{\text{hot or cold}}}{(\dot{m}\, C_p)_{min}\, (T_{\text{hot in}} - T_{\text{cold in}})}$$

With a stream capacitance ratio of about 1.0 and countercurrent flow, this effectiveness value is in the practical range. Third, all of the recovered heat is used to preheat boiler feedwater. Generally the waste stream is much smaller than the boiler feed stream, with the exception of can cooling water in canning plants. Thus increasing the flow rate of the acceptor stream will not result in large increases in recovered heat. Fourth, in unit operations using indirect heating with steam, potentially 75 percent of the condensate could be recovered and returned to the boiler as feedwater. This figure was ascertained in consultation with the industrial cooperators and seems representative of experience for the food industry. The losses are due to vents, steam traps, and flashing in non-pressurized return lines, etc. It was assumed the clean-up water was the only waste-heat stream which could be used as a waste-heat source. Generally for canning, meat processing, and dairy processing, clean-up with hot water sufficient for santizing is used during non-production hours. Because the boiler demand at that time is small, the potential for waste-heat recovery is minimal.

The calculations in these three scenarios illustrate several important points on waste-heat recovery in canning plants. Generally there are sufficient quantities of partially heated water which can serve as boiler feedwater. The two most apparent sources are can cooling water and cooker condensate. By using heat recovery schemes and condensate recycle it would be possible to reduce boiler energy requirements by 5 to 10 percent.

Situation I.

The assumptions are:

(1) condensate to the boiler is not recycled,

(2) blowdown is 10 percent of the boiler feed rate,

(3) all waste streams are compatable with acceptor streams, and

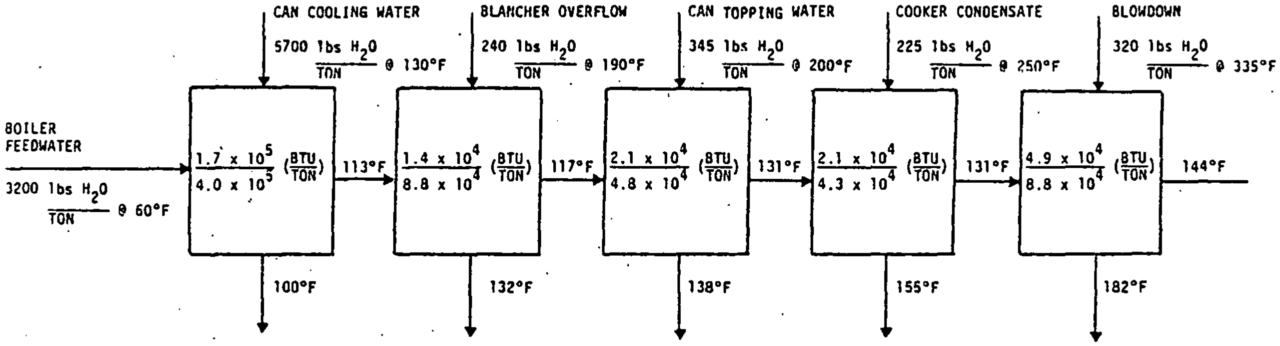
(4) no direct use is made of a waste stream as boiler feed water.

These assumptions result in the waste-heat recovery scenario illustrated in Figure 2-15. (An example of the detailed calculation for a cheese plant is given in Appendix A .) The data are for a canning plant processing 13 tons of raw peas per hour. The boiler feed water is preheated by indirect heat exchanger with successively warmer waste-heat streams. The waste-heat streams are: (1) can cooling water at 130°F, (2) blancher overflow at 190°F, (3) can topping water at 200°F, (4) cooker condensate at 250°F, and (5) boiler blowdown at 335°F. Based on a 75 percent heat exchanger effectiveness, the extracted heat from each waste stream is given by the numerator in the ratio expressed in the respective box. The denominator is the heat energy that could be extracted if the waste-heat stream could be cooled to 60°F. Thus the ratio represents the fraction of heat which can be removed from the waste-heat stream. The temperature of each waste-heat stream after heat extraction is calculated, as is the temperature of the boiler feed stream after each operation.

In this situation the net result is preheating the boiler feedwater from 60°F to 144°F by indirect exchange with the waste-heat streams. Approximately 27.5 x 10^4 BTU of waste-heat per ton of raw peas is recovered in this scheme, accounting for about 45% percent recovery based on a reference temperature of 60°F. Assuming the boiler operates at 125 psig (335°F), the enthalpy contributed by the waste-heat sources represents 7.3 percent of the total enthalpy required in the boiler.

Figure 2-15

System Diagram for Situation I: Canning Plant



Situation II.

The assumptions are:

(1) condensate returned to the boiler is 75 percent,

(2) blowdown is 10 percent of the boiler feed rate,

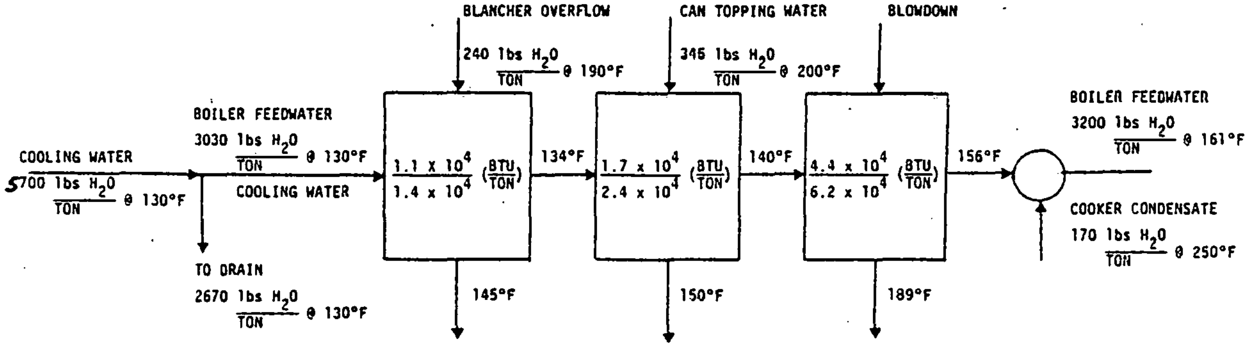
(3) all waste streams are compatable with acceptor streams, and

(4) direct use is made of some acceptable waste streams as boiler feedwater.

The resulting scenario for waste heat recovery is presented in Figure 2-16. In this case, can cooling and cooker condensate were assumed to be acceptable boiler feedwater streams. Since the can cooling water flow rate was larger than the boiler feed rate, nearly 47 percent of the can cooling water would be discharged from the plant. For this situation then, the boiler feedwater is available at 130°F. After indirect exchange with blancher overflow, can topping water and boiler blowdown streams, the boiler feedwater is preheated from 130°F to 146°F. Cooker condensate water is then mixed with the boiler feedwater resulting in an average boiler feedwater temperature of 161°F. This is 17°F higher than that achieved in Situation I. The heat recovered by indirect heat exchange represents 72 percent of the recoverable heat based on a reference temperature of 130°F. This recovery scheme would reduce the enthalpy requirement in the boiler by 8.8 percent.

Figure 2-16

System Diagram for Situation II: Canning Plant



Situation III.

The assumptions are:

(1) condensate return to the boiler is 75 percent,

(2) there is no blowdown for heat recovery,

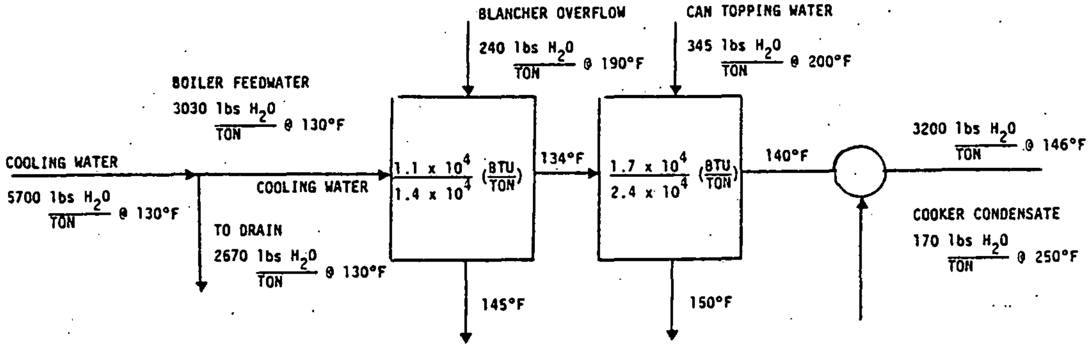
(3) clean-up wastewater is not compatible with acceptor streams, and

(4) direct use is made of some acceptable waste streams as boiler feedwater.

Figure 2-17 presents the analysis of this situation. As in Situation II, can cooling water and cooker condensate are used as boiler feedwater, while blancher overflow and can topping water are used for indirect heat exchange. In this case, the boiler feed is heated from 130°F to 146°F with a resulting 74 percent energy recovery from the blanching overflow and can topping water (relative to a reference temperature of 130°F). Boiler energy requirements could be reduced 7.5 percent in this scenario.

Figure 2-17

System Diagram for Situation III: Canning Plant



Meat Processing

Because the meat industry is one of the most energy intensive in the food and kindred products sector, many opportunities exist for energy recovery. The major acceptor streams are boiler feedwater and clean-up water, although in some processed meat product plants there is a need for warm water for thawing and tempering. Furthermore, since the end product is usually stored under refrigeration, waste heat from the compressors can be used. One potentially major source of waste heat not considered in this study is the animal body heat extracted post-slaughter. Currently technology does not exist to use this waste heat.

The industrial cooperators pointed out several current applications of waste-heat recovery in meat processing plants. In one situation, approximately 75 percent of the water used in the boiler is condensate returned to the boiler at a temperature of about 210°F. The 25 percent boiler make-up water is preheated using boiler blow-down to about 150°F. The resultant mixed stream temperature is about 195°F; this is preheated to about 225°F by steam in a deaerating feedwater heater. This is then either used directly as boiler feedwater or is heated to 250-270°F in a boiler economizer.

Another heat recovery system uses the vapors from inedible rendering cookers to preheat water. Water is heated in a direct contact condenser to about 175°F. This is then used to heat water from 55° to 130°F in a plate heat exchanger. The cooled water is then recirculated through a closed loop to the direct contact condenser. It was estimated that this waste heat recovery project represented an annual savings of $24,500 based on present fuel costs and 80 percent boiler efficiency. At other plants, heat recovery from rendering operations includes using indirect condensers with a glycol recovery loop and subsequent recovery of the heat from the glycol solution with a plate heat exchanger.

Energy utilization and potential for efficiency improvements in the meat processing industry are currently being investigated under a DOE contract at Purdue University. An example of the potential for energy efficiency improvements is presented in Table 2-2 (Wilson et al., 1979). The investigators considered the following sources for heat recovery: (1) heat from the refrigeration condensers used to chill the carcass, (2) heat from the hair singer exit gas recovered to preheat water used in the dehairing operation, (3) heat from the steam vent stack from the rendering process recovered to preheat feedwater and (4) hot air from the ring drier recycled to dry the blood. This resulted in a nearly 80 percent decrease in steam requirements and a 50 percent decrease in total energy requirements. Another alternative considered was direct skinning rather than dehairing. Although this resulted in a considerable reduction in energy used in processing the meat more energy input would be required to use the skin. (Perhaps in this case, therefore, there is no net reduction in energy use in considering the by-product use.) According to Wilson et al. (1979) the heat recovery schemes are all cost effective with net ratio of saving to captial cost of from 3/1 to 5/1.

To estimate the potential waste-heat recovery in selected meat processing operations, calculations were made for three scenarios. The assumptions on performance of heat exchangers, identification of acceptor streams, the return of condensate, and compatability of acceptor and waste streams were the same as those for the canning industry.

Table 2-2 [†]

Dehairing and Evisceration Energy and Water Consumption

BASIS: 1.0 POUND CHILLED CARCASS

	Dehairing and Evisceration		
	Without Heat Recovery	With Heat Recovery	Skinning
Steam (BTU)	203.7	44.7	34.2
Gas (BTU)	78.2	78.2	0
Electrical (WH)	1.92	2.12	1.42
Refrigeration (BTU)	60.6	6.06	56.4
TOTAL (BTU)[††]	318.8	160.4	67.2
Water (LB)	1.60	1.91	2.03

Refrigeration COP = 3

[†] From Wilson et al. 1979.

[††] WH = 3.414 BTU

Situation I.

Based on conversations with industrial cooperators, approximately 50 pounds of steam are required in slaughtering operations for every one hundred pounds live animal weight. The assumptions made for the first situation are:

(1) no condensate is recycled to the boiler,

(2) blowdown is 10 percent of boiler feed rate,

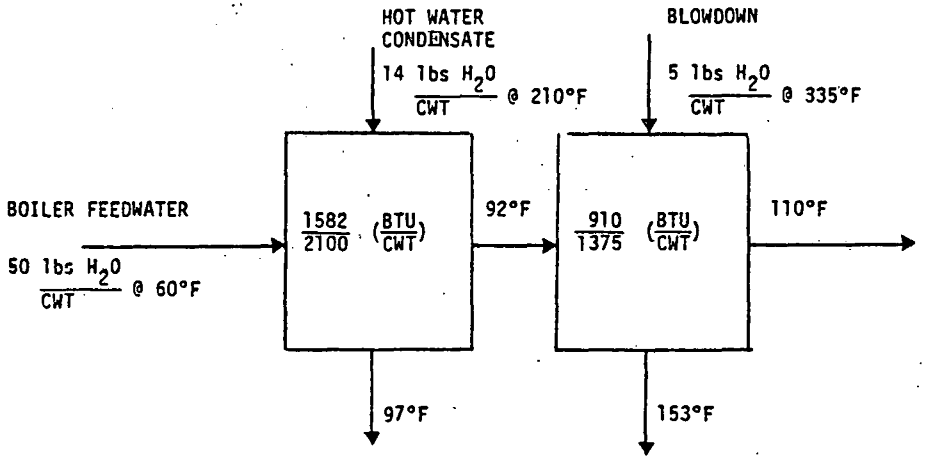
(3) all waste streams are compatible with acceptor streams, and

(4) no direct use is made of a waste stream as boiler feedwater.

The resulting calculations are shown in Figure 2-18. In meat processing, it was assumed that waste hot water was not available for heat recovery because of the water composition (blood, fat, etc.). Therefore only condensate from heating the water and boiler blowdown stream were included in the waste heat recovery. Under these conditions, the boiler feedwater is heated from 60°F to 110°F using 72 percent of the extractable heat (referenced to 60°C) from the waste heat streams. The 2120 BTU/CWT extracted from the waste heat streams represents 4.4 percent of the boiler energy requirements.

Figure 2-18

System Diagram for Situation I: Meat Processing



CWT = hundred weight

Situation II.

The assumptions are:

(1) 75 percent of condensate is returned to the boiler,

(2) blowdown is 10 percent of the boiler feed rate,

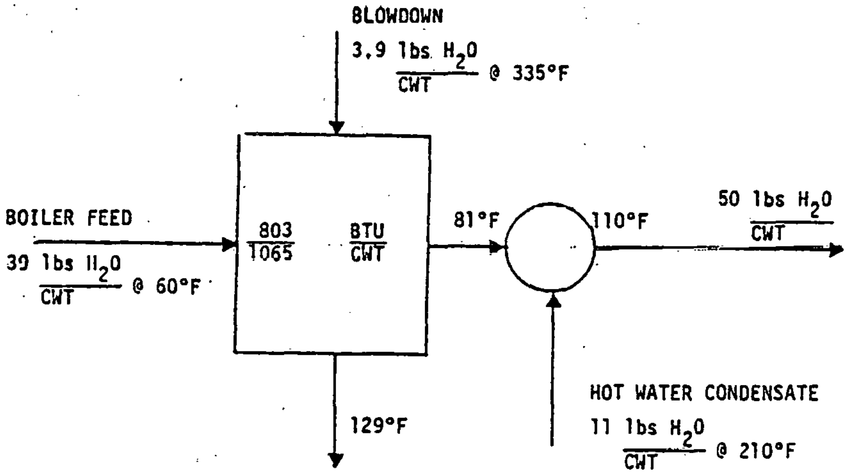
(3) all waste streams are compatible in the acceptor streams, and

(4) direct use is made of some acceptable waste streams as boiler feedwater.

The situation is diagrammed in Figure 2-19. Boiler blowdown is the only waste heat source and the condensate from heating hot water is used directly as boiler feedwater. In this case 75 percent of the waste heat is recovered from the boiler blowdown (reference temperature 60°F) and contribution to boiler energy demand is about 4.3 percent of the total. This is about the same contribution as that obtained in Situation I. The similarity results from the assumption that only 75 percent of the condensate is returned to the boiler. In actual practice, the blowdown may be allowed to flash down to de-aerator pressure (5 psig, 225°F) and the flash steam used directly. Then the 225°F water is routed through the heat exchanger.

Figure 2-19

System Diagram for Situation II: Meat Processing



CWT = hundred weight

Situation III.

The assumptions diagrammed in Figure 2-20 are:

(1) 75 percent condensate is returned to the boiler,

(2) there is no blowdown for heat recovery,

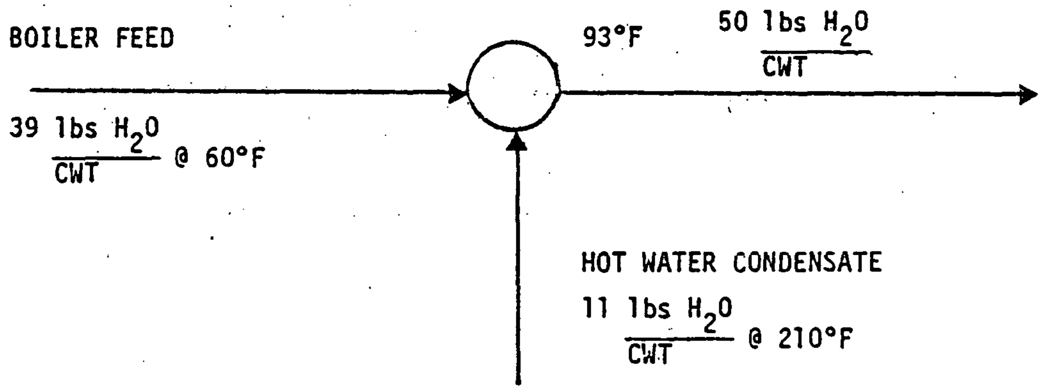
(3) clean-up waste water is not compatable with accepter streams, and

(4) direct use is made of some acceptable waste streams as boiler feedwater.

For meat processing this scenario results in returning condensate as boiler feedwater since all other hot water sources are considered too highly polluted for either heat recovery or direct use in the boiler. In this case, returning the condensate would reduce boiler energy input by 2.9 percent.

Figure 2-20

System Diagram for Situation III: Meat Processing



CWT = hundred weight

Dairy Processing

In many respects the dairy industry offers the most desirable opportunities for waste-heat recovery. The industry traditionally has used indirect heat exchanger for heating fluid products, thus allowing the processor to capitalize on condensate recovery systems. Vacuum evaporators produce high quality water which can be used for boiler feedwater. Refrigeration is essential for product manufacture and storage. These all present excellent opportunities for waste-heat recovery, and all are being used to some degree in the industry. Although it was not possible in this project to estimate the extent of energy recovery technology currently practiced by the industry, the potential for its use is certainly present.

Energy use in a dairy plant is even more plant specific than in canning and meat processing. This is a result of the tremendous latitude in product mix. For that reason, estimates on energy use for various products are difficult to generate. Recently Knopf et al. (1978) completed a study for DOE on energy use in a dairy plant. The resulting energy requirements, based on actual measurements of unit operations, are shown in Table 2-3. These data are from a plant producing per month 1.27 x 10^6 gallons of fluid milk, 62,000 gallons of ice cream, 50,000 gallons of ice cream mix and 500,000 pounds of cottage cheese. A comparison of the measured energy to the energy estimated from fuel bills using an assumed efficiency of the boiler is given in Table 2-4. Only 50.8 percent of the steam was accounted for by direct measurement. (In this study the assumed boiler efficiency was much too large and alerted company personnel to check the boiler.) A companion study by Marks et al. (1980) studied energy use in cottage cheese production. The results are shown in Table 2-5. Both process

Table 2-3

Breakdown of Fluid Product Energy Requirements

Use	Steam	Recirculating Sweet Water	Glycol	Required Refrigeration	Separators Electricity	Average Packaging	TOTAL
	BTU / lb Product	lb of H_2O / lb Product	lb of Glycol / lb Product	BTU of Ref. / lb Product	BTU / lb Product	BTU / lb Product	BTU / lb Product
Fluid Milk	14.1	4.1	2.5	41	3.25	9.9	71.25
Chocolate Milk	28.2	8.3	5	41	2.4	9.9	84.5
Ice Cream Mix	25.6	7.6	4.5	35.2	9.85		79.5
Skim Milk for Cottage Cheese	14.1				3.25		17.35

Knopf, et al. (1978)

Table 2-4

Overall Plant Energy Correlations[†]

USE	STEAM	ELECTRICITY	WATER
Refrigeration-Compressors		48.8%	59.5%
HTST-Pasteurizer	13.0%		recirculating
Separator-Homogenizer		4.7%	
Packaging		2.2%	
Cottage Cheese	20.9%		12.9%
Ice Cream			
Clean Up (140°F)	16.9%		9.9%
% Accounted For	50.8%	55.7%	82.3%

[†] Knopf et al. 1978.

Table 2-5

Utility Usage for Cottage Cheese Production[b]

UNIT OPERATION	PROCESS STEAM BTU[a]	SANITATION STEAM BTU	ELEC. BTU	REF. BTU	WATER lbs.
RECEIVING		42.6	32.6	4.8	0.50
SEPARATOR			2.7		
HOMOGENIZER			3.9		
PASTEURIZER	103	46.8			0.55
HEATING	244		2.5		0.73
COOKING	349		4.2		0.73
1st WASH			0.41	20.7	3.44
2nd WASH			0.41	27.4	1.82
DRESSING	2.4		1.8	13.3	
CREAMING			0.85		
CLEANING		41.8			0.49
PACKING			0.72		
STORAGE			12.6	104.1	
	698	131.2	62.7	170.3	8.26

[a] BTU/lb product

[b] Marks et. al., 1980.

Table 2-6

Energy Conservation Opportunities for a Specific Wisconsin Dairy Plant[†]

The following list of energy conservation opportunities were identified from site visits and energy balance studies:

Conservation Projects:

1. Insulate steam piping.
2. Install necessary piping and pumps to return condensate from the pasturizer and vats.
3. Install piping, storage tank and heat exchanger to recover whey heat to preheat wash water.
4. Install a heat recovery system on the exhaust from the main cheese room.
5. Isolate steam unit heaters during summer months.
6. Use hose nozzles and thermostatic mixing valves for washdown water control.

[†] Donohue and Associates, Inc. (1980)

and sanitation steam requirements can be reduced through heat recovery from the waste streams that are generated.

The potential for waste-heat recovery in some specific Wisconsin plants was illustrated in a study by Donohue and Associates, Inc. (1980) for the Wisconsin Department of State Planning and Energy. They identified several energy conservation opportunities in each of four plants. In only one plant did they evaluate waste-heat recovery systems. The opportunities they identified are given in Table 2-6. An evaluation of items 2 and 3, which are heat recovery opporuntities, is given in Tables 2-7 and 2-8. The conclusion was that neither project was economically justified in today's economy.

For plants having evaporator capacity, the vapor from the milk (referred to as cow water) is an excellent boiler feedwater source. Currently the industry is increasing the number of effects so evaporator economy results in 2-5 pounds of water evaporated per pound of steam input. When these multiple effect evaporators are coupled with mechanical or thermal recompression, more vapor is generated than can be used as boiler feed. Consequently, the real problem lies in identifying acceptor streams for the waste heat.

To assess the potential for waste-heat recovery in selected dairy processing situations, calculations were performed for the same three scenarios as for canning and meat processing. The same assumptions were also applied to these situations.

TABLE 2-7†

Install Necessary Piping and Pumps to Return Condensate from the Pasturizer and Vats.

Condensate is a valuable resource which should not be wasted. When condensate is returned to the boiler, savings are realized in two ways. The primary savings result from the heat content of the water. Makeup water to the boiler generally runs about 59°F, whereas condensate may be 120°F or higher. Replacing cold makeup water with hot condensate can result in considerable savings by reducing the energy required to heat the boiler water.

Secondary savings are realized by the reduction in net water required to run the boiler and improved water quality. Improved water quality will result in reduced water treatment and blowdown requirements. Because less makeup is required, the well pump will run less reducing electric bills.

The majority of the condensate at cheese plants is formed at the pasturizer and cooking vats. Measurements showed the following quantities of condensate were being formed at the Hamm's plant.

At the Pasturizer: $5{,}850\ ft^3/yr$ @ 161°F

At the Cheese Vat: $1{,}453\ ft^3/yr$ @ 175°F

The following calculations show the cost, savings and payback for returning that amount of condensate.

Btu Savings:

$Btu = QD\ \ T\ C_p$

Where Q = Condensate Formed ($ft3/yr$)

D = Density of Water (Lb/ft^3)

ΔT = Temp. Dif. Between Condensate & Makeup Water (°F)

C_p = Specific heat of water (Btu/Lb °F)

@ Pasturizer

$$Btu = (5{,}850\ ft^3/yr)(62.4\ Lb/ft^3)(161° - 59°F)(1\ Btu/Lb\ \ F)$$

$$= 37 \times 10^6\ Btu/yr$$

@ Cheese Vats

$$Btu = (1{,}453)(62.4)(175 - 59)(1) \quad = \underline{10.5 \times 10^6\ Btu/yr}$$

TOTAL 47.5×10^6 Btu/yr

Assume a 10% loss in return piping

TOTAL 43×10^6 Btu/yr

Dollar Savings:

$$\frac{(43 \times 10^6\ Btu/yr)(\$0.32/Therm)}{(100{,}000\ Btu/Therm)(0.84\ Eff).} = \$164/yr$$

Cost:

Based on proposed layout, the estimated costs would be:

Floor Demolition	$[illegible]73
Concrete Work	
Condensate Pit	$ 750
Pipe Trench	$1,000
Piping	$ 432
Insulation	$ 280
Duplex Condensate Pump	$ 425
TOTAL	$3,087

$$\text{Payback: } \frac{\$3087}{\$164} = 18.8 \text{ Years}$$

NOTE: The above costs include contractor's labor and profit. The cost and payback period may be reduced significantly if the owner dies the work himself. Also, if chemical, blowdown, and electricity savings are included, the savings may be increased, resulting in a quicker payback.

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† From Donohue and Associates, Inc. 1980.

Table 2-8†

Install Piping, Storage Tank and Heat Exchanger to Recover Heat From Whey for Preheating Wash Water

A major area for potential heat recovery identified from the energy balance was the whey system. Approximately 49,000 pounds of whey is produced on the average day. Utilizing the heat available in the whey to heat wash water will result in savings. Energy normally required to heat wash water will be reduced.

Using a flat plate heat exchanger, the savings is as follows:

Gas Savings:

Based on our field measurements, there is an estimated 28,000 pounds of wash water used per day.

From manufactuer's data, a heat exchanger was selected that will raise water 30°F.

$$\# \text{ Btu} = (28{,}000 \text{ Lb/day})(30°\text{F})(1 \text{ Btu/Lb °F})(260 \text{ days/yr})$$

$$= 218 \times 10^6 \text{ Btu/yr}$$

Dollar Savings:

$$\frac{(218 \times 10^6 \text{ Btu/yr})(\$0.32/\text{Therm})}{(100{,}000 \text{ Btu/Therm})(0.85 \text{ Eff}).} = \$820$$

Costs:

500 Gallon underground storage tank	$ 1,480
Tank installation	350
Excavation	64
Insulation (material)	96
Insulation (installation)	61
Heat Exchanger	7,000
Pumps	615
Misc. Piping & Controls	1,282
TOTAL	$10,348

Payback:

$$\frac{\$10{,}348}{\$820} = 12.6 \text{ Years.}$$

---

† From Donohue and Associates, Inc.,1980.

Situation I.

The assumptions made are:

(1) there is no recycle of condensate to boiler,

(2) blowdown is 10 percent of the boiler feed rate,

(3) all waste streams are compatable with acceptor streams, and

(4) no direct use is made of a waste stream as boiler feedwater.

This scenario was applied to two plants: a fluid milk plant, (illustrated in Figure 2-21), and a cheese plant, (Figure 2-22). For the fluid milk plant, the boiler feedwater could be heated from 60°F to 151°F by waste heat recovery schemes. Approximately 59 percent of the waste heat (reference temperature 60°F) was recovered from the sources, accounting for about 7.9 percent of the total boiler energy requirements. For a typical cheese plant with no evaporator or drying capacity, about 23 percent of the potentially recoverable energy could be used reducing boiler energy requirements by 9.7 percent.

Figure 2-21

System Diagram for Situation I: Fluid Milk Plant

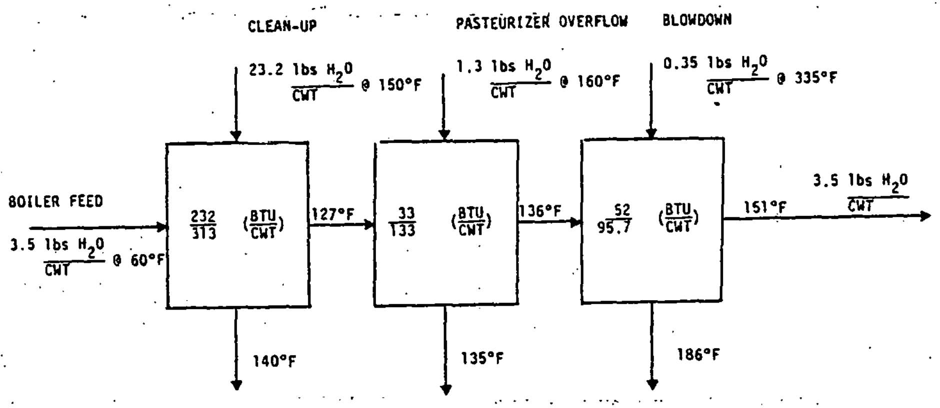
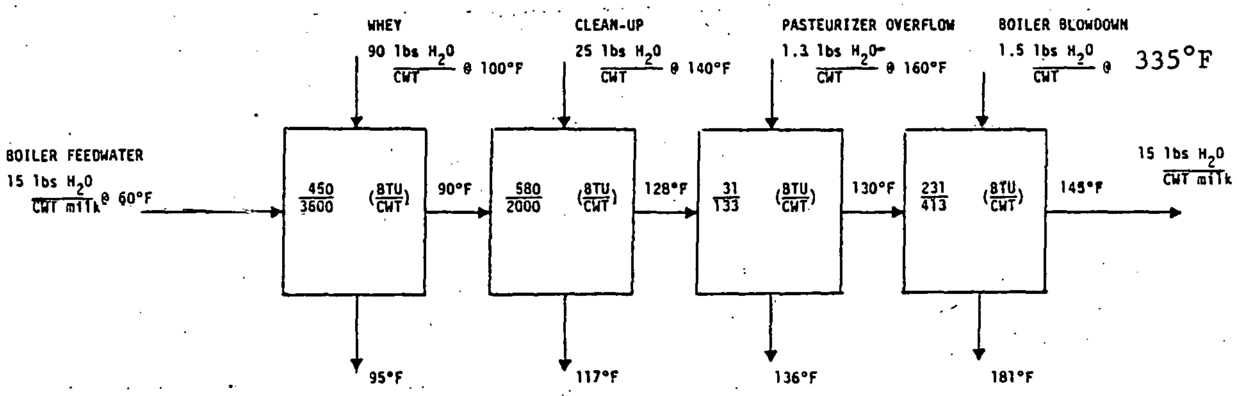


Figure 2-22

System Diagram for Situation I : Cheese Plant



CWT = hundredweight

Situation II.

The assumptions are:

(1) 75 percent condensate is returned to the boiler,

(2) blowdown is 10 percent of the boiler feed rate,

(3) all waste streams are compatable with acceptor streams, and

(4) direct use is made of some acceptable waste streams as boiler feedwater.

The calculations for the fluid milk plant and the cheese plant are shown in Figures 2-23 and 2-24, respectively. For fluid milk only the pasteurizer overflow stream was considered an acceptable boiler feedwater source, whereas, for cheese plants, both pasteurizer overflow and curd cooking condensate were considered acceptable. In fluid milk processing, 69 percent of the waste heat energy could be recovered for the boiler feedwater, reducing the total boiler demand by 7.7 percent. In cheese plants, 16 percent of the waste heat is available, technically accounting for 8.8 percent of the boiler demand.

Figure 2-23

System Diagram for Situation II : Fluid Milk Plant

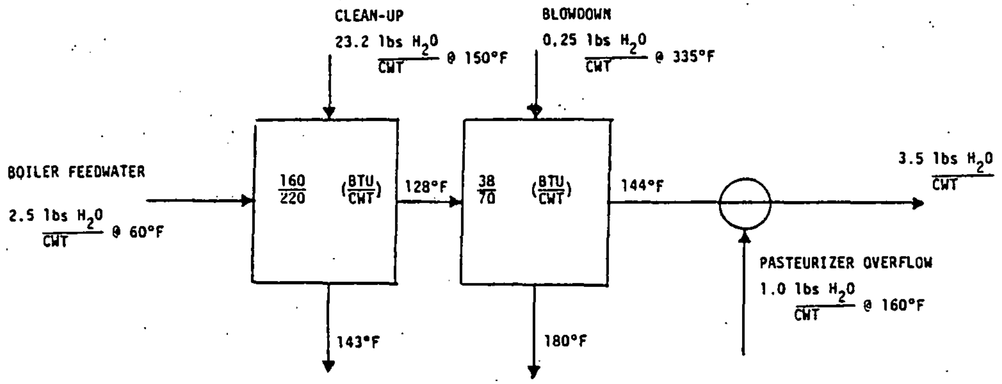
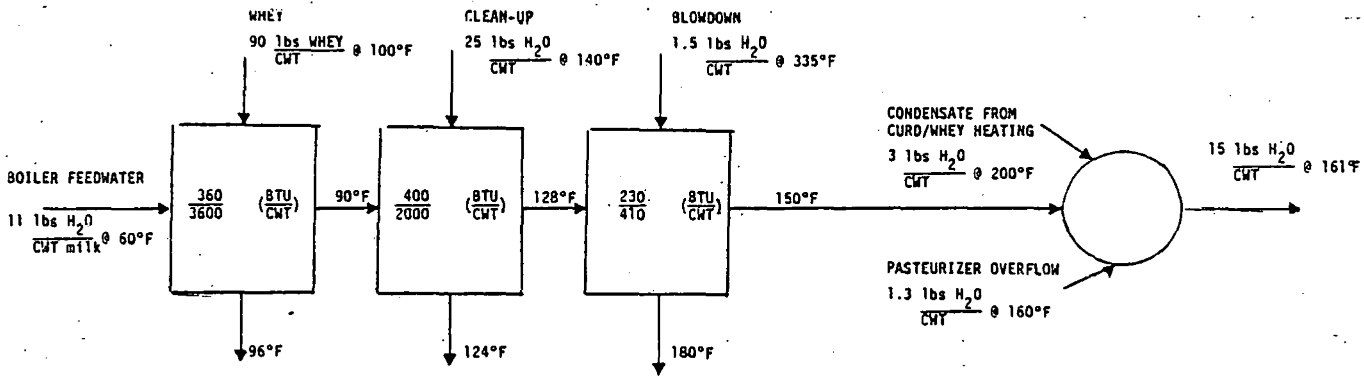


Figure 2-24

System Diagram for Situation II: Cheese Plant



CWT = hundredweight

Situation III.

The assumptions are:

(1) 75 percent condensate is returned to the boiler,

(2) no blowdown is used for heat recovery,

(3) clean-up waste water is not compatable with acceptor streams, and

(4) direct use is made of some acceptable waste streams as boiler feedwater.

The results for fluid milk and cheese plants are presented in Figures 2-25 and 2-26, respectively. In fluid milk processing 69 percent of the waste heat could be recovered reducing boiler energy requirements by 2.6 percent. In the cheese plant 10 percent of the energy could be recovered contributing 5.1 percent to the boiler energy demand.

Figure 2-25

System Diagram for Situation III: Fluid Milk Plant

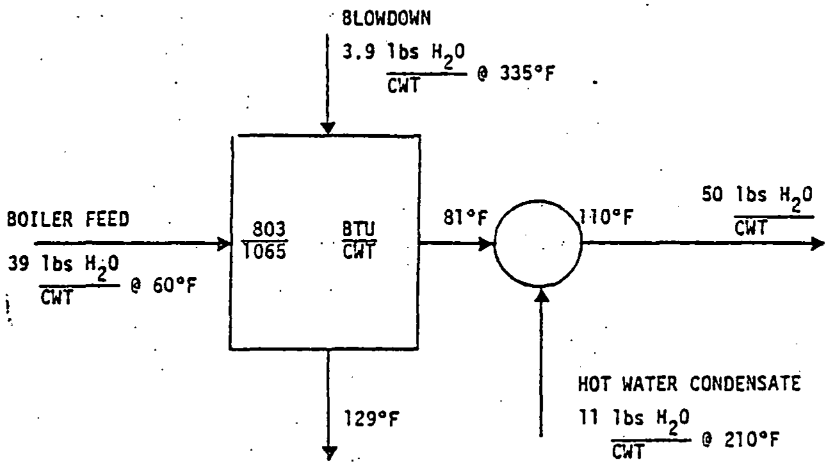


Figure 2-26

System Diagram for Situation III: Cheese Plant

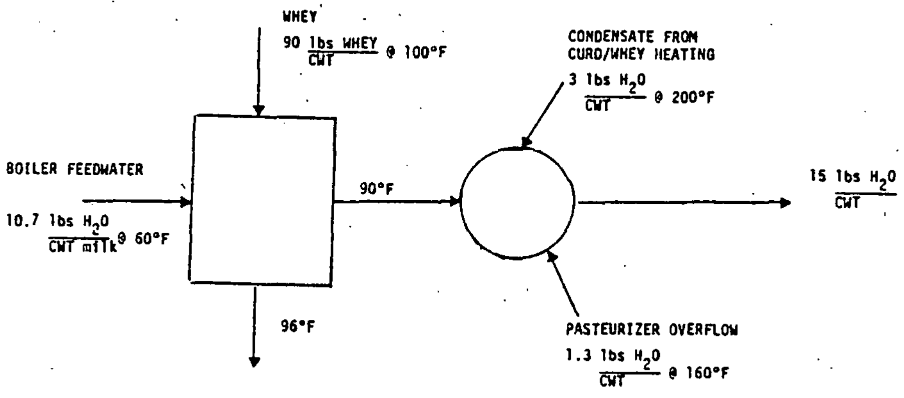


Table 2-9

Summary of Waste Heat Recovery Potential Under Various Scenarios

Food Industry Subsector	Situation[a]					
	I		II		III	
	PRE(%)[b]	BFE(%)[c]	PRE(%)	BFE(%)	PRE(%)	BFE(%)
Canning	45	7.3	72	8.8	74	7.5
Meat Processing	72	4.4	75	4.3	-	2.9
Fluid Milk	59	7.9	69	7.7	69	2.6
Cheese	23	9.7	16	8.8	10	5.1

[a] Situation I (1) no recycle of condensate to boiler
(2) blowdown is 10% of boiler feed rate
(3) all waste streams are compatable with accepter stream
(4) no direct use of waste stream as boiler feedwater

Situation II (1) 75% condensate return of indirect heating to boiler
(2) blowdown is 10% of boiler feed rate
(3) all waste streams are compatable with acceptor streams
(4) direct use of some acceptable waste stream as boiler feedwater

Situation III (1) 75% condensate return of indirect heating to boiler
(2) no blowdown for heat recovery
(3) clean-up waste water not compatable with accepter stream
(4) direct use of some acceptable waste stream as boiler feedwater

[b] PRE% means Potentially Recoverable Energy expressed as a percent of the energy content of the waste streams relative to the temperature of the boiler feedwater as a reference.

[c] BFE% means Boiler Feedwater Energy contributed by indirect waste heat recovery expressed as a percent of the total energy for the boiler.

CONCLUSION

The potential exists for waste heat recovery in the food processing industry. In canning, meat processing and manufacturing, and dairy processing, waste heat streams can be identified which can be used directly as boiler feedwater. There are also several opportunities for indirect heat exchange using waste streams generated simultaneously with the demand for boiler feedwater and hot water for processing. A summary of waste heat recovery potential under various scenarios is given in Table 2-9. Based on our analysis, it is possible to reduce boiler energy requirements from 15 to 50 percent if all waste heat could be extracted from the heat sources, that is, by reducing the temperature to boiler feedwater temperature. In most cases this would require identifying acceptor streams outside the plant or using other means of recouping and storing the heat from the waste stream. In practice, it is more likely that for the food processing industry it is technically feasible to recover heat energy from waste streams either directly or indirectly, and by doing so reduce boiler energy requirements from 3 to 10 percent.

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CHAPTER III

WASTE HEAT RECOVERY IN THE WISCONSIN PULP AND PAPER INDUSTRY

This chapter presents a technical characterization of paper and pulp manufacturing in Wisconsin and assesses the potential for waste heat recovery. The procedure is similar to that followed in Chapter II. Energy flow descriptions are developed for typical plants based upon the information developed from technical literature and the participating firms. Major waste-heat streams and potential acceptor streams are then identified and quantified, and potential waste-heat recovery is calculated for these streams.

OVERVIEW

Paper and board production takes place in two major steps: the manufacture of pulp from pulpwood, waste paper, or other fibers, and the formation of paper and paperboard (see Figure 3-1). The pulp may be bleached before paper formation. Most pulpmills in Wisconsin are integrated pulp and paper mills that perform both steps. Wisconsin pulpmills supply around 65 percent of the woodpulp consumed in Wisconsin papermills. The remainder is imported as dried woodpulp from other states and Canada. Woodpulp production capacity has not changed much over the last 15 years (Foell et al., 1980). The mix of pulping processes used in Wisconsin differs from the national process distribution, as can be seen in Table 3-1. The most striking difference is Wisconsin's heavy reliance on the sulfite process, while the sulfate process is dominant nation-wide. A description of these processes is given in a later section.

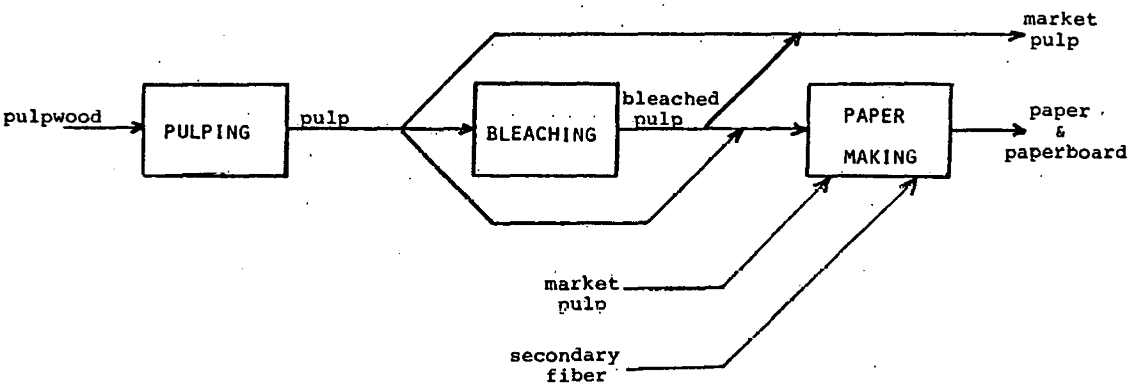

Figure 3-1

General Diagram of Pulp and Paper Manufacturing

Table 3-1

Woodpulp Production Capacity, Distribution by Process, Wisconsin and U.S.

	Sulfite	Sulfate	Mechanical	Semi-Chemical	Other
Wisconsin	28%	29%	26%	17%	---
U.S.	5%	68%	16%	8%	3%

ENERGY CONSUMPTION PATTERNS

Trends in energy consumption are shown in Table 3-2. The paper industry consumes 90 percent of all the coal used in all industry (excluding electric utilities) in the state. While coal use has remained relatively constant over the years, there has been a marked increase in the use of oil and, to a lesser degree, electricity. The industry increasingly relies on non-fossil fuels such as wood, bark, and spent liquors, and the 250 to 300 million kilowatt hours (kWh) it generates annually through hydropower. In 1977, the Wisconsin paper industry derived 80 percent of its energy requirements from fossil fuels, down from 86 percent in 1972 (Foell et al., 1980). More recent data indicate that, in 1979, reliance on fossil fuels was further reduced to 75.6 percent of total energy use (<u>Wisconsin Paper News</u>, 1980). This compares to a national average of 53.4 percent for 1978. Most of the difference lies in the use of spent liquors. Because Wisconsin papermills use much imported pulp and a considerable amount of waste paper (especially for tissue paper), less spent pulping liquor is available for energy production.

The different pulping process mix (Table 3-1) is also an important factor. Energy recovery from sulfate liquors always has been a standard procedure,

Table 3-2

Energy Consumption in the Wisconsin Pulp and Paper Industry.

		1972		1977	
			billion Btu		billion Btu
purchased electricity	(million kWh)	1750	5934	2070	7051
purchased steam	(billion Btu)	2219	2219	3120	3120
coal	(million ton)	1.38	36079	1.24	32594
residual fuel oil	(million gallon)	26.1	3918	56.6	8483
distillate fuel oil	(million gallon)	6.08	869	11.7	1677
l.p.g.	(million gallon)	1.95	179	1.30	120
natural gas	(billion cubic foot)	27.7	28528	18.7	19211
other fuels	(billion Btu)	----	----	3.0	3
hogges fuels (wood)	(thousand ton)	30.4	234	131	1012
bark	(thousand ton)	173	1559	270	2428
spent liquor	(thousand ton)	647	8671	961	12879
self-generated hydro	(million kWh)	295	1006	255	870
other self-generated energy	(billion Btu)	255	255	274	274
energy sold	(billion Btu)	3056	3056	3159	3159
Total, less sold			86396		86561

Source: American Paper Institute

because burning the liquors is part of the chemical recovery process.[1] This is not the case, however, with sulfite pulpmills. Mechanical pulpmills do not generate spent liquors. Thus Wisconsin's comparatively large sulfite and mechanical pulping capacity limits the use of spent liquor as an energy source. Despite this, however, energy recovery from spent liquors has increased by almost 10 percent a year since 1972.

The paper industry also has the largest electric cogenerating capacity in the state. It produces an estimated 2 billion kWh of electric power through cogeneration annually.

Table 3-3 shows that virtually all the coal is consumed by the larger mills (over 500 billion Btu annual fuel consumption).[2]

DESCRIPTION OF PROCESSES

The pulping processes important in Wisconsin are the sulfite, sulfate (kraft), groundwood, and semi-chemical processes. Sulfite and sulfate pulping are chemical processes in which woodchips are reduced by chemical action under steam pressure. Groundwood pulping is a mechanical method. Semi-chemical pulping is a combination of chemical and mechanical reduction of wood.

The Sulfite Process

Figure 3-2 shows the main process steps in sulfite pulp production. Pulpwood is debarked and chipped before entering the digester. In the digester the chips are cooked with an acid pulping liquor at temperatures of approximately 280°F, under pressure of 75 to 90 psi. Temperatures and cooking time vary

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[1] The section, Description of Processes, describes this in greater detail.

[2] A more extensive discussion of factors influencing fuel use patterns may be found in "Industrial Energy Use in Wisconsin: Consumption Patterns and Conservation Measures," Foell et al., 1980.

Table 3-3. Fuel Consumption in Pulp and Paper Mills as a Function of Total Fuel Energy Consumed, 1976.

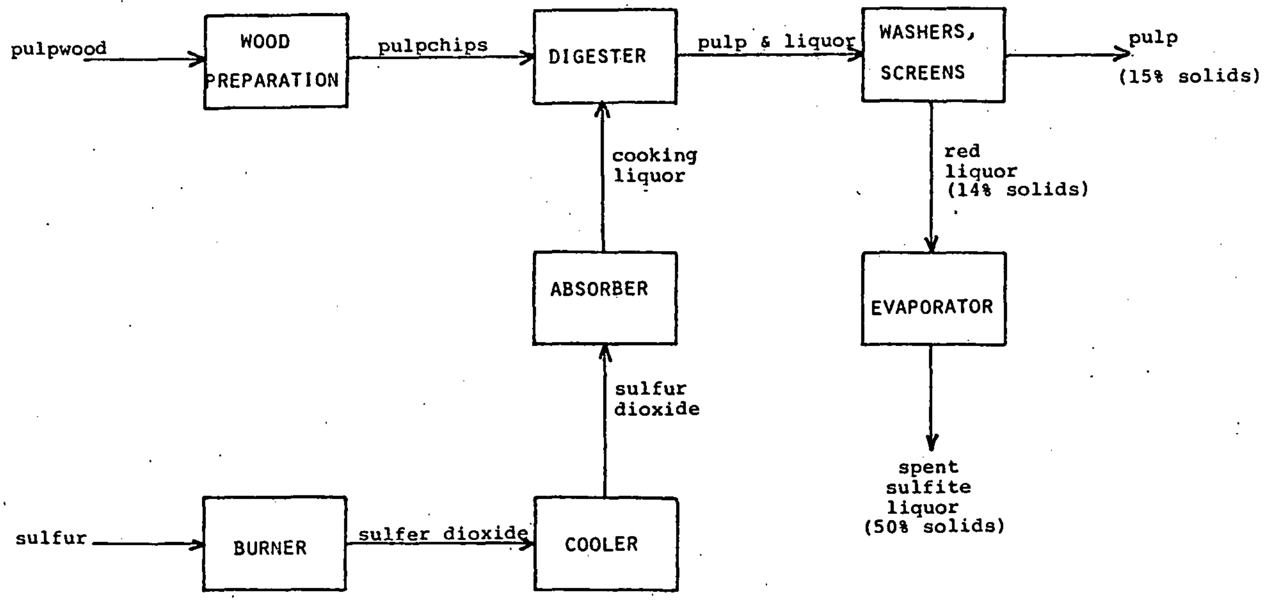
Annual Fuel Consumed (10^9 Btu)

		< 150	150 - 500	500-2000	> 2000	Total
Number of firms reporting		13	12	17	16	58
Coal	(10^9 Btu)	.5	1,364.5	3,614.5	33,002.8	37,982.3
Oil	(10^9 Btu)	138.2	337.2	2,141.6	6,349.0	8,966.0
Gas	(10^9 Btu)	451.6	2,139.7	10,026.8	12,772.7	25,390.8
LPG	(10^9 Btu)	----	5.2	35.5	23.5	64.1
Wood	(10^9 Btu)	----	146.2	749.4	5,984.8	6,880.5
Liquor	(10^9 Btu)	----	----	61.2	5,010.3	5,071.5
Total	(10^9 Btu)	590.3	3,992.9	16,629.0	63,143.1	84,355.2

Source: Wisconsin Boiler Survey, Department of Natural Resources, Madison, Wisconsin.

Figure 3-2

Diagram of Major Processes in Sulfite Pulping



with the type of pulpwood and the desired grade of pulp. Steam and acid are released during the cooking operation to avoid excessive pressures. After the cooking is completed the pulp and liquor are released into the blow tank. Then the pulp is washed and screened and the red liquor is usually concentrated in an evaporator before disposal. There are, however, many uses for spent sulfite liquor, such as use in adhesives or alcohol and yeast production. The liquor contains sulfite vanillin which may be used to flavor vanillin (Calkin and Witham, 1957).

The cooking liquor is a solution of sulfurous acid and calcium, magnesium, sodium, or ammonia bisulfite. This acid solution is prepared by absorption of sulfur dioxide:

$$SO_2 + H_2O \rightleftarrows H_2SO_3 \qquad (1)$$

$$\underset{\text{limestone}}{CaCO_3} + 2H_2SO_3 \longrightarrow Ca(HSO_3)_2 + CO_2 + H_2O \qquad (2a)$$

or: $$\underset{\text{lime}}{CaO} + H_2O + 2H_2SO_3 \longrightarrow Ca(HSO_3)_2 + 2H_2O \qquad (2b)$$

or: $$MgO + 2H_2SO_3 \longrightarrow Mg(HSO_3)_2 + 2H_2O \qquad (2c)$$

or: $$\underset{\text{soda}}{Na_2CO_3} + 2H_2SO_3 \longrightarrow 2NaHSO_3 + CO_2 + H_2O \qquad (2d)$$

or: $$NH_3 + H_2O + H_2SO_3 \longrightarrow NH_4(HSO_3) + H_2O \qquad (2e)$$

Sulfur dioxide is produced by burning sulfur. The sulfur dioxide requires rapid cooling to below 400°F to prevent formation of sulfur trioxide and to facilitate better absorption in water.

Opportunities for recovery of chemicals and energy from spent liquors depends on the type of acid liquor used. Possibilities for recovery of soda or magnesium oxide (involving evaporation and burning of the liquors) exist, but recovery of ammonia or lime is not feasible (Jones, 1973). Ammonia-base liquor may be burned for energy recovery, resulting in the loss of the ammonia. Burning of calcium base liquor causes scaling on the equipment ($CaSO_4$)(Jones, 1973). The average heating value of the spent sulfite liquor is around 8,000 Btu per pound of dry solids.

The Sulfate (kraft) Process

The major differences between sulfite and sulfate pulping is the use of an alkaline cooking liquor and the kraft chemical recovery process (Figure 3-3). Pulpwood is chipped and cooked with the cooking liquor under pressures of 100-110 psi at maximum temperatures around 350°F. After cooking the pulp and liquor are released into the blow tank, then washed and screened.

The active agents in the cooking liquor, or white liquor, are sodium hydroxyde (NaOH) and sodium sulfide (Na_2S). Because the liquor is recovered from black (or spent) liquor, the white liquor also contains limited amounts of sodium carbonate ($NaCO_3$), sodium sulfate (Na_2SO_4), and sodium thiosulfate ($Na_2S_2O_3$).

The first step in the recovery of chemicals from the black liquor is concentration of the liquor to around 50 percent solids in the evaporator. The liquor then is burned in the recovery furnace, yielding around 3,100 Btu per pound of concentrated liquor. This energy is recovered in the form of steam. In the furnace most of the sodium sulfate is reduced to sodium sulfide. Any make-up salt (Na_2SO_4) is added to the black liquor before it enters the recovery furnace. The residue (smelt, mostly Na_2CO_3 and Na_2S) is dissolved in return water from the lime and dreg washers. This solution (green liquor) is clarified, and lime is added in the slaker, resulting in the partial precipitation of calcium carbonate and formation of sodium hydroxide:

$$Na_2CO_3 + CaO + H_2O \longrightarrow CaCO_3 \downarrow + 2NaOH$$

This reaction is completed in the causticizer. The calcium carbonate (lime mud) is then separated from the liquor in the white liquor clarifier. The liquor is returned to the digester. The lime mud ($CaCO_3$) is washed and reduced to lime (CaO) in the lime kiln. The lime is reused in the slaking process.

The Groundwood Process

Figure 3-4 shows a simplified flow diagram for groundwood pulping. This grade of pulp is primarily used in manufacturing newspaper and cheaper grades of bookpaper (Calkin and Wilham, 1957). Spruce is the most desirable wood for this process, but groundwood mills in Wisconsin use large amounts of balsam fir, aspen, and other wood species.

Several types of grinders are employed, but all rely on the grinding action of a large grinding stone. Debarked logs are ground whole while water is added. In the thermo-mechanical process, a more recent variation on groundwood pulping, the wood is steamed before refining. After thickening, the pulp is often bleached with peroxide.

The Neutral Sulfite Semi-Chemical (NSSC) Process

NSSC pulping is the oldest and most common semi-chemical pulping process. This high-yielding method is especially well suited for hardwoods. The pulpwood is debarked and chipped (Figure 3-4). The chips are cooked in a digester

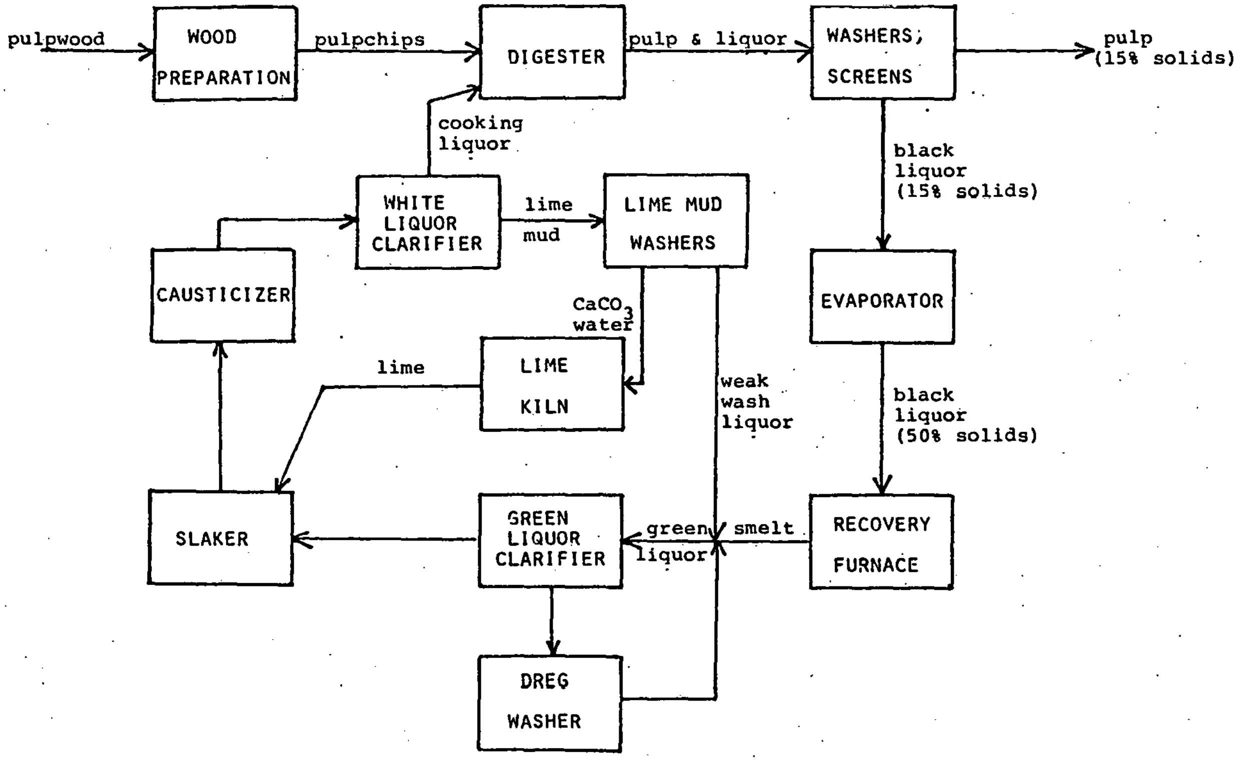
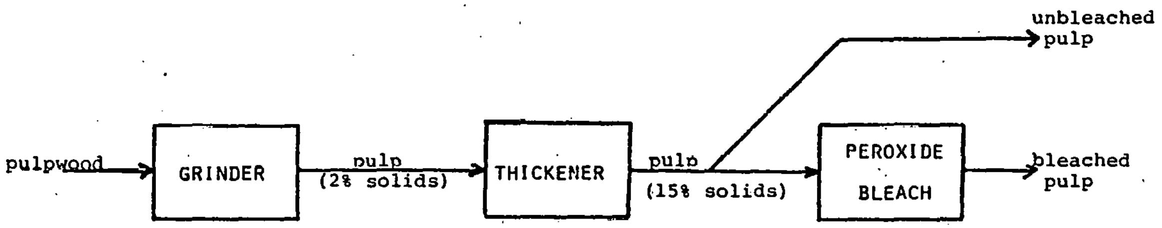


Figure 3-3

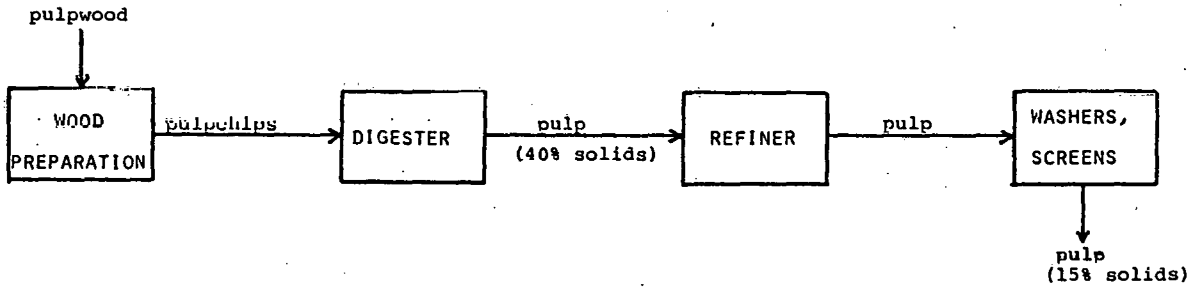
Diagram of Major Processes in Kraft Pulping

Figure 3-4

Diagram of Major Processes in Groundwood and NSSC Pulping



GROUNDWOOD PULPING



NEUTRAL SULFITE SEMICHEMICAL PULPING

Figure 3-5

Diagram of Major Processes in Three-Stage and Five-Stage Bleaching

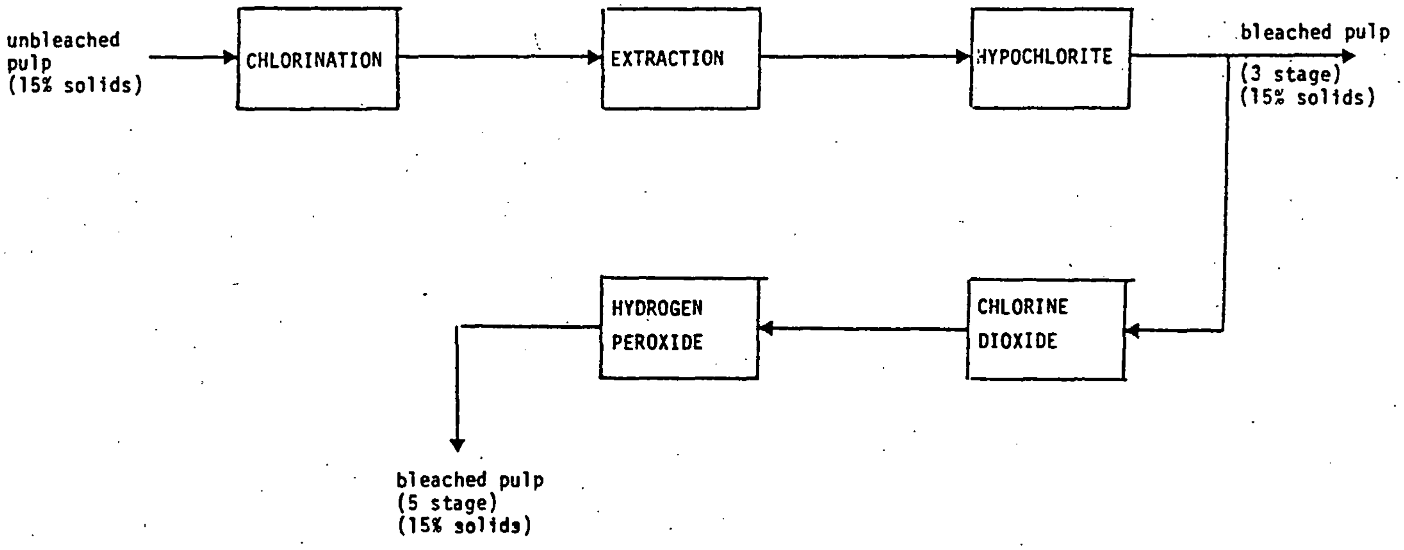
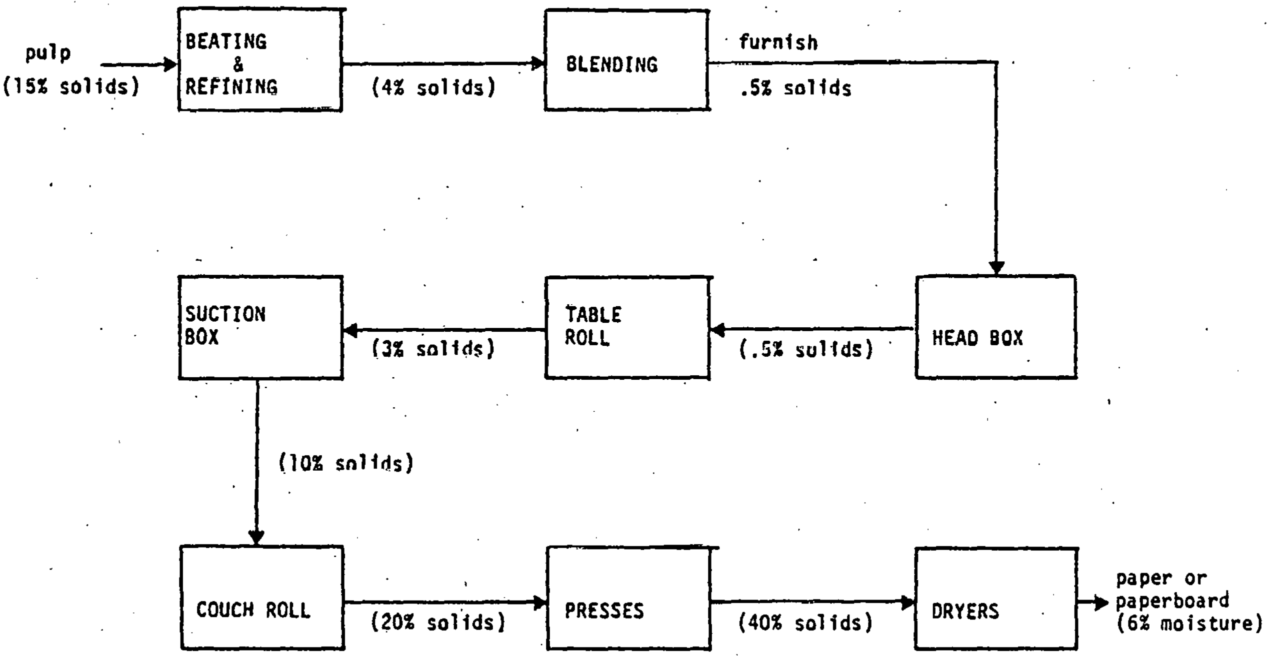


Figure 3-6

Diagram of Major Processes in Papermaking



for several hours with a cooking liquor at maximum temperatures of 320 - 350°F. The cooking liquor is a solution of sodium sulfite and sodium bicarbonate. After cooking, the pulp is mechanically refined before washing.

Bleaching

Bleaching of pulp is necessary for many uses. Residual lignin and coloring materials in the fibers are removed. Many bleaching processes are available, and different processes are often combined in a multistage process. Figure 3-5 shows a typical three-stage or five-stage process. The three-stage process is commonly used to bleach sulfite pulp; five-stage bleaching is often employed for kraft pulp bleaching.

The first stage is chlorination of residual lignin, which is then dissolved and removed in the extraction stage. The actual bleaching takes place in the hypochlorite stage where the pulp is oxidized with calcium or sodium hypochlorite. Three-stage bleaching provides sufficient brightness for sulfite pulp. Sulfate pulp needs more consecutive bleaching to reach a brightness comparable to three-stage bleached sulfite pulp. Often the pulp is again chlorinated and bleached with hypochlorite. Figure 3-5 shows an alternative, using chlorine dioxide and hydrogen peroxide as bleaching agents. Peroxide bleaching is commonly used to bleach groundwood pulp.

Paper Manufacturing

Pulp from the pulpmill needs more treatment and often chemical additives to make it suitable for paper formation. The pulp is diluted, typically to .5 percent solids before beating and refining (Figure 3-6). Both are mechanical processes. Beaters are used to brush and fray the fibers which are then cut in Jordan, disc, or other refiners. Non-fibrous additives, such as rosin, alum, and clay, may be added in the beater or head box.

The refined fiber is fed from the headbox onto the Fourdrinier wire, a fine mesh wire supported by table rolls (Figure 3-7). The rolls carry off the water from the wire and suction boxes under the wire remove more water. The couch roll is at the end of Fourdrinier wire and also removes water by suction. At this point the paper is formed. Water drained from the Fourdrinier (white water) is recycled. The paper sheet is then fed through a series of presses and dryers to dry the paper sheet to 5 - 6 percent moisture.

WASTE HEAT RECOVERY

To assess the potential for waste heat recovery several steps need to be taken. These include:

1. identification and quantification of major waste heat streams and potential acceptor streams in a typical plant,
2. selection of example cases, and
3. calculation of recovery potential.

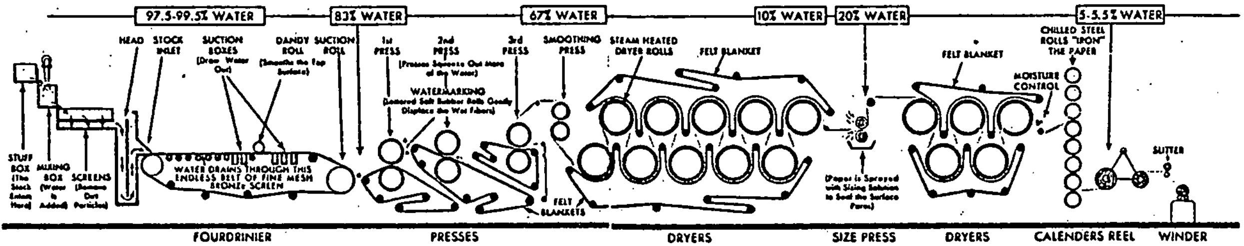
The first problem in this process is defining a typical plant. Even if we distinguish several pulping processes, actual energy requirements vary with the species of pulpwood, grade of pulp or paper, time of year, and many other factors. Size and nature of waste heat and acceptor streams also depend on the type of equipment used. For instance, heating may take place by direct steam injection or indirect heating with steam, gas or oil. In Table 3-4 more specific examples are given.

Waste Heat and Acceptor Streams

Figures 3-8 through 3-12 identify and quantify major waste heat and potential acceptor streams. All values are expressed per oven-dry ton of pulp or paper produced. Quantities and temperatures are based on data from

Figure 3-7

Diagram of Operations on a Fourdrinier Papermaking Machine (Calkin and Witham, 1957)



Courtesy Hammermill Paper Co.

Table 3-4

Technological and Physical Parameters that Significantly Affect the Nature of Waste-Heat and Acceptor Streams

Process	Options
dryers	steam, hot air
digester	direct steam injection, indirect steam heating
bleaching	direct steam injection, indirect steam heating
evaporator	steam, gas-oil-fired
make-up water	well water, surface water

---

the literature (Hall et al., 1975 and Brown et al., 1979) and on data supplied by cooperating paper companies. The temperature of make-up water is based on the annual average water temperature in Wisconsin. In sulfite and kraft pulping, we assumed direct steam injection into the digester. We also chose steam dryers and evaporators for our typical plant. Steam heating in the bleach plant is assumed to be indirect.

Description of Typical Plants

To obtain an indication of waste-heat recovery potential, sample calculations were made for specific waste-heat and acceptor streams in a typical kraft pulp and paper mill and a typical sulfite pulp and paper mill. (These two pulping processes account for almost 60 percent of Wisconsin woodpulp production capacity.) Mechanical processes do not offer many opportunities for waste-heat recovery. Data for semi-chemical pulping were insufficient for similar calculations. Moreover, this process accounts for only 12 percent of capacity (2 mills) in Wisconsin and 8 percent nation-wide.

Calculations were made for two base situations:

1. All electric power is purchased.
2. Part or all of electric power requirements are cogenerated.

Typical Kraft Pulp and Paper Mill Characteristics

bleached pulp production:	200 ton/day
paper production:	350 ton/day
5-stage bleaching process	
boiler efficiency:	70 percent
condensate return:	80 percent
total steam requirements:	3,956,000 lbs/day
recovery boiler steam production:	2,717,000 lbs/day
electric power consumption:	278,000 kWh/day

case a. no cogenerated power (Figure 3-13a)

purchased electricity: 278,000 kWh/day at 10,500 Btu/kWh =	2.91×10^9 Btu/day
fossil fuel consumption =	1.89×10^9 Btu/day
total =	4.80×10^9 Btu/day

case b. cogenerated power (Figure 3-13b)

purchased electricity: 200,562 kWh/day at 10,500 Btu/kWh =	2.11×10^9 Btu/day
fossil fuel consumption =	2.33×10^9 Btu/day
total =	4.44×10^9 Btu/day

Typical Sulfite Pulp and Paper Mill Characteristics

bleached pulp production:	200 ton/day
paper production:	350 ton/day
3-stage bleaching process	
boiler efficiency:	70 percent
condensate return:	80 percent
total steam requirements:	4,684,000 lbs/day
no recovery boiler	
electric power consumption:	237,500 kWh/day

case a. no cogeneration (Figure 3-14a)

purchased electricity: 237,500 kWh/day at 10,500 Btu/kWh =	2.49×10^9 Btu/day
fossil fuel consumption =	7.21×10^9 Btu/day
total =	9.70×10^9 Btu/day

case b. cogenerated power (Figure 3-14b)

credit for electricity sold: 55,250 kWh/day at 5,736 Btu/kWh† =	$-.32 \times 10^9$ Btu/day
fossil fuel consumption =	8.89×10^9 Btu/day
net total =	8.57×10^9 Btu/day

---

†Heat rate for cogenerated power. Although this power replaces power generated with an average heat rate of 10,500 Btu/kWh, we used the lower heat rate for reasons of consistency in our calculations.

Selected Waste Heat and Acceptor Streams

Figures 3-8 through 3-12 show a variety of potential waste-heat streams and acceptor streams. Waste-heat streams with a high recovery potential are:

1. blow stream from digester,
2. water vapor from evaporator,
3. water vapor from paper dryer, and
4. vapor condensate from evaporator.

Heat recovery systems for streams 1, 2, and 3 appear to be relatively standard, but often no heat is recovered from stream 4. Therefore, the vapor condensate was selected as heat source stream.

Potential acceptor streams are (Ellerbe, 1975, p. 44-46):

1. pulp washer,
2. boiler feedwater,
3. water for bleach plant,
4. black or red liquor,
5. tall oil† (heating facilitates pumping), and
6. evaporator condensate (preheat before steam stripping).

Many plants already are heating pulp washwater through waste-heat recovery. Boiler feedwater and bleach water (2 and 3) appear to be less commonly used as acceptor streams, and were therefore chosen as examples.

Calculations are made for several cases as shown in Table 3-5.

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†Tall oil is a dark odorous liquid before refining that contains principally resin acids and fatty acids; it is recovered from the black liquor.

Figure 3-8

Waste-Heat and Potential Acceptor Streams in a Sulfate Pulpmill

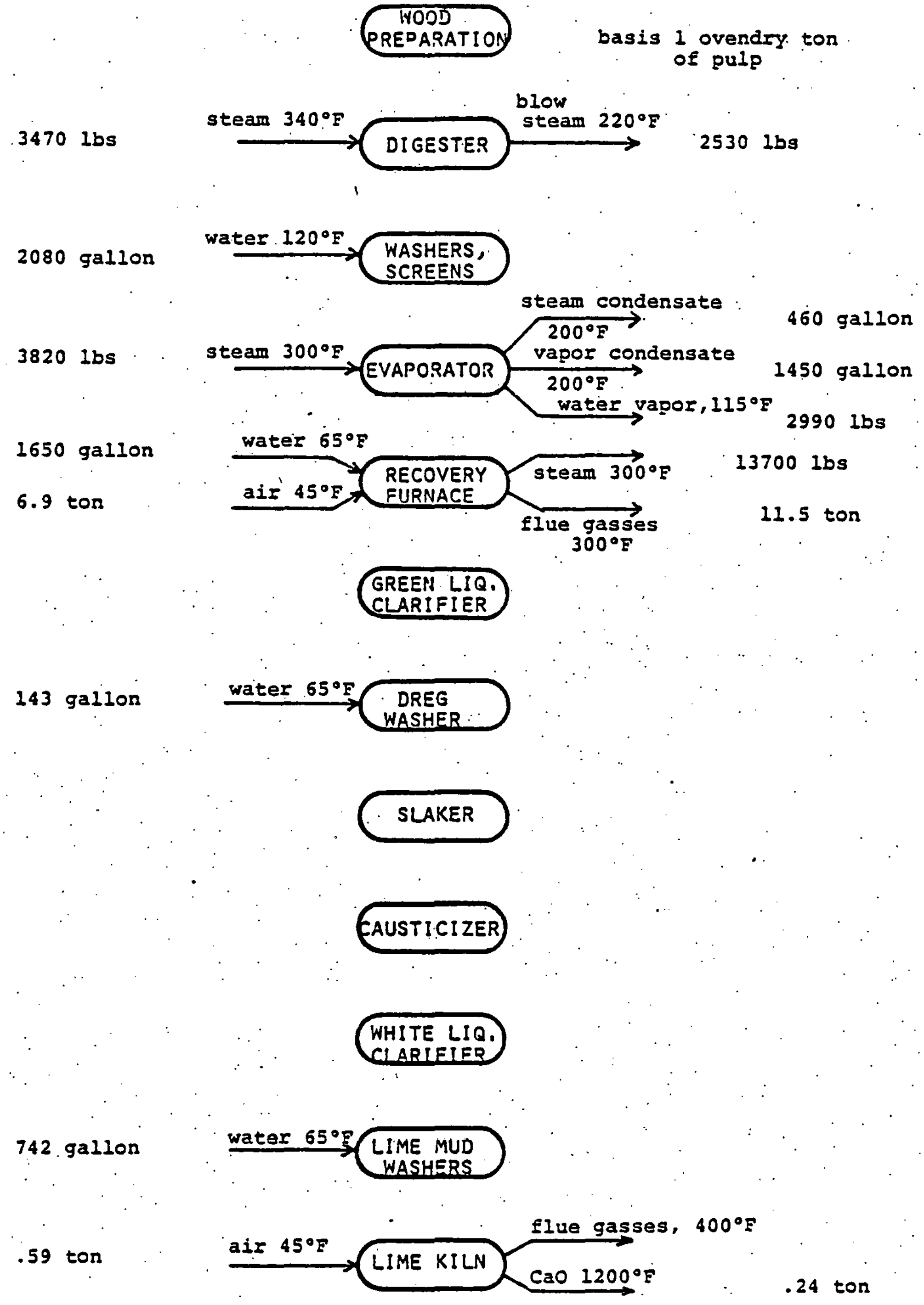


Figure 3-9

Waste-Heat and Potential Acceptor Streams in a Sulfite Pulpmill

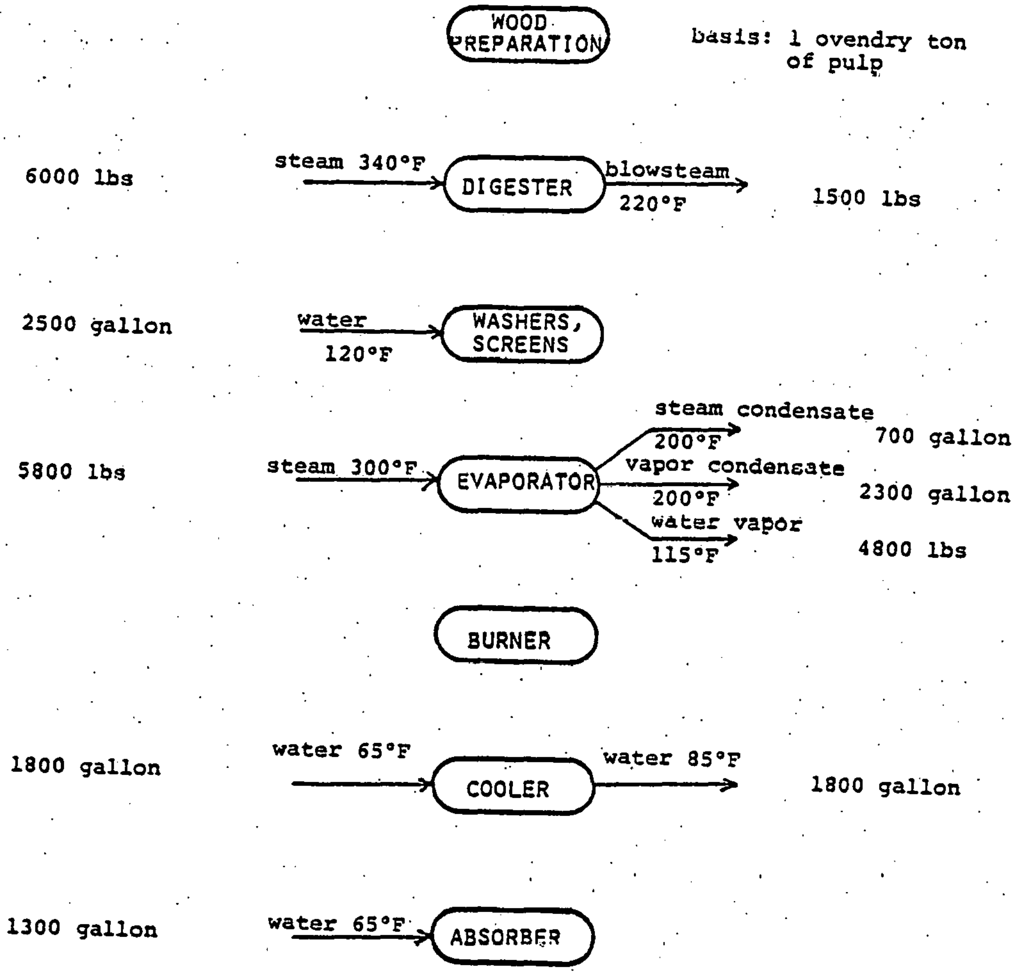
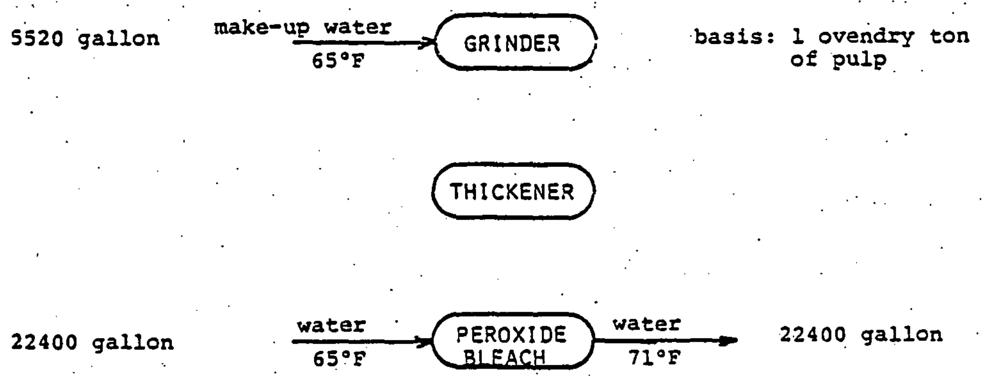
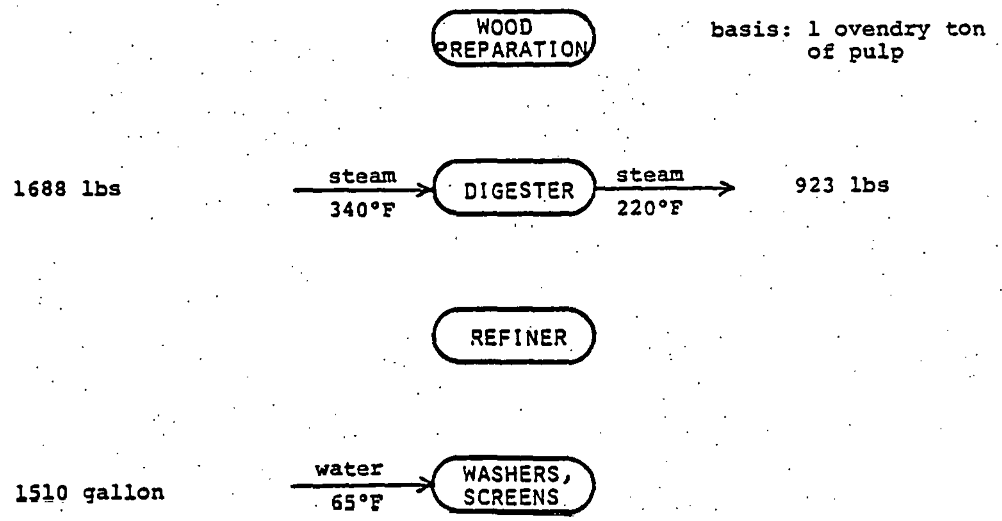


Figure 3-10

Waste-Heat and Potential Acceptor Streams in a Groundwood Pulpmill, and a Neutral Sulfite Semichemical Pulpmill



GROUNDWOOD PULPING



NSSC PULPING

Figure 3-11

Waste-Heat and Potential Acceptor Streams in Five-Stage Bleaching Plant and a Three-Stage Bleaching Plant

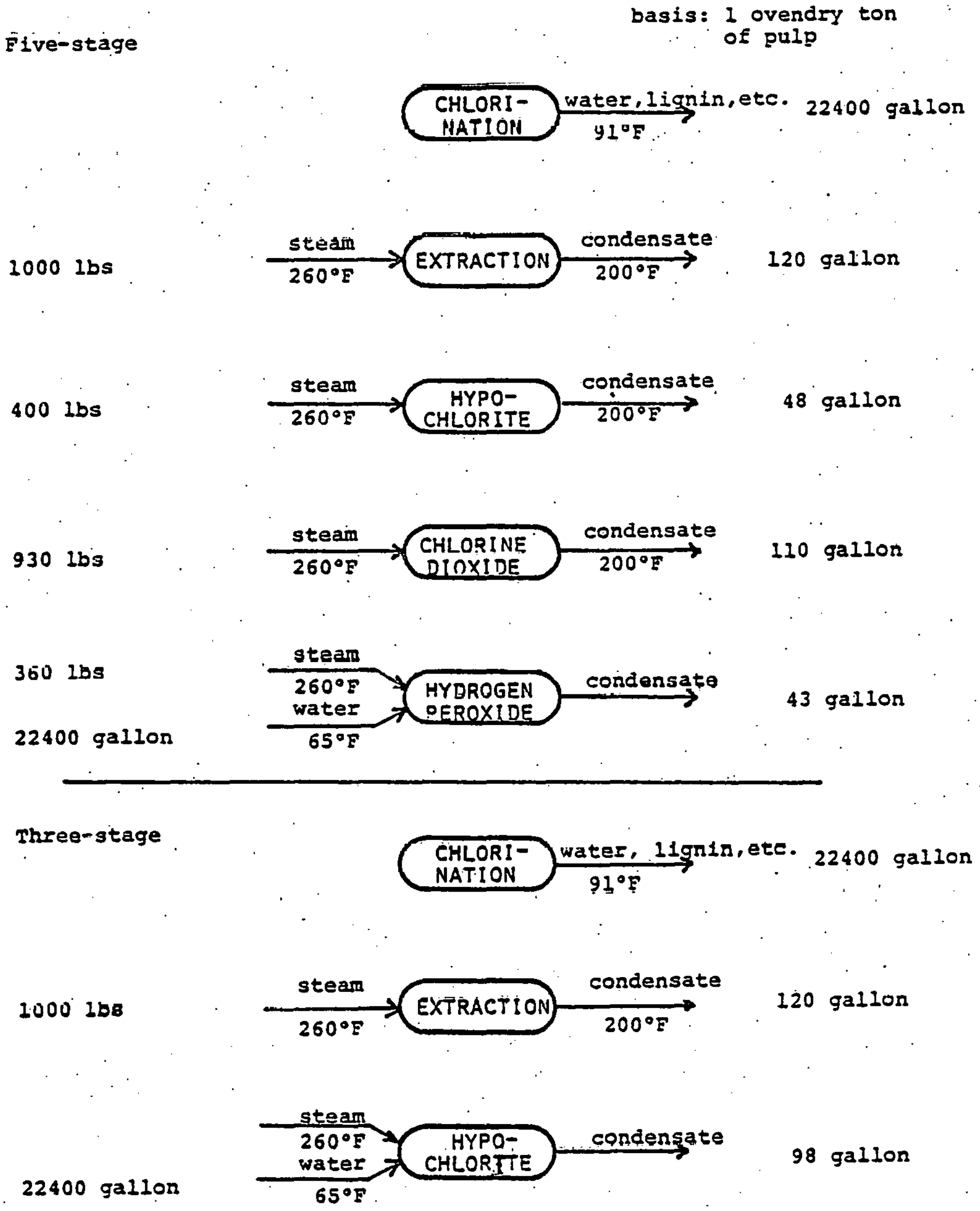


Figure 3-12

Waste-Heat Streams and Potential Acceptor Streams in a Paper Mill

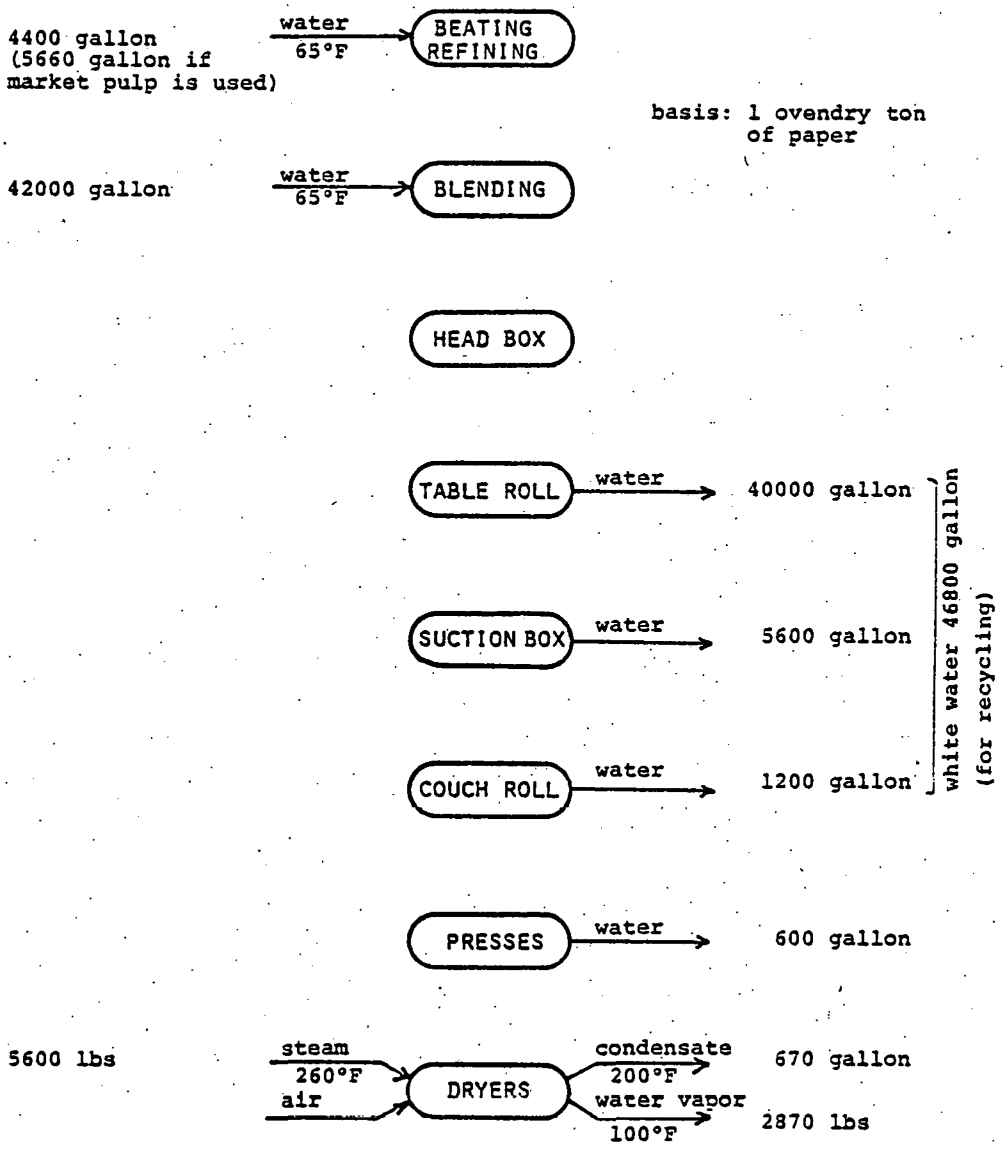


Figure 3-13a

Steam, Fuel, and Boiler Feed Water Requirements for "Typical" Kraft Pulp Paper Mill Without Cogeneration Equipment

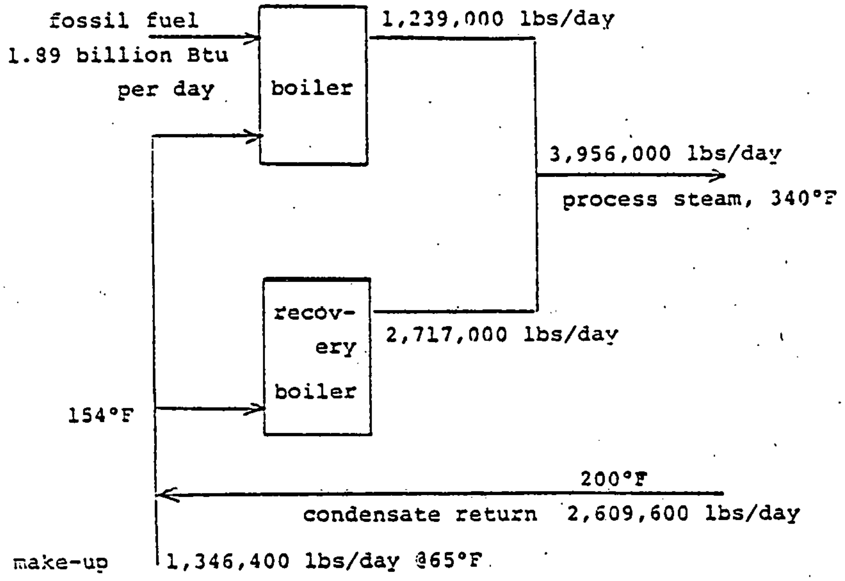


Figure 3-13b

Steam, Fuel, and Boiler Feed Water Requirements for "Typical" Kraft Pulp Paper Mill With Cogeneration Equipment

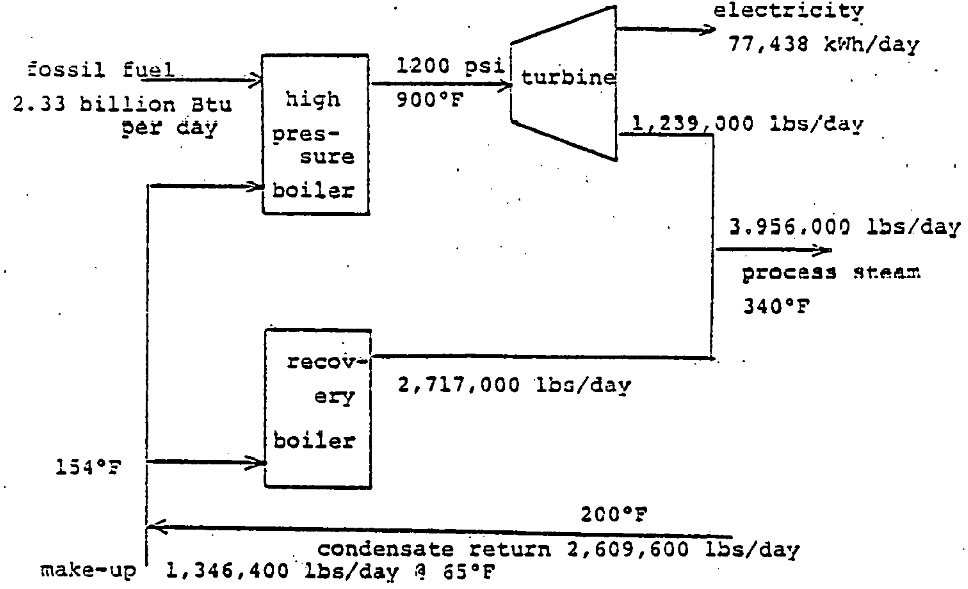


Figure 3-14a

Steam, Fuel, and Boiler Feed Water Requirements for Typical Sulfite Pulp and Paper Mill Without Cogeneration Equipment

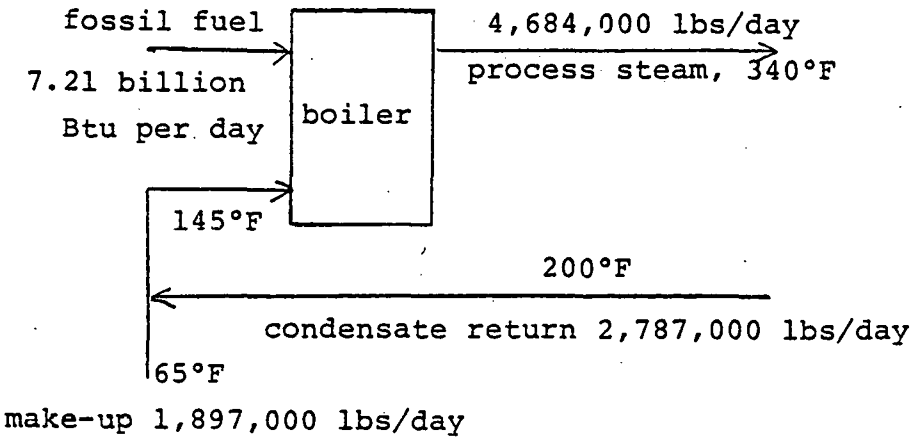


Figure 3-14b

Steam, Fuel, and Boiler Feed Water Requirements for Typical Sulfite Pulp and Paper Mill with Cogeneration Equipment

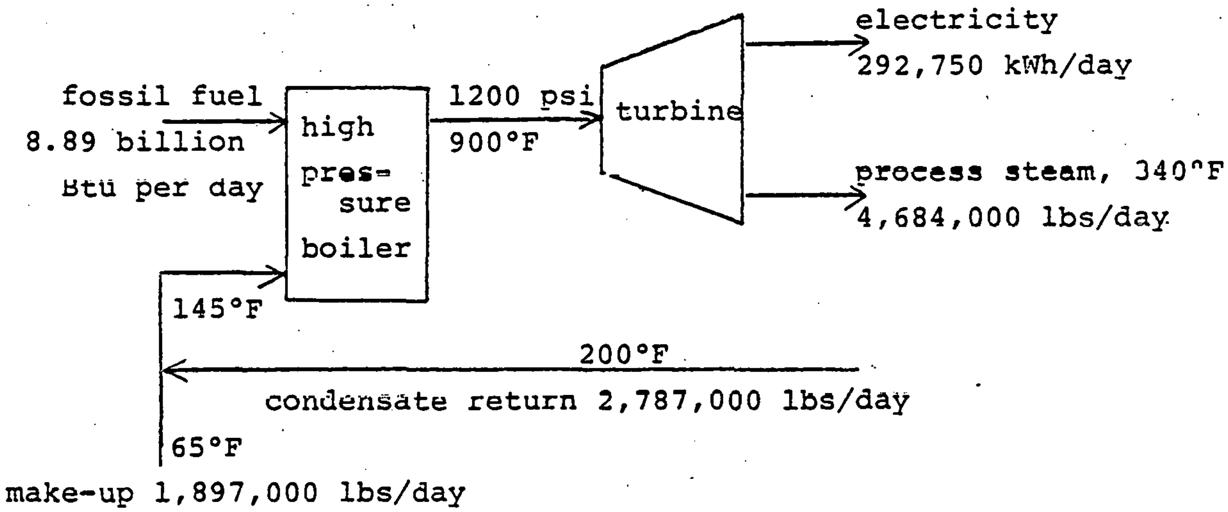


Table 3-5

Situations Used for Sample Calculations

Situation	Waste Heat Stream	Acceptor Stream(s)	Cogeneration
1a	vapor condensate	boiler feedwater	no
1b	vapor condensate	boiler feedwater	yes
2a	vapor condensate	bleach water	no
2b	vapor condensate	bleach water	yes
3a	vapor condensate	boiler feedwater & bleach water	no
3b	vapor condensate	boiler feed water and bleach water	yes

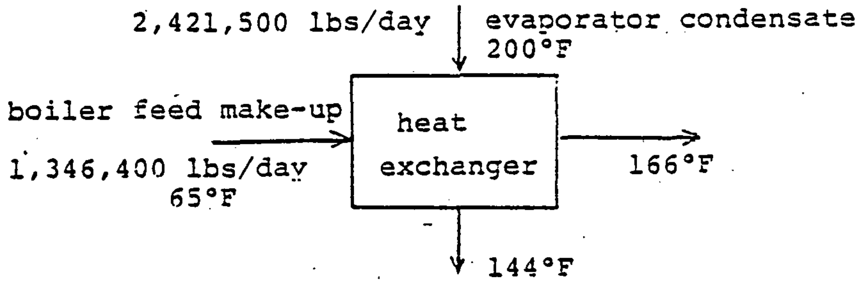
Sample Calculations

Several assumptions were made to simplify the task of calculating heat recovery. Only liquid/liquid heat exchangers were considered, with an assumed effectiveness (ε) of .75[†]. No attempt was made to optimize the heat exchanger size in any way. Based upon information from the industry workshops, it also was assumed that all streams coincide at all times. Cost effectiveness of these heat recovery measures has not been calculated. Other assumptions have been described earlier. The sample calculations are in Figures 3-15 through 3-20.

[†] Effectiveness is defined as the ratio of the actual heat transferred and the maximum possible: $Q_{act} = \varepsilon Q_{max}$. The maximum possible Q_{max} is determined by the temperatures of the streams and the flowrate of the smallest stream. (See Section 2, p, 34)

Figure 3-15

Sulfate Mill, Situation 1-a and 1-b



SULFATE MILL

Situation 1-a (Figure 3-15)

no cogeneration

waste-heat stream:	evaporator vapor condensate 2,421,500 lbs/day @200 F
acceptor stream:	boiler feed make-up water 1,346,400 lbs/day @ 65 F

heat transferred	136 million Btu/day
fuel savings	195 million Btu/day
or	4.1% of energy consumed.

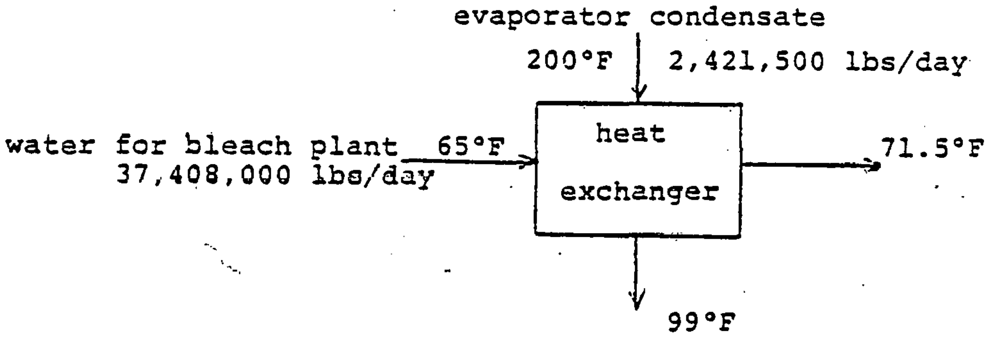
Situation 1-b

Same as 1-a, with cogeneration

Heat transferred	136 million Btu/day
fuel savings	195 million Btu/day
or	4.4% of energy consumed.

Figure 3-16

Sulfate Mill, Situation 2-a and 2-b



SULFATE MILL

Situation 2-a (Figure 3-16)

no cogeneration

waste heat stream:	evaporator vapor condensate 2,421,500 lbs/day @200 °F
acceptor stream:	water for bleach plant 37,408,000 lbs/day @ 65 °F

heat transferred	244 million Btu/day
fuel savings	349 million Btu/day
or	7.3% of energy consumed.

Situation 2-b

Same as 2-a, with cogeneration

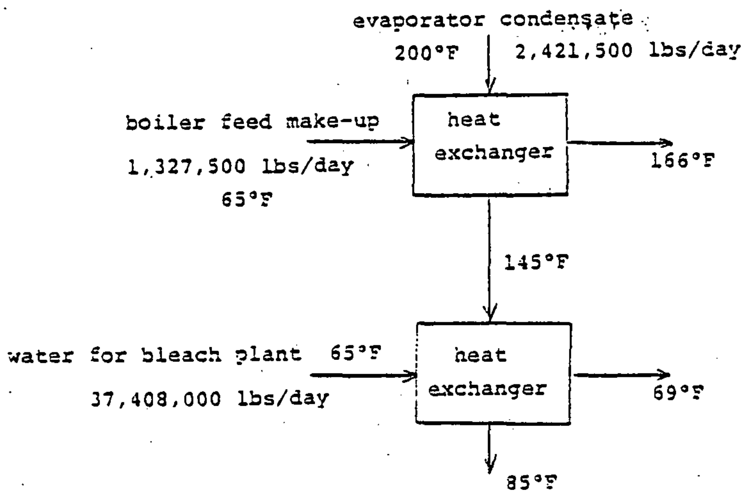
heat transferred	244 million Btu/day
fuel savings	349 million Btu/day
reduction in cogenerated power*	15288 kWh/day
reduction in savings	73 million Btu/day
net savings	276 million Btu/day
or	6.2% of energy consumed.

---

*The heat recovered results in a decrease in steam demand and consequently in a reduction in cogenerated power. This loss is made up with purchased power, which increases energy consumption by 4764 Btu/kWh of cogenerated power lost. (4764 Btu is the difference in heat rates for cogenerated and purchased electricity).

Figure 3-17

Sulfate Mill, Sutuation 3-a and 3-b



SULFATE MILL

<u>Situation 3-a</u> (Figure 3-17)

no cogeneration

waste heat stream: evaporator vapor condensate
2,421,500 lbs/day @ 200 °F

acceptor stream 1: boiler feedwater make-up water
1,327,500 lbs/day* @ 65 °F

acceptor stream 2: water for bleach plant
37,408,000 lbs/day @ 65 °F

heat transferred to stream 1	134 million Btu/day
heat transferred to stream 2	<u>145 million</u> Btu/day
total	279 million Btu/day
fuel savings	399 million Btu/day
or	8.3% of energy consumed.

<u>Situation 3-b</u>

Same as 3-a, with cogeneration

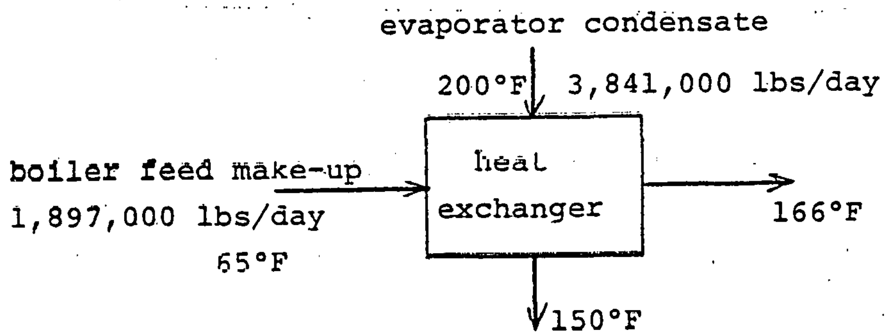
total heat transferred	279 million Btu/day
fuel savings	399 million Btu/day
reduction in cogenerated power	9058 kWh/day
reduction in savings	43 million Btu/day
net savings	356 million Btu/day
or	8.0% of energy consumed.

---

*This flow is less than in situation 1-a and 1-b. Preheating the water for the bleach plant results in a reduction in steam demand, leading to lower boiler feed water requirements.

Figure 3-18

Sulfite Mill, Situation 1-a and 1-b



SULFITE MILL

Situation 1-a (Figure 3-18)

no cogeneration

waste heat stream:	evaporator vapor condensate 3,841,000 lbs/day @ 200 °F
acceptor stream:	boiler feed make-up water 1,897,000 lbs/day @ 65 °F

heat transferred	192 million Btu/day
fuel savings	274 million Btu/day
or	2.8% of fuel consumed.

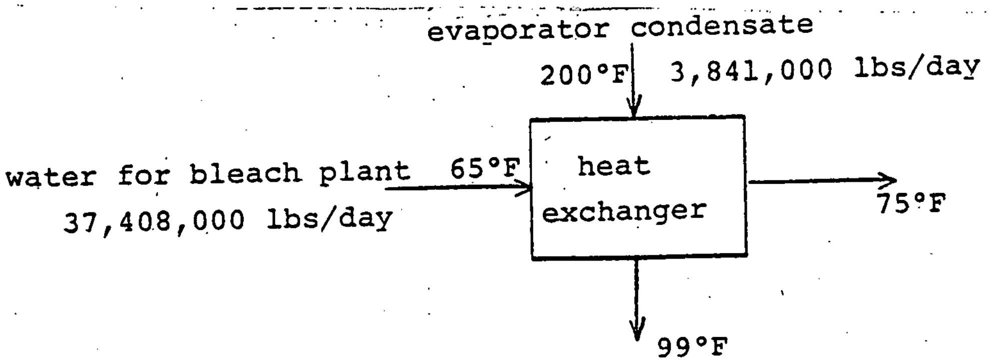
Situation 2-b

Same as 1-a, with cogeneration

heat transferred	192 million Btu/day
fuel savings	274 million Btu/day
or	3.2% of fuel consumed/

Figure 3-19

Sulfite Mill, Situation 2-a and 2-b



SULFITE MILL

Situation 2-a (Figure 3-19)

no cogeneration

waste heat stream: evaporator vapor condensate
3,841,000 lbs/day @ 200 °F

acceptor stream: water for bleach plant
37,408,000 lbs/day @ 65 °F

heat transferred	374 million Btu/day
fuel savings	534 million Btu/day
or	5.5% of energy consumed/

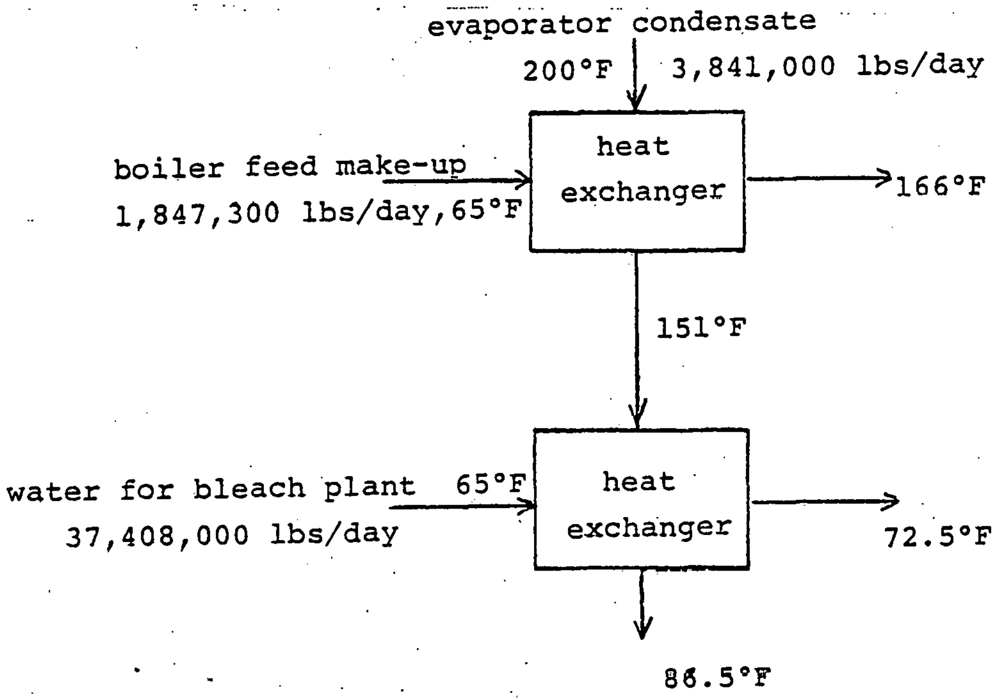
Situation 2-b

Same as 2-a, with cogeneration

heat transferred	374 million Btu/day
fuel savings	534 million Btu/day
reduction in cogenerated power	22750 kWh/day
reduction in savings	108 million Btu/day
net savings	426 million Btu/day
or	5.0% of energy consumed.

Figure 3-20

Sulfite Mill, Situation 3-2 and 3-b



SULFITE MILL

Situation 3-a (Figure 3-20)

no cogeneration

waste heat stream:	evaporator vapor condensate 3,841,000 lbs/day @ 200 °F
acceptor stream 1:	boiler feed make-up water 1,847,300 lbs/day @ 65 °F
acceptor stream 2:	water for bleach plant 37,408,000 lbs/day @ 65 °F

heat transferred to acceptor stream 1	186 million Btu/day
stream 2	248 million Btu/day
total	434 million Btu/day
fuel savings	620 million Btu/day
or	6.4% of energy consumed.

Situation 3-b

Same as 3-a, with cogeneration

Same as 3-a, with cogeneration

total heat transferred	434 million Btu/day
fuel savings	620 million Btu/day
reduction in cogenerated power	15480 kWh/day
reduction in savings	74 million Btu/day
net savings	546 Million Btu/day or 6.4% of energy consumed

CONCLUSION

Substantial amounts of energy can be saved by means of waste heat recovery, especially in chemical pulp and paper mills. Calculated savings for sample applications are in the order of 4 to 8 percent of total energy requirements. It is not clear, however, if these applications are economically feasible. The section on optimization of heat exchanger area may be used as a guide to determine feasibility in specific plant situations.

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CHAPTER IV

INDUSTRIES' ECONOMIC ANALYSIS OF ENERGY CONSERVATION PROJECTS

This chapter examines the economic criteria and decision processes used by firms to assess the merit of a particular energy conservation project. The goals of the economic criteria are discussed in relation to project selection and the value of the firm. Rate of return, payback period, and life cycle analysis are discussed and compared as alternative approaches to conservation project selection.

OVERVIEW

The six firms interviewed used variations on the payback and rate of return analysis methods for their economic analysis of potential energy conservation projects. Three firms used only the payback method in their analyses, two firms relied on the rate of return method, and one used both methods.[1]

In this chapter, economic analysis techniques are defined and compared for their project selection characteristics when management's objective is to maximize the firm's value. This analysis shows that the payback method often results in the rejection of projects which could raise the firm's value.

The principle of life cycle costing is presented in this chapter's last section. Our purpose in discussing life cycle costing and the other analytical methods of economic analysis is not to provide a comprehensive description of them, but instead to make general statements about their usefulness in analyses directed toward making informed decisions on project opportunities.[2]

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[1] More detailed information about these methods is contained in Chapter VI.

[2] Haley and Schall (1973), Mao (1969), Thueson, Fablycty, and Thueson (1977), and Weston and Brigham (1975) give more comprehensive treatments of these topics.

GOAL OF ECONOMIC ANALYSIS

Investment policy guides management in selecting between investment alternatives. The investment policy is assumed to be established to make best economic use of the capital resources available to the firm. "Best economic use" is defined as the use of capital funds in a way maximizing the value of the incremental cash flows from those funds. The cash flows are incremental in that they make a change to the firm's cash flow that would have occurred had there been no additional investment. By making the best economic use of available capital funds, management is acting in the owner's best interest because it is maximizing the firm's value resulting in the maximization of the value of the owner's income from the firm.

Value of the Firm and Project Selection

The firm's value equals the sum of the discounted present value of the firm's cash flow over the period it is in business. A mathematic representation of the firm's value (V) is

$$V = \sum_{t=1}^{T} \frac{C_t}{(1+k)^t} \qquad (1)$$

where T is the number of years the firm is in business, C_t is the cash flow in year t, and k is the cost of capital, expressed as a rate per period, for the firm. Incorporating the cost of capital term in the equation accounts for the time-value of future cash flows.[3]

Cash flow (C_F) in the year t is defined as the difference between cash income (X_t) and cash investments (I_t) in year t and can be expressed as

---

[3] The variable "k" is also referred to as the discount rate.

$$C_t = X_t - I_t \tag{2}$$

Cash income is the difference between cash revenues and expenses. Investment is the outlay for goods or services yielding future cash income.

If the firm's investment policy is to maximize the firm's value, then it is necessary to choose those projects whose present values are greater than zero. For example, consider a situation where a firm is only going to operate for one more year, assuming that all income occurs only at the year's end. Before making additional investments, the firm's value (V'), can be stated as

$$V' = X_o + \frac{X_1'}{(1+k)} \tag{3}$$

where X_o is the sum of the present cash income and X_1' is the sum of the present cash income (X_o) plus the discounted value of the year end cash income resulting from previous investments. In this case, cash flow equals cash income because no additional investment has yet been made.

Suppose a potential project requiring an investment (I_o) will cause an incremental change in the year-end cash income amounting to ΔX_1. Investing in the project will give the firm a new value (V) of

$$V = (X_o - I_o) + \frac{(X_1' + \Delta X_1)}{(1+k)} \tag{4}$$

The change in value ($V - V'$), equals:

$$\Delta V = \frac{\Delta X_1}{(1+k)} - I_o \tag{5}$$

In other words, the change in value from investing I_o is the discounted value of the incremental cash flow less the initial investment cost.

Expression (5) is the net present value of the investment (I_o). Thus, the change in the firm's value equals the net present value or net present worth of the project. The firm benefits by this investment if the change in value is greater than zero. This will be the case if the investment's net present value exceeds zero. Therefore, the decision rule in project selection is to select only those projects having a positive net present value. The net present value of a cost reduction project is also referred to as its life cycle savings.

Of course, cash flows from investments generally last over several periods, so that the net present value (PNV) of undertaking a multi-period project is

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+k)^t} - I_o \qquad (6)$$

where the cost of capital (k) is constant over the years of the project's life (n). As in the one period case shown above, a project is accepted if the NPV is greater than zero.

Analysis of Savings Streams From Energy Conservation Projects

There are two characteristics of a savings stream from an investment in an energy conservation project; both should be considered in any economic analysis. First, the savings will probably continue for many years because the project affects equipment or buildings with long service lives. One interviewed industrial cooperator said:

> In [the] paper process, [equipment life] tends to be a much longer term. You're installing something that's going to be used for 30 or 40 years.

Second, the cost savings will likely grow over the life of the project. Oil, coal and natural gas prices have been escalating at 29, 16, and 21 percent per year over the last few years in Wisconsin.[4] Although the energy savings from the project may remain the same, the cost savings will increase with the energy prices.

Payback Period Analysis

A project's payback is the length of time taken for the incremental cash flow created by the project to equal the investment cost. It is the answer to the question, "How long will it take before the project pays for itself?" The payback period can be represented mathematically as:

$$I_o = \sum_{t=1}^{n^*} \Delta C_t \qquad (7)$$

where n* equals the payback period. The project is acceptable if its payback period is less than the criterion. In the firms we interviewed, the payback criterion ranged from 1 to 4 years.

The payback period analysis has several advantages. First, the analysis is not time-consuming, nor does it require sophisticated forecasts of future income and costs. Second, it may be particularly useful in project selection when there is very rapid obsolescence in the investment. For example, rapid payback on computer systems should be expected because of the speed at which innovations enter the computer market. This particular advantage may not be so applicable to the food and paper industries, where the basic production technology is well established. Third, payback period analysis could be

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[4] See Chapter VI for fuller discussion of energy prices trends in Wisconsin.

useful in selecting projects when limited, short-term capital funds are used for the investments. In at least one firm, small conservation projects were often funded out of operating budgets. To avoid exceeding budget limits, the payback period had to be short, generally less than one year. Therefore, payback was an important factor in project selection.

There are several shortcomings, however, to the payback method. It ignores savings, or positive incremental cash flows, occurring beyond the payback period. This shortcoming biases project selection away from projects having increased savings over time and toward projects having a large savings in the initial years of the project's life. The payback method fails to take into account the time-value of money. This shortcoming biases project selection away from those projects with long-run savings. As a result of these shortcomings, payback analysis will not necessarily give proper guidance in choosing projects which will add to the firm's value.

Rate of Return Method

The rate of return method for economic analysis considers future savings and the time-value of money, thus overcoming the conceptual flaws of the payback period method. The rate of return method also can lead to project selection that increases the firm's value, because the rate of return method will cause selection of the same projects as the net present value method when there is a savings every year over the project's life. The rate of return method can produce different results, however, when used in selecting between two projects with different lives (Haley and Schall, 1973).

A project's rate of return is determined by finding the discount rate at which the net present value of the project is zero. That is, the following equation is solved for r:

$$0 = \sum_{t=1}^{n} \frac{\Delta C_t}{(1+r)^t} - I_o \qquad (8)$$

where r is the rate of return of the project. A project is selected if the rate of return is greater than the chosen criterion rate of return or hurdle rate. The firms we interviewed who employed rate of return analysis used 20 and 25 percent return criteria.

The rate of return method has advantages and disadvantages. The main advantage is that it can provide a way to make investment decisions which increase the firm's value. One disadvantage is that it requires long-term savings estimates to the end of the project's expected life. Another disadvantage is that there can be computational difficulties. For example, under certain circumstances, multiple rates of return are computed (Mao, 1969).

Comparison of the Payback and Rate of Return Methods

Since both methods of economic analysis are often used, we compared their project selection characteristics. First, we investigated the relationship of the rate of return over differing project lives for a given payback period. Second, for a given rate of return, we computed the payback period for projects of different lives. The results in both cases show that the payback period method can reject projects which could otherwise provide moderate to high rates of return for the firm.

Table 4-1 gives the rates of return equivalent to various payback periods when the savings is the same every year.[5] Any table entry is the rate of return for a project of specified life and payback. For example, a project with a 5 year life and a 2 year payback would yield a 41 percent rate of return. The results show that a project lasting longer than the payback period can yield a high return, as high as a 100 percent return for projects with a one year payback. In general, the maximum rate of return for long-lived projects with a constant savings, approximately equals the reciprocal of the payback period. For example, a two year payback criterion means that accepted projects with long lives must have a one-half or a 50 percent return.

Another interpretation of the numbers in the table is that they are the minimum acceptable rates of return for a project with the specified life and payback. In the previous example, projects with 5 year lives must have returns exceeding 41 percent to be acceptable under a 2 year payback period criterion. Projects lasting longer than 10 years and with rates of return less than 31 percent would be unacceptable under a 3 year payback criterion. Table 4-1 shows that a project with a constant savings and a 20 percent return will be rejected in almost every case examined where its life exceeded its payback.

Tables 4-2 and 4-3 give the values of the payback for projects with rate of returns 10 and 20 percent respectively over varying project lives. The tables give payback periods for projects with constant annual savings, for savings growing at 5 or 25 percent per year, and for savings growing at 5 or 25 percent of the first year's savings. In the last case, if the first year's savings was $1000, then the savings in the second year would be $1000 plus

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[5] Assuming constant savings over the life of the project is the same as assuming the energy savings and the energy prices remain unchanged.

Table 4-1

Rate of Return Equivalent[†] to Given Payback Period[**]

Project Life	Payback Period			
(Years)	1 year	2 years	3 years	4 years
1	0%			
2	62	0%		
3	84	23	0%	
4	93	35	13	0%
5	97	41	20	8
10	100	49	31	21
20	100	50	33	25

[†] Constant Annual Savings

**NOTE: All table entries are rounded to the nearest whole number.

Table 4-2

Payback Period Equivalent to a 10% Rate of Return

Project Life (Years)	Constant Annual Savings	Annual Savings Growing at the Compounded Rate		Annual Savings Growing By a Percentage of the First Years Savings	
		5%	25%	5%	25%
2	1.7	1.7	1.8	1.7	1.8
3	2.5	2.5	2.6	2.5	2.6
4	3.2	3.2	3.4	3.2	3.3
5	3.8	3.9	4.1	3.9	4.0
10	6.1	6.5	7.5	6.4	6.9
20	8.5	9.7	13.6	9.3	10.3

Table 4-3

Payback Period Equivalent to a 20% Rate of Return

Project Life (Years)	Constant Annual Savings	Annual Savings Growing at the Compounded Rate		Annual Savings Growing By a Percentage of the First Years Savings	
		5%	25%	5%	25%
2	1.5	1.5	1.6	1.5	1.6
3	2.1	2.1	2.2	2.1	2.2
4	2.6	2.6	2.8	2.6	2.8
5	3.0	3.1	3.4	4.1	3.3
10	4.2	4.5	5.6	4.5	5.0
20	4.9	5.5	8.9	5.4	6.2

$250. In the third year, the savings would be $1000 plus $500, and so forth. Referring to Table 4-3, a 10 year project with a 20 percent rate of return and a constant annual savings would have a payback of 4.2 years. If savings were growing at a compounded rate of 25 percent per year, then the payback would be 5.6 years.

Table 4-3 can be used to determine what projects with a 20 percent rate of return would be rejected by a certain payback period criterion. For example, all 20 percent return projects with lives greater than 5 years would be rejected by a payback period criterion of 3 years. All projects with lives of 3 years or greater are rejected by a 2 year payback criterion. In the worst case, a 1 year payback would reject all 20 percent return projects with lives greater than 1 year. Thus, concluded above, the payback period analysis is highly biased against long-lived projects.

Table 4-3 also shows that the payback method's bias increases against projects having increasing savings over time. A 20 percent return project with a life of 10 years would be acceptable under a 5 year payback criterion whereas a 20 percent return project with the same life, but with a savings growing at 25 percent per year, would not be accepted, even though in terms of their rates of return they are equivalent. Both would add value to the firm with a cost of capital of 15 percent, but the 5 year payback criterion would cause rejection of the project with growing savings. The results suggest that if a firm is trying to maximize its value, then the rate of return method is preferrable to payback analysis for project selection. Payback analysis could be somewhat meaningful only if the criterion payback varied with the project's life, the minimum required rate of return for the firm, and the pattern of the savings' growth.

In summary, this investigation shows that the payback period method of investment analysis has severe drawbacks when evaluating energy conservation projects. It tends not to afford selection of projects with long lives and increasing savings, two important characteristics of energy conservation projects. More generally, the method can cause rejection of projects which would otherwise add to the firm's value and benefit the firm's owners.

Project Selection Under Capital Budgeting

So far we have discussed the case where the firm considers projects individually, without concern for alternatives. As long as the project met the established criterion, it was acceptable. This approach must be modified when projects must be selected to maximize the firm's value under a capital budgeting constraint. In this case, the task is to select the best combination of projects maximizing the firm's value. The problem requires ranking potential project combinations and selecting the one that has the maximum value without requiring more capital than available.

One method of finding the optimum project combination is to use the net present value, or the rate of return method, to analyze all possible combinations. Under the net present value method, project combinations meeting the budget constraint with the highest net present value would be accepted. Using the rate of return method requires comparing each possible combination on an incremental basis to find the one yielding the highest return. Other analytical methods are possible, including linear programming, and are described by Haley and Schall (1973) and Mao (1969).

Payback analysis of the possible project combinations is not effective in selecting the value-maximizing combination. As discussed above, payback period analysis does not give a true indication of a project's value. Therefore, it cannot yield the best prioritization of investment opportunities.

Life Cycle Analysis

The purpose of using life cycle analysis as part of the evaluation of a potential conservation project is to estimate the present value of the various savings and costs over the project's life. Any project with positive life cycle savings adds value to the firm and should be undertaken.

Tables 4-4, 4-5, and 4-6 present a detailed description of a life cycle savings equation for an energy conservation project. Table 4-4 gives the basic components of the equation. Supplemental equations and definitions of variables are provided in Tables 4-5 and 4-6.

The basic equation for determining the life cycle savings has seven terms. The first three terms (fuel savings, depreciation and salvage value) add to the life cycle savings, whereas the last four terms (investment, operations and maintenance, miscellaneous, and property tax costs) reduce it. The terms accounting for annual savings and costs (terms 1, 2, 5, 6 and 7) are tax-adjusted by the effective marginal income tax rate (R). The initial investment cost (term 4) is reduced by the availability of investment and energy tax credits, R_i and R_e, respectively. We assume that the credits occur in the first year.

The discount rate (k) is the rate at which the firm could receive a return in the best alternative use of the funds it has available; that is, it represents the opportunity cost for the firm's capital. Without capital budgeting restrictions, this rate would be the firm's tax-adjusted, weighted average cost of capital defined in Table 4-6. This definition assumes that the cost of capital is composed of two parts, the cost of new debt and of

Table 4-4

Life Cycle Savings From Energy Conservation Projects

	Term	Description
	$LCS =$	Life Cycle Savings Equals
1)	$\sum_{t=1}^{n} \frac{Q_a \quad C_{F,t}(1-R)}{(1+k)^t}$	Tax Adjusted Fuel Savings
2)	$+ \sum_{t=1}^{n} \frac{(DEP)_t R}{(1+k)^t}$	Depreciation Tax Savings
3)	$+ \frac{SV}{(1+k)^n}$	Salvage Value
4)	$-I(1 - R_i - R_e)$	Initial Investment Cost Net of Tax Credits
5)	$- \sum_{t=1}^{n} \frac{(OM)_t(1-R)}{(1+k)^t}$	Tax Adjusted Operation and Maintenance Expenses
6)	$- \sum_{t=1}^{n} \frac{(MISC)_t(1-R)}{(1+k)^t}$	Tax Adjusted Miscellaneous Project Expenses
7)	$- \sum_{t=1}^{n} \frac{(AV)_t R_p (1-R)}{(1+k)^t}$	Property Tax Net of Federal Tax Deduction

equity. The tax adjustment (1-R) to the cost of new debt reflects the deductibility of interest on debt. With capital budgeting constraints, a higher discount rate would be used to reflect the marginal investment opportunities which must be foregone because of the capital shortage. It is assumed that the cost of capital is the same in every year of the project's life. This assumption can be relaxed merely by allowing k to vary each year.

Figure 4-5 gives supplemental equations providing the values of the appropriate terms in the basic life cycle equation. The assessed value (AV_t) for computing the property tax can be estimated as the inflation adjusted, book value of the project's assets. Alternative expressions for the assessed value may be needed to reflect local tax codes.

There are several methods for estimating future fuel savings and operations and maintenance costs as well as for determining annual depreciation; Figure 4-5 gives several methods for each. Escalating fuel savings, and operations and maintenance costs suggest the use of either the compounded or linear growth equations. Accelerated depreciation, using sum of the digits or double-declining balance depreciation methods, offers tax advantages over straight-line depreciation and, therefore, gives higher life cycle savings than does straight-line depreciation.

In summary, life cycle analysis can help the firm make economic use of its capital resources in maximizing its value. Life cycle analysis offers definite advantages over the payback method of economic analysis in that it includes all projected savings and costs over the project's life and takes into account the time-value of money whereas the payback method does neither. Since the firm's value is determined by the discounted value of its future cash flows, life cycle analysis is consistent with the objective of maximizing the value of a firm.

Table 4-5

Supplemental Equations for Determining Life Cycle Savings

	Equation		Description
1)	$(AV)_t = P\left[I - \sum_{m=1}^{t} (DEP)_m\right](1+h)^t$		Assessed Property Value
2)	$C_{F,t} = C_{F,1}$		Fuel Price in Year 1
	$C_{F,t}(1+f)^t$		Fuel Price with Compounded Growth
	$C_{F,1}[1+b(t-1)]$		Fuel Price with Linear Growth from Year 1.
3)	$(DEP)_t = (I-SV_d)/N_d$	$t \leq N_d$	Straight-line Depreciation
	$(I-SV_d)\frac{2(N_d-t+1)}{N_d(N_d+1)}$	$t \leq N_d$	Sum of the Digits Depreciation
	$\frac{2}{N_d}I\left(1-\frac{2}{N_d}\right)^{t-1}$	$t \leq N_d$	Double-Declining Balance Depreciation*
	0	$t > N_d$	Zero Depreciation After Depreciation Period N_d.
4)	$(OM)_t = (OM)_1$		Operations and Maintenence Cost in Year 1
	$(OM)_1(1+g)^t$		Operations and Maintenance Cost with Compounded Growth
	$(OM)_1[1+c(t-1)]$		Operations and Maintenance Cost with Linear Growth

* Year N_d depreciation must include an additional amount required to totally depreciate the asset.

Table 4-6

Definitions of Terms Used in Life-Cycle Savings Equations

Term	Definition
$(AV)_t$	Assessed property value in year t.
b	Annual linear growth rate of fuel price.
c	Annual linear growth rate of O & M costs.
$C_{F,t}$	Fuel price in year t ($/Million BTU).
$(DEP)_t$	Depreciation in year t.
f	Annual compounded growth rate of fuel price.
g	Annual compounded growth rate of O & M costs.
h	Annual inflation rate.
I	Initial investment costs
k	Weighted average cost of capital ($k = (1-R)r_D w_D + r_E w_E$).
$(MISC)_t$	Miscellaneous expenses in year t.
n	Project life in years.
N_d	Depreciation life of project.
$(OM)_t$	Operations and maintenance expense in year t.
P	Proportion of the project's inflation adjusted book value which is assessed a property tax.
Q_a	Actual annual energy savings (Million BTU).
r_D	Cost of new debt.
r_E	Cost of equity.
R	Effective marginal income tax rate ($R = R_f + R_f R_s$)
R_e	Energy tax credit rate.
R_i	Investment tax credit rate.
R_p	Property tax rate.
SV	Salvage value in year n.
SV_d	Salvage value in year N_d.
t	Particular year in project's life.
w_D	Proportion of bonded-indebtedness in firm's capital structure.
w_E	Proportion of equity in firm's capital structure.
$\sum_{t=1}^{n}$	Mathematical symbol meaning the sum from t=1 to t=n.

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CHAPTER V

INDUSTRIAL WASTE HEAT RECOVERY

Corporate or plant energy engineers appear often to avoid life cycle analysis because it is less transparent and convenient than alternatives such as payback analysis. This chapter presents a simple and convenient procedure for determining the economic feasibility of waste-heat recovery that incorporates the life cost evaluation methods discussed in Chapter IV. This procedure involves (1) determining if recovery of heat from various streams is cost effective, (2) determining whether a heat exchanger or heat pump is needed, and (3) determining the optimum size of the exchanger or heat pump to be used.

OVERVIEW

In industrial waste heat recovery, the thermal energy in a waste stream is recovered by transferring heat from the waste stream to an acceptor stream. If the temperature of the acceptor stream is lower than that of the waste stream, a conventional heat exchanger may be employed. If the temperature of the acceptor stream is higher than that of the waste stream, a heat pump may be used to pump heat from the lower to the higher temperature. Although it is always technically feasible to recover heat using either a heat exchanger or heat pump, it is not always cost effective to do so. The value of the energy saved must offset the cost of the equipment. In the case of heat pumps, the value of energy saved must also offset the operating costs of the heat pump.

Life cycle cost procedures are necessary for evaluating heat recovery systems. Expenditures for recovery devices occur at the present, but fuel savings occur in the future. While these savings increase due to fuel inflationary rises, their value today is offset because the savings are realized in the future. A life cycle cost analysis allows an accurate estimate of the costs and benefits of the heat recovery devices.

There are several general requirements necessary for heat recovery techniques to be cost effective. First, both waste and acceptor streams must be simultaneously available for many hours throughout the year. Second, temperature differences are important. In heat exchanger applications, larger temperature differences yield greater energy savings. In heat pump applications, however, smaller temperature differences allow higher heat pump coefficients of performance and are more cost effective. Third, the flow rates of both acceptor and waste streams should be comparable so the temperature changes of each are comparable. Finally, heat recovery techniques save heating fuel which is relatively low in cost. Because heat exchangers and heat pumps are relatively expensive, many heat recovery applications are not cost effective.

The following sections include procedures developed for evaluating the various heat recovery techniques. The first two procedures concern heat exchangers and the third applies to heat pumps. For each procedure, a worksheet is provided to allow the engineer to readily evaluate the techniques and determine fuel and economic savings.

In the first heat exchanger procedure (A), a generalized method of evaluating exchangers is developed. This introduces the concept of breakeven fuel cost; this is the fuel price below which no heat exchanger is cost effective. The procedure than allows determination of the optimum heat exchanger size. The method is more sophisticated that that needed by the practicing engineer interested only in specific applications. The second heat exchanger procedure (B) is a simplified version of the first, and allows a ready determination of the cost effectiveness of several exchangers. The third procedure (C) allows determination of cost effectiveness of heat pumps.

Each of these selection procedures was written to be a useful, stand-alone tool for the economic evaluation of either heat exchangers or heat pumps. It was anticipated that a plant engineer interested in evaluating an exchanger or heat pump for a specific application would be mainly interested in these sections of the report. These sections are self-contained for this purpose, and are divided into sections as follows.

A. Selection of Heat Recovery Heat Exchangers for Industrial Applications.

A.1 Procedure

A.2 Worksheet

A.3 Example Calculations

B. Simplified Procedure for Selection of Heat Recovery Heat Exchangers for Industrial Applications.

B.1 Procedure

B.2 Worksheet

B.3 Example Calculations

C. Selection of Heat Pumps for Industrial Applications.

C.1 Procedure

C. Worksheet

C.3 Example Calculations

A. SELECTION OF HEAT RECOVERY HEAT EXCHANGERS FOR INDUSTRIAL APPLICATIONS

This selection procedure gives the plant engineer an analytical tool with which to evaluate the economics of a given heat recovery application. From the limited contacts with industrial representatives, it appears that economical and operational optimization of a heat exchanger is entrusted mainly to the company manufacturing the exchanger. Thus whether this optimization is truly achieved for a particular project cannot be answered directly. It is hoped that this procedure and worksheet will allow the plant engineer to determine the feasibility of a heat exchanger for his application. The procedure could also be used to evaluate heat exchangers already in operation.

The procedure and worksheet are divided up into four parts: (1) data required, (2) evaluation of break-even fuel cost (C_F*),(3) evaluation of optimum heat exchanger size, and (4) life cycle savings for non-optimum heat heat exchangers. In Appendix B, the theory behind the optimization and the break-even fuel cost is developed.

A.1 Procedure

Data

The information required in this section concerns the application of a waste heat recovery heat exchanger. This includes flow and temperature information for the waste and acceptor streams, economic and performance parameters for the heat exchanger types under consideration, and economic parameters of the fuel that the exchanger would replace.

Application Thermal Parameters

The information required is the flow rate, specific heat, and inlet temperature for each stream. The maximum heat transfer is given by

$$Q_{max} = N\ C_{min}\ (T_{wi} - T_{pi}) \qquad (1)$$

where Q_{max} is the maximum heat transfer, N is the number of coincident hours for the streams per year, C_{min} is the smaller of the two values of the mass flow rate - specific heat product ($\dot{m}Cp$) for the acceptor and waste streams. T_{wi} is the temperature of the waste stream, and T_{pi} is the temperature of the acceptor stream. The actual heat transfer (Q_{act}) for any heat exchanger is given in terms of the heat exchanger effectiveness (ε)[1] as

$$Q_{act} = \varepsilon\ Q_{max} \qquad (2)$$

where ε is the ratio of the actual heat transferred (Q_{act}) to the maximum possible (Q_{max}).

Heat Exchanger Parameters

The information required here relates to the thermal performance and the cost of the types of heat exchanger under consideration. This facilitates selection of a heat exchanger appropriate to the heat recovery application.

The conductance (U) represents the total transfer coefficient for heat flow from one fluid to another. The conductance is assumed to be constant for a given heat exchanger geometry and to be independent of the exchanger's size. It is either obtained from the manufacturer or determined from data available.[1]

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[1] See Heat Transfer Principles, F. Kreith, for heat exchangers performance theory and methods for obtaining U from data.

The area on which the conductance is based may be any representative area (e.g., shell side area, frontal area).

The heat exchanger cost has been found to be generally a linear function of the area:

$$\text{Cost} = C_o + C_a A \tag{3}$$

where C_o is the base cost, C_a is the area dependent cost, and A is the area. The base cost (C_o) represents the costs of those items needed for all sizes of heat exchangers. This includes the cost of heat exchanger supports, piping, valves, and other materials that do not depend on heat exchanger size. The area dependent cost (C_a) is based on the same area as the conductance. To determine these two parameters several quotations on heat exchangers of different sizes may be obtained from a single manufacturer.

Application Economic Parameters

The parameters required in this section are specific to the application. Fuel cost (C_F) is the cost of delivered heat currently used to heat the process stream. The first parameter (P_1) is the present worth factor for the series of annual costs of fuel required to heat the process stream. It includes fuel escalation, taxes, and rate of return on capital:

$$P_1 = F(n,f,k)(1 \quad R) \tag{4}$$

where n is the number of years the heat exchanger is expected to last, f is the annual fuel inflation rate, k is the allowable rate of return on investment, and R is the combined state and federal tax rate. Given a constant fuel inflation rate (f), F(n,f,k) is given by:

$$\begin{aligned} F(n,f,k) &= \frac{1}{(k-f)}\left[1 - \left(\frac{1+f}{1+k}\right)^n\right] \qquad \text{if } f \neq k \\ &= \frac{n}{1+k} \qquad \text{if } f = k \end{aligned} \tag{5}$$

The second parameter (P_2) is the present worth of all owning costs. P_2 is close to unity. If tax credits are allowed, however, the value of P_2 is

$$P_2 = 1 - (tc) \tag{6}$$

where tc is the tax credit fraction.[3]

The life cycle savings (LCS) obtained by installing a given heat exchanger are given by

$$LCS = P_1\ C_F\ \varepsilon\ Q_{max} - P_2\ (C_o + C_a A) \tag{7}$$

The first term ($P_I\ C_F\ \varepsilon\ Q_{max}$) represents the present worth of the cost of fuel that would have been used in the boiler, while the second term [$P_2\ (C_o + C_a A)$] is the capital cost of installing a heat exchanger with a specified area (A). A positive value for LCS means a heat exchanger is cost effective.

Installation of a heat exchanger may increase plant maintenance costs, and these must be subtracted from the fuel savings. To do this, the additional annual maintenance costs should be estimated. These annual costs should be multiplied by a present worth factor equal to F(n,g,d)(1 - R), where g is the expected inflation rate for maintenance. Life cycle maintenance costs can then be subtracted from life cycle savings to more nearly reflect actual savings.

Break-Even Fuel Cost C_F^*

The general relationship between life cycle savings and heat exchanger area is illustrated in Figure 5-1 for three different values of fuel cost (C_F). For all fuel costs, life cycle savings are negative for small areas. In general, LCS increases with area, reaches a maximum, and then decreases. Beyond the

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[3] For an exact determination, see "Economic Evaluation and Optimization of Solar Heating Systems," M.J. Brandemuehl and W.A. Bechman, Solar Energy Journal, 1978.

Figure 5-1

Life Cycle Savings

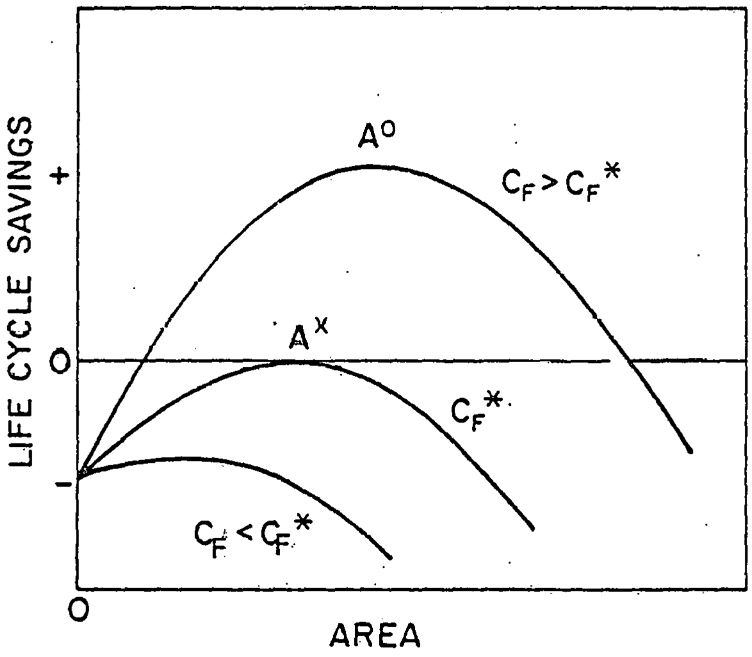
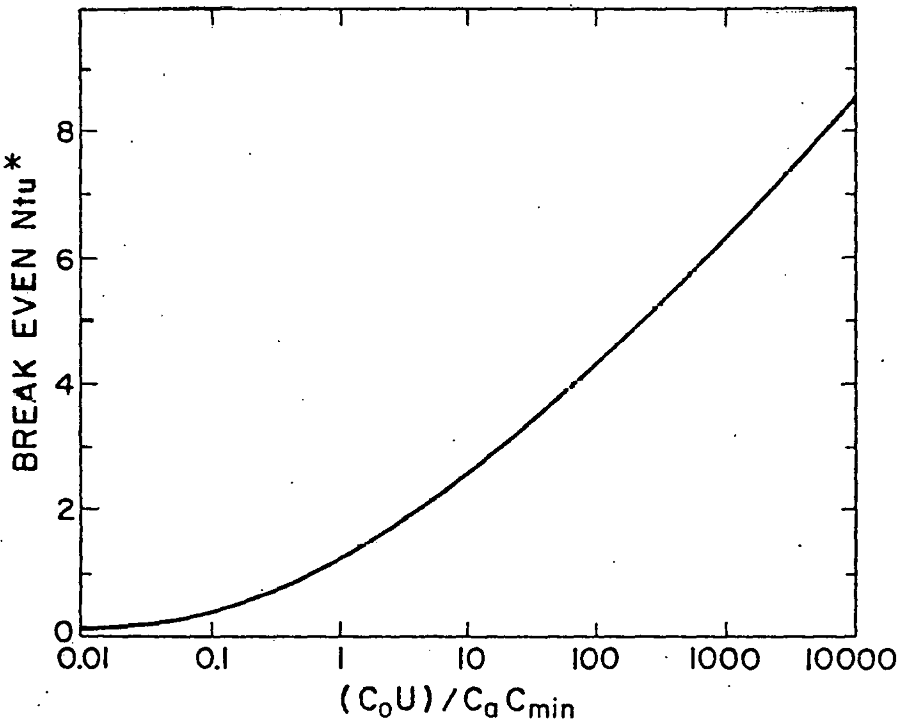


Figure 5-2

Break Even Ntu



maximum, the cost of added heat exchanger area does not produce proportionate savings.

There is one value of fuel cost C_F^* for which the optimum size exchanger (A^*) yields zero life cycle savings. At this fuel cost, there is no advantage of either the boiler or the heat exchanger over the other. If the actual fuel cost is less than C_F^*, it is cheaper to purchase fuel. If it is greater, a heat exchanger would produce savings. Thus, C_F^* can be used to determine whether any heat exchanger is cost effective.

The calculation of the break-even fuel cost includes several steps given in a section of the worksheet (p.130) and Figure 5-2. The number of transfer units, (Ntu^*), and corresponding area (A^*) represent the best type of heat exchanger (counterflow). These provide a measure of whether the best type of heat exchanger is cost effective. The effectiveness of this optimum heat exchanger for counterflow exchangers is given in Figure 5-4.

At the end of section 2.0 on the worksheet, C_F and C_F^* are compared. This allows determination of whether any heat exchanger would be cost effective in this application.

Optimum Heat Exchanger Area and Maximum Life Cycle Savings

If the actual fuel cost is greater than the break-even fuel cost, then there is an area for which the life cycle costs are maximum. Calculation of the optimum area can be found by following the steps in this section.

The optimum number of transfer units (Ntu°) depends on the particular type of heat exchanger selected. The selection is made using Figure 5-3 to determine the value of Ntu°. The effectiveness for the actual heat exchanger is given in Figure 5-4.

LIFE CYCLE SAVINGS FOR NON-OPTIMUM AREAS

The optimum area may not be one that is available from the manufacturer. The steps in this section allow determining the life cycle savings for non-optimum areas.

Figure 5-3

Optimum Ntu°

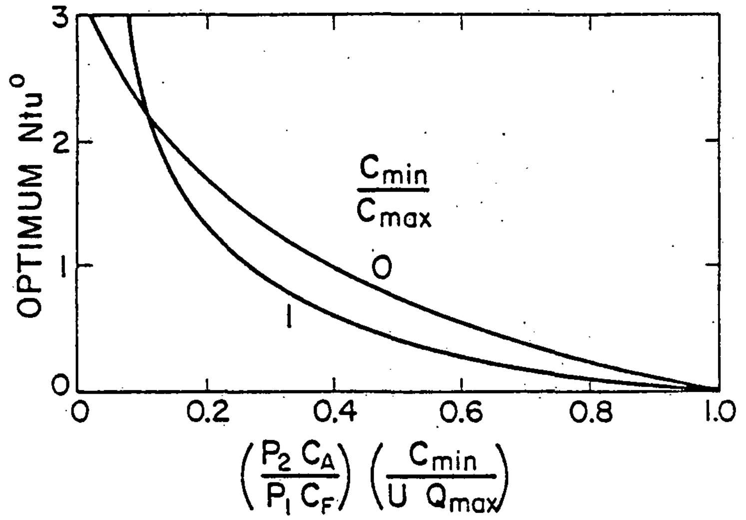
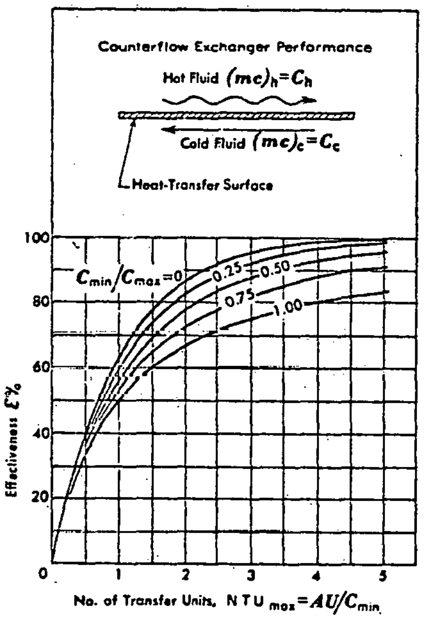
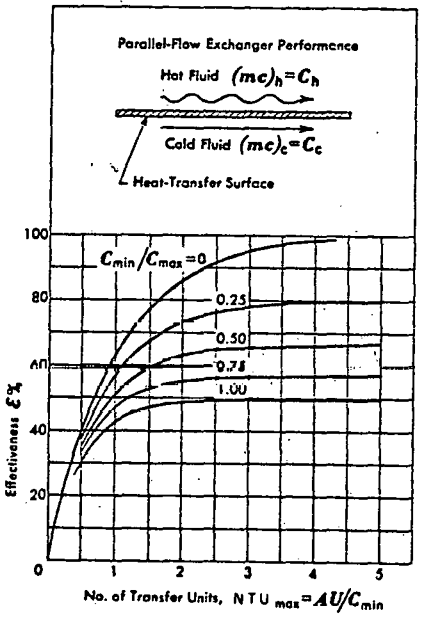


Figure 5-4

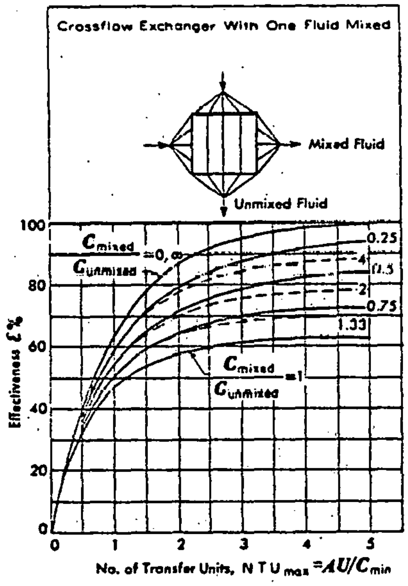
Heat Exchanger Performance†



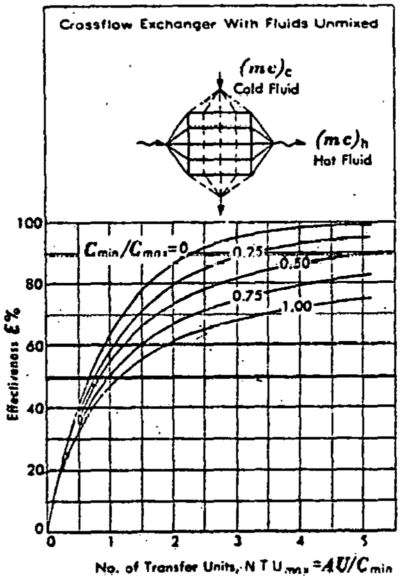
Heat transfer effetiveness as a function of number of transfer units and capacity rate ratio; counterflow exchanger.



Heat transfer effectiveness as a function of number of transfer units and capacity rate ratio; parallel-flow exchanger.



Heat transfer effectiveness as a function of number of transfer units and capacity rate ratio; crossflow exchanger with one fluid mixed.



Heat transfer effectiveness as a function of number of transfer units and capacity rate ratio; crossflow exchanger with fluids unmixed.

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† From Heat Transfer Principles, F. Kreith.

A.2 WORKSHEET FOR HEAT EXCHANGER EVALUATION, A

DATA REQUIRED

Application Thermal Parameters

Waste Stream: flow rate ($\dot{m}$) ______lbm/hr

specific heat (Cp) ______Btu/lbmF

capacitance rate ($C = \dot{m}Cp$) ______Btu/hrF

Inlet temperature (T_{wi}) ______F

Process Stream: flow rate ($\dot{m}$) ______lbm/hr

specific heat (Cp) ______Btu/lbmF

capacitance rate ($C = \dot{m}Cp$) ______Btu/hrF

Inlet temperature (T_{pi}) ______F

Number of coincident hours/year (N) ______hr

Minimum capacitance rate (C_{min}) ______Btu/hrF

Inlet temperature difference ($\Delta T=[T_{wi}-T_{pi}]$) ______F

Maximum heat transfer ($Q_{max} = NC_{min}\ \Delta T$) ______Btu

Heat Exchanger Parameters

Conductance (U) ______Btu/hr ft^{2}F

Base Cost (C_o) ______\$

Area dependent cost (C_a) ______\$/ft^2

Economic Parameters

Displaced fuel price (C_F) ______\$/Btu

Number of years of analysis (n) ______ yrs

Fuel inflation rate (f) ______ decimal

Allowable rate of return (k) ______ decimal

Combined tax rate (R) ______ decimal

Present worth of fuel costs (P_1) (See equation 4) ______ \$

Tax credit on investment (tc) ______ decimal

Present worth of owning costs (P_2) (See equation 6) ______ \$

BREAK-EVEN FUEL COST C_F^*

$C_o U/C_a C_{min}$ ______

Number of transfer units, N_{tu}^* (Figure 5-2) ______

Optimum area A^* ($A^* = N_{tu}^* C_{min}/U$) ______ ft^2

Optimum effectiveness ε^* (Figure 5-4) ______

Break-even fuel cost C_F^* ______ \$/Btu

$$C_F^* = \left(\frac{P_2 C_a}{P_1}\right) \left(\frac{A^* + C_o/C_a}{\varepsilon^* Q_{max}}\right)$$

Is C_F greater than C_F^*?

__________ If yes, heat exchanger is cost effective.

__________ If no, heat exchanger is not cost effective.

OPTIMUM AREA AND MAXIMUM LIFE CYCLE SAVINGS

$\frac{P_2 C_a}{P_1 C_F} \cdot \frac{C_{min}}{Q_{max} U}$ ______

Optimum number of transfer units N_{tu}° (Figure 5-3) ______

Optimum effectiveness ε° (Figure 5-4) ______

Optimum area A° ______ft^2

$(A^\circ = N^\circ_{tu}\ C_{min}/U)$

Life cycle fuel savings $P_1\ C_F\ \varepsilon^\circ Q_{max}$ ______\$

First costs $P_2\ (C_o + C_a A^\circ)$ ______\$

Life cycle savings (LCS = Fuel - First) ______\$

NON-OPTIMUM HEAT EXCHANGERS AREA

Area A	______ft^2	______ft^2	______ft^2
$N_{tu}(N_{tu} = AU/C_{min})$	______	______	______
ε (Figure 5-4)	______	______	______
Life cycle fuel costs $(P_1\ C_F\ \varepsilon\ Q_{max})$	______\$	______\$	______\$
Life cycle first costs $P_2(C_o + C_a\ A)$	______\$	______\$	______\$
Life cycle savings (Fuel-First Cost)	______\$	______\$	______\$

A.3 EXAMPLE CALCULATION

DATA REQUIRED

Application Parameters

Assume that there is a waste stream (water) flowing at 1000 gpm and 180°F, and it has been proposed that this stream could be used to preheat water entering at 500 gpm and 70°F. It has also been estimated that the waste stream is available for 100 hr per year. From this information the following thermal parameters can be calculated.

Waste Stream

$\dot{m}$ = 1000 gpm x 60 min/hr x .1337 ft^3/gal x 62.4 lbm/ft^3

= 500,600 lbm/hr

Cp = 1.00 Btu/lbm F

C = 1.00 x 500,6000 = 500,600 Btu/hr F

T_{wi} = 180°F

Process Stream

$\dot{m}$ = 500 gpm x 60 min/hr x .1337 ft^3/gal x 62.4 lbm/ft^3

= 250,300 lbm/hr

Cp = 1.00 Btu/lbm F

C = 1.00 x 250,300 Btu/hr F

T_{pi} = 70°F

N = 100 hr

C_{min} = 250,300 Btu/hr F

ΔT = 180°F - 70°F = 110°F

Q_{max} = 100 x 250,300 x 110 = 2.75×10^9 Btu/yr

Heat Exchanger Parameters

The heat exchanger type is a counterflow shell and tube exchanger. Data on the heat exchanger are tabulated below.

Tube Length (ft)	Surface Area (ft^2)	Cost ($)	Conductance (Btu/hr ft^2F)
1.5	158	5650	857
3.0	312	6850	853
4.5	475	8050	850
6.0	622	9250	848
7.5	790	10,400	847

An average value of the conductance (U) of 850 Btu/hr ft^2F will be used.

A plot of cost as a function of area yields a linear relationship. The data may be fit by eye or by least squares to the form.

$$\text{Cost} = Co + C_a A$$

For this exchanger,

$$Co = \$4480 \text{ and } C_a = \$7.55/ft^2$$

Economic Parameter

The cost of fuel currently used is assumed to be coal at a delivered heating price of $\$2/10^6$ Btu.

The economic parameter P_1 is evaluated assuming the life of the exchanger is 10 years, the acceptable rate of return or discount rate is 15 percent, the fuel inflation rate is 12 percent, and the tax rate is 45 percent. Then

$$F(10, 0.12, 0.15) = 7.74$$

$$P_1 = (1 - 0.45)\ 7.74 = 4.26$$

The allowable tax credit is 20 percent. The first cost present worth factor is then

$$P_2 = (1 - 0.20) = 0.80$$

BREAK-EVEN FUEL COST CALCULATIONS

$$\frac{C_o U}{C_a C_{min}} = \frac{\$4480 \left(850 \text{ Btu/hr ft}^2\text{F}\right)}{\$7.55/\text{ft} \left(250{,}300 \text{ Btu/hrF}\right)} = 2.02$$

From Figure 5-2, the optimum Ntu* is found to be 1.5.

The optimum area is calculated as

$$A^* = N^*_{tu} \; C_{min}/U = (1.5)(250{,}300)/850$$

$$= 442 \text{ ft}^2$$

The optimum effectiveness is from Figure 5-4. The capacitance ratio is 0.5 and the effectiveness at an Ntu of 1.5 is 0.68.

The break-even fuel cost is

$$C^*_F = \frac{(P_2 \; C_a)(A^* + C_o/C_a)}{P_1 \; \varepsilon^* \; Q_{max}} = \frac{(0.80)(\$7.55/\text{ft}^2)}{4.26} \; \frac{(442 + 4478.0/7.55)}{(0.68)(2.75 \times 10^9)}$$

$$= \$0.78/10^6 \text{ Btu}$$

Since C^*_F is less than the displaced fuel cost of $\$2/10^6$ Btu, the heat exchanger is cost effective.

OPTIMUM AREA AND LIFE CYCLE SAVINGS

The value of the optimum area parameter is calculated first:

$$\frac{P_2C_A}{P_1C_F} \; \frac{C_{min}}{Q_{max}\,U} = \frac{0.80\left(\$7.55/\text{ft}^2\right) \qquad 250{,}300 \text{ Btu/hr F}}{4.26(2 \times 10^{-6} \text{ \$/Btu})(2.75 \times 10^{9} \text{ Btu})(850 \text{ Btu/hrft}^2\text{F})}$$

$$= 0.076$$

From Figure 5-3, Ntu = 2.2

From Figure 5-4, the effectiveness of the exchanger is 0.79, and the optimum area is

$$A^\circ = \frac{N_{tu}\; C_{min}}{U} \quad \frac{2.2\;\left(250{,}300 \text{ Btu/hrF}\right)}{850 \text{ Btu/hrft}^2\text{F}} = 648 \text{ ft}^2$$

The life cycle fuel savings are

$$P_1C_F\,\varepsilon Q_{max} = 4.26\;(2 \times 10^{-6} \text{ \$/Btu})(0.79)(2.75 \times 10^{9} \text{ Btu})$$
$$= \$18{,}509$$

The first costs are $P_2\ (Co + C_a\ A) = 0.80(4478\$ + (7.55\$/\text{ft}^2)(648 \text{ ft}^2)$

$$= \$7396$$

The life cycle savings are \$18,509 - 7496 = \$11,013

HEAT EXCHANGERS OF NON-OPTIMUM AREA

The table in section 1.2 shows that only certain size heat exchangers can be purchased. The optimum heat exchanger area of 648 ft^2 is bracketed by the 6 and 7.5 ft. long units. The life cycle savings of each of these is calculated as shown on the work sheet. It is seen that both of the life cycle savings are very close to the optimum. Near the optimum size, the selection is not critical, and many alternatives will yield close to the optimum value.

EXAMPLE
WORKSHEET

DATA REQUIRED

Application Thermal Parameters

Waste Stream: flow rate ($\dot{m}$) 500,600 lbm/hr

specific heat (Cp) 1.0 Btu/lbmF

capacitance rate ($C = \dot{m}Cp$) 500,600 Btu/hrF

Inlet temperature (T_{wi}) 180 F

Process Stream: flow rate ($\dot{m}$) 250,300 lbm/hr

specific heat (Cp) 1.0 Btu/lbmF

capacitance rate ($C = \dot{m}Cp$) 250,300 Btu/hrF

Inlet temperature (T_{pi}) 70 F

Number of coincident hours/year (N) 100 hr

Minimum capacitance rate (C_{min}) 250,300 Btu/hrF

Inlet temperature difference ($\Delta T=[T_{wi}-T_{pi}]$) 110 F

Maximum heat transfer ($Q_{max} = NC_{min}\ \Delta T$) 2.75×10^{9} Btu

Heat Exchanger Parameters

Conductance (U) 850 Btu/hr ft^2F

Base Cost (C_o) 4,480 $

Area dependent cost (C_a) 7.55 $/$ft^2$

Economic Parameters

Displaced fuel price (C_F) 2.0×10^{-6} $/Btu

Number of years of analysis (n) 10

Fuel inflation rate (f) 0.12

Allowable rate of return (k) 0.15

Combined tax rate (R) 0.45

Present worth of fuel costs (P_1) 4.26
(See equation 4)

Tax credit on investment (tc) 0.20

Present worth of owning costs (P_2) 0.80
(See equation 6)

BREAK-EVEN FUEL COST C_F^*

$C_o\ U/C_a\ C_{min}$ 2.02

Number of transfer units, N_{tu}^* (Figure 5-2) 1.5

Optimum area A^* ($A^* = N_{tu}^*\ C_{min}/U$) 442 ft^2

Optimum effectiveness ε^* (Figure 5-4) 0.68

Break-even fuel cost C_F^* 0.78×10^{-6} \$/Btu

$$C_F^* = \left(\frac{P_2 C_a}{P_1}\right)\left(\frac{A^* + C_o/C_a}{\varepsilon^*\ Q_{max}}\right)$$

Is C_F greater than C_F^*?

X If yes, heat exchanger is cost effective.

If no, heat exchanger is not cost effective.

OPTIMUM AREA AND MAXIMUM LIFE CYCLE SAVINGS

$\frac{P_2 C_a}{P_1 C_F} \cdot \frac{C_{min}}{Q_{max}\ U}$ 0.076

Optimum number of transfer units N_{tu}° 2.2
(Figure 5-3)

Optimum effectiveness ε° (Figure 5-4) 0.79

Optimum area A° 648 ft^2

$(A^\circ = N^\circ_{tu}\ C_{min}/U)$

Life cycle fuel savings $P_1\ C_F\ \varepsilon^\circ Q_{max}$ 18,509 \$

First costs $P_2\ (C_o + C_a A^\circ)$ 7,496 \$

Life cycle savings (LCS = Fuel - First) 11,013 \$

NON-OPTIMUM HEAT EXCHANGERS OF NON-OPTIMUM AREA

Area A	622 ft^2	790 ft^2	- ft^2
$N_{tu}(N_{tu} = AU/C_{min})$	2.11	2.69	-
ε (Figure 5-4)	0.77	0.82	-
Life cycle fuel costs $(P_1\ C_F\ \varepsilon\ Q_{max})$	18,041 \$	19,213 \$	- \$
Life cycle first costs $P_2(C_o + C_a\ A)$	7,400 \$	8,320 \$	- \$
Life cycle savings (Fuel-First Cost)	10,641 \$	10,893 \$	\$

B. SIMPLIFIED PROCEDURE FOR SELECTION OF HEAT-RECOVERY HEAT EXCHANGERS FOR INDUSTRIAL APPLICATIONS

This simplified selection procedure gives the plant engineer an analytical tool for evaluating the economics of a given heat recovery application. From the limited contacts with industrial representatives, it appears that the economic optimization of a heat exchanger is entrusted mainly to the company manufacturing the exchanger. Whether this optimization is truly achieved for a particular project cannot be answered directly. This procedure and worksheet allows the plant engineer to determine the feasibility of a heat exchanger for his application. The procedure could also be used to evaluate heat exchangers already in operation.

The procedure and worksheet are divided up into two parts. The first lists the data required for application. The second is the procedure required for determining that heat exchanger that produces maximum life cycle savings.

B.1 Procedure

Data

The information required in this section concerns the application of a waste-heat recovery heat exchanger. This includes flow and temperature information for the waste and process streams, economic and performance parameters for the heat exchanger types under consideration, and economic parameters of the fuel the exchanger would replace.

Application Thermal Parameters

The information required is the flow rate, specific heat, inlet temperature for each stream, and the number of coincident hours for the streams per year. This information is needed to determine the cost and performance of the heat exchangers that might be employed.

Application Economic Parameters

The parameters required in this section are specific to the application. Fuel cost (C_F) is the cost of delivered heat currently used to heat the process stream. The first parameter (P_1) is the present worth factor for the series of annual costs of fuel required to heat the process stream. It includes fuel escalation, taxes, and rate of return on capital:

$$P_1 = F(n, f, k)(1 - R) \tag{1}$$

where n is the number of years the heat exchanger is expected to last, f is the annual fuel inflation rate, k is the allowable rate of return on investment, and R is the combined state and federal tax rate. Given a constant fuel inflation rate (f), F(n, f, k) is given by:

$$F(n, f, k) = \frac{1}{k-f}\left[1 - (\frac{1+f}{1+k})^{n}\right] \qquad \text{if } f \neq k$$

$$= \frac{n}{1+k} \qquad \text{if } f = k$$

The second parameter (P_2) is the present worth of all owning costs. P_2 is close to unity. If tax credits are allowed, however, the value of P_2 is given by

$$P_2 = 1 - (tc)$$

where tc is tax credit fraction.[3]

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[3] For an exact determination, see "Economic Evaluation and Optimization of Solar Heating Systems," M.J. Brandemuehl and W.A. Bechman, Solar Energy Journal, 1978.

Heat Exchanger Parameters

The information required here is the performance and cost information on feasible heat exchangers. For a given application and heat exchanger type, many heat exchangers could be installed. It is important to pick the heat exchanger that is most cost effective for the given situation. This requires selecting several heat exchangers of differing sizes and determining their corresponding costs. Either the manufacturer's catalog information or a suppliers quotations may be used to obtain the heat transfer rate (q, Btu/hr) and the first cost.

Life Cycle Savings

The life cycle savings (LCS) obtained by installing a given heat exchanger are given by

$$LCS = P_1\, C_F\, N \cdot q - P_2\ (\text{First Cost})$$

The life cycle savings of the heat exchangers are then determined. The exchanger with the maximum value of savings is the most cost effective.

B.2 WORKSHEET FOR HEAT EXCHANGER EVALUATION, B

DATA REQUIRED

Application Thermal Parameters

Waste Stream: flow rate ($\dot{m}$) ______lbm/hr

specific heat (C_p) ______Btu/lbmF

Inlet temperature (T_{wi}) ______F

Process Stream: flow rate ($\dot{m}$) ______lbm/hr

specific heat (C_p) ______Btu/lbmF

Inlet temperature (T_{pi}) ______F

Number of coincident hours/year (N) ______hr

Economic Parameters

Displaced fuel price (C_F) ______$/Btu

Number of years of analysis (n) ______

Fuel inflation rate (f) ______

Allowable rate of return (k) ______

Combined tax rate (R) ______

Present worth of fuel costs (P_1) ______

Tax credit on investment (tc) ______

Present worth of owning costs (P_2) ______

Heat Exchanger Parameters

Heat transfer rate, q (Btu/hr) ______ ______ ______ ______

First Cost ($) ______ ______ ______ ______

LIFE CYCLE SAVINGS

Fuel savings, P_1 NC_f q $______ $______ $______ $______

First costs, P_2 (First) $______ $______ $______ $______

Savings, (Fuel) - (First) $______ $______ $______ $______

B.3 EXAMPLE CALCULATIONS

DATA REQUIRED

Application Parameters

Assume that there is a waste stream (water) flowing at 1000 gpm and 180°F, and it has been proposed that this stream could be used to preheat water entering at 500 gpm and 70°F. Also assume that the waste stream is estimated to be available for 100 hr per year. From this information, the following thermal parameters can be calculated.

Waste Stream

$\dot{m}$ = 1000 gpm x 60 min/hr x .1337 ft^3/gal x 62.4 lbm/ft^3

= 500,600 lbm/hr

C_p = 1.00 Btu/lbm F

T_{wi} = 180°F

Process Stream

$\dot{m}$ = 500 gpm x 60 min/hr x .1337 ft^3/gal x 62.4 lbm/ft^3

= 250,300 lbm/hr

C_p = 1.00 Btu/lbm F

T_{pi} = 70°F

N = 100 hr

Economic Parameters

The currently used fuel and its cost are assumed to be coal at a delivered heating price of \$2/10^6 Btu.

The length of the analysis will be 10 years. The fuel will be assumed to inflate at an annual rate of 12 percent. The acceptable rate of return is 15 percent, and the combined tax rate is 45 percent. Then

$$F(10, 0.12, 0.15) = 7.74$$

$$P_1 = (1-0.45)\ 7.74 = 4.26$$

The allowable tax credit is 20 percent. The first cost present worth factor P_2 is

$$P_2 = (1 - 0.20) = 0.80$$

1.3 Heat Exchanger Parameters

The heat exchanger is a counter flow shell and tube type. Quotations are obtained on four sizes of exchangers. These costs include installation of the unit.

LIFE CYCLE SAVINGS

The life cycle fuel and first costs are calculated, and then the life cycle savings. For the examples chosen, the smallest heat exchanger is not cost effective. Although energy is saved with this exchanger, there is an overall cost to the company. The third exchanger is the most cost effective. There is little difference, however, between the second, third, and fourth exchangers in terms of life cycle savings; all are essentially equal. The larger exchangers save more energy, but the added first costs nearly balance these savings.

DATA REQUIRED

Waste Stream: flow rate ($\dot{m}$) 500,000 lbm/hr

specific heat (C_p) 1.0 Btu/lbmF

Inlet temperature (T_{wi}) 180 F

Process Stream: flow rate ($\dot{m}$) 250,000 lbm/hr

specific heat (C_p) 1.0 Btu/lbmF

Inlet temperature (T_{pi}) 70 F

Number of coincident hours/year (N) 100 hr

Economic Parameters

Displaced fuel price (C_F) 2×10^{-6} \$/Btu

Number of years of analysis (n) 10

Fuel inflation rate (f) 0.12

Allowable rate of return (k) 0.15

Combined tax rate (R) 0.45

Present worth of fuel costs (P_1) 4.26

Tax credit on investment (tc) 0.20

Present worth of owning costs (P_2) 0.80

Heat Exchanger Parameters

Heat transfer rate, q (Btu/hr)	10.7×10^6	19.5×10^6	22.0×10^6	23.4×10^6
First Cost (\$)	11,600	16,000	18,500	20,000

LIFE CYCLE SAVINGS

Fuel savings, $P_1 N C_f q$	\$9116	\$16,614	\$18,744	\$19,937
First costs, P_2 (First)	\$9,280	\$12,800	\$14,800	\$16,000
Savings, (Fuel) - (First)	\$ -164	\$ 3,814	\$3,944	\$3,937

C. SELECTION OF HEAT PUMPS FOR INDUSTRIAL APPLICATIONS

This selection procedure gives the plant engineer an analytical tool for evaluating the economics of a given heat pump application. It is hoped that this procedure and the accompanying worksheet will allow the plant engineer to determine the economic feasibility of a heat pump in a given situation. The procedure can likewise be used to evaluate a heat pump currently in operation.

The basis of the selection process is described first. A worksheet is then presented that allows the economics of a heat pump application to be determined. An example is then presented to illustrate the method.

C.1 Procedure

Thermal Performance of Heat Pumps

Heat pumps have the potential for reclaiming energy from a waste stream and pumping this energy to a higher temperature process stream. The heat pump extracts the energy from the waste stream, which lowers its temperature. Through the work supplied to the heat pump compressor, energy is delivered to the process stream. The energy balance for the heat pump relates the heat absorbed in the evaporator (Q_{abs}), the work into the heat pump ($\dot{W}$), and the delivered energy (Q_{del}) by

$$Q_{del} = \dot{W} + Q_{abs} \tag{1}$$

The delivered energy is also termed the heat pump capacity (Cap). The heat pump coefficient of performance (COP) is defined as the ratio of the delivered energy to the work input (W):

$$COP = \frac{Cap}{\dot{W}} \tag{2}$$

The value of COP depends on the temperature difference between the waste and process streams; the value decreases as the difference increases. Values of COP range from 2 to 6 for commercially available heat pumps.

When used in a heating application, the energy delivered (Cap) equals the product of the process stream flow rate ($\dot{m}$), specific heat (C_p), and the difference between the outlet (T_o) and inlet (T_i) process stream temperature.

$$\text{Cap} = (\dot{m}\ C_p)(T_o - T_i) \tag{3}$$

The purchased energy required to deliver this heat is the work required. On an annual basis this can be evaluated as the capacity times the number of hours per year (N) that the waste and process streams are coincident and divided by the heat pump COP. The annual cost of this energy (C_{energy}) is the annual work times the cost of fuel (C_E) (usually electricity) used to drive the compressor.

$$C_{Energy} = C_E\ N\ \text{Cap}/\text{COP} \tag{4}$$

The heat pump replaces heating energy equal to the capacity of the heat pump times the number of hours it is used. The fuel that must be supplied equals the heating energy divided by the furnace efficiency (η_F). The cost of fuel displaced is the fuel energy times the cost of fuel (C_F), and is given by

$$C_{Heating} = C_F\ \text{Cap}\ N/\eta_F \tag{5}$$

Life Cycle Costs and Savings

A heat pump is cost effective if the life cycle savings of its application are positive. The life cycle savings is the difference, calculated in life cycle costs, between using conventional fuels and using a heat pump. These life cycle costs are the present worth of fuel and owning costs. The present worth factor (P_1) for a series of fuel payments that escalate at an annual fuel inflation rate (f) over a period of years (n), with an acceptable rate of return (k) and with a combined state and property tax rate (R), can be written as

$$P_1 = (1-R) \quad F(n,f,k) \tag{6}$$

where

$$F(n,f,k) = \frac{1}{(k-f)} \left[1 - \left(\frac{1+f}{1+k}\right)^n\right] \text{if } f \neq k$$

$$= \frac{n}{1+k} \qquad \text{if } f = k \tag{7}$$

The present worth factor (P_2) for the owning costs is a complicated function of economic parameters, but is usually close to unity. If tax credits are allowed, however, the value of P_2 is

$$P_2 = 1 - (tc) \tag{8}$$

where (tc) is the tax credit fraction.[4]

The life cycle conventional fuel costs are then given by

$$LCC_{\text{conv. fuel}} = P_1 \, C_F \, \text{Cap} \, N/\eta_F \tag{9}$$

---

[4] For more information on these parameters, see "Economic Evaluation and Optimization of Solar Energy Systems," M.J. Brandemuehl and W.A. Deckman, Solar Energy Journal, 1978.

The life cycle heat pump costs are

$$LCC_{\text{Heat Pump}} = P_1\ C_E\ N\ \text{Cap/COP} + P_2\ (\text{First Costs}) \qquad (10)$$

The life cycle savings become

$$LCS = P_1\ \text{Cap}\ N \left[\frac{C_F}{\eta_F} - \frac{C_E}{\text{COP}}\right] - P_2\ (\text{First costs}) \qquad (11)$$

Installing a heat pump may increase maintanance costs, and these must be subtracted from the fuel savings. To do this, additional annual maintenance costs should be estimated. These annual costs should be multiplied by a present worth factor [F(n,i,k)(1 - t)], where i is the expected maintenance inflation rate. This inflation rate (i) is probably close to the general inflation rate. The life cycle maintenance costs can then be subtracted from the life cycle savings to more nearly reflect actual savings.

A preliminary estimate of a heat pump's economic feasibility can be made. From equation (11), it can be seen that the life cycle savings will always be negative if the term

$$\frac{C_F}{\eta_F} - \frac{C_E}{\text{COP}} < 0 \qquad (12)$$

This provides a quick determination of whether to further consider a heat pump. The heat pump COP must be greater than the term $C_E \eta_F / C_F$. Even if the COP is greater than this value, a heat pump may not be cost effective unless the hours of operation and the heat delivered are sufficiently large.

Work Sheet

The work sheet aids in evaluating the heat pump's economic feasibility. It is divided into a series of sections relating to application, plant economics, heat pump parameters, and life cycle costs. These are described briefly.

Application Parameters

The information required is the flow rate, specific heat, inlet temperature of waste and process streams, and number of coincident hours each is available.

Economic Parameters

The information required here is the expected fuel inflation rate (f), the allowable rate of return on the energy saving investment (k), the number of years of the economic analysis (n), the income tax rate (R) and the tax credit (tc). These allow calculation of the present worth factors P_1 and P_2. Conventional fuel costs, (C_F), heating plant efficiency (η_F), and electricity cost (C_E) are also required.

Heat Pump Parameters

The information required here is found in the manufacturer's performance and price catalogs. For a given application, use of several heat pumps of different capacity will probably be possible. The COP and first cost will depend on the capacity.

Preliminary Feasibility

At this point, the preliminary economic feasibility of the heat pump can be obtained for each unit. The COP is compared to the group of parameters to determine if further consideration is warranted.

Life Cycle Savings

In this section, the life cycle savings of the heat pump are computed. If the savings are positive, the heat pump is cost effective. The heat pump with the largest savings is the best investment.

C.2 WORKSHEET FOR HEAT PUMP EVALUATION

Application Parameters

Process Stream: Flow rate ($\dot{m}$) ______ lbm/hr

Specific heat (C_p) ______ BTU/lbmF

Inlet temperature (T_i) ______ F

Waste Stream: Inlet temperature (T_w) ______ F

Number of coincident hours (N) ______ hr

Economic Parameters

Fuel inflation rate (f) ______ decimal

Allowable rate of return (k) ______ decimal

No. of years of analysis (n) ______ years

F (N,f,k) (See equation 7) ______

Combined state and federal tax rate (R) ______

P_1 (See equation 6) ______

Tax credit (tc) ______

P_2 (See equation 8) ______

Conventional fuel cost (C_F) ______ $/Btu

Conventional heating efficiency (η_F) ______

Electricity cost (C_E) ______ $/Btu

(¢/kWh)/341300)

Heat Pump Parameters

(Found on manufacturer's data sheets)

Capacity (Cap), Btu/hr (See equation 3) ______ ______ ______

COP (See equation 2) ______ ______ ______

First Cost, $ ______ ______ ______

Preliminary Feasibility

$C_E\ \eta_F/C_F$			

Is heat pump feasible? (Is COP greater than this value?)

Yes			
No			

Life Cycle Savings

Fuel Savings, $			

$$P_1 Cap\ N \left[\frac{C_F}{\eta F} - \frac{C_E}{COP}\right]$$

First Costs			
LCS, $			

C.3 EXAMPLE CALCULATIONS

This section carries out a sample calculation. A filled in worksheet is included to demonstrate the method of evaluation.

Application Parameters

It will be assumed for this example that a process stream of water at 100 gpm is needed at 130°F. There is available a waste stream of water at 90°F. Over the course of the year, there are 1500 hours of plant operation during which both the process and waste streams are flowing.

Economic Parameters

The fuel inflation rate will be taken to be 12 percent, the allowable rate of return on energy conserving investments is 15 percent, and the analysis will be carried out for a 10 year period. Then

$$F(10, 0.12, 0.15) = 7.74$$

The combined state and federal tax rate is 45 percent, then

$$P_1 = (1 - 0.45)\ 7.74 = 4.26$$

There will be a 20 percent tax credit allowed, and the first cost present worth factor (P_2) is

$$P_2 = 1 - 0.2 = 0.8$$

The fuel currently used will be fuel oil in a boiler at 70¢/gallon, or \$5.10 x 10^{-6}/Btu. The boiler efficiency is 81 percent.

Heat Pump Parameters

The heat pumps considered in this analysis are commercially available heat pumps. There are several units available in the temperature range of the application. These units range in heating capacity from 20 to 60 tons. Three units will be considered; they are given in section 4.3 of the work sheet. The nominal COP of the units is the same. The costs include installation.

Preliminary Estimate

The cost of electricity (C_E) is compared to the current cost of heating the flow (C_F/η_F). The parameter is

$$\frac{C_E \quad \eta_F}{C_F} = \frac{11.70 \times 10^{-6} \times 0.8}{5.10 \times 10^{-6}} = 1.83$$

The heat pump COP is 4.66. Since this is greater than 1.83, all of the heat pumps are less costly in terms of fuel use than conventional boilers. The use of a heat pump needs to be considered further to see if the fuel savings are greater than the first costs.

Life Cycle Savings

The life cycle fuel savings are given by the term

$$P_1 \text{ Cap } N \left[\frac{C_F}{\eta_F} - \frac{C_E}{\text{COP}} \right]$$

These values are listed for the three heat pumps. The first costs are then subtracted from the fuel savings to determine the life cycle savings.

Only the two largest heat pumps are cost effective. While the smallest heat pump does save fuel, the savings are not sufficient to balance the first costs. Of the two larger heat pumps, the largest capacity unit saves the most energy and money. The largest unit, however, may not always be the most cost effective. In some applications, a large capacity unit may either cool the waste stream down or heat the process stream up beyond the temperature limits of the heat pumps. This will reduce COP and capacity. The manufacturers catalog and rating procedure will have to be consulted.

EXAMPLE WORKSHEET FOR HEAT PUMP EVALUATION

Application Parameters

Process Stream: Flow rate ($\dot{m}$) 50,060 lbm/hr

Specific heat (C_p) 1.0 BTU/lbmF

Inlet temperature (T_i) 130 F

Waste Stream: Inlet temperature (T_w) 90 F

Number of coincident hours (N) 1500 hr

Economic Parameters

Fuel inflation rate (f) 0.12

Allowable rate of return (k) 0.15

No. of years of analysis (n) 10

F (N,f,k) (See equation 7) 7.74

Combined state and federal tax rate (R) 0.45

P_1 (See equation 6) 4.26

Tax credit (tc) 0.20

P_2 (See equation 8) 0.80

Conventional fuel cost (C_F) 5.1×10^{-6} \$/Btu

Conventional heating efficiency (η_F) 0.81

Electricity cost (C_E) 11.7×10^{-6} \$/Btu

(¢/kWh)/341300)

Heat Pump Parameters

(Found on manufacturer's data sheets)

Capacity (Cap), Btu/hr (See equation 3)	488,000	732,000	976,000
COP (See equation 2)	4.66	4.66	4.66
First Cost, \$	15,900	18,700	21,600

Preliminary Feasibility

$C_E \; \eta_F / C_F$	1.83	1.83	1.83
Is heat pump feasible? (Is COP greater than this value?)			
Yes	X	X	X
No			

Life Cycle Savings

Fuel Savings, $	12,050	18,075	24,100
$P_1 \mathrm{Cap}\; N \left[\frac{C_F}{\eta F} - \frac{C_E}{COP}\right]$			
First Costs	12,720	14,960	17,280
LCS, $	-670	3,115	6,820

CHAPTER VI

INSTITUTIONAL ASPECTS OF INDUSTRIAL ENERGY CONSERVATION

As well as the economic and technical factors discussed in earlier chapters, a firm's organization and objectives influence the adoption of energy conservation projects, including projects for recovering heat from low temperature waste streams. The organization determines who searches for project ideas, who evaluates their applicability, and who decides which ideas will be implemented. The firm's objectives affect the project approval criteria and motivate activities either aiding or deterring the firm's general conservation effort. Understanding these institutional aspects therefore facilitates a broad assessment of the market potential of waste-heat recovery systems.

This chapter first reviews the effect rising energy prices have had on a firm's motivation to seek conservation possibilities. It then outlines how the six firms respond to those ideas in organizing their own conservation activities. It next identifies the channels, or people searching for conservation ideas, and the sources they use. At this point particular emphasis is placed on the energy staffs hired to assist the firm in its conservation efforts. The chapter then describes the major characteristics of and participants in the evaluation and final decision processes. Finally, it gives the interviewees' list of barriers to the adoption of waste-heat recovery systems and a list of their recommendations of ways the state and federal government might promote the diffusion of waste-heat recovery projects.

OVERVIEW

To learn more about how these institutional features affect the adoption of energy conservation projects, we conducted on-site interviews with six firms, three each from the food and paper products industries. This chapter summarizes the results of those interviews.

A firm's energy conservation efforts are multifaceted, dealing with any aspect of its plant or operations offering the potential for energy efficiency improvements. Figure 6-1 is a matrix categorizing a firm's possible energy conservation actions. The matrix's columns identify areas of energy use.

Figure 6-1

Energy conservation possibility matrix

		Energy User		
		Existing Process Equipment (Old Technology)	New Process Equipment (Current Technology)	Non-process Equipment
Action Taken	Plant Improvements			
	Operation Improvements			

These end-uses are either equipment involved directly in production processes or equipment that provides the environmental support for those processes or for general operations. One person we interviewed called energy use by non-process equipment "background use" because it was for such purposes as lighting, heating, and ventilation, but not for production. Within the process equipment category, an additional distinction is made between energy conservation possibilities for existing process equipment and for new equipment using new process technologies. The high energy efficiency of new process equipment may offer greater energy savings than most conservation possibilities involving existing equipment, so investing in new process equipment is definitely an energy conservation possibility.

After identifying the energy users, the firm can make improvements in either operations or the plant itself to save energy. These categories are given in the rows of the Figure 6-1 matrix. Projects for recovering heat from waste streams are plant modifications and thus could affect any of the three energy users. An example of an operations improvement might be to re-examine the process requirements and determine if the equipment is adjusted to avoid unneeded energy use. Although such operational improvements are im-important for saving energy, this chapter emphasizes the effects of institutions on the adoption of plant energy conservation improvements.

The following interview summaries are organized to detail what we found to be the general flow of energy conservation ideas from inception to final project approval: this flow is represented in Figure 6-2. The first step in this flow is the idea search. We found that the interviewed firms rely in varying degrees on the six idea sources given in Figure 6-2. The next step in the flow is submitting the idea for evaluation. Submittal is generally

Figure 6-2

Steps in

intra-firm plant improvement idea flow

Sources:

Vendors
Consultants
Trade Publications
Personal Experience
Other Firms and Plants
Educational Meetings

Channels:

Energy Staff
Engineering
Management
Plant Personnel

Evaluators:

Energy Staff
Engineering
Plant Personnel
Quality Assurance

Decision-Makers:

Management
Board of Directors

done by the channel, or the person who made the idea search. This person is frequently someone from one of the groups listed in Figure 6-2. After the idea is introduced, it is carefully evaluated for technical feasibility and economic potential chiefly by the energy staff if there is one, the engineering staff, and the plant or division personnel. The final decision is then made by management, who weighs the evaluation results as well as their own judgments and perceptions of the idea's value to the firm.

ECONOMIC MOTIVATION FOR ENERGY CONSERVATION AND THE INDUSTRIAL RESPONSE

Energy Price Trends and Their Effect Upon Costs

Undoubtably, financial savings from lowered energy use is a major motivation for energy conservation investments. These savings are becoming more substantial than in the past due to the recent, high growth rates of energy prices. For example, between 1975 and 1979, the prices in Wisconsin of middle distillate oil and coal rose 29.4 percent and 15.9 percent, respectively. Between 1974 and 1979, natural gas prices increased 21.4 percent annually. On a per million BTU basis, the 1979 prices for #2 fuel oil, natural gas, coal, and electricity were approximately \$5.20, \$2.60, \$2.00 and \$8.00, respectively (Foell et al., 1980).

Rising prices affected total costs in the food and paper industries differently depending on each industry's energy mix and the proportion of total costs attributable to energy. The energy mix, however, is not the same in the two industries. In 1976, oil, gas, and coal comprised respectively 10, 69, and 2 percent of the total energy purchased in the Wisconsin food industry (Foell et. al., 1980). Thus, natural gas was the most important source of purchased energy. In the paper industry those figures were

9, 32 and 44 percent respectively for oil, gas, and coal purchases, so the paper industry is purchasing much more coal for their production processes than is the food industry. The remaining energy purchases are for electricity and other fuels such as wood and refuse. The portion of total energy purchases attributable to these energy sources was approximately the same for both industries. In the food and paper industries respectively, 13 and 11 percent of purchases went for electricity. Other fuel purchases amounted to about 6 and 5 percent of each industry's energy purchases.

Of course, the energy mix of these industries is in constant flux. They alter their mix for reasons such as the changing relative price advantages of one energy source over another, changing environmental regulations, and varying supply availability. Until 1975, electricity and gas purchases were increasing in proportion to all energy purchases. Most recently, however, the energy use trend in the food and paper industries has been toward increasing reliance on electricity and coal. (Foell et al., 1980).

Those firms consuming the higher priced fuels have a much higher economic incentive for conservation. One industry representative interviewed stated:

> I know that other companies very close to us and within the state might be on gas or oil with a much higher return on investment for a similar project than we do have on coal.

This particular staffer's company priced co-generated steam at $1.30 per million BTU's and found that

> When you're competing on an energy project (say for heat recovery at $1.30 per MMBTU) in this economy is ridiculous. There's no way you can match up the capital cost to justify it on that basis. For a guy burning oil, his ROI will come four times faster.

In some cases the prices have not yet risen sufficiently to justify conservation projects that are technically feasible. One energy staffer lamented

> Two projects . . . at least seven years old . . . still aren't making the economic criteria. We're practically cheating ourselves trying to say "isn't there some way we can make this thing work?"

In another case, a small firm has exhausted its conservation projects given the present prices. An engineer from that firm said,

> I am sure we've looked at all the higher level energy recovery sources. We've already got more low level energy than we can use, so it's not economically worth going after at this time. If the fuel price goes . . . it'll become economically feasible to recover it.

A second factor affecting the impact of rising energy prices on an industry's total costs is the proportion of total costs attributable to energy. The 1976 energy costs were about 1.1 and 5 percent of the value of shipments for the Wisconsin food and paper industries respectively (Foell, et al., 1980). Table 6-1 shows that the six cooperating firms had energy costs of about 1 percent of sales if they were in the food industry and 5 to 10 percent if they were in the paper industry. The paper industry is much more energy intensive than the food industry in terms of the share energy costs are of total costs; thus the paper industry's total costs are more affected by the energy price increases. This effect on the paper industry is mitigated somewhat by the paper industry's relatively high proportion of total energy purchases for coal, which has a lower price growth rate than oil or natural gas.

Industrial Response to the Rising Energy Prices

The fact that total energy use for the Wisconsin food and paper industries fell by 8 and 1.3 percent, respectively, between 1971 and 1976, while production rose, suggests that these industries have been successful in finding ways to conserve in the face of rising energy prices. As further

Table 6-1

Summary of Companies Participating in Workshops and Site Interviews

Company	Industry	Annual Sales (millions)	Number of Plants	Primary Energy Sources	Energy Cost as Proportion of Sales
A	Paper	30	2	Natural Gas	10%
B	Paper	400	9	Coal, hydro, and liquor	5%
C	Paper	70	2	Coal and hydro	NA
D	Food	1500	70	Natural Gas	1%
E	Food	80	7	Natural Gas	1%
F	Food	1000	9	Natural Gas and Coal	1%

evidence of this active concern for conservation, all six cooperating firms reported an increase in energy efficiency since the federal government's industry conservation program began in 1972. In this section, we examine the institutional ways the interviewed firms have promoted conservation.

Energy Staffs

In response to rising energy prices, the larger firms have established energy staffs, people who spend a majority of their time seeking and promoting energy conservation opportunities. Large firms in both industries have such staffs. These people function either within the corporate engineering office or under corporate operations management. The largest energy staff had three members, with a fourth to be added shortly. All the energy staffers seemed to have technical backgrounds, most in engineering. Three firms interviewed had full-time energy staffs. A fourth smaller firm had added a utility engineer working half-time on energy matters for the assistant director of operations.

In contrast, most of the smaller firms we interviewed have not added personnel to fulfill energy conservation duties. For them, energy conservation is another of the many responsibilities their personnel must fulfill to keep the firm in business. As one engineer from a small firm described it,

> We have no official head of energy conservation or official program as such. The energy projects are handled like any other project.

The decision whether to locate the energy staff in the engineering or the operations side of the organization appears to depend on how much emphasis is placed on the plant personnel to improve their operational efficiency.

In a firm where operations personnel have the chief responsibility for organizing conservation activities, the person we interviewed said that his organization had given him the conservation responsibility because "we want energy conservation to be a line responsibility." His firm's conservation activity emphasizes operational improvements and coming up with ideas for plant improvements on existing equipment. On the other hand, firms with energy personnel within the engineering staffs appear to emphasize mainly plant improvements and, unless approached for advice, leave most operational improvement ideas to the operations personnel. From within the engineering staff, an energy staff would not have the authority to directly influence operations. This may explain why those energy staffs do not seem to spend much time on operational improvements. In a firm with energy personnel within the engineering staff, an energy staffer found that he had to be careful how he presented operation and even process equipment improvement suggestions. Because the responsibilities in those areas were organizationally separated from the engineering function, suggestions concerning operations or process equipment improvements could be misinterpreted as an intrusion into another's domain, thus causing undesired conflict between the energy staff and other personnel.

Energy Conservation Responsibilities at the Plant Level

For large and small firms alike, energy conservation responsibilities at the plants are additional duties. More than the smaller firms, however, the larger firms seem to have formalized these responsibilities. Most have individuals appointed as energy coordinators who are typically plant engineers, plant technologists, production supervisors, maintenance managers, or operations managers such as boilerhouse superintendents. In one instance, a firm has organized committees of additional personnel within a division as well as appointing a coordinator. These committees are composed of a key production person, technical and maintenance representatives, and department managers. They meet regularly to discuss energy conservation potentials within their areas, looking for both operations and plant improvement ideas.

Energy conservation activities within the divisions and plants of the firms we interviewed depended upon the conservation focus of top division and plant managements. One energy staffer stated that, at his firm, "All of the people at the plant report to the plant manager and the plant manager has the responsibility of energy conservation." The energy staffs thus seem to have little direct influence over the division or plant conservation programs. One energy staffer said, "We do not dictate how they [division managers] run their energy program." Consequently, the amount of time spent on conservation activity varies between divisions and plants within the same firm. In the words of one energy staffer, "Each [division] has a manager, and each one operates a little differently in his own realm."

Reporting Systems

Not only have the firms we interviewed hired energy staffs, assigned energy conservation responsibilities or increased staff time spent on energy conservation activities, but they have also set up reporting systems to track energy use. These reports both meet federal requirements and serve as management tools in the conservation effort. The energy staffs have the responsibility of coordinating the reports, although energy coordinators at the division or plant level often seem more involved in data gathering.

The statistics reported are, by and large, monthly aggregates for a particular plant or division and are sometimes adjusted to account for capacity utilization. The firms are reporting energy use in terms of the quantity of use per amount of product produced, for example, BTU's per pound or case.

Energy staffers differ on the question of whether to include costs in energy reports for management. One energy staffer who favored the use of costs said,

> I guess something we realized fairly soon, but probably not soon enough is that the best way to put all of these things is not to talk about millions of BTU's . . . but always dollars . . . I want to . . make it mandatory [to include costs in energy reports].

But another energy staffer prefers to use a BTU basis only for reporting, because doing so does not confuse real energy savings with rising energy prices.

The reports provide information on energy use at the plant level, but do not go into much detail beyond that, giving energy use neither for a particular product such as energy used per pound of peas, nor for a particular process such as energy used by the digestor in a pulp plant. Often the firms are not capable of detailed energy flow accounting largely because of the lack of energy use metering within the plants. The data for the reports are obtained from central metering, which does not permit determination of the energy flows to a particular process or piece of equipment. Older plants may not have sufficient metering because, when they were constructed, the need for detailed monitoring of energy flows was not as great as today. On the other hand, it can be difficult to track energy flows even with new installations that include submetering. One energy staffer noted that plant modifications after the new installation is operational sometimes destroy the submetering's effectiveness: "New installations are adequately metered, but you're really getting into a spider web of little heater lines not related to the process. . . ." The larger firms intended to add more meters within the plants to better quantify the process energy flows. None of the smaller firms, however, plan for such additional metering. As one person in a small firm said,

> We've got one gas meter [at each plant] and we don't meter any of our steam, so to have good controls on it [energy use] on an hour-to-hour, day-to-day basis. We've never felt justified in putting the investment [in more metering].

Energy Conservation Objectives and Managerial Incentives

At least three of the firms we interviewed have gone beyond merely reporting energy use at the plants; they have set energy savings objectives for division and plant managers. This appears to be an important move toward increasing division and plant energy conservation efforts, considering the discretion division and plant managers have over energy conservation activities within their area of responsibility.

A problem exists, however, in setting conservation objectives. There are variables beyond a manager's control which influence energy use, thus making it difficult, if not unfair, to hold managers strictly accountable for meeting the objectives. One variable influencing energy use is the product mix. A person from one firm stated:

> We've got them [the plant managers] involved in establishing energy objectives on a per case basis, but it is not the sort of thing that we can do a good job of controlling from day to day because our product mix varies from day to day.

A second variable is production level. Not only does energy use rise with higher production, but efficiency does also. Energy efficiency improves as production increases because plants have fixed and idle-time energy uses, so that the average energy use per production unit decreases as output increases. Many of the fixed energy uses relate to the non-process equipment--such as lighting, heating, ventilation--as well as to idle-time energy uses within the production process--such as bringing a boiler up to the temperature needed to begin production.

In any food or paper industry plant, the degree to which production relates to energy use will vary. The stronger the relationship, however, the less the plant manager can control total energy use, and the more an energy use objective would have to take into consideration the production level.

One interviewee from the food industry reported that his energy consumption went up half as fast as production; therefore, about 50 percent of this firm's energy use could be considered variable. Another person in the food industry believed that his firm's energy use was as much as 80 percent variable.

Since there are factors affecting energy use but beyond plant management's control, none of the firms have placed significant emphasis on meeting declared conservation objectives; however, one firm is moving toward a system where the plant manager's merit pay is based partially on an evaluation of how well energy conservation objectives are met. One energy staffer commented on this subject:

> We haven't found goals particularly effective because they're subject to so many variations. Our primary goal is just to make progress every year as compared to the previous year. If it's marginal, we try to pressure them [the division managers] to see if it could be increased, and if it's quite good, we give them a little pat on the back.

In another firm an interviewee said,

> Because of the problems . . . all we do is take a year end figure and say "What kind of an energy percentage do you feel you [the plant manager] could logically knock off?" . . . If you ask the plant people to give you an objective, the chances are that they will be tougher on themselves than you are, so I like to go by the principle that they establish their own objectives.

Regarding a critique of how well the manager had performed in meeting the objective, this interviewee said,

> It isn't that formal really, except that a plant manager has a certain set of standards that he is expected to perform against. He has an annual review and he covers each of these items.

The lack of sub-metering has several effects upon the success of a managerial incentive program incorporating energy conservation objectives. One effect is that without detailed information about the relationship between energy use and variables outside a manager's control, it is difficult to determine how well the manager is managing the variables within his control. A second effect is that the manager is less capable of monitoring energy flows within his plant. In turn, he is not able to establish measurable criterion for evaluating the plant personnel's performances. One energy staffer noted,

> It's one of the big problems of not having metering by function or production line. . . because there is no emphasis for the production supervisor to reduce his utility cost. It's all thrown in a big lump for the plant. It doesn't come out on his report cards.

The economics of energy also influences the incentives for conservation by division and plant management. In the case of the firm that had placed the cost of cogenerated steam at $1.30 per million BTU's, the energy staffer said,

> It [conservation] is left up to the divisions. The only conflicts or problems we have are in the styles of maybe just two division managers out of the bunch . . . . It's shown up in their performance. They're the lagging ones . . . . It might be easy, for instance, if they happened to be burning oil. They happen to be the divisions in which their steam is worth $1.30 or so. How hard can you pound on them to save energy if their energy by current standards is practically free? They certainly aren't capable of putting in the capital projects.

The smaller firms we interviewed do not use energy conservation objectives in their energy management activities. A person from a small firm said,

> I won't say that we have had a real specific goal . . . . I think the goal has been to cut our energy usage as much as we can practically do. We have a long way to go before we can reach that goal.

INTRA-FIRM IDEA CHANNELS AND THEIR SOURCES

Channels for Energy Conservation Ideas

We have seen in our site interviews that ideas for plant improvement benefitting energy conservation can come from a variety of people within the firm. The firm's engineering staff can be motivated to provide ideas by their exposure to the technical aspects of plant systems and because of their involvement in the design and renovation of those systems. Management can be motivated to bring ideas into the firm by their incentive to minimize costs wherever possible. Plant personnel can be motivated to generate ideas by their detailed knowledge of the particular plant or the equipment's operation. The final major group introducing new ideas is the energy staff specifically responsible for finding energy conservation ideas. Because of their particular responsibility in the energy conservation area, we will take a more detailed look at the ways the energy staff work for energy conservation.

The energy staff often learns of conservation ideas' applicability to their company through plant energy audits or surveys. One energy staffer described his work in this area:

> We also provide services to the plants, primarily in the form of energy surveys and analysis of conservation projects . . . . We provide advice on what's available, how much it's going to save them and we will also survey their plants, walk through to see where there are opportunities for savings and make recommendations.

Energy staffs also disseminate information helpful in conserving energy. One energy staff member said,

> We give [top management] reports and special studies. For instance, if there would be some advanced technology for some process to analyze in the energy area, we would provide them with reports or management summaries . . . .

The energy staffs must work closely with the plant personnel in assessing potential conservation ideas not only because the plant personnel have to approve the idea and work with any project done at their plant, but also because they are the persons most informed about the technical aspects of their plant. In one case, the energy staffer became involved in actually designing an energy project for a plant and reported that he had to work closely with plant personnel.

In general, the energy staffs do not do much detailed engineering on conservation projects; corporate or plant engineers do the detailed engineering, technical assessment, and design work. One energy staffer who designed a project found it unique that "it broke with past practices of dreaming up energy projects and writing them on sheets and sending them out and waiting for something to happen." In his case, however, he found the project very time-consuming and ended up focusing all of his attention on one plant for six to nine months; during this time little was done about energy conservation projects for other plants in his firm. His attitude now is one of trying to help plant personnel examine opportunities for conservation:

> The person at the plant level is tied up in a lot of other things. He has deadlines and worries. If we can help him organize so that no more can they come to us and say "Well, we want to do something but we don't know what to do." I want to give them something so that they will never be able to come back and say that.

He also tries to communicate to the plant personnel a "feeling for relative priorities" so that they just "don't go out and fix the leaking cold water faucets . . . ," but concentrate on projects with large energy saving potential.

One energy staff found it easier both to come up with plant improvement ideas and to gain the plant personnel's acceptance because he had worked in the plants before becoming an energy staff member:

> Two of us initially had been working in many of the activities and were familiar with them, sometimes in great detail. We can pick projects as well as they do. We probably tend to come up with more conceptual ideas for projects than individual decisions. We expect they will expand the applications, but we also check up on that.

Another energy staffer reported that he was getting involved in the actual design procedures for new plants and for major plant renovations to insure that energy conservation is considered in some depth in the design:

> We're trying to look at what we can be doing to really change our approach and our methods, not what are we going to . . . do next month. I feel very strongly that a lot of my time right now has to be invested in development of design and construction standards for the company as a whole. There's nothing like getting something included automatically everytime there is an expansion project or new construction and spending a lot of time on the initial design of the components.

When it comes to basic technological changes for the firm, cooperation of operations, maintenance, engineering and management personnel of the organization seems necessary to properly evaluate alternative technologies. For one firm, the energy staff has joined a committee of top corporate management, quality assurance, research and machine development personnel which is investigating methods for process improvements to insure that energy conservation is considered.

Sources

The people who are bringing energy conservation ideas into the firms are turning to a variety of sources for those ideas. These sources have differing degrees of perceived credibility and usefulness in the firm's energy conservation program. This section presents the predominant sources among the firms we interviewed.

The first major source of ideas is the equipment vendor. A small firm's engineer said,

> We make tremendous use of vendors because they have a wealth of knowledge about the equipment they sell that we will probably never have because they know their specific piece of equipment.

Of course, the people we interviewed realized that the goal of a vendor is to sell the product and not necessarily to do so in the firm's best interests. They also realized that the vendor was sometimes not perfectly familiar with the technical aspects of the firm's processes, and that this might result in an incorrect design. As a result, the vendor's work is carefully critiqued. One energy staffer said, "We give them a specification as to how much heat we want recovered and then we look at what they came out with. Another energy staffer noted that, "A lot of times they'll [vendors] fall flat on their face because they don't know what it's costing us for energy . . . ."

Some of the energy staffers mentioned during our interviews a need for independent testing of equipment vendor's claims concerning the savings potential of their products. They are looking for more certainty in the savings estimates for conservation projects, especially when the estimates come from vendors. Another energy staffer isn't as concerned about misleading claims by vendors. He said, "If you go to a reputable firm, they are there to help you because they want to repeat business."

A second source of ideas is the consultant. Consultants were reported to be used by large and small firms in identifying conservation projects. In some cases, consultants had performed energy audits which provided a project list serving as a basis for investment decisions. One energy staffer said that he liked to use consulting firms not because they gave him any new ideas, but because management seemed to accept their ideas more readily.

He said: "Within industry there's always a willingness to accept outside experts' testimony before you own people." If there is such a willingness, it does not seem to extend to all aspects of the firm's operations, particularly the process equipment. As one energy staffer put it,

> When it comes to analyzing our process and improving our techniques in that area-- there I don't think you want anybody outside. All you would be doing is educating them as to what you do anyway.

Thus, when it comes to their own process, the firms believe that they are their own best experts and do not want outside assistance. Along the same line, another interviewee stated,

> Energy conservation is a nuts and bolts operation. There isn't anything an outsider can do for you on that.

One firm who has frequently used consultants prefers consultants capable of following through on their recommendations and actually installing the specified equipment. The energy staffer from that firm said that doing so allows "more rapid implementation and development of our game plan . . . ."

Another important source of ideas is the experiences of people in other divisions within the firm. This source has a high degree of acceptability because not only is it from someone in the same organization, but it is also from someone who has practically installed and observed the performance of a particular project. One energy staffer said,

> An important corporate level function is conducting energy program meetings quarterly in which people share what they have done. If some program seems particularly successful, the person overseeing it would be encouraged to tell other divisions about it.

Trade magazines are also mentioned as a good source of ideas for plant energy conservation improvements. The publications mentioned during the interviews were Energy User News, Energy Plant Management, and Energy Manager. Of particular interest in these publications are, once again, examples of what other firms have done, how they did it, and how much was saved. Government publications were not mentioned as an idea source. One person interviewed said that government publications were too general to be of any specific use. Few of the energy staffs even seemed aware of state government reports on industrial energy use and conservation.

Other sources listed were seminars by Wisconsin Extension (a University program) and industry workshops on energy.

EVALUATION AND APPROVAL OF PLANT IMPROVEMENT PROJECTS

Technical and Economic Evaluations

All of the interviewed people reported that any plant improvement idea is given close evaluation on both technical and economic grounds before final approval is granted. Technical and economic evaluation procedures varied by company. The technical aspects of the idea seem to be most commonly reviewed by the plant personnel familiar with the details of how the idea would fit into their particular situation, by the engineering staff at the corporate level, and by the energy staff, if there was one. In one company, corporate engineering mainly involved itself with major technical projects, leaving divisions to do much of their own engineering for smaller projects. In smaller companies, the engineering staff was frequently contacted for advice, even on small projects. One exception is a firm having a utility engineer working in the operations division; in this case, the utility engineer was capable of designing and advising on those projects requiring a moderate amount of engineering. Projects requiring considerable time were given to the company's engineering department.

Economic evaluations were done by any number of people, depending upon the company. In some cases the person submitting the idea worked with the energy staff on the economic analysis. In one case, the engineering staff, with the energy staff's help, prepared economic details on the proposal. In another instance, an industrial engineering staff conducted the analysis after receiving the raw economic data from the submitter.

Table 6-2 summarizes the various economic analysis techniques described by the people interviewed. The table is broken down by (1) the technique, (2) the before- and after-tax acceptance criterion using that particular technique, (3) whether current or forecasted energy prices were used to project the energy cost savings over the economic analysis period, (4) a description of the price forecast used, if any, and (5) the length of the economic analysis period.

Only two analytical techniques were used: the payback period and rate of return methods.[1] With payback period analysis, the number of years taken until the amount of the cost savings equals the initial investment cost of a project is called the payback period. One year payback means that after one year, the cost savings will equal the initial cost. A project is accepted if its payback period is less than the criterion period.

The rate of return method determines the annual rate at which future savings must be discounted in order to give a project a net present value or

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[1] These methods are described in greater detail in Chapter IV.

Table 6-2

Summary of Economic Analysis Techniques Used by the 6 Firms Interviewed

Company	Analytical Technique	Before Tax Criterion	After Tax Criterion	Current or Forecasted Energy Prices?	Forecast	Economic Analysis Period
A	Payback Period	4-5	---	Current[††]	NA	NA
B	Rate of Return	---	25%	Gas Prices forecasted (in marginal cases only)	25% for gas over next 2 yrs	Project Life
C	Payback	1 year	2 years	Current[††]	NA	NA
D	Payback and Rate of Return (up to division)	2 years (payback) 25% (ROR)	---	Forecasted	10% per yr for next 5 years	5
E	Payback Period	3 years	---	Current	NA	NA
F	Rate of Return	---	20%	Forecasted	Inflation[†] plus 3½ percent, After '82, inflation plus 3%	Project Life

[†] 9 to 10% inflation rate assumed

[††] Qualitative consideration of future prices

worth equal to zero. The rate of return can be thought of in terms of a common loan with equal annual payments. The rate of return for such a loan is the interest rate at which, at the end of the loan's term, the amount of principle is zero. The rate of return criterion for acceptance is that the project's rate exceeds a particular selected criterion or hurdle rate.

For one large firm, there was no one standard analytical technique; the firm's divisions were given considerable discretion in project selection of projects costing less than $100,000. The decentralization of the company allowed each division to act as its own profit center and, therefore, to choose its own economic analytical technique for project selection. Consequently, both the payback and rate of return methods were used.

As can be seen from Table 6-2, the payback period acceptance criterion varied anywhere from 1 to 4 years and the rate of return criterion was either 20 or 25 percent. Whether the criterion was applied before- or after-tax also depended upon the company. For at least one firm, the payback period acceptance criterion depended upon the initial cost of the project; for smaller projects with payback periods of less than one year, it was possible to obtain funding almost immediately out of the annual operating budget rather than waiting for approval in the next year's capital budget. As a person from that firm put it, "We've been taking care of . . . energy projects on an expense basis." Only small, low payback period projects, however, could be handled this way.

When asked why payback analysis is preferred over life cycle analysis, interviewees in those firms using payback analysis gave several reasons. One reason given was that the firm had plenty of projects already meeting the payback criteria; their problem was a lack of capital investment funds. Another related reason, as mentioned earlier, was that the firm needed a short payback to stay within the operating budget. The last reason was that the interviewee believed that management did not really understand how life cycle cost analysis could be of value in evaluating projects.

Four of the six firms interviewed reported some attempt to account for higher future energy prices in their economic analysis. Two firms gave energy projects preference over other projects by using a longer payback period criterion than that used for non-energy conservation projects. In one of these firms, 4 years was used instead of the 2 to 2-and-one-half year criterion required of non-energy related projects; the second firm considered future cost savings as a qualitative factor in the project approval process.

Three firms, who happened to be the largest of the six firms interviewed, incorporated price forecasts into their economic analysis. No one source of the forecasts was named; the firms seemed to collect price information mainly from energy suppliers and then judge for themselves, based on their own cost trends, what was the most reasonable price forecast. One energy staffer reported that his firm used forcasted prices only when they believed that prices could be estimated with high accuracy and when the price increase was anticipated to be significant, exceeding 10 percent.

Uncertainty about future savings plays a role in preparing savings estimates by at least one energy staffer. He reported that he kept his estimates conservative, saying, "I'd say we're fortunate in that we've always been found to be conservative and I'm going to keep it that way." In his opinion, this was necessary not only to avoid over-estimating the savings, which would result in accepting an uneconomic project, but also to maintain the credibility of the energy staff's proposals.

Although treating all projects in the same manner, one firm selected its minimum rate of return at a level that hedged against the possibility that the actual savings from a project would be less than estimated. Thus, risk adjustments to the acceptance criterion is one way the firms are accounting for uncertainty in future cost savings.

The interviewees gave three reasons for not incorporating future price forecasts in their economic analyses. First, there was too much uncertainty about future prices. Second, time in a small firm was too constrained for personnel to get involved in estimating future prices. Finally, using future prices was unnecessary because it was only the shortage of capital that prevented approval of more energy conservation projects.

PROCEDURES AND CRITERIA FOR PROJECT APPROVAL

The method for project approval after technical and economic evaluations are completed is fairly similar in all the firms we interviewed. In general, projects with reasonably low initial costs are approved by the division management if the firm is large, or by the firm's president if the firm is small. Typically, projects exceeding $50,000 to $100,000 are approved by the Board of Directors after top management has accepted them.

Regarding capital funds availability, it generally seems that the low to moderately expensive projects with very good return or payback are readily fundable in most of the firms we interviewed. One energy staffer said that his firm has ample funding for such lucrative projects:

> [T]he company just has this big pool of money that is not budgeted for any specific use. If you get the return, you get the money.

A person from a small firm said,

> [N]one of our engineering projects are limited to funds. Everytime anybody has an idea that can save energy or save the company money, we aren't limited to wait until next year. We can go ahead with that project now if we can show that we have a payback. Why wait until next year to start saving money if we can do it now?

The budget for larger capital projects seem to be much tighter than for smaller ones. One interviewee said that when the time comes to review annual capital funds requests, "usually four times as much funding is requested as there is available."

The people we interviewed offered several factors that might be considered in the top management's final decision to approve a project. Economic criterion and technical evaluation appear to be the most important considerations in the final approval process. Favorable public relations from the conservation efforts was mentioned by one energy staffer as a factor in deciding to approve a project. Supply availability, especially of natural gas, was given as a factor in those projects involving conversion to alternative fuels. Substitution of capital for labor was also mentioned as a consideration, although it does not appear to have much relevance to decisions concerning recovery of heat from low temperature waste streams because recovery of that heat will not likely eliminate any labor.

A large percent of energy conservation project ideas are approved. Across five of the six firms participating in this study, a mean of 58 percent of project ideas considered over the last five years were approved and were either completed or are still under construction.[2] Of the remaining

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[2] One interviewee was not aware of the project idea statuses. Means are of reported percentages, so they may not equal the actual percentages of the total number of project ideas from all five firms.

projects, 38 percent were rejected because they did not meet economic criteria, 17 percent because they were not technically feasible, and 21 percent because they were inconsistent with corporate plans for plant utilization; 24 percent are still being evaluated. Thus, failure to meet economic criteria is the most frequent reason for disapproval of energy conservation projects.

REPORTED BARRIERS TO ADOPTING WASTE-HEAT RECOVERY PROJECTS AND RECOMMENDATIONS FOR GOVERNMENT INVOLVEMENT

Based on the interviews, a list was prepared of what seemed to be the most serious barriers to the adoption of low temperature, waste-heat recovery systems. Each interviewee was given the opportunity to indicate which barriers were applicable to his firm. The list and the breakdown of the interviewees' responses by industry are given in Table 6-3.

Barriers 1 through 3 pertain to the technical feasibility of low temperature, waste-heat recovery systems. Unless there are low temperature, waste streams available, unless those streams are accessible, and unless there are acceptor streams to use the recovered heat, these heat recovery systems will be of little use. Significantly, only one interviewee believed that the availability of waste-heat streams was a serious problem for his firm, and even then, this problem only existed in some divisions. Thus, almost all of the interviewees find low temperature waste-heat streams available for heat recovery systems.

The accessibility of waste-heat streams was a more serious problem; half the firms apparently have this problem. Diffuse waste streams or streams that are difficult to reach with a heat transfer system (piping or ducting) are only as inaccessible as economics dictate; therefore, the accessibility problem is not only technical, but also economic. Since the economics of con-

Table 6-3

Reported Most Serious Barriers to the Use of Heat Recovery Systems for Low Temperature Waste-Heat Streams†

Potential Barrier	Industry		
	Food	Paper	Total
1. Availability of streams for heat recovery	0	1	1
2. Accessibility of streams for heat recovery	2	1	3
3. Lack of acceptor streams for heat recovery	2	2	4
4. Lack of technical information on heat recovery methods	1	0	1
5. Lack of confidence in vendor's performance claims	1	0	1
6. Lack of information on how other firms have implemented these systems and on the savings they achieved	0	0	0
7. Lack of information about specific energy flows within the firm's plants	1	2	3
8. Lack of information about future energy prices	0	2	2
9. Lack of information about future energy supplies	0	0	0
10. Lack of capital funds	1	2	3
11. Failure to meet firm's economic return criteria	1	3	4

†Numbers in the table represent the number of firms reporting that the potential barrier was in fact an actual barrier for them. Multiple response is responsible. Firms interviewed included 3 from food industry and 3 from paper and pulp industry.

servation projects are influenced by many factors including energy prices, and economic evaluation methods, the seriousness of the accessibility barrier becomes temporal. As energy prices continue to rise, and evaluation methods evolve, accessibility problems should lessen.

Of the three technical feasibility barriers, the lack of acceptor streams was listed most often. This problem is common among firms in both industries, with two interviewees from each industry agreeing that it was a serious problem. Perhaps, as with the accessibility problem, economic factors enter into their assessment of the degree of severity. A more thorough discussion of this barrier along with the other technical feasibility problems was given in Chapters II and III of this report.

Barriers 4 through 9 relate to information deficiencies the interviewees have. The most frequently listed barrier concerned the lack of information about specific energy flows within the plants; one-half of the interviewees found it a serious problem. Lack of information about future energy prices was a barrier for two firms. One or no interviewees declared the other information-related barriers as serious problems.

Lack of capital funds and failure to meet the firm's economic return criteria, barriers 10 and 11, were among the most frequently listed barriers. Three interviewees found capital funding to be a barrier. Four interviewees listed failure to meet economic return criteria as a serious barrier. Real or perceived economic barriers are as common as the technical barriers when it comes to the industry's assessments of the opportunities for the adoption of low temperature waste-heat recovery systems.

The interviewees made the following recommendations of ways the government could help promote the diffusion of low temperature waste-heat recovery projects.

1. Sponsor local seminars. These would be especially helpful for smaller firms or even divisions of larger firms because they would provide an opportunity for plant personnel, who otherwise do not get the chance, to meet other people working on energy conservation or to attend educational sessions on available energy conservation technology.
2. Aid in verifying the truthfulness of equipment vendors' claims about their products' performance.
3. Organize case histories of other firms' work regarding recovery of low temperature waste heat.
4. Give low interest loans for energy-related equipment.
5. Maintain or increase the investment and energy tax credit.
6. Become more active in research efforts to discover ways to recover energy from waste materials.

References

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CHAPTER VII

SUMMARY AND FINAL OBSERVATIONS

The results of the study described in the preceding chapters demonstrate that a significant potential exists for recovery of low-temperature waste heat in the food and paper industries. However, the studies and interviews with the six collaborating firms have demonstrated that there are significant barriers, either real or perceived, to the implementation of this recovery. The predominant barriers identified by these firms are:

lack of information about energy flows in the plants,
lack or inaccessibility of acceptor streams for heat recovery, and
inadequate economic incentives or lack of capital funds.

A number of additional important barriers and concerns were expressed.

We believe that substantial parts of these barriers could be removed over time through the improvement of industry's information and through better understanding of the potential heat recovery. Our institutional and informational recommendations in this direction are discussed in this chapter. However, we cannot emphasize strongly enough the pre-eminence of economic criteria in heat-recovery evaluation and implementation. Although it is always technically feasible to recover heat using a heat exchanger or heat pump, it is not always cost effective to do so. The value of the energy saved must offset the cost of the recovery equipment. In the case of heat pumps, the value of energy saved must offset in addition the operation costs of the heat pumps.

There are several general requirements necessary for heat recovery techniques to be cost effective. First, both waste and acceptor streams must be simultaneously available for many hours throughout the year. Second, temperature differences are important. In heat exchanger applications, larger temperature differences yield greater energy savings. In heat pump applications, however, smaller temperature differences allow higher heat pump coefficients of performance and the heat pump is more cost effective. Third, the flow rates of both acceptor and waste streams should be comparable so the temperature change of each are comparable.

Because heat exchangers and heat pumps are relatively expensive, many heat-recovery applications are not cost effective. This importance of first costs of heat recovery equipment should be considered in establishing Research and Development strategies for waste-heat recovery technology. At the present time, it is not evident that the new heat-recovery technologies under development will have appreciable first-cost advantages over conventional equipment.

We have several observations about the economics and institutional implications of our study. One observation is that there is a need for a comprehensive guide to engineering and economic evaluation of energy conservation projects. Energy conservation projects must provide firms an economic benefit if they are to be implemented yet conservation projects often fail to meet minimum economic acceptance criteria. A majority of the interviewees said that insufficient economic justification is a major barrier to acceptance of waste-heat recovery projects. Although economic evaluations are important because of the significance they have in selecting worth-while projects, we have found firms using evaluation methods which do not highlight the real economic value of energy conservation projects. Likewise, some firms do not conduct engineering analyses which optimize energy savings potentials, thus causing the underestimation of achievable cost savings.

We believe that a comprehensive guide to conservation project evaluation would help firms reduce the time it takes to conduct such analyses and would explain to management the significance of those analyses. Both the lack of time for conducting and the inadequate understanding of life cycle cost analysis were given as reasons for not using that technique in their economic evaluations. A general procedure for estimating life cycle costs should be an integral part of the guide.

We believe that a guide would be helpful in promoting increased use of life cycle cost and optimization techniques. One food industry representative intended to apply those techniques after hearing about them in one of our workshops even though his firm had not used those techniques in the past.

A consequence of increased use of life cycle cost analysis is that firms will increase their interest in energy price and supply forecasts. It will become more important as a result to have these forecasts available. Since few firms have or use forecasts now, it seems that there will be a need for the state or federal governments to become more involved in preparing, disseminating, and updating such forecasts.

We observed that many firms need additional metering of their energy flows. Energy flows are commonly metered only at the supply source to the facility; consequently, there is often insufficient information on how energy is used by specific processes or equipment, and on how that use might vary depending upon product type and production level. The lack of energy flow information makes economic evaluation of potential projects difficult, inhibits the monitoring of equipment performance, and makes conservation objectives for operating personnel difficult to administer and enforce. Installation of additional metering could be improved with government financing.

Motivation for more metering could be increased through promotion in trade literature or energy conservation seminars, conferences or workshops.

We found that there is a continuing need for technical and economic information on low temperature, waste-heat recovery systems. Some interviewees viewed the lack of information about implemented systems, achieved savings, and consistency of equipment vendor's claims with actual performance as a serious barrier to adopting heat recovery projects in their firms. One interviewee felt that this is a particular problem for smaller firms and plant personnel of larger firms who frequently do not have the time or opportunity to gather information on energy conservation projects.

We believe that one way to meet these needs is through the use of in-depth case studies in which selected firms are given engineering analyses of potential and implemented conservation projects. A final report of such analyses could be widely distributed and concisely presented at regional information seminars. Firms not using outside engineering services could be shown through such studies the type and quality of engineering reports which can be produced to motivate them to contract for those services. At the same time, specific ideas of what has been and can be done in the way of conservation will be shared among interested firms. The studies could be conducted under total government funding or with cost sharing between the government and the cooperating firms.

Another observation is that smaller firms may benefit from direct technical assistance from outside agencies. The smaller firms tend not to have any staff for energy conservation program and project development. At the same time, they are not likely to be able to afford outside engineering services. Direct aide in either financing those services, or even the establishment of an office of technical assistance within state government offering qualified technical services, could be useful in helping smaller firms discover opportunities for energy conservation (such as with heat recovery systems).

A final observation is that detailed engineering and economic analyses on specific, potential applications for low temperature waste-heat recovery systems are the next logical step after our analyses in this study. Such follow-up analyses would be helpful in examining how economical particular installations would be in using streams that we believe will provide technically recoverable waste heat. The in-depth case study approach described above would be an excellent method for conducting these analyses.

APPENDIX A

SAMPLE CALCULATION OF POTENTIAL WASTE HEAT RECOVERY CHEESE PLANT
(See Figure 2-22)

Acceptor Stream

Boiler feedwater	15 lb feedwater/100 lb milk (cwt)

Waste Heat Streams

Whey	90 lb whey/cwt at 100°F
Clean-up	25 lb water/cwt at 140°F
Pasteurizer Overflow	1.3 lb water/cwt at 160°F
Boiler Blowdown	1.5 lb water/cwt at 335°F

Maximum Theoretical Recoverable Energy (MTRE)

$\text{MTRE} = \Sigma m_i \, Cp_i \, (T_i - T_r)$

where m_i = mass of waste heat stream (=) pounds/cwt

Cpi = heat capacity of waste stream i (=) BTI/lb °F

T_i = initial temperature of waste heat stream (=) °F

T_r = temperature of boiler feedwater (=) °F

Technically Feasible Recoverable Energy

Heat Balance $(m \, C_p \, \Delta T)_{cold} = (\dot{m} \, C_p \Delta T)_{hot}$

Exchanger efficiency $= 0.75 = \dfrac{(\dot{m} C_p \Delta T)_{\text{hot or cold stream}}}{(\dot{m} C_p)_{min} \, (T_{\text{hot in}} - T_{\text{cold in}})}$

Cascade the indirect recovery going from coldest to hotest waste heat stream

Situation I. no recycle (T_r = 60°F)
10% Blowdown
all compatable
no direct use

Whey

$$E = 0.75 = \frac{(m \, C_p \Delta T)_c}{(m \, C_p)_c (T_h - T_c)} = \frac{\Delta T_c}{(100-60)}$$

$\Delta T_c = 30°\text{F}$

$T_{\text{cold out}} = 60 + 30 = 90°\text{F}$

$(m \, C_p \Delta T)_{cold} = (m \, C_p \Delta T)_{hot}$

$(15)(1)(30) = (90)(1)(\Delta T_h)$

$\Delta T_h = 5°\text{F}$

$T_{\text{hot out}} = 100 - 5 = 95°\text{F}$

Energy Recovered $= (\dot{m} \, C_p \Delta T)_{hot} = (90)(1)(5) = 450 \ \dfrac{\text{BTU}}{\text{cwt}}$

Clean-up

$T_{cold\ in} = 90°F$

$E = 0.75 = \frac{\Delta T_c}{(140-90)}$

$\Delta T_c = 38°F$

$T_{cold\ out} = 90+38 = 128°F$

$(15)(1)(38) = (25)(1)\Delta T_h$

$\Delta T_h = 23°F$

$T_{hot\ out} = 140-23 = 117°F$

Energy Recovered $= (m\ C_p\Delta T)_{hot} = (25)(1)(23) = 580\ \frac{BTU}{cwt}$

Pasteurizer Overflow

$T_{cold\ in} = 128°F$

$E = 0.75 = \frac{\Delta T_h^{\dagger}}{160-128}$

$\Delta T_h = 24°F$

$T_{hot\ out} = 160-24 = 136°F$

$(1.3)(1)(24) = (15)(1)\Delta T_c$

$\Delta T_c = 2°F$

$T_{cold\ out} = 128+2 = 130°F$

Energy Recovered $= (m\ C_p\Delta T)_h = (1.3)(1)(24) = 31\ \frac{BTU}{cwt}$

†Note: Calculate ΔT_h because $(mC_p)_{hot} < (mC_p)_{cold}$

Blowdown

$T_{cold\ in} = 130°F$

$F = 0.75\ \frac{\Delta T_h}{(335-130)}$

$\Delta T_h = 154°F$

$T_{hot\ out} = 335 - 154 = 181°F$

$(1.5)(1)(154) = (15)(1)(\Delta T_c)$

$\Delta T_c = 15°F$

$T_{cold\ out} = 130 + 15 = 145°F$

Energy Recovered $= 231\ \frac{BTU}{cwt}$

$$\frac{\text{Total Recovered Energy}}{\text{MTRE}} = \frac{450+580+31+231}{(90)(1)(100-60)+(25)(1)(140-60)+(1.3)(1)(160-60)+(1.5)(1)(335-60)}$$

$$\left(\frac{\text{Recovered Energy}}{\text{MTRE}}\right)100 = \text{Percent Recoverable Energy} = 23\%$$

$$\text{Fraction of Boiler Feedwater Energy Input} = 1 - \left(\frac{hg/335\text{ F} - hf/T_{\text{cold out}}}{hg/335\text{ F} - hf/60\text{ F}}\right)$$

where h_g = enthalpy of water vapor (=) BTU/lb
h_f = enthalpy of liquid water (=) BTU/lb
(reference temperature 32°F)

$$\text{BFE }(\%) = \text{Boiler Feedwater Energy} = 1 - \left(\frac{1189 - 113}{1189 - 28}\right) 100$$

BFE (%) = 9.7%

Conversion Factors:

$$\frac{\text{BTU}}{\text{ton}} \times 1.16 = \frac{\text{KJ}}{\text{metric ton}}$$

$$\frac{\text{Pounds}}{\text{ton}} \times 0.23 = \frac{\text{KG}}{\text{metric ton}}$$

$$\frac{\text{Pounds}}{\text{CWT}} \times 0.45 = \frac{\text{KG}}{\text{cwt}}$$ CWT = 100 pounds weight

$$\frac{\text{BTU}}{\text{pound}} \times 2.3 = \frac{\text{KJ}}{\text{KG}}$$

APPENDIX B

CONDITIONS FOR OPTIMUM EXCHANGER SIZE AND BREAK-EVEN FUEL COST

In this appendix, the conditions for selection of the optimum heat exchanger size and for the break-even fuel cost will be developed. The life cycle savings (LCS) are given by

$$LCS = P_1 \, C_F \, \varepsilon \, Q_{max} - P_2 \, (Co + C_a \, A) \tag{A-1}$$

The maximum life cycle savings with respect to area are determined by the condition

$$\frac{\partial LCS}{\partial A} = P_1 \, C_F \, Q_{max} \frac{\partial \varepsilon}{\partial A} - P_2 \, C_a = 0 \tag{A-2}$$

or, at the optimum condition:

$$\left(\frac{\partial \varepsilon}{\partial A}\right)^{\circ} = \frac{P_2 \, C_a}{P_1 \, C_F \, Q_{max}} \tag{A-3}$$

The effectiveness of heat exchangers is given in terms of Ntu, C_{min}/C_{max}, and flow arrangement. These are shown graphically in Figure 5-4. Equation (A-3) can be rewritten as

$$\left(\frac{\partial \varepsilon}{\partial Ntu}\right)^{\circ} = \left(\frac{P_2 \, C_a}{P_1 \, C_F}\right)\left(\frac{C_{min}}{Q_{max} \, U}\right) \tag{A-4}$$

To facilitate the calculation, the value of $\left(\frac{\partial \varepsilon}{\partial Ntu}\right)^{\circ}$ was calculated for counter flow heat exchangers and plotted as a function of the group on the right hand side of equation (A-4). This graphical relation is given in Figure 5-3 with ε° as a function of the right hand side of equation (A-4).

The break-even fuel cost is given by the same condition as equation (A-4). In addition, as shown in Figure 5-1, the life cycle cost is also zero.

Equation (A-1) can be rewritten for LCS equal to zero as

$$\left(\frac{P_2}{P_1}\frac{C_a}{C_F}\right)\left(\frac{C_{min}}{Q_{max}\ U}\right)^{*} = \frac{\varepsilon^*}{\left(\frac{C_o\ U}{C_a\ C_{min}} + N_{tu}^*\right)} \tag{A-5}$$

Equating Equations (A-4) and (A-5) yields the break-even condition:

$$\left(\frac{\partial\varepsilon}{\partial N_{tu}}\right)^{*} = \frac{\varepsilon^*}{\left(\frac{C_o\ U}{C_a\ C_{min}} + N_{tu}^*\right)} \tag{A-6}$$

This condition was evaluated for the best heat exchanger type; this is the counter flow exchanger with C_{min}/C_{max} equal to zero. For this exchanger,

$$\varepsilon^* = 1 - e^{-Ntu^*} \tag{A-7}$$

This relation was used to eliminate ε^* in equation (A-6). Ntu* was then plotted against $(C_o\ U)/C_a\ C_{min})$ in Figure 2. This break-even fuel cost then represents the minimum fuel price that would allow using the best heat exchanger while still saving money.