55
5-29-80
pwa
ENERGY

DR. 1269

DOE/CS/40255-1

MASTER

POTENTIAL INDUSTRIAL APPLICATIONS FOR FLUIDIZED-BED
WASTE HEAT RECOVERY SYSTEMS

By
D. Cox
M. Lytton
C. Rao

December 1979

Work Performed Under Contract No. AC01-79CS40255

The MITRE Corporation
Metrek Division
McLean, Virginia

U. S. DEPARTMENT OF ENERGY

Division of Industrial Energy Conservation

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

"This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy \$13.00
Microfiche \$3.50

Potential Industrial Applications for Fluidized-Bed Waste Heat Recovery Systems

D. Cox
M. Lytton
C. Rao

MASTER

December 1979

MTR-79W00468

Sponsor: Department of Energy
Contract No.: DE-AC01-79CS40255

The MITRE Corporation
Metrek Division
1820 Dolley Madison Boulevard
McLean, Virginia 22102

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Kum

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ABSTRACT

The purpose of this study is to develop information on potential applications of Fluidized-Bed Waste Heat Recovery Systems (FWHRS) in U.S. industries that will assist the Department of Energy (DOE) in their decision to plan and participate in a demonstration project of the FWHRS. The study included a review of the literature and personal contacts (via telephone) with industry personnel with the objective to identify a limited number of applications. Technical and economic assessments for specific applications were accomplished by developing generalized design, performance and cost parameters that could be applied based on selected critical characteristics of each potential application of the FWHR system. Waste energy streams identified included flue gas and off-gas from boilers, furnaces and kilns. Utilization of the waste energy recovered included electric power generation, preheating combustion air and boiler feedwater, and drying. A course of action is recommended to the Department of Energy regarding generic users for demonstration projects.

ACKNOWLEDGEMENT

The authors wish to acknowledge the contributions of Joan Tahami in preparing the industry process and FWHRs application figures and providing editorial and production support.

TABLE OF CONTENTS

	<u>Page</u>
LIST OF ILLUSTRATIONS	ix
LIST OF TABLES	x
 1.0 SUMMARY	 1-1
2.0 INTRODUCTION	2-1
2.1 Background	2-1
2.2 Purpose and Objectives of Study	2-1
2.3 Scope of Study	2-2
2.4 Study Approach	2-2
 3.0 TECHNICAL AND ECONOMIC ASSESSMENT PARAMETERS	 3-1
3.1 Technical Assessment	3-1
3.1.1 Available Energy in Waste Streams	3-1
3.1.2 Service/Utilization	3-1
3.1.3 Industrial Process/Plant Factors	3-3
3.1.4 Energy Conservation Potential	3-4
3.1.5 Summary of Technical Feasibility Analysis	3-5
3.2 Economic Assessment	3-7
3.2.1 Equipment Costs	3-7
3.2.2 Installation Costs	3-9
3.2.3 Operating Costs	3-9
3.2.4 Costs Not Included in Assessment	3-9
3.2.5 Value of Fuel Saved by Heat Recovery	3-11
3.2.6 Payback Period	3-11
3.2.7 Factors Influencing Commercial Application of FWHRs	3-11
REFERENCES - TECHNICAL AND ECONOMIC ASSESSMENT PARAMETERS	3-14
 4.0 INDUSTRIES ANALYZED	 4-1
4.1 Preliminary Screening Criteria	4-1
4.1.1 Energy Consumption	4-1
4.1.2 Size of Industry -- Companies and Plants	4-1
4.1.3 Waste Energy Characteristics	4-2
4.1.4 FWHRs Application Within Industry and Potential for Other Industries	4-2
4.1.5 Industry Receptivity	4-3
4.1.6 Criteria Considered But Not Used for Preliminary Screening	4-3
4.2 Industries Screened	4-3
4.2.1 Initial Identification of Potential Industries	4-3
4.2.2 Industries Screened	4-4
4.3 Industry Selections from Screening	4-5

TABLE OF CONTENTS (Continued)

	<u>Page</u>
5.0 CEMENT INDUSTRY	5-1
5.1 Significance of Industry in U.S. Economy	5-1
5.2 Major U.S. Producers	5-2
5.3 Basic Process Description	5-6
5.4 Industry Waste Heat Production	5-6
5.4.1 Waste Heat Sources and Amounts	5-8
5.4.2 Current Waste Heat Recovery and Utilization	5-10
5.5 Potential FWHR Applications	5-11
5.6 Technical and Economic Assessment	5-13
5.6.1 Application #1: FWHR Using Preheater Bypass Gas	5-15
5.6.2 Application #2: FWHR Using Exhaust Gas Stream	5-15
5.6.3 Summary of FWHR Applications in Cement Industry	5-15
5.7 Summary of Industry Comments	5-22
5.7.1 Industry Comments	5-22
5.7.2 Industry Receptivity	5-23
REFERENCES - CEMENT INDUSTRY	5-24
 6.0 STEEL INDUSTRY	 6-1
6.1 Significance of Industry in U.S. Economy	6-1
6.2 Major U.S. Producers	6-1
6.3 Basic Process Description	6-3
6.4 Industry Waste Heat Production	6-8
6.4.1 Sources and Amounts	6-8
6.4.2 Current Recovery and Utilization	6-15
6.5 Potential FWHR Applications	6-15
6.6 Technical and Economic Assessment	6-16
6.6.1 Application #1: FWHR Using Flue Gas From Reheat Furnace With Recuperator	6-17
6.6.2 Application #2: FWHR Using Flue Gas From Reheat Furnace Without Recuperator	6-17
6.6.3 Summary of FWHR Applications in Steel Industry	6-17
6.7 Summary of Industry Comments	6-24
6.7.1 Industry Comments	6-24
6.7.2 Industry Receptivity	6-25
REFERENCES - STEEL INDUSTRY	6-26
 7.0 ALUMINUM INDUSTRY	 7-1
7.1 Significance of Industry in U.S. Economy	7-1
7.2 Major U.S. Producers	7-1
7.3 Basic Process Description	7-1
7.4 Industry Waste Heat Production	7-3
7.4.1 Sources and Amounts	7-3
7.4.2 Current Recovery and Utilization	7-7
7.5 Potential FWHR Applications	7-9

TABLE OF CONTENTS (Continued)

	<u>Page</u>
7.6 Technical and Economic Assessment	7-9
7.6.1 Application #1: FWHRs Using Flue Gas for Electric Power Generation	7-9
7.6.2 Application #2: FWHRs Using Flue Gas for Air Preheating	7-9
7.6.3 Summary of FWHRs Applications in Aluminum Industry	7-14
7.7 Summary of Industry Comments	7-14
7.7.1 Industry Comments	7-14
7.7.2 Industry Receptivity	7-14
REFERENCES - ALUMINUM INDUSTRY	7-17
8.0 HEAVY CRUDE OIL INDUSTRY	8-1
8.1 Significance of Industry in U.S. Economy	8-1
8.2 Major U.S. Producers	8-1
8.3 Basic Process Description	8-1
8.4 Industry Waste Heat Production	8-4
8.4.1 Source and Amount	8-4
8.4.2 Current Recovery and Utilization	8-6
8.5 Potential FWHRs Applications	8-6
8.6 Technical and Economic Assessment	8-7
8.6.1 Application #1: FWHRs Using Flue Gas for Boiler Feedwater Heating	8-7
8.6.2 Application #2: FWHRs Using Flue Gas for Combustion Air Preheating	8-11
8.6.3 Summary of FWHRs Applications in Heavy Crude Oil Recovery	8-11
8.7 Summary of Industry Comments	8-11
REFERENCES - HEAVY CRUDE OIL INDUSTRY	8-16
9.0 PETROLEUM REFINING INDUSTRY	9-1
9.1 Significance of Industry in U.S. Economy	9-1
9.2 Major U.S. Producers	9-1
9.3 Basic Process Description	9-3
9.4 Industry Waste Heat Production	9-5
9.4.1 Sources and Amounts	9-5
9.4.2 Current Recovery and Utilization	9-10
9.5 Potential FWHRs Applications	9-10
9.6 Technical and Economic Assessment	9-11
9.6.1 Applications #1 & #2: FWHRs Using FCC Regenerator Off-Gas	9-11
9.6.2 Summary of FWHRs Applications in Petroleum Refining Industry	9-16

TABLE OF CONTENTS (Continued)

	<u>Page</u>
9.7 Summary of Industry Comments	9-16
9.7.1 Industry Comments	9-16
9.7.2 Industry Receptivity	9-17
REFERENCES - PETROLEUM REFINING INDUSTRY	9-18
 10.0 CHEMICAL INDUSTRY	 10-1
10.1 Significance of Industry in U.S. Economy	10-1
10.2 Major U.S. Producers	10-1
10.3 Basic Process Description	10-3
10.4 Industry Waste Heat Production	10-5
10.4.1 Sources and Amounts	10-5
10.4.2 Current Waste Heat Recovery and Utilization	10-8
10.5 Potential FWHRs Applications	10-8
10.6 Technical and Economic Assessment	10-11
10.6.1 Application #1: FWHRs Using Flue Gas from Nodulizing Rock Kiln	10-11
10.6.2 Application #2: FWHRs Using Flue Gas from Fluidized-Bed Calciner	10-11
10.6.3 Summary of FWHRs Applications in Chemical (Phosphate Rock) Industry	10-18
10.7 Summary of Industry Comments	10-18
REFERENCES - CHEMICAL INDUSTRY	10-19
 11.0 STUDY RESULTS	 11-1
11.1 Characteristics of Potential FWHRs Applications	11-1
11.2 Technical and Economic Assessments	11-3
11.3 Waste Heat Recovery and Utilization Potential for FWHRs	11-6
 12.0 CONCLUSIONS AND RECOMMENDATIONS	 12-1
12.1 Conclusions	12-1
12.2 Recommendations	12-2
 APPENDICES	
A FWHRs TECHNICAL AND ECONOMIC PARAMETERS	A-1
B TECHNOLOGY STATUS FLUIDIZED-BED WASTE HEAT RECOVERY	B-1

LIST OF ILLUSTRATIONS

<u>Figure Number</u>		<u>Page</u>
3.1	Single-Stage FWHR System (Simplified Schematic)	3-2
3.2	Technical Feasibility of FWHR System	3-6
3.3	FWHRS Equipment Cost	3-8
5.1	Dry Process Cement Plant Schematic	5-7
5.2	FWHRS Using Bypass Gas Stream (Cement Plant)	5-16
5.3	FWHRS Using Exhaust Gas Stream (Cement Plant)	5-19
6.1	Steel Industry Process - Coal to Coke	6-4
6.2	Steel Industry Process - Steelmaking	6-6
6.3	FWHRS Using Reheat Furnace Flue Gas with Recuperator	6-18
6.4	FWHRS Using Reheat Furnace Flue Gas without Recuperator	6-21
7.1	Aluminum Plant Flowsheet	7-4
7.2	FWHRS Using Flue Gas for Power Generation (Aluminum Industry)	7-10
7.3	FWHRS Using Flue Gas for Combustion Air Preheating (Aluminum Industry)	7-13
8.1	Steam Generator for Heavy Crude Oil Recovery	8-5
8.2	FWHRS for Boiler Feedwater Heating (Heavy Crude Oil Recovery)	8-8
8.3	FWHRS for Air Preheating (Heavy Crude Oil Recovery)	8-12
9.1	Fluid Catalytic Cracking Flowsheet (Petroleum Refining)	9-4
9.2	FWHRS Using FCC Regenerator Flue Gas (Petroleum Refining)	9-12
10.1	Defluorinated Rock Process for Animal Feed Phosphorus Supplement	10-6
10.2	Nodulizing Phosphate Rock Process for Electric Furnace Phosphorus	10-7
10.3	FWHRS for Nodulizing Kiln (Chemical Industry)	10-12
10.4	FWHRS for Drying and Preheating Rock (Chemical Industry)	10-15

LIST OF TABLES

<u>Table Number</u>		<u>Page</u>
1.1	Summary of Potential FWHRs Applications in Six Industries	1-3
3.1	Comparison of Estimated Costs of Equipment for 10MW Steam Power Generation Plant	3-10
3.2	Fuel Costs and Savings from Heat Recovery	3-12
5.1	Cement Industry Production Capacity-1978	5-1
5.2	Cement Industry Sales and Revenue	5-2
5.3	Cement Industry Energy Consumption & Industrial Rank Compared to Major Industrial Energy Consumers	5-3
5.4	Energy Consumption, Efficiency and Sources in Cement Production	5-4
5.5	Top 13 Cement Companies	5-5
5.6	Energy Balances for Dry & Wet Process Cement Plants	5-9
5.7	Major Waste Heat Sources from Cement Plants	5-8
5.8	Cement Plants by Process & No. of Kilns	5-10
5.9	Cement Plant Profile by Age, Process & Capacity	5-11
5.10	Preheater Bypass Waste Heat Potential	5-12
5.11	Utilization of Preheater Waste Heat Recovery To Generate In-Plant Electric Power	5-14
5.12	Technical Assessment of FWHRs in Cement Industry Application #1 - Preheater Bypass Gas	5-17
5.13	Economic Assessment of FWHRs in Cement Industry Application #1 - Preheater Bypass Gas	5-18
5.14	Technical Assessment of FWHRs in Cement Industry Application #2 - Exhaust Gas Stream	5-20
5.15	Economic Assessment of FWHRs in Cement Industry Application #2 - Exhaust Gas Stream	5-21
6.1	Major U.S. Steel Producers	6-2
6.2	1978 Steel Industry Fuel Consumption	6-9
6.3	Coke Oven Typical Energy Balance	6-10
6.4	1978 Sources of Fuel Energy for the Steel Mill-Coke Oven Complex	6-11
6.5	Waste Energy Conservation Potential	6-12
6.6	Reheat Furnace Energy Consumption	6-13
6.7	Typical Dry Quench Coke Energy Balance	6-14
6.8	Technical Assessment of FWHRs in Steel Industry Application #1 - Flue Gas from Reheat Furnace with Recuperator	6-19
6.9	Economic Assessment of FWHRs in Steel Industry Application #1 - Flue Gas from Reheat Furnace with Recuperator	6-20

LIST OF TABLES (Continued)

	<u>Page</u>
6.10 Technical Assessment of FWHRs in Steel Industry Application #2 - Flue Gas from Reheat Furnace without Recuperator	6-22
6.11 Economic Assessment of FWHRs in Steel Industry Application #2 - Flue Gas from Reheat Furnace without Recuperator	6-23
7.1 1978 Major U.S. Primary Aluminum Producers	7-2
7.2 Energy Consumption-Primary Aluminum Producers	7-5
7.3 Energy Consumption According to Plant Operation	7-6
7.4 Typical Energy Consumption According to Operation	7-7
7.5 Technical Assessment of FWHRs in Aluminum Industry Application #1 - Flue Gas from Melt Furnace for Electric Power	7-11
7.6 Economic Assessment of FWHRs in Aluminum Industry Application #1 - Flue Gas from Melt Furnace for Electric Power	7-12
7.7 Technical Assessment of FWHRs in Aluminum Industry, Application #2 - Flue Gas from Melt Furnace for Combustion Air Preheating	7-15
7.8 Economic Assessment of FWHRs in Aluminum Industry Application #2 - Flue Gas from Melt Furnace for Combustion Air Preheating	7-16
8.1 Current Major Corporations Active in California Steam EOR	8-2
8.2 Technical Assessment of FWHRs in Heavy Crude Oil Recovery, Application #1 - Boiler Feedwater Heating	8-9
8.3 Economic Assessment of FWHRs in Heavy Crude Oil Recovery, Application #1 - Boiler Feedwater Heating	8-10
8.4 Technical Assessment of FWHRs in Heavy Crude Oil Recovery, Application #2 - Combustion Air Preheating	8-13
8.5 Economic Assessment of FWHRs in Heavy Crude Oil Recovery, Application #2 - Combustion Air Preheating	8-14
9.1 1978 Major U.S. Petroleum Refiners-Top 15	9-2
9.2 Fluid Catalytic Cracking Units in U.S.	9-7
9.3 Typical FCC Regenerator Operation Parameters	9-8
9.4 1979 Petroleum Refining Energy Requirements	9-9
9.5 Technical Assessment of FWHRs in Petroleum Refining Industry, Application #1 & 2 - Off-Gas from FCC Regenerator	9-13
9.6 Economic Assessment of FWHRs in Petroleum Refining Industry, Application #1 - Off-Gas from FCC Regenerator	9-14

LIST OF TABLES (Concluded)

<u>Table Number</u>		<u>Page</u>
9.7	Economic Assessment of FWHRs in Petroleum Refining Industry, Application #2 - Off-Gas from FCC Regenerator	9-15
10.1	1976 Chemical Industry Group Products Value & Energy Consumption	10-2
10.2	Defluorinated Phosphate Rock Producers	10-3
10.3	Nodulized Rock-Electric Furnace Phosphorus Producers	10-4
10.4	U.S. Production of Phosphate Rock - 1976	10-5
10.5	Typical Defluorinated Rock Calcining	10-9
10.6	Nodulized Phosphate Rock Operations	10-10
10.7	Technical Assessment of FWHRs in Chemical Industry, Application #1 - Nodulizing Rock Calciner	10-13
10.8	Economic Assessment of FWHRs in Chemical Industry, Application #1 - Nodulizing Rock Calciner	10-14
10.9	Technical Assessment of FWHRs in Chemical Industry, Application #2 - Defluorinated Rock Kiln	10-16
10.10	Economic Assessment of FWHRs in Chemical Industry, Application #2 - Defluorinated Rock Kiln	10-17
11.1	Characteristics of Potential FWHRs Applications	11-2
11.2	Summary of Technical and Economic Assessment	11-4
11.3	Waste Heat Recovery and Utilization Potential for FWHRs	11-7

1.0 SUMMARY

The Office of Industrial Programs in the Department of Energy (DOE)/Conservation is interested in identifying processes in U.S. industry for potential applications of fluidized-bed waste heat recovery systems (FWHRS). The FWHRS is an emerging technology that has potential advantages over conventional heat recovery equipment. These advantages include high heat transfer coefficient, uniform bed temperature with a rapid drop in inlet waste gas temperature which minimizes structural material problems, heat exchanger tube scrubbing from the bed material which minimizes fouling and an inherent thermal storage capability. The concept of an FWHRS was first commercialized in the United Kingdom in 1974 by Stone-Platt Fluidfire, Ltd. Recent advances in fluidized-bed combustion and, particularly, in fluidized-bed waste heat recovery indicate the FWHRS may be suitable for some industrial processes where waste energy streams are not being utilized.

The purpose of this study is to develop information on potential applications of FWHRS in U.S. industries that will assist the DOE in their decision to plan and participate in a demonstration project of the FWHRS. The objectives of the study include identifying specific processes in U.S. industries having waste heat gas streams which are not being utilized; evaluating the technical and economic feasibility of using an FWHRS; and recommending, if appropriate, potential uses of FWHRS where DOE's participation in a demonstration project appears justified on the basis of the potential national energy savings.

The study included a review of the literature and personal contacts (via telephone) with industry personnel with the objective to identify a limited number of applications. The technical and economic assessments were accomplished by developing generalized design, performance and cost parameters that could be applied based on selected critical characteristics of each potential application of the FWHR system.

All major industry groups were examined based on preliminary screening criteria including energy consumption, size of industry, waste energy characteristics, application diversity within and outside the specific industry, and industry receptivity.

The following industries were selected as having the greatest potential for FWHRS application based on waste heat recovery and utilization and industry receptivity.

- Cement Industry
- Steel Industry
- Primary Aluminum Industry

- Heavy Crude Oil Recovery Industry
- Petroleum Refining Industry
- Chemical Industry

In each industry, one or more waste heat sources were targeted and the recovery and utilization were evaluated with realistic reference to the specific industry requirements as disclosed in telephone interviews.

The applications for FWHRS in the six industries and the technical and economic assessments are summarized in Table 1.1. Waste energy streams identified included flue gas and off-gas from boilers, furnaces and kilns. Utilization of the waste energy recovered included electric power generation, preheating combustion air and boiler feedwater, and drying. The analysis of the six industries indicates that the FWHRS applications are technically and economically feasible and that the plant applications have widespread utility with in and outside the specific industries identified. The applications have favorable ratios of energy recovered to energy expended for the recovery, ranging from 2.8 to 26. Payback periods, ranging from 0.6 to 4.3 years, are within the usual industry economic standards.

Although the potential applications for FWHRS appear to be very attractive from the energy recovery and economic standpoint, design studies, including possibly additional R&D, may be required for some of these applications. FWHRS units are commercially available for relatively small industrial applications (20 million Btu/hour), although the performance of this technology has not been thoroughly established. Technical and economic data on scale-up of this technology is needed for widespread commercial applications in the large industrial processes identified in this study.

The potential waste heat that can be recovered and utilized by widespread application of FWHRS in the six industries identified is estimated to be 242 trillion Btus annually. This potential energy savings is based on an evaluation of each industry considering the number of plants available for retrofitting and industry operation practices.

Processes in the six industries were found to be highly suitable for FWHRS application. It is recommended that application of the FWHRS should be promoted in the six industries identified in this study, particularly the steel (furnace flue gas), cement (kiln gas) and the heavy crude oil (boiler flue gas) industries. A successful demonstration program of the FWHRS sponsored by the federal government should provide potential industrial users the confidence to use the fluidized-bed waste heat recovery system. The potential energy

TABLE 1.1
SUMMARY OF POTENTIAL FWHS APPLICATIONS IN SIX INDUSTRIES

INDUSTRY (Nominal Plant Size)	WASTE ENERGY STREAM	HEAT AVAILABLE FOR RECOVERY (Million Btu/Hr)	SERVICE APPLICATION	ENERGY CONSERVATION PARAMETER(2)*	SIMPLE PAYBACK PERIOD
CEMENT Application #1 (1700 Tons/Day)	Preheater Bypass Gas	27.4	Electric Power Generation	24	1.9
Application #2 (1700 Tons/Day)	Kiln Exhaust Gas	60.8	Electric Power Generation	19	3.2
STEEL Application #1 (250 Tons/Hr)	Flue Gas from Reheat Furnace With Recuperator	74.4	Electric Power Generation	13	2.5
Application #2 (250 Tons/Hr)	Flue Gas from Reheat Furnace Without Recuperator	140.4	Electric Power Generation	24	2.0
ALUMINUM Application #1 (90,000 Lbs. Cap)	Flue Gas from Melt Furnace	22.6	Electric Power Generation	22	2.1
Application #2 (90,000 Lbs. Cap)	Flue Gas from Melt Furnace	20.0	Combustion Air Preheating :	24	2.5
HEAVY CRUDE OIL Application #1 (50 MM Btu/Hr)	Flue Gas from Boiler	2.8	Boiler Feedwater Heating	8.1	4.3
Application #2 (50 MM Btu/Hr)	Flue Gas from Boiler	2.8	Combustion Air Preheating	2.8	
PETROLEUM REFINING Applications #1 (33,000 Bbl/Day)	Off-gas from FCC Regenerator	42.3	Steam Generation	19	1.1 0.6 **
CHEMICAL Application #1 (5,000 Tons/Day)	Flue Gas from Nodulizing Rock Calciner	38.0	Electric Power Generation	8	1.9
Application #2 (1,800 Tons/Day)	Flue Gas from Defluorinated Rock Kiln	41.6	Drying and Preheating Rock	26	0.7

*2 = Energy Recovered/Energy Expended for Recovery
**Uses Existing Balance of Steam Plant Equipment

savings and the industry receptivity justifies the federal government's promotion of FWHRs use in industry. Research and development also should be performed on advanced fluidized-bed waste heat recovery systems incorporating improved operational characteristics (i.e., active beds, larger capacities, different bed materials, and higher temperatures) to broaden their application in industry. The R&D efforts should emphasize making available technical and economic information necessary to enable equipment vendors to provide commercial FWHRs units with performance guarantees.

2.0 INTRODUCTION

2.1 Background

The current National Energy Plan (NEP-II) of the United States places major emphasis on energy conservation efforts to achieve the national energy goal of reduced dependence on imported oil. To meet this goal, the Department of Energy has major research, development and demonstration (R,D&D) programs in waste heat recovery and utilization. Many of these programs are directed at industrial processes since they are major energy consumers and thus, potential sources of major waste energy.

Heat recovery from waste energy streams has been practiced for many years in some industries. These industries were usually large installations where fuel savings would justify the capital investment in heat recovery equipment. However, with recent trends in fuel costs and advancements in heat recovery equipment, the applications for waste heat recovery equipment that are technically and economically viable have possibly broadened.

One advanced technology that has potential advantages over conventional heat recovery equipment is the fluidized-bed waste heat recovery system (FWHRS). This system was developed based on significant R&D over the past twenty years directed at heat transfer associated with fluidized-bed combustion. A considerable body of data exists that relates heat transfer to bed material and particle size, fluidizing velocity, air distributor/pressure drop and bed mixing, and heat exchanger configuration. The concept of an FWHRS system was first commercialized in the United Kingdom in 1974 by Stone-Platt Fluidfire Ltd. The unit, installed on a ceramic kiln, recovered heat from the kiln exhaust gases to provide low pressure steam used in heating water for office heating.

The recent advances in fluidized-bed combustion, particularly in fluidized-bed waste heat recovery, indicate the FWHRS system may be suitable for some industrial processes where waste energy streams are not being utilized. Because of this, the Office of Industrial Programs in the DOE/Conservation is interested in identifying potential applications in U.S. industry for FWHRS systems.

2.2 Purpose and Objectives of Study

The purpose of this study is to develop information on potential applications of the FWHRS in U.S. industries. This information will be provided to DOE to support their decision to plan and participate in a demonstration project of the FWHRS.

Objectives of the study are as follows:

- (1) Identify specific processes within U.S. industries that have potential use for waste heat recovery systems based on quantity of heat, temperature and pressure levels, and use of the recovered heat.
- (2) Evaluate the potential applications of FWHR systems based on their technical and economic feasibility and their potential energy savings.
- (3) Recommend, if appropriate, potential industrial users of FWHR systems, where DOE's participation in a demonstration project appears justified.

2.3 Scope of Study

This study included a review of the literature and personal contacts (via telephone) with industry personnel with the objective of identifying applications (three or four) that show the greatest potential for application of FWHR systems. Time did not permit an exhaustive literature search and only limited interviews with industry personnel were conducted since the study was performed over approximately a three-month period.

The technical and economical assessments were accomplished by developing generalized design, performance and cost parameters that could be applied based on selected critical characteristics of each potential application of the FWHR system. As such, these assessments do not reflect the site specific plant characteristics (e.g., space limitations) that may be critical in determining whether the FWHR is technical and economically viable.

2.4 Study Approach

The study approach to determine the potential applications for fluidized-bed waste heat recovery systems in U.S. industry consisted of the following:

- (1) A literature search and review identified industries for initial screening based on predetermined criteria.
- (2) Personnel responsible for plant operations and energy conservation in specific industries were contacted to obtain process characteristics, conservation practices and receptivity to participating in government-sponsored waste heat recovery projects.

- (3) Specific industrial process waste energy streams were analyzed to determine the technical feasibility and practicality of the potential FWHR system applications.
- (4) An economic assessment of those applications that appear to be technically feasible was performed to determine the net dollar savings and simple payback period to recover the capital investment.
- (5) Depending on the technical and economic assessments and the receptivity of specific industries, potential industrial users of FWHR systems are recommended where DOE's participation in a demonstration project appears justified.

Preliminary screening criteria used in the review of industry process information from literature sources and industry personnel interviews are delineated in Section 4.1. These criteria take into consideration the quantity of waste heat (thus potential total energy savings), temperature levels of waste energy streams, and compatibility of the recovered energy form with industry process/plant needs.

Contacts with industry personnel included persons working in executive positions and directly in plant operations; equipment vendors and engineer-contractors; and persons in the various trade associations. The persons in specific industries were generally high level executives responsible for plant operations and/or energy R&D and conservation programs.

The technical and economic assessments were made for typical waste energy streams and process/plant operations for specific industrial processes that met the initial screening criteria. These assessments were performed based on generalized design, performance and cost parameters derived for this study (see Section 3.0).

A course of action is recommended to DOE regarding the potential use of FWHR systems in various industrial processes and the desirability of DOE's participation in a demonstration project.

3.0 TECHNICAL AND ECONOMIC ASSESSMENT PARAMETERS

Heat recovery from waste streams is a common industrial practice; the examples include waste heat boilers, recuperators, economizers and air preheaters used extensively in various industries. The fluidized-bed waste heat recovery system (FWHRS), shown in Figure 3.1, uses a fluidized-bed to transfer heat from waste gas streams to a thermal fluid. A fluidized-bed provides a high heat transfer coefficient while maintaining a uniform temperature across the bed.

3.1 Technical Assessment

The technical feasibility of FWHRS application in an industry depends on the following factors:

- Available energy in waste stream
- Potential service utilization of recovered heat
- Industrial process/plant factors
- Energy conservation potential.

3.1.1 Available Energy in Waste Streams

The total sensible heat available per unit time depends on the mass flow rate, temperature (above a standard reference temperature), and specific heat of the waste stream. However, the available heat is the difference between total sensible heat and heat remaining in the exit gas stream from the stack. In this study, it was assumed that thermal properties of waste gas streams can be approximated by those of nitrogen, the principal constituent of industrial waste gas streams. Accordingly, the data for sensible heat of nitrogen, as shown in Clarke and Davidson⁽¹⁾, have been used to compute the sensible heat and available energy of the waste gas streams (Figures A.1 and A.2, Appendix A). Figure A.2 shows graphically the energy available in waste gas as a function of gas flow rate, waste gas temperature, and stack gas temperature.

3.1.2 Service/Utilization

The feasibility of waste heat recovery systems depends on finding a suitable application. In particular, temperature of the waste gas must be sufficient to meet the temperature requirements of some process/plant service. The temperature level of recovered heat depends on waste stream temperature and on heat exchanger design. If available at a high enough temperature, this heat can be used to produce steam for electric power generation; at a relatively low

FIGURE 3.1
SINGLE-STAGE FWHR SYSTEM
(SIMPLIFIED SCHEMATIC)

temperature, its use will be limited to low temperature applications such as space heating, preheating and drying. Estimated service temperatures for various applications are shown in Table A.1, Appendix A.

3.1.3 Industrial Process/Plant Factors

The design, operation and performance of FWHRs will be influenced by two types of industrial process/plant factors--waste stream characteristics and process/plant operations.

Waste Stream Characteristics: Some constituents of the waste gas streams -- dust, moisture, corrosive and condensable species -- could impose constraints on the FWHRs design and performance. For example, corrosive and condensable species in waste gas might require a minimum temperature for the FWHR exhaust gas, thereby setting material requirements for heat exchanger tubes. The nature and quantity of dust may require the use of abrasion resistant materials for heat exchanger components. Constraints on performance of heat exchanger components due to constituents of the waste gas stream can be overcome by proper design and materials selection. However, environmental regulations and health concerns regarding the stack plume could impose a minimum gas temperature, usually greater than the dew point temperature.

FWHR systems have the potential for using sorbents as bed material to remove undesirable compounds. In some instances, such gas characteristics might enhance the application of FWHR systems.

Another potential advantage of FWHR systems is their application to gas streams which foul conventional heat exchangers. FWHR internals should experience less fouling because of the scrubbing action of the bed, but this has not been established conclusively.

Process/Plant Operation: Characteristics of both the waste stream and the process for which the heat is recovered could affect the FWHR design/operation. For example, hot-gas from a basic oxygen furnace is intermittent; although a FWHR system for intermittent streams is conceivable, further development probably would be necessary for such applications.

Equipment size is important in an existing plant because space might be limited. A requirement for portability also could affect requirements on equipment size. FWHR systems are compact because of their heat transfer coefficients, so this could make them advantageous compared to conventional equipment.

3.1.4 Energy Conservation Potential

Energy conservation involves promoting more efficient use of fuels, including the utilization of energy in waste heat streams in place of other energy. The energy conservation potential depends on the efficient recovery and utilization of the waste heat.

Energy Recovered: For each industry considered, the FWHR is assessed to determine the energy recovered and the energy expended to recover the waste heat. For this analysis, it is assumed that the available heat above the stack gas temperature is fully recovered and utilized; losses associated with the specific FWHR design and method of energy utilization are neglected.

Energy Expended: The primary energy expended is for driving the FWHR fan; energy consumed by auxiliary equipment (e.g., water pumps) is significantly less and is not considered in this analysis. Energy to drive the induced draft fan is required to overcome the pressure drop across the fluidized-bed. The pressure drop across a fluidized-bed primarily results from the passage of gas through a distributor plate and the bed material; this pressure drop is shown qualitatively in Figure A.3, Appendix A. For shallow beds (3 to 6 inches expanded) the pressure drop is estimated to be 6 to 8 inches of water.* Data from tests at United Technologies Research Center (UTRC) on a small Stone-Platt Fluidfire FWHR unit support this estimate. The pressure drop across deeper beds (48 inches expanded) can be as much as 60 to 90 inches of water.

The power required to overcome the pressure drop is estimated as follows:

Fan power, BHP = $\text{CFM} \times \text{Static Head} / 6,356 E_s$, where

BHP = Brake horsepower

CFM = Volumetric flow rate at suction temperature and pressure,
cubic feet per minute

Static Head = Pressure drop across the bed, inches of water
(assumed 10 inches of water for shallow beds in
this study)

E_s = Static efficiency, assumed to be 60 percent.

*Telephone conversation with J. Bugai, Granco Equipment Company.

The fan power is used to determine the expended energy and the electric power operating costs. The energy resource expended for the fan electric power is determined assuming a fuel to electric power conversion efficiency of 30 percent. For those FWHRS applications where the recovered energy is used to generate electric power, the fan power is used as the expended energy.

Energy Conservation: The energy conservation for each potential application is determined based upon the difference between the energy recovered and the energy expended. The energy conservation is used to determine the annual savings in energy costs. The energy cost savings are based upon the cost of the specific fuel type, if known, saved as a result of the utilization of the waste heat.

An energy conservation parameter, Z , is defined to provide a measure of the merit of the FWHRS in recovering waste heat for a specific application. This factor is defined as the ratio of the energy recovered to the energy (resource) expended to recover the waste heat.

Applications where Z is 1.0 or less are considered technically unjustified, since the energy expended is equal to or greater than the energy recovered. Although it may be desirable to pursue some applications with a $Z \approx 1.0$ because of the types of energy involved (e.g., energy expended is electric power produced from hydro to conserve more valuable fuel oil), it is highly unlikely that the application would be economically justified. For applications where the waste heat is used to generate electric power, a value of Z approaching 1.0 is obviously technically and economically unjustified.

Any application with a value of $Z = 6$ or greater is considered a highly favorable FWHRS application. This value is typical of small power generation plants (i.e., up to 5 MW capacity) where approximately 15 percent of the power generated is consumed for the plant operation.

3.1.5 Summary of Technical Feasibility Analysis

The available heat of a waste gas stream, Q_2 , Figure 3.2, is the difference between the sensible heat, Q_1 , and the heat remaining in the exit (stack) gas at a temperature, T_s . T_s is set by the design based on an analysis of several factors, including the following:

- Potential dew point temperature, T_{s1} , of the exit gas stream. T_{s1} is important for environmental and health reasons as well as for materials durability requirements.

FIGURE 3.2
TECHNICAL FEASIBILITY OF FWHR SYSTEM

- Condensation temperature, T_{S2} , of species with a potential for fouling heat exchanger surfaces.
- Heat utilization (service) temperature, T_{S3} .

The two major factors that must be considered in determining the technical feasibility of FWHRs in a specific application include (1) the presence of a stream with high available heat content and (2) a low fan power requirement. In this analysis, the technical feasibility is evaluated based on the energy conservation parameter (discussed in Section 3.1.3).

3.2 Economic Assessment

The economic assessment of FWHRs applications covers the equipment, installation, and operating costs as well as an evaluation of projected savings from energy conservation.

3.2.1 Equipment Costs

FWHR Unit: The equipment costs, obtained from Granco Equipment Company, are shown in Figure 3.3 for three waste gas flow rates and three applications at one waste gas temperature. These equipment costs reflect the semi-custom design/fabrication status of the FWHRs. Equipment costs per million Btu/hr capacity decrease rapidly with increasing flow rates and temperatures of waste gas streams, as shown in Figure 3.3. Additional detailed data provided by Granco are given in Appendix A.

Auxiliary Equipment Costs: The FWHRs, as provided by the vendor, consists of a fluidized-bed system, heat exchanger and induced draft fan. In addition, in some applications it may become necessary to acquire auxiliary equipment. For example, to cogenerate process steam/heat and electric power, the following additional equipment is needed:

- Water circulating pump, water/steam drum, etc.
- Water treatment equipment
- Steam turbine-generator
- Electrical switch gear and other associated equipment.

In some potential FWHR applications, a sorbent may be used as a bed material; in such instances, the solids handling and feeding system and the sorbents would be additional costs.

FIGURE 3.3
FWHRS EQUIPMENT COST

Equipment costs for steam/power generation plants were based on data from Burns & Roe (See Appendix A). Table 3.1 indicates the relative costs of boiler, balance of plant and electrical power generating equipment determined from these data. These auxiliary equipment costs were used in assessing the applications for the FWHRs.

3.2.2 Installation Costs

Since the semi-custom designed FWHR unit is shop fabricated and delivered as a packaged unit, on-site installation costs are expected to be minimal. These installation costs include civil engineering work, ducting and plumbing as needed. According to the equipment vendor, these costs are small. However, these costs may range from 50 to 150 percent of the equipment costs. In the economic assessments of the FWHRs applications, 50 percent of the equipment cost is assumed to cover the installation costs.

3.2.3 Operating Costs

Operating costs include those for maintenance, manpower and electric power. Maintenance costs are uncertain because only limited operational experience exists for the FWHRs. According to the vendor, the maintenance problems and equipment down-time with the FWHR system are expected to be minimal. Annual cost of maintenance, including both scheduled and unscheduled, was estimated to be 10 percent of the total plant installed cost.

Manpower costs depend on the equipment reliability and the degree of automation. Although the vendor feels that no dedicated manpower is essential to operate the system, this need may exist in the initial stages. Manpower costs were assumed to be negligible for applications analyzed in this study.

Electric power costs are incurred from the fan required to operate a fluidized-bed and the equipment used to circulate the thermal fluid. Electric power costs for thermal fluid circulation are common to all heat recovery systems, but the electric power cost for the fan needed to overcome the fluidized-bed pressure drop is unique to the FWHR system. The fan electric power cost was estimated based upon 50 mills/kWh.

3.2.4 Costs Not Included in Assessment

There are several costs that may be significant but are not included in the economic assessment. These costs include the following:

- Land, local taxes and insurance (site specific)

TABLE 3.1
COMPARISON OF ESTIMATED COSTS OF EQUIPMENT
FOR 10MW STEAM POWER GENERATION PLANT

(1979 Dollars)

Equipment	\$ /KW	
	Conventional Power Plant*	FWHRS Power Plant
Steam Generator	64	75**
Balance of Steam Plant	64	64
Steam Turbine Generator	190	190
Electrical Switch Gear	32	32

*10MW size plant estimated from Burns & Roe Data (escalated 1976 dollars at 8% per year)

**Estimated from Granco Equipment Company FWHRS Data.

- Capital recovery, including interest and depreciation (plant-specific)
- Federal (and state) income taxes on gross income (plant-specific)
- Potential costs involved in the disposal of solids, liquids and gaseous streams (from FWHR applications) in an environmentally acceptable manner (site and plant-specific)
- Costs for solids handling and feeding equipment, if required
- Costs of sorbents, if required.

3.2.5 Value of Fuel Saved by Heat Recovery

The yearly value of fuel saved by recovering waste heat depends on the type of fuel saved -- coal, gas, oil or electricity. Assumed fuel costs and the value of the fuel saved from heat recovery are shown in Table 3.2. Net yearly value of fuel saved is the dollar savings from waste heat recovery minus the cost for electric power for the FWHR fan.

The value of fuel saved by heat recovery also depends on the fraction of recovered heat actually used and the duration of use. These factors are process and plant specific. For this analysis, it was assumed that all the recovered heat is fully utilized.

3.2.6 Payback Period

A simple payback period is computed as the time required to pay the investment cost and annual operating costs from the net yearly savings:

Payback Period, Years Savings = Total Cost/Net Yearly Savings.

In this analysis, several essential factors (e.g., interest, depreciation of equipment, local taxes and insurance, federal and state taxes and the potential costs associated with disposal of solids, gaseous or liquid streams which might result from FWHR technology application) have not been included. However, these factors would be considered by industry in evaluating the potential of FWHR systems for commercial applications.

3.2.7 Factors Influencing Commercial Application of FWHR

Other factors that are likely to influence commercial implementation of FWHR are as follows:

TABLE 3.2

FUEL COSTS AND SAVINGS FROM HEAT RECOVERY
(Assumed 1979 Energy Costs)

Energy Type	Energy Costs, \$/10 ⁶ Btu	*Annual Savings Per 10 ⁶ Btu/Hr of Heat Recovery, \$/Year
Coal	1.50	10,800
Gas	2.00	14,400
Oil	4.00	28,800
Electricity	15.00**	108,000

*Operating Year - 300 Days, 24 Hours per Day

**Equivalent Energy Costs Based on 50 Mills/KWH.

- Future fuel prices
- Age of the plant/projected plant life (plant specific)
- Availability of new technology/competitive waste heat exchangers.

These factors were not addressed in the economic analysis of the potential FWHRs applications.

REFERENCES - TECHNICAL AND ECONOMIC ASSESSMENT PARAMETERS

1. Clarke, L. and Davidson, R. L., Manual for Process Engineering Calculations, McGraw-Hill Book Company, New York, 1962.

4.0 INDUSTRIES ANALYZED

4.1 Preliminary Screening Criteria

4.1.1 Energy Consumption

The first criterion in the preliminary screening was to determine major industrial consumers of energy. The guide used was the "Annual Survey of Manufacturers: Fuels and Electric Energy Consumed" issued annually by the Bureau of Census. The survey breaks down energy consumption between fossil fuels and electric power. Each industry group (SIC three-digit code) and each industry segment (SIC four-digit code) were specifically examined for consumption of hydrocarbons, i.e., coal, fuel oil, natural gas, as well as electric power. The top industries (SIC four-digit code) in energy consumption were then selected and ranked.

The amount of energy consumption is usually a determinant of the waste energy produced. The larger the energy consumption the more likely is the prospect that the waste energy produced will be significant in amount and possibly available for recovery. Also, when an industry consumes major amounts of energy it is more likely to be operating processes at various temperature levels ranging from low to very high. Furthermore, large industrial energy consumers usually operate more complex industrial processes. As the complexity increases, there are more steps in each process. This produces additional manufacturing situations where waste heat is generated at different temperature levels. These complex processes, from a thermodynamics viewpoint, have to reject large amounts of heat energy as waste. Many process operations have to be at elevated temperatures which results in heat rejection at higher temperatures. Therefore, selecting energy consumption as the preliminary screening criterion is a recognition that this is a leading index to discovering sources of waste heat suitable for recovery and utilization.

4.1.2 Size of Industry -- Companies and Plants

The second criterion for selection was the size of the industry. Obviously, the industry has to be large enough to rank within the top energy consumers. But, more importantly, the industry should consist of many companies and therefore many plants so that there should be the opportunity for multiple applications of waste heat recovery and utilization. Further, the existence of many companies within an industry ensures that there will be different viewpoints and attitudes regarding adoption of new technology and equipment. A monolithic industry with few companies might tend to have a uniformity of business attitudes which would preclude innovation

and adaptation to new ideas and methods. Finally, and very important, the industry must be significant in the U.S. economy.

4.1.3 Waste Energy Characteristics

Obviously, the larger the amount of waste energy in an industry, the greater the opportunities for recovery and utilization. However, it is important that the sources of waste heat be relatively few and therefore concentrated. Many industries have relatively enormous amounts of waste heat which issue from many sources within their plant operations. But the sources may be so numerous that the waste heat from a single source is relatively small. Also, waste heat may be rejected at temperature levels that are so low thermodynamically, it is not feasible to recover the energy because either recovery is too costly in terms of capital investment or utilization is foreclosed technically because of the Second Law of thermodynamics. Finally, the waste heat has to possess a suitable temperature level and amount for economic utilization to (a) produce steam for plant purposes or generation of in-plant electric power, or (b) preheat process streams for plant operations.

4.1.4 FWHR Application Within Industry and Potential for Other Industries

Selection of industries was further affected by the characteristics of FWHR. Industries with waste heat temperature levels below 400-500°F were rejected. Desirable selections were those industries with waste heat temperature levels above 1000°F.

Particular attention was given to industries with high temperature levels of waste heat in the range of 1200°F to 2300°F. Special opportunities existed at the higher temperatures because many waste gas streams contain corrosive components which destroy the metals used in waste heat boilers and recuperators at these temperatures. Also, there exists the normal weakening and failure of metallurgy operating at high temperatures for long periods of time. Additional consideration was given to waste gas streams with particulates. Particulates will cause problems in waste heat boilers and recuperators, e.g., build-up and bridging, which reduces heat transfer surface and gas stream flow, and erosion of metal surfaces weakened by high temperature exposure.

Significantly important in selecting industries for FWHR application was the potential for similar application in other industries. As an example, successful demonstration of the FWHR using a flue gas from a kiln or furnace in one industry will most likely be readily adaptable to a flue gas waste heat being discharged from a kiln or furnace in many other industries which in no way

resemble the first industry in processes or products. This situation would have a multiplier effect on a demonstration program by increasing and enhancing the U.S. government investment in promoting technology innovation in waste heat recovery and utilization, and by simultaneously increasing the ability of a DOE program to further the national program to reduce consumption of energy, particularly those fuels derived from hydrocarbon sources.

4.1.5 Industry Receptivity

In order to evaluate the suitability of industries for FWHR application and demonstration programs, telephone interviews were held with major companies in each industry and with leading equipment vendors and engineer-contractors servicing each industry. The receptivity of industry to waste heat recovery and utilization by advanced technology and equipment innovations was the first criterion. The second criterion was their attitude toward a demonstration program. Telephone interviews with equipment vendors and engineer-contractors were used to gauge the interest of those parties who would have to engineer, fabricate and install the FWHR.

4.1.6 Criteria Considered but Not Used for Preliminary Screening

The following criteria were not used for screening:

- Environmental considerations
- Improving efficiency of plant operations other than reduction of energy consumption and utilization of waste heat
- Improving specifications of plant products
- Location of plants, except that there should be numerous plants with geographic distribution or that potential applications beyond a particular industry would result in affecting many other plants with a wider geographic distribution
- Number of employees in a particular industry.

4.2 Industries Screened

4.2.1 Initial Identification of Potential Industries

As noted in Section 4.1, the preliminary screening criteria resulted in a list of the top industries to be further examined. This list was subjected to further screening by reference to the Drexel Report, "Energy Analysis of 108 Industrial Processes - Phase I of

Industrial Applications Study," June 1979, by Dr. B. B. Hamel and Dr. H. L. Brown. The Drexel Report identifies industries by SIC and breaks down plant processes by the process step and the energy consumption and output by amount and temperature level. The Drexel Report had some preliminary utility in this study. However, its screening application was limited because the study was based on typical averaged plant data within a specific industry. As a result, the data did not apply satisfactorily to real, specific plant operations which develop significant waste heat. As an example, in the cement industry (SIC 3241), the report did not mention the operation that appears to have the most available current source of waste heat which is not being conserved or utilized by any company. However, the Drexel Report was used as preliminary screening check before commencing industry telephone interviews.

The second screening step in initial identification was the willingness of specific industries to discuss their waste heat problem areas and their receptivity to demonstration programs for FWHR application.

The third screening step in initial identification was a combination of the following technical criteria based on a technology assessment of the FWHR:

- Amount of waste heat and source
- Availability of waste gases at reasonably elevated temperatures, above 800°F, and suitable pressure conditions
- Potential use of the recovered heat energy to reduce energy consumption in specific plants or to utilize the energy to (a) produce steam for plant operation purposes or to generate in-plant electric power, and (b) preheat process plant streams.
- Reduction in consumption of hydrocarbon fossil fuels
- Ability to retrofit the FWHR application to existing plant conditions.

4.2.2 Industries Screened

Basically, the following industry groups were covered before proceeding in detail to the SIC four-digit code:

<u>Industry Group</u>	<u>SIC Code</u>
Paper and Allied Products	26

Chemicals and Allied Products	28
Petroleum and Allied Products	29
Stone, Clay, Glass Products	32
Primary Metal Industries	33

The following industries were screened:

<u>Industry</u>	<u>SIC No.</u>
Steel Mills & Blast Furnaces	3312
Petroleum Refining	2911
Industrial Organic Chemicals	2869
Papermills	2621
Paperboard Mills	2631
Cement, Hydraulic	3241
Industrial Inorganic Chemicals	2819
Nitrogenous Fertilizers	2873
Phosphatic Fertilizers	2874
Primary Aluminum	3334
Cyclic Crudes & Intermediates	2865
Plastics Materials and Resins	2821
Alkalies and Chlorine	2812
Glass Containers	3221
Pressed and Blown Glass	3229
Primary Copper	3331
Primary Lead	3332

4.3 Industry Selections from Screening

After screening the initial selection of 17 industries, the following industries were selected as having (a) the greatest potential for FWHR application based on waste heat recovery and utilization and (b) the best potential for industry receptivity based on telephone interviews:

- Cement Industry
- Steel Industry
- Primary Aluminum Industry
- Heavy Crude Oil Recovery Industry
- Petroleum Refining Industry
- Chemical Industry

In each industry, one or more waste heat sources were targeted

and the recovery and utilization of waste energy were evaluated with realistic reference to the specific industry requirements as disclosed in telephone interviews.

5.0 CEMENT INDUSTRY

5.1 Significance of Industry in U.S. Economy

Cement, SIC Code 3241, is a part of industry segment "Stone, Clay and Glass Product," SIC Code 32. The latest information available covers the year 1976 and indicates that SIC 32 ranked number 15 among U.S. manufacturing industries with a total value of \$31 billion for products shipped compared to \$1,186 billion for all industries.⁽¹⁾ The cement industry does not include concrete. The cement industry shipped \$2.6 billion as compared to \$10.0 billion value for the concrete industry (SIC 327). The industry production statistics, as of December 1978, are given in Table 5.1.^(2,3)

TABLE 5.1

CEMENT INDUSTRY PRODUCTION CAPACITY-1978

No. of U.S. Plants, Dec. 1978	160
No. of States with Plants	40
Production Capacity-Cement Clinker	89 Million Tons/Yr.
Ten Leading Cement States	63% of Capacity
Ten Largest Producers	50% of Capacity

In the year 1972, the number of active plants was 174.⁽⁴⁾ The nine percent decline in six years is due mainly to replacement of older small plants by larger more energy efficient plants or to phase-out of non-competitive plants due to increasing costs of production.

The cement industry product sales revenue has shown a relatively modest 8.4 percent increase (compounded annually) in the seven year period from 1972 while tonnage cement sales have correspondingly declined 1.5 percent annually. This indicates a relatively static production industry, as shown in Table 5.2.^(1,2,5) It also emphasizes a possible need for energy conservation as a means of bringing down production costs (dollars per ton) that has been steadily increasing.

TABLE 5.2

CEMENT INDUSTRY SALES AND REVENUE

Year	Sales-Million Tons	Revenue	
		(Billion Dollars)	(Avg. \$/Ton)
1972	81.4	1.7	10.90
1975	67.8	2.1	31.00
1978	74.6	3.0	40.20

At the end of 1978, the selling range of bulk cement in major metropolitan areas⁽¹⁾ was \$42 to \$62 per ton.

The cement industry is ranked sixth among all of the U.S. industries in the consumption of purchased fuels and electric power. The Bureau of Census⁽⁶⁾ has developed the data (see Table 5.3) which indicates that the cement industry consumes about 3.5 percent of the total energy consumed by all industries in the U.S.

The cement industry has been engaged in an overall energy conservation program since 1973. The key feature of this program has been a switch to coal-burning capability. In 1978, the industry achieved an 85 percent coal-burning capability with a goal of 90 percent by 1980. An overall picture of energy consumption (see Table 5.4) indicates a significant switch in energy source from natural gas to coal in the period 1972-1978.⁽³⁾

5.2 Major U.S. Producers

At the end of December 1978, the U.S. cement industry consisted of 49 companies operating 160 plants producing cement clinker. The top 13 companies, representing 63 percent of the industry capacity and 55 percent of the plants, are shown in Table 5.5.⁽⁸⁾

Cement production is a regional or local area industry primarily because of the low value-to-weight ratio of the product. Generally, the plants are located within 150 to 200 miles of their principal customers and markets. Beyond that distance, the land transportation costs become excessive in relation to the product value. However, distribution areas can be significantly extended in those situations where plants have access to water transportation, such as barge and boat. Cement plants are located in 40 states. The top 15 states have 80 percent of the capacity and 74 percent of the plants.

TABLE 5.3

CEMENT INDUSTRY ENERGY CONSUMPTION & INDUSTRIAL RANK
 COMPARED TO MAJOR INDUSTRIAL ENERGY CONSUMERS

<u>Rank</u>		<u>SIC Code</u>	<u>Industry</u>	<u>Purchased Fuels & Electric Power Annual Consumption (Trillion Btu)</u>	
<u>1976</u>	<u>1977</u>			<u>1976</u>	<u>1977</u>
1	1	3312	Blast Furnace & Steel Mill	1,427	1,390
2	2	2911	Petroleum Refining	1,218	1,186
3	3	2869	Industrial Organic Chem. n.e.c.	1,098	1,063
4	4	2621	Papermills	588	565
5	5	2631	Paperboard Mills	465	475
6	6	3241	Cement, Hydraulic	434	449
7	7	2819	Indust. Inorganic Chem. n.e.c.	421	422
8	9	2873	Nitrogenous Fertilizers	300	245
9	8	3334	Primary Aluminum	297	323
10	11	2865	Cyclic Crudes & Intermediates	171	148
Total - All U.S. Industry				12,625	12,738

TABLE 5.4

ENERGY CONSUMPTION, EFFICIENCY, AND SOURCES
IN CEMENT PRODUCTIONA. Consumption/Efficiency

	<u>1972</u>	<u>1975</u>	<u>1978</u>
Production, Actual (1000 Tons) ⁽¹⁾	80,700	66,800	77,500
Energy Equivalent Prod. (1000 Tons) ⁽²⁾	75,300	62,800	74,550
Production Energy Efficiency ⁽²⁾ (Million BTU/Tons)	6.75	6.50	6.13

B. Energy Sources

	<u>1972</u>		<u>1975</u>		<u>1978</u>	
Trillion BTU/Year	<u>(T BTU/Y)</u>	<u>(%)</u>	<u>(T BTU/Y)</u>	<u>(%)</u>	<u>(T BTU)</u>	<u>(%)</u>
<u>Energy Source</u>						
Coal/Coke	183	36.0	183	44.2	288	63.0
Natural Gas	231	45.5	166	40.1	90	19.7
Oil	61	12.0	36	8.7	43	9.4
Electric Power ⁽³⁾	33	6.5	29	7.0	36	7.9
<u>Totals</u>	508	100	414	100	457	100

Notes: (1) 1972 & 1975 production figures from Ref. 1 for Portland cement only. 1978 value was estimated from Bureau of Census 1977 data.

(2) "Energy Equivalent Tons" of Production is a number developed by the Portland Cement Association to ensure comparability of data from different years when evaluating energy.

(3) Portland Cement Association reports electric energy consumption as BTU/Year by calculating KWH/Year multiplied by 3412.2 BTU/KW. They do not include the utility power-plant efficiency of 35%.

TABLE 5.5

TOP 13 CEMENT COMPANIES
TOTAL PRODUCTION CAPACITIES AND NO. OF PLANTS

<u>Company</u>	<u>Capacity December 1978</u>	
	<u>Million tons/year</u>	<u>No. Plants</u>
Lone Star Industries	6.893	10
Ideal Basic Industries	6.370	13
General Portland	4.892	8
Martin-Marietta	4.736	8
Marquette (Gulf Western)	4.532	11
Amcord	4.301	5
Medusa	3.810	6
Universal Atlas (U.S. Steel)	3.806	8
Kaiser Cement and Gypsum	3.743	5
Dundee	3.480	3
National Gypsum	3.468	3
California Portland	3.030	3
Lehigh Portland (Portland Zement AG)	3.030	5
Totals	56.091	88
Percent U.S. Industry	63%	55%

5.3 Basic Process Description

Portland cement comprises 95 percent of the U.S. hydraulic cement output (SIC 3241); the remainder is masonry cement and specialty and natural cements. Ninety-seven percent of Portland cement is used in preparation of concrete, a combination of cement, sand, aggregate (gravel, etc.), and water. One ton of Portland cement is used to make four cubic yards of concrete.

Portland cement production in the U.S. is accomplished by either of two processes, wet or dry. As of the end of 1978, 53 percent of the plants employed the wet process, 42 percent used the dry, and the remaining 5 percent had dual wet and dry facilities. In the wet process, the crushed and proportioned raw materials are ground with water, thoroughly mixed, and fed as a slurry into the kiln. In the dry process, the raw materials are ground, mixed, and fed into the kiln in their dry state. Beyond this point, both processes are similar. The trend is toward replacement of many older, less energy-efficient wet process plants with dry process plants, equipped with preheaters, to reduce fuel requirements. The wet process allowed a more effective grinding of raw materials, but it wasted energy in the evaporation of the slurry water. The dry process, through use of the suspension preheater and dryer units (such as the roller mill), makes fuller use of the formerly waste heat gases from the kiln exit and clinker cooler vents. The dry process also permits employment of the precalciner so that the fuel use is now split between kiln and precalciner such that more efficient energy usage is promoted by effectively using thermal energy in achieving calcination in two steps at a lower total thermal energy requirement.

Cement process production varies in details from plant to plant because of the following basic variables: raw material composition, type of fuel, alkali content of raw material, type of process (i.e., wet or dry), and energy conservation program equipment, i.e., suspension preheater, precalciner, and roller mill. A typical cement plant flowsheet illustrating the dry process is shown in Figure 5.1.

5.4 Industry Waste Heat Production

Energy consumption and, thus, waste heat production are influenced by many variables, although the primary factors are the type of process, wet or dry, and the extent of adoption of new technology for energy conservation.

S-7

FIGURE 5.1
DRY PROCESS CEMENT PLANT SCHEMATIC

5.4.1 Waste Heat Sources and Amounts

Data on waste heat sources were developed by the Portland Cement Association (PCA) in June 1975 for the Federal Energy Administration.⁽¹⁰⁾ The PCA developed an energy balance based on the best or most efficient plant operations. This energy balance for a 1975 dry process plant with suspension preheater indicated 45 percent less fossil fuel required than for a 1978 U.S. plant, i.e., 2.98 million Btu/Ton in 1975 compared to the U.S. average of 5.45 million Btu/Ton in 1978 for all dry process plants. Similar heat balance results were indicated by PCA for wet process plants. In order to reflect the real existing situations in U.S. plants in 1978, the energy balances obtained from PCA have been adjusted to reflect the energy efficiency of current (1978) processes, including the effect of plant capacity.

The energy balance used for definition of the waste heat is shown in Table 5.6 for the averaged U.S. plant as of 1978. By necessity, Table 5.6 becomes a comparative estimate for an overall view of U.S. plants, but does not indicate any particular plant operation.

The major sources of waste heat from cement process plants are summarized in Table 5.7.

TABLE 5.7

MAJOR WASTE HEAT SOURCES FROM CEMENT PLANTS

<u>Source</u>	<u>Process</u>	<u>Temperature</u>
Radiation and Convection	All	Varies
Clinker Cooler Excess Air	All	300-1400°F
Exhaust Gas	Wet Dry Dry with Sus. Preheater	500-700°F 700-1800°F 500°F
Preheater By-Pass Gas	Dry with Sus. Preheater	1800-2000°F

TABLE 5.6

ENERGY BALANCES FOR DRY & WET PROCESS CEMENT PLANTS
(1000 BTU/TON) -

	<u>Dry Long Kiln</u>	<u>Susp. Preheater Dry Kiln</u>	<u>Susp. Preheater & Bypass Dry Kiln</u>	<u>Wet Long Kiln</u>
A. <u>Heat Supplied</u>	5452	4200	4700	6678
B. <u>Heat Required</u>				
Theoretical Heat	1522	1522	1522	1522
<u>Waste Heat Sources</u>				
• Water Evaporation	30	40	40	2860
• Exit Gas Heat	2100	1160	1160	900
• Dust Sensible Heat	190	40	40	0
• Clinker Sensible Heat	90	100	100	50
• Clinker Cooler Excess Air	480	710	710	180
• Radiation & Convection	880	470	470	1160
• Unaccounted For	160	158	158	6
• Preheater Bypass = 25%	-	-	500	-
Total Heat Required	5452	4200	4700	6678

Note : Bypass is estimated to be 16,000 Btu/Ton per each 1% Bypass Flow.
Bypass can vary from 0% to 100%. A typical bypass flow can be 25%
of the exit gas from the kiln, which is assumed here for example.

5.4.2 Current Waste Heat Recovery and Utilization

The radiation and convection losses are unavoidable, except through better insulation. The clinker cooler excess air above 700°F is used as combustion air. The lower temperature vent air, formerly vented to the atmosphere in the range of 300°F to 700°F, is now being utilized as much as possible for drying purposes, such as drying the pulverized coal feed and the raw mix in the roller mill. If the temperature level is high enough, it is introduced into one of the earlier stages of the suspension preheater.

In earlier plants, the exhaust gas streams were discharged as high as 1800°F to 2000°F. However, process changes from wet to dry and the incorporation of the suspension preheater and flash calciner have contributed to a reduction in the temperature level and the quantity of heat vented into the atmosphere. The exhaust gas streams are generally cooled to about 500°F and vented to the atmosphere through the baghouse filter or ESP.

Many cement manufacturing plants have either switched or will be switching to coal firing. Because of the alkali content of the raw material, the cement clinker could contain more than permissible quantities of alkalies. To ward off this problem, a significant part of the kiln exhaust gases are made to bypass the suspension preheater and flash furnace where the alkali compounds could condense back on the raw material; in some instances, as much as 40 percent kiln exhaust gases at temperatures of about 1800°F to 2000°F are bypassed.

The preheater bypass is a feature of dry process plants. At present, there are approximately 60 kiln units in the U.S. with preheaters (see Table 5.8). Information on plant age, process and

TABLE 5.8

CEMENT PLANTS BY PROCESS & NO. OF KILNS(8)

	<u>Wet Process</u>	<u>Dry Process</u>	<u>Wet & Dry Process</u>	<u>Total</u>
No. of Plants	85	67*	8	160
No. of Kilns	180	143*	17	340
Percentage	53%	42%	5%	100

Note* About 60 of the 143 plant units have suspension preheaters.

capacity is presented in Table 5.9. The waste heat energy potentially available for recovery from the preheater bypass estimated from data shown in Table 5.10 is 12 trillion Btu/yr. Recovering this waste heat would represent 2.6 percent of the cement industry's energy requirements based upon their consumption of 457 trillion Btu's in 1978.

TABLE 5.9
CEMENT PLANT PROFILE BY AGE, PROCESS, & CAPACITY
(1000 TONS/YEAR CLINKER)

<u>Year Built</u>	<u>Wet</u>		<u>Dry</u>	
	<u>Total Cap.</u>	<u>Avg. Cap.</u>	<u>Total Cap.</u>	<u>Avg. Cap.</u>
1976	0	0	3086	514
1971-75	5772	412	9402	470
1966-70	8960	373	3833	383
1961-65	8561	357	7171	312
1956-60	10702	218	7305	221
1951-55	4815	178	5029	157
1946-50	3979	153	1265	127
1941-45	1187	170	264	132

5.5 Potential FWHRs Applications

The potential applications for use of the waste heat in the clinker cooler excess air, the exhaust gas and the preheater bypass gas are as follows:

- Preheating/calcining raw materials
- Drying coal and raw materials
- Preheating primary and secondary air for combustion
- Generation of steam/electric power.

TABLE 5.10

PREHEATER BYPASS WASTE HEAT POTENTIAL

No. of Kilns	340	(See Table 5.8)
No. of Dry Process Kilns	143	(See Table 5.8)
No. of Preheaters	60	(See Table 5.8)
No. of Preheater Bypass Units	60	(Assumed)
Avg. Temp. of Bypass Inlet	1900°F	(Assumed)
Avg. Temp. of Bypass Exit	680°F	(Assumed)
Avg. Bypass Waste Heat Potential*	16,000 BTU/Ton Per % Bypass	(Ref. 10, page 145)
Avg. Plant Capacity (New Plants)	500,000 Tons/Yr	(See Table 5.9)
Avg. Preheater Bypass Flow	25%	(Assumed)
Total Waste Heat U.S.	12 Trillion BTU/Yr	

* Based upon assumed inlet and exit gas temperatures.

The waste heat is currently being used to varying degrees for these purposes depending upon the type of process (i.e., wet or dry) and the type of fuel and raw materials used.

The application considered most desirable for the FWHRS is the generation of steam for in-plant electric power. A typical size dry process cement plant producing 1700 tons/day requires 275,000 kWh based upon an overall average plant consumption of 162 kWh/Ton in 1978.⁽⁸⁾ Using an FWHRS to produce high pressure steam from the suspension preheater bypass gas could produce a significant amount of in-plant electric power. For a typical application defined in Table 5.11, the FWHRS could produce approximately 15 percent of the total plant electric power requirement. For some plants the clinker cooler excess air and the exhaust gas could be used to increase the amount of steam, thus electric power, generated.

Historically, the cement industry had a tradition of using waste heat for producing in-plant electric power. In the early 1920s, the industry started a shift to purchased electric power. In 1978, there remained only about eight plants still generating electric power from waste heat. The two major plant operations still in existence are:

<u>Company</u>	<u>Plant Location</u>	<u>Electric Power</u>
National Gypsum	Alpena, Michigan	45,000 KW
Riverside Cement (Amcord)	Riverside, California	17,000 KW

The U.S. Department of Energy is encouraging co-generation by industrial plant operators. The concern of plant operators that local private utilities will not cooperate on revised rate schedules should diminish with federal assistance.

5.6 Technical and Economic Assessment

The proposed applications analyzed include the following:

- (1) Steam/electric power generation with heat recovered from the preheater bypass gas stream from a dry process cement plant equipped with preheater and calciner.
- (2) Steam/electric power generation with heat recovered from the exhaust gas stream from a dry process cement plant not equipped with preheater and calciner.

The technical and economic assessment is provided in the following subsections for these two applications using the approach developed in Section 3.0.

TABLE 5.11

UTILIZATION OF PREHEATER WASTE HEAT RECOVERY
TO GENERATE IN-PLANT ELECTRIC POWER

<u>Assumptions</u>	
Plant Capacity	1700 tons/day
Preheater By-Pass	≈25%
Bypass Inlet Temperature	1900°F
Bypass Exit Temperature	680°F
Boiler Feedwater Inlet	625 psia & 70°F
Boiler Discharge Steam	615 psia & 650°F
Bypass Waste Heat Available	16,000 Btu/ton per percent Bypass
Steam Turbine Efficiency	60%
 <u>Calculations</u>	
Bypass Waste Heat Available	30 Million Btu/Hour
Electric Power Generated	40,000 KWH/Day

5.6.1 Application #1: FWHRs Using Preheater Bypass Gas

The proposed FWHRs application, shown in Figure 5.2, consists of power generation using bypass waste gas stream from a 1700 TPD cement manufacturing (dry process) plant.

The FWHRs is sized to handle a waste gas stream of 20,000 SCFM. In addition to a FWHRs, the required equipment includes the balance of steam plant (e.g., water circulating pumps, steam drum, deaerator, water conditioning, and treatment equipment) and turbogenerator with associated equipment.

The technical and economic assessment, summarized in Tables 5.12 and 5.13, addresses a coal-fired cement manufacturing plant. The results of the analysis should be equally applicable to FWHRs applications in gas- or oil-fired cement manufacturing plants.

5.6.2 Application #2: FWHRs Using Exhaust Gas Stream

The proposed FWHRs application, shown in Figure 5.3, uses waste heat from the exhaust gas stream (80,000 SCFM) of a 1700 TPD coal-fired dry process cement plant not equipped with preheater and calciner for in-plant electric power generation.

The proposed system consists of a staged-bed concept and includes, in addition to the FWHRs, the balance of steam plant, turbo-generator and associated equipment.

The technical and economic assessment is summarized in Tables 5.14 and 5.15. The results of these analyses are generally applicable to FWHRs applications in gas- or oil-fired cement plants.

5.6.3 Summary of FWHRs Applications in Cement Industry

The proposed applications appear to be technically and economically viable; the application of FWHRs for heat recovery from the preheater bypass gas stream (application #1) is economically attractive and is likely to be well-received by the cement industry. The second application is also economically attractive; the power plant size is a respectable 4000 KW. The FWHRs application would eliminate the need for the current practice of water spraying to cool the exhaust gases. The FWHRs applications are feasible with dry process cement plants whether the kilns are oil-, gas- or coal-fired.

In addition to the dry process plants, there could be several wet process plants with potential for FWHRs applications. However, these applications were neither examined nor analyzed.

FIGURE 5.2
FWHR USING BYPASS GAS STREAM
(CEMENT PLANT)

TABLE 5.12

TECHNICAL ASSESSMENT OF FWHRs IN CEMENT INDUSTRY
APPLICATION #1 - PREHEATER BYPASS GAS
(1700 TPD PLANT)

WASTE GAS STREAM CHARACTERISTICS

Gas Temperature	1900°F
Flow Rate (Assumed $\approx$ 25% Bypass)	20,000 SCFM
Heat Available	27.4 Million BTU/HR
Stack Gas Temperature	700°F
Corrosive Species	SO ₂ , H ₂ SO ₄ , Alkali Cmpds., HF, HCl
Condensible Species	H ₂ SO ₄ , Alkalies

SERVICE/APPLICATION CHARACTERISTICS

Type	Electric Power Generation
Steam	600 PSIG, 650°F

ENERGY CONSERVATION POTENTIAL

Energy Expended (Fan Power)	118 HP (87.8 KW)
Energy Recovered (Power Generated)	2,140 KW
Net Energy Conservation (Power)	2,050 KW
Energy Conservation Parameter (Z) *	24

POTENTIAL TECHNICAL PROBLEMS

- Fouling due to alkali compounds; corrosion due to SO₂, H₂SO₄, HF, HCl and alkali compounds.

* Z > 6 Highly Favorable Energy Conservation

TABLE 5.13

ECONOMIC ASSESSMENT OF FWHRs IN CEMENT INDUSTRY
APPLICATION #1 - PREHEATER BYPASS GAS
(1700 TPD PLANT)

FWHRs COSTS

FWHR Unit	\$178,000
Balance of Steam Plant	137,000
Auxiliary Systems	474,400
Total Equipment	<u>\$789,400</u>
Installation Cost	<u>\$394,700</u>
Total Installed Cost	\$1,184,100

OPERATING COSTS (ANNUAL)

Electric Power (Fan Power)	\$31,700
Maintenance (Scheduled & Repair)	118,400
Total Operating	<u>\$150,100</u>

SAVINGS FROM CONSERVATION

Savings Per Year (Electric Power)	\$769,300
Net Savings Per Year (Electric Power)	\$619,200
Pay Back Period	1.9 Years

ECONOMIC CONSIDERATIONS

- Utilities' cooperation with in-plant electric power generation
- Net energy conserved can be increased by staged-bed concept to reduced 700°F stack gas temperature, although it may not be economically justified (case not analyzed).

FIGURE 5.3
FWHR USING EXHAUST GAS STREAM
(CEMENT PLANT)

TABLE 5.14

TECHNICAL ASSESSMENT OF FWHS IN CEMENT INDUSTRY
APPLICATION #2 - EXHAUST GAS STREAM
(1700 TPD PLANT)

WASTE GAS STREAM CHARACTERISTICS

Gas Temperature	1000 ⁰ F
Flow Rate	80,000 SCFM
Heat Available	60.8 Million BTU/HR
Stack Gas Temperature	350 ⁰ F
Corrosive Species	SO _x , H ₂ SO ₄ , HCl, HF, Alkalies
Condensible Species	H ₂ SO ₄ , Alkalies

SERVICE/APPLICATION CHARACTERISTICS

Type	Electric Power Generation
Steam	600 PSIG, 650 ^U F

ENERGY CONSERVATION POTENTIAL

Energy Expended	328 HP (245 KW)
Energy Recovered	4,740 KW
Net Energy Conservation	4,495 KW
Energy Conservation Parameter (Z)*	19

POTENTIAL TECHNICAL PROBLEMS

- Fouling due to alkali compounds; corrosion due to SO₂, H₂SO₄, HF, HCl and alkali compounds

*Z > 6 Highly Favorable Energy Conservation

TABLE 5.15

ECONOMIC ASSESSMENT OF FWHRs IN CEMENT INDUSTRY
APPLICATION #2 - EXHAUST GAS STREAM
(1700 TPD PLANT)

FWHRs COSTS

FWHRs UNIT	\$1,243,200
Balance of Steam Plant	303,500
Auxiliary Systems	1,052,500
Total Equipment	<u>\$2,599,200</u>
Installation Cost	<u>\$1,299,600</u>
Total Installed Cost	<u>\$3,898,800</u>

OPERATING COSTS (ANNUAL)

Electric Power (Fan Power)	\$88,200
Maintenance (Scheduled & Repair)	389,900
Total Operating	<u>\$487,100</u>

SAVINGS FROM CONSERVATION

Savings Per Year	\$1,706,700
Net Savings Per Year	\$1,228,600
Pay Back Period	3.2 Years

ECONOMIC CONSIDERATIONS

- Utilities' cooperation with in-plant electric power generation
- Net energy conserved can be increased by staged-bed concept to reduced 700°F stack gas temperature, although it may not be economically justified (case not analyzed).

5.7 Summary of Industry Comments

5.7.1 Industry Comments

The cement industry and major equipment vendors are actively promoting waste heat energy conservation programs. The Portland Cement Association (PCA), the industry trade association, indicated that the industry is constantly striving to reduce its energy consumption which represents approximately one-third of the cost of production. Lone Star Industries (#1 producer), Martin-Marietta (#4) and the PCA consider the preheater bypass to be potentially the best current application available for FWHRs since the other sources of waste heat energy in cement plants are being handled by some combination of the following: suspension preheater, roller mill, and the use of excess hot vent air from the clinker cooler for drying functions. Energy consumption is being reduced by switching from the wet to the dry process and by use of the precalciner in which fuel is allocated between this unit and the kiln in order to promote energy efficiency of calcination.

The industry currently has a coal-burning capability in 85% of its capacity which they expect to raise to 90% by 1980. The industry relied on coal as fuel for 63% of its energy in 1978. Hence, waste energy conservation in the cement industry may increasingly be equated more so with coal usage reduction.

Of the 340 kilns in operation at the end of 1978, 143 or 42% were dry processes. About 60 out of the 143 had suspension preheaters and only 3 had a precalciner unit. Hence, the waste energy conservation program in progress has still a long way to go before the various elements are completed.

Ideal Basic (#2 producer) is employing the latest technologies such that some of its plants are now rejecting waste gas at 180°F to 200°F. Hence, its plant waste temperature level is too low for practical use of a FWHRs.

National Gypsum Company (#11 producer) at its Alpena, Michigan cement plant (2.3 million tons/year) is co-generating steam turbine electric power with its waste heat from the exit gases of nine kilns. The turbine generator complex has 45,000 KW capacity.

Riverside Cement Corporation (Amcord Corp. - #6 producer) at its Riverside, California 1.15 million tons/year plant is operating a 17,000 KW capacity steam turbine electric power generator off the waste heat energy in the exit gases from seven kilns. At the end of 1978, there were only eight plants remaining out of 160 which retained the ability to cogenerate their in-plant power requirements --

partially or all. All companies contacted, as well as the PCA, were interested in generating on-site electric power with a FWHRs application.

Fuller Company (Bethlehem, Pa.) and Allis-Chalmers, Cement and Chemical Systems Division (Milwaukee, Wis.) are major suppliers of plant equipment to the cement industry. They consider the preheater bypass to be the location in the process where waste heat energy is now being thrown away for which there is currently no waste conservation technology being considered. All other process locations where waste heat is being lost are being considered by the various cement corporations for energy recovery and utilization if retrofit is feasible and the economics of retrofit are satisfactory.

5.7.2 Industry Receptivity

Industry comments on FWHRs application were that, if equipment vendors were to offer such equipment with performance guarantees, then the industry would be receptive to sponsoring demonstration programs. The equipment vendors were of the same viewpoint, adding that they would engineer and fabricate FWHRs units for retrofit in demonstration programs if (a) the technology was ready for commercial adaption, and (b) there was some kind of subsidy to take care of one-time costs incurred in developing, fabrication, and installing an FWHRs.

REFERENCES-CEMENT INDUSTRY

1. Statistical Abstract of U.S., 1978, U.S. Department Commerce, p. 816.
2. "U.S. Cement Industry", 2nd. Ed., Portland Cement Assoc., March 1978
3. "1978 Energy Report U.S. Portland Cement Industry", Portland Cement Assoc., April 1979.
4. Statistical Abstract of U.S., ibid, p. 769.
5. "Cement", Mineral Commodity Profile, MCP-26, U.S. Dept. of Interior, Nov. 1978, p. 6.
6. "Annual Survey of Manufactures, 1976: Fuels and Electric Energy Consumed", M76(AS)-4.1, p. 8, Bureau of Census, U.S. Dept. of Commerce. NOTE: 1977 data obtained verbally from Bureau; not yet published.
7. Engineering News Record, Jan. 4, 1979, p. 34.
8. Portland Cement Association, Skokie, Illinois. Private communication.
9. "U.S. Cement Industry", 2nd. Ed., Portland Cement Assoc., Exhibit 20, p. 20, March 1978.
10. "Energy Conservation Potential in the Cement Industry," Conservation Paper No. 26, Federal Energy Administration, Chapter 4, p. 62-222, June 1975. See Table 4-20, p. 118 and Table 4-24, p. 132.

6.0 STEEL INDUSTRY

6.1 Significance Of Industry In U.S. Economy

Steel production is a critical factor in the U.S. economy. Steel, SIC Code 331, is a part of the industry segment "Primary Metal Industries", SIC 33. The latest information available (year 1976) indicates that SIC 33 ranked fifth among all U.S. manufacturing industries with a total value of \$93 billion for all products shipped.⁽¹⁾ The steel industry represented \$46.7 billion of these shipments. Since the total value for all manufacturing industries was \$1,186 billion, steel represents 4.0%.

The steel production industry is the largest energy consumer among all U.S. industry. In 1977, the industry's consumption of purchased fuels and electric power was 1,390 trillion Btu or 11% of the total purchased energy consumed by all U.S. industry.⁽²⁾ In 1978, the industry consumed 1,538 trillion Btu.⁽³⁾ Estimates of the sources for the purchased energy are as follows:

Coal/Coke	33%
Natural Gas	39%
Fuel Oil	17%
Electric Power	11%

In addition, the industry had captive sources of coal and coke and manufactured on-site electric power from coal.

Raw steel production in the U.S.^(2,3) has fluctuated in recent years with economic conditions, as follows:

1972	133.2 Million Tons
1975	116.6 Million Tons
1976	128.0 Million Tons
1977	125.3 Million Tons
1978	136.7 Million Tons

6.2 Major U.S. Producers

The major U.S. steel producers and statistics on their operations are provided in Table 6.1.^(3,4,5)

TABLE 6.1

MAJOR U. S. STEEL PRODUCERS

<u>Company</u>	<u>1978 Raw Steel Production Million Tons</u>	<u>1978 Total Revenue Million Dollars</u>	<u>No. of Plants</u>	<u>No. of Blast Furn.</u>	<u>Plant Locations</u>
U.S. Steel	31.3	11,050	12	62	Ala., Ill., Ind., Minn., Ohio, Pa., Utah
Bethlehem	18.8	6,185	5	27	Ind., Md., N.Y., Pa.
National Steel	10.5	3,750	3	10	Ill., Mich., W. Va.
Republic Steel	10.0	3,479	7	15	Ala., N.Y., Ohio
Jones Laughlin	Not available	Not available	3	11	Pa., Ohio
Inland Steel	8.6	3,248	1	9	Ind.
Armco	8.5	4,357	4	6	Ky., Ohio, Texas

The above seven top producers account for approximately 75% of the U.S. production of raw steel and operate in 13 states. In all, there are 20 steel companies operating 187 blast furnaces in 15 states. There are a total of 91 companies operating 154 plants. These companies produced a total of 136.7 million tons of raw steel in 1978. With the exception of Armco, which has diversified, the other six companies are basically steel operations. U.S. Steel has significant cement and chemical businesses, but the steel operation is greatly predominant. Data on Jones Laughlin is not available owing to a recent merger between LTV, its parent, and Youngstown Steel, which resulted in operation changes.

6.3 Basic Process Description

The steel production process, depicted in Figures 6.1 and 6.2, covers the manufacture of coke, iron, steel, and the production of commercial products.

The major coke process equipment is the slot chamber oven; the beehive process has become relatively insignificant. Crushed coal is fed to a battery of chamber ovens; under a cycle of 18 hours of heating the coal to 2400°F in a closed chamber, the volatiles are driven off resulting in a carbonized-product about 91% carbon.⁽⁶⁾ Approximately, 0.7 tons of coke product are produced per ton of coal charged. The remainder consists of coke breeze, gas, tar, light oil, and ammonia. The carbonization process cycle is about 18 hours. In each 12.5 minute period, one of the slot chambers is discharged of its coke product. A typical coke battery may contain up to 87 chambers. Thirty-eight tons of coal will be charged to a chamber, and about 27 tons of coke will be discharged. The coke is discharged at 1950°F. It is transported through a water quench tower where it is cooled to about 400°F. The various volatile by-products are processed in the by-product plant to produce valuable chemicals. The coke-oven gas is used as fuel for the coking battery and for the blast furnace. The coke breeze is a mixture of carbonized bony coal, slaty rock and finer coke particles used for fuel, which amounts to about 5% by weight of the coal charged.

The steelmaking process starts at the blast furnace.⁽⁷⁾ About 1.7 tons of iron-ore, 0.50 to 0.65 tons of coke, 0.25 tons of limestone, and 1.8 to 2.0 tons of air are charged to the blast furnace. From these materials are produced 1.0 ton of iron, 0.2 to 0.4 ton of slag, 0.05 ton of flue dust and 2.5 to 3.5 tons of blast furnace gas. The function of the coke is to provide the heat required for smelting and also to supply the chemical reactants (primarily carbon monoxide) for reducing the iron ore. In addition, it supplies the carbon that dissolves in the hot metal (about 70 to 80 pounds for every ton of iron). The gas issuing from the top of the blast furnace with a calorific value of 85-100 Btu/SCF, is used as fuel.

The blast furnace iron is usually transported as molten iron in rail conveyor cars to one of three types of furnaces, namely electric, open hearth, or basic oxygen (BOF), to make steel. The BOF has rapidly displaced the open hearth in the last decade. The electric furnace is used for producing specialty steels.

From the furnaces, the steel is transported to one of three operations: continuous slab, casting, or ingot mold. The solidified steel, either slab, billet, or bloom, then passes through a variety

FIGURE 6.1
STEEL INDUSTRY PROCESS—COAL TO COKE

FIGURE 6.1
STEEL INDUSTRY PROCESS—COAL TO COKE
(CONTINUED)

From iron ore, limestone and coal in the earth's crust to space-age steels — this fundamental flowline shows only major steps in an intricate progression of processes with their many options.

SOURCE: "Steelmaking Flowlines,"
American Iron & Steel Institute,
Washington, D.C. 3/78

FIGURE 6.2
STEEL INDUSTRY PROCESS—STEELMAKING

FIGURE 6.2
STEEL INDUSTRY PROCESS—STEELMAKING
(CONTINUED)

of forming and heating operations to produce various commercial steel items.

The operations in a coke oven battery in a steel mill are varied and complex. There are a variety of sources of fuel and inputs with diverse applications. The overall aspects of energy inputs into steel plants are shown in Table 6.2 based on 1978 data from the American Iron and Steel Institute.⁽⁸⁾

Table 6.2 indicates that the steel industry consumed internally, in the steel mill portion, 2,223 trillion Btu to produce 136.7 million tons of steel. The coke oven operation, which precedes steel-making, is indicated in a typical energy balance⁽⁹⁾ shown in Table 6.3 for the slot chamber type oven. Although coke oven operations are fairly standardized, there are differences between plants based on age and technology improvements. As of July 1979, there were approximately 11,400 coke ovens in the U.S. of the slot chamber types; the bee-hive oven type has become insignificant industrially. The 1978 total U.S. coke production was about 63 million tons. The steel industry produced 45 million tons of coke (71%) for captive use. This means the steel industry coke ovens consumed 111.3 trillion Btus.

Based on the data in Tables 6.2 and 6.3, the basic sources of fuel energy for steel industry are defined in Table 6.4.

It should be noted that of the 2,334 trillion Btu, a total of 1,538 trillion Btu (66%) was purchased energy fuel; the remainder was derived from captive in-plant sources.

Table 6.2 indicates that the two largest fuel consumption areas in the steel mill are the blast furnaces and the heating and annealing furnaces. The fossil fuel sources are about evenly divided between coal and natural gas/oil/hydrocarbon.

6.4 Industry Waste Heat Production

6.4.1 Sources and Amounts

The potential for waste energy conservation in the coke oven steel mill complex is outlined in Table 6.5. These data are derived from several sources (10,11, 12,13,14,15) and based on the 1978 production of 136.7 million tons of steel. The various plant streams and operations carry waste fuel and waste heat that could potentially be conserved. However, recovery of this waste energy is not too practical in some of the plant operations. If all the 312 trillion Btus of potential energy savings could be accomplished, this would amount to 20% of the purchased energy in 1978.

TABLE 6.2

1978 STEEL INDUSTRY FUEL CONSUMPTION
ACCORDING TO PLANT OPERATION

<u>Fuel Type</u>	<u>Blast Furnaces</u>	<u>Steel Melting Furnaces</u>	<u>Heating & Annealing Furnaces</u>	<u>Other</u>	<u>Totals Fuel Units</u>
Fuel Oil - Million Gals.	633 (91.2)	290 (41.8)	648 (93.3)	333 (48.0)	1904
Tar & Pitch - Million Gals.	79 (11.4)	56 (8.1)	- -	11 (1.6)	146
LPG-Million Gals.	- -	- -	16 (1.5)	9 (0.8)	25
Natural Gas - BCF	53 (51.9)	57 (55.9)	327 (320.5)	156 (152.9)	593
Coke Oven Gas - BCF	271 (135.5)	5 (2.5)	250 (125.0)	190 (95.0)	716
Blast Furnace Gas - BCF	2575 (244.6)	- -	198 (18.8)	1655 (157.2)	4428
Electric Pwr.-Billion KWH	6 (58.5)	25 (243.7)	3 (29.2)	24 (234.0)	58
Totals-Trillion Btu	(593.1)	(352.0)	(588.3)	(689.5)	

Notes: () Equivalent Energy in Trillion Btu

Fuel Oil - 144,000 Btu/gal.

Tar & Pitch - 144,500 Btu/gal.

LPG - 93,500 Btu/gal.

Natural Gas - 980 Btu/SCF

Coke Oven Gas - 500 Btu/SCF

Blast Furnace Gas - 95 Btu/SCF

Electric Power - 84% Purchased; 16% In-Plant Generated

9750 Btu/kWh (35% Generator Station Efficiency)

Fuel consumption refers only to the steel manufacturing operations.

The coke oven battery energy consumption of 111.3 trillion Btu is indicated in Table 6.4 under category, "Coal".

TABLE 6.3

COKE OVEN TYPICAL ENERGY BALANCE

<u>Heat Input</u>	<u>BTU/Ton Coke</u>
Coal	2,050
Air	0
Fuel Gas *	2,050
Combustion of Fuel Gas, HHV *	2,078,400
Exothermic Heat of Carbonization	390,700
Total	<u>2,473,200</u>

<u>Heat Output</u>	<u>BTU/Ton Coke</u>
Coke, 1945°F	969,900
Coke Oven Gas, 1220°F	317,500
Water Vapor, 1220°F	258,200
Tar & Light Oil, 1220°F	81,700
Stack Gas, 515°F	454,400
Radiation & Convection	319,500
Total	<u>2,473,200</u>

Note: * Fuel Gas Sources: 78% Coke Oven Gas (500 BTU/SCF)
22% Enriched Blast Furnace Gas

TABLE 6.4
1978 SOURCES OF FUEL ENERGY
FOR THE STEEL MILL-COKE OVEN COMPLEX

<u>Source</u>	<u>Trillion BTU</u>	<u>% Total</u>
Coal*	911	39
Oil & Hydrocarbon	277	12
Natural Gas	581	25
Electric Power	565	24
Totals	<u>2334</u>	<u>100</u>

Note: * Coal includes coke oven gas, coke-derived blast furnace gas, fuel gas to coke oven, in addition to coal.

TABLE 6.5
WASTE ENERGY CONSERVATION POTENTIAL

<u>Plant Operation</u>	<u>Potential Saving Million BTU/Ton Step</u>	<u>Industry Potential Saving Trillion BTU</u>
<u>Waste Gas Streams</u>		
Reheat & Annealing Furnaces	0.7	96
Soaking Pits	0.2	18
Coke Oven Flue Gas	0.1	5
Dry Quench Coke	0.7	32
<u>Waste Fuel Streams</u>		
Blast Furnace Gas	0.7	32
BOF Gas	0.5	23
<u>Others</u>		
Control & Optimization	0.7	64
Continuous Casting	2.4	33
Preheat Coking Coal	0.2	9
Total		312

Note: Estimates based on recoverable waste heat energy from waste gas streams and improved modes of operation.

Three areas in the steel industry process that appear most promising for waste heat conservation are the following:

- Reheat furnaces
- Dry quench coke
- Coke oven flue gas.

A typical reheat furnace energy consumption (13,14) is shown in Table 6.6 for a 250 ton/hour unit.

TABLE 6.6
REHEAT FURNACE ENERGY CONSUMPTION

	Million BTU/Ton
Heat to Steel	0.73
Stack Gas Loss	0.70
Heat Loss Through Walls	0.10
Heat Loss to Water-Cooled Walls	0.37
Heat Loss Through Slots	0.04
Heat Loss Through Doors	0.60
Total Heat Output	2.00

A typical furnace will operate on natural gas or coke oven gas. The stack gas exits to the atmosphere at 2300°F. In recent years about 50% of the furnaces have been retrofitted with recuperators. The stack gas is cooled to 2000 °F with an air bleed before entering the recuperator in order to extend equipment life. The recuperator preheats furnace combustion air to about 900°F. The stack gas stream is vented to the atmosphere at about 1400°F. There have been proposals to put a waste heat boiler on the 1400°F flue gas to generate steam for electric power. (14)

It has been estimated that an average steel mill of approximately 4 million tons/year production capacity would have five (5)

reheat furnaces of 250 tons/hour capacity each. The number of reheat furnaces in the U.S. steel industry may range from 170 to 350, with the capacity size ranging from 50 to 400 tons/hour. The total potential waste heat energy available for recovery would be 96 trillion Btu annually.

The hot coke discharges from the coke oven battery chamber ovens at 1945°F. It is rapidly conveyed to a water quench system where it is cooled to below 400°F. For many years, proposals have been made to adopt the dry quench system to recover the waste heat energy. The dry quench technology has been developed and is in operation in Russia and Japan. The hot coke is quenched by an inert gas recycle which rejects the heat acquired to a waste heat boiler. The boiler generates high pressure superheated steam for a steam turbine generator to produce in-plant electric power. A typical energy balance is shown in Table 6.7 for the dry quench waste heat recovery.

TABLE 6.7

TYPICAL DRY QUENCH COKE ENERGY BALANCE*

<u>Heat Input</u>	<u>Million BTU/Ton</u>
Hot Coke, 1945°F	970,000
Inert Gas Recycle, 400°F	160,000
Total	1,130,000
<u>Heat Output</u>	
Cooled Coke, 450°F	202,000
Inert Gas Recycle, 1700°F	860,000
Loss Thru Walls (Est.)	68,000
Total	1,130,000

*Sources: References 9, 12, 15, 16.

Since there are no operational plants in the U.S. and data from Japan and Russia are fragmentary, exact energy balances are not possible. The inert gas recycle will reject 700,000 Btu/ton of coke quenched to a waste heat recovery system. Since the steel industry produced 45.1 million tons of captive coke in 1978, the potential heat recovery is 31.6 trillion Btu.

The coke oven flue gas offers a waste heat gas stream at 515°F, as indicated in Table 6.3. Assuming the gas stream is cooled to 300°F, it has the potential to reject approximately 110,000 Btu/ton of coke to a waste heat recovery system. Because the underfiring of a coke oven is dependent on two different sources of fuel gas, namely coke oven gas and enriched blast furnace gas, the stack flue gas will

vary in combustion and heat content. Hence, the Btu content may be variable.

6.4.2 Current Recovery and Utilization

The steel industry does not recover the heat in the coke oven stack flue gas. There is no dry quench coke operation in the U.S.; therefore, the sensible heat residing in the hot coke is lost to the atmosphere. Approximately one-half of the 170 to 350 reheat furnaces are equipped with metal recuperators to partially recover the waste heat in the reheat furnace stack gas and utilize it to preheat the fuel combustion air to 900°F. This conservation program only started a few years ago.

The steel industry has been reluctant to develop energy conservation in these areas because of two basic reasons:

- Large capital investments required result in unsatisfactory ROI profit situations which make recovery of waste energy economically undesirable; and
- Retrofitting waste energy conservation equipment to existing plants poses many problems, such as lack of space to fit in equipment, excessive cost of retrofit which makes recovery of waste heat economically unattractive, and impact of regulations that may make plant obsolete.

6.5 Potential FWHRs Applications

Approximately 9.3% of the steel industry's purchased fossil fuel-derived energy could be saved by recovering the waste heat from the reheat furnaces, the coke quench process and the coke oven flue gas. In the year 1976 for which the latest cost figures are available⁽²⁾, the Bureau of Census determined that the purchased energy of 1,427 trillion Btu cost \$3.116 billion. An 8.6% saving of energy in 1976 would have amounted to about \$268 million. The magnitude of such a saving would have very positive effects, such as:

- Steel industry profits would increase
- Ability of domestic industry would improve to combat imports
- Steel industry would have more internal capital investment funds generated to upgrade the industry and increase industry employment and productivity.

The major problem is that the industry apparently does not have the capital investment funds. The industry in each case has to decide between the value of waste energy conservation investment and

a competing investment in replacement or modernizing plant equipment. The latter produces immediate results, namely, more production. Waste energy conservation takes a much longer time in payout of project costs before the monetary advantage becomes a reality.

The two modes of utilization of recovered waste heat would be (1) preheating air for combustion or drying raw material, and (2) developing high-pressure superheated steam for turbine-generator to produce in-plant electric power. The dry quench coke and the reheat furnace setups are suitable for waste heat recovery to provide steam turbine generated electric power. The coke oven flue gas situation is only suitable for preheat drying air or low pressure steam. Since steel mills typically have an abundance of low pressure steam, the only application in this case would be drying raw material, such as coal for the coke oven battery.

Installation of a dry quench coke system with waste heat recovery requires a great deal of space. According to the steel industry and construction contractors, there is not much space available for such a retrofit in existing steel mills. Also, the retrofit would be exceedingly costly as compared to a "greenfields" project. Installation of a FWHRs on a reheat furnace also poses retrofit space problems. Should there be a recuperator in place, this would increase the problem. There should be no space problem as regards a FWHRs for the coke oven stack flue gas.

Apparently, there would be no dry quench coke operation problems as regards a FWHRs application. A dry quench coke system should improve environmental pollution control. Also, the licensors of the dry quench process claim other advantages, including improved coke quality; improved blast furnace operation due to the coke quality, decreased coke breeze which means higher coke yield, and improved breeze quality which permits it to be used as a sinter fuel. The major problem in implementing the dry quench coke process is that there is no current operational experience in the U.S.

6.6 Technical and Economic Assessment

The proposed FWHRs applications analyzed for the steel industry are as follows:

- (1) Steam/electric power generation with heat recovery from the flue gas from the reheat furnace with a recuperator.
- (2) Steam/electric power generation with heat recovery from the flue gas from reheat furnace without a recuperator.

The technical and economic assessment of these proposed applications is provided in the following subsections; these analyses are based on the approach developed in Section 3.0.

6.6.1 Application #1: FWHRs Using Flue Gas From Reheat Furnace With Recuperator

The proposed FWHR application, shown in Figure 6.3, raises steam for electric power generation using recovered heat from the flue gas of the steel reheat furnace (250 tons/hr throughput) with a recuperator.

The proposed application requires a two-stage FWHR system, balance of steam plant, turbo-generator and associated equipment. The technical and economic analyses of the proposed FWHR application are provided in Tables 6.8 and 6.9.

6.6.2 Application #2: FWHRs Using Flue Gas From Reheat Furnace Without Recuperator

The proposed FWHR application, shown in Figure 6.4, recovers heat from the flue gas of a 250 tons/hr throughput steel reheat furnace without a recuperator. Steam is raised to generate electric power for in-plant use.

The proposed application uses a staged fluidized bed concept and requires an FWHR system, balance of steam plant, turbo-generator and associated equipment. The technical and economic analyses of the proposed FWHR application are provided in Tables 6.10 and 6.11.

6.6.3 Summary of FWHR Applications in Steel Industry

The two applications analyzed appear to be technically and economically feasible. The use of FWHRs could eliminate the need for the use of recuperators, which are known to burn out frequently. The FWHR system has a potential for longer term trouble-free operation.

Although the FWHR appears to be commercially viable, the potential problem areas -- corrosion, erosion, fouling -- need to be resolved at the design stage. Furthermore, the performance of FWHR systems needs to be established over a long period of continuous operation.

FIGURE 6.3
FWHRS USING REHEAT FURNACE
FLUE GAS WITH RECUPERATOR

TABLE 6.8

TECHNICAL ASSESSMENT OF FWHRs IN STEEL INDUSTRY
APPLICATION #1 - FLUE GAS FROM REHEAT FURNACE WITH RECUPERATOR
(250 TONS/HR FURNACE)

WASTE GAS STREAM CHARACTERISTICS

Gas Temperature	1400°F
Flow Rate	60,000 SCFM
Heat Available	74.4 Million BTU/HR
Stack Gas Temperature	350°F
Corrosive Species	Not Available
Condensible Species	Not Available

SERVICE/APPLICATION CHARACTERISTICS

Type	Electric Power Generation
Steam	600 PSIG; 650°F

ENERGY CONSERVATION POTENTIAL

Fan Power	600 HP (450 KW)
Energy Resource Expended	5.1 Million BTU/HR
Energy Recovered	5,800 KW
Net Energy Conservation	5,350 KW
Energy Conservation Parameter (Z)*	13

POTENTIAL TECHNICAL PROBLEMS

- Operation of staged bed systems needs to be established.

*Z > 6 Considered Highly Favorable Energy Conservation

TABLE 6.9

ECONOMIC ASSESSMENT OF FWHRs IN STEEL INDUSTRY
APPLICATION #1 - FLUE GAS FROM REHEAT FURNACE WITH RECUPERATOR
(250 TONS/HR FURNACE)

FWHRs COSTS

FWHR Unit	\$1,003,800
Balance of Steam Plant	391,300
Auxiliary Systems	1,357,300
Total Equipment	<u>\$2,752,400</u>
Installation Cost	<u>\$1,376,200</u>
Total Installed Cost	<u>\$4,128,600</u>

OPERATING COSTS (ANNUAL)

Electric Power (Fan Power)	\$162,000
Maintenance (Scheduled & Repair)	412,900
Total Operating	<u>\$574,900</u>

SAVINGS FROM CONSERVATION

Savings Per Year	\$2,199,600
Net Savings Per Year	\$1,624,700
Payback Period	2.5 Years

FIGURE 6.4
FWHR USING REHEAT FURNACE
FLUE GAS WITHOUT RECUPERATOR

TABLE 6.10

TECHNICAL ASSESSMENT OF FWHRs IN STEEL INDUSTRY
APPLICATION #2 - FLUE GAS FROM REHEAT FURNACE WITHOUT RECUPERATOR
(250 TONS/HR FURNACE)

WASTE GAS STREAM CHARACTERISTICS

Gas Temperature	2300 ^o F
Flow Rate	60,000 SCFM
Heat Available	140.4 Million BTU/HR
Stack Gas Temperature	350 ^o F
Corrosive Species	Not Available
Condensible Species	Not Available

SERVICE/APPLICATION CHARACTERISTICS

Type	Electric Power Generation
Steam	600 PSIG; 650 ^o F

ENERGY CONSERVATION POTENTIAL

Fan Power	600 HP (450 KW)
Energy Resource Expended	5.1 Million BTU/HR
Energy Recovered	10,950 KW
Net Energy Conservation	10,500 KW
Energy Conservation Parameter (Z)*	24

POTENTIAL TECHNICAL PROBLEMS

- Operation of staged bed systems needs to be established.

*Z > 6 Considered Highly Favorable Energy Conservation

TABLE 6.11

ECONOMIC ASSESSMENT OF FWHRs IN STEEL INDUSTRY
APPLICATION #2 - FLUE GAS FROM REHEAT FURNACE WITHOUT RECUPERATOR
(250 TONS/HR FURNACE)

FWHRs COSTS

FWHR Unit	\$1,111,200
Balance of Steam Plant	700,800
Auxiliary Systems	2,430,900
Total Equipment	<u>\$4,242,900</u>
Installation Cost	<u>\$2,121,500</u>
Total Installed Cost	<u>\$6,364,400</u>

OPERATING COSTS (ANNUAL)

Electric Power (Fan Power)	\$162,000
Maintenance (Scheduled & Repair)	636,500
Total Operating	<u>\$798,500</u>

SAVINGS FROM CONSERVATION

Savings Per Year	\$3,942,000
Net Savings Per Year	<u>\$3,143,500</u>
Payback Period	2.0 Years

6.7 Summary of Industry Comments

6.7.1 Industry Comments

U.S. Steel Corporation, the leading steel producer, representing 23% of U.S. capacity and Koppers Company, a major engineer-contractor in the coke oven-steel mill industry, were interviewed. Their comments were essentially similar, namely:

- Lack of sufficient capital investment resources restrain the steel industry from retrofitting waste heat energy recovery projects.
- Retrofit programs which were evaluated are so relatively costly that steel industry investment criteria cannot be achieved as regards ROI or payout period.
- Currently, with the exception of a proposed new U.S. Steel Corporation plant in the area of Conneaut, Ohio, which has remained in the proposed stage for over two years, there are no plans for a "greenfield" project. Hence, there is no opportunity to try out a number of waste energy conservation technologies and equipment at reasonable capital investment that would prove the advantages of waste energy conservation.

U.S. Steel Corporation's investment policy requires a payout time of no more than three (3) years, or a 50% to 60% ROI. The FWHR application has been evaluated by U.S. Steel and was found to have an unsatisfactory "payout." Details of their analysis were not available.

Koppers Company is interested in engineering the latest waste energy conservation concepts into a coke oven battery project if they could receive a purchase order from a steel mill. Koppers Company has analyzed Russian dry quench coke technology offered by Nippon Steel Company, the licensor. Koppers is interested in recovering waste heat from the coke oven blue gas and the hot coke.

Pennsylvania Engineering Corporation is the U.S. licensor for the dry quench coke technology being offered by Waagner-Biro, Vienna, Austria. Pennsylvania Engineering has completed a study for Inland Steel which has submitted a proposal to DOE for a demonstration program at its Indiana steel plant. The dry quench project with waste heat recovery is estimated to cost about \$20 million.

6.7.2 Industry Receptivity

U.S. Steel Corporation is interested in participation in a FWHRs project. On the basis of experience with another demonstration program, they suggest that cost-sharing be extended beyond project engineering, equipment and material procurement, and construction costs to the operational phases, namely, project demonstration plant operation, maintenance, and change order costs.

REFERENCES-STEEL INDUSTRY

1. Statistical Abstract of U.S., 1978, U.S. Dept. of Commerce.
2. "Annual Survey of Manufacturers, 1976: Fuels and Electric Energy Consumed", M76 (AS)-4.1, p.8, Bureau of Census, U.S. Dept. of Commerce.
3. American Iron & Steel Institute, Wash., D.C. Private communications.
4. "Annual Reports-1978": U.S. Steel, Bethlehem, Republic Steel, Inland Steel, Armco.
5. "Blast Furnaces-U.S. and Canada", Iron and Steel Engineer, Sept. 1978, p.63-64.
6. "Encyclopedia of Chemical Technology", 3rd Edition, Vol. 6, p.284-305.
7. "The Making, Shaping and Treating of Steel", 9th Edition (1971), U.S. Steel Corp., Pittsburgh, Pa.
8. "Annual Statistical Report 1978", Tables 38,40,45, 46 (p.69,70,75,76). Also, "Pig Iron and Raw Steel Production", AIS-7, 1/19/79. American Iron & Steel Institute, Washington, D.C.
9. "Kirk-Othmer: Encyclopedia of Chemical Technology, 3rd Edition, Vol. 6, p.284-305.
10. "Potential for Energy Conservation in the Steel Industry", Document No. PB-244097, Battelle Columbus Laboratories, May 30, 1975 (prepared for FEA). Note Table I-1, pg. I-32.
11. "Energy Conservation in the Steel Industry", 84th General Meeting American Iron & Steel Institute, New York, New York, May 26, 1976.
12. "Dry Coke Quenching", Iron and Steel Engineer, July 1977, p. 73-79.
13. "Furnace Design Improvements", F.J. Vereecke, Iron & Steel Engineer, Aug., 1977, p.33-39.
14. "Electricity from Waste Gases", T.A. Blanchard, Iron & Steel Engineer, May 1978, p.54-59.

15. "Dry Coke Quenching", R. Kemmetmueller, Iron & Steel Engineer, Yearbook 1973, p. 440-447.
16. "Chemical Engineers Handbook", R.H. Perry & C.H. Chilton, Table 3-201, p. 3-136.

7.0 ALUMINUM INDUSTRY

7.1 Significance of Industry in U.S. Economy

The primary aluminum industry (SIC 3334) consists of 31 plants, employ 28 thousand people, and in 1977 shipped \$4.616 billion of products or 0.34% of all U.S. manufactures. The plants were located in 17 states. There were 12 major companies in the primary aluminum business which have a total annual production capacity of 5.2 million tons of virgin metal. The producers make the virgin metal from ore.^(1,2,3) The secondary producers have facilities devoted to producing metal from scrap. This industry, classified SIC 3341, is not addressed in this study.

In 1977, the primary aluminum industry produced 4.5 million tons valued at \$4.526 billion.⁽¹⁾ The primary industry consumed 322.8 trillion Btu of purchased fuels and energy in 1977⁽⁴⁾ at a cost of \$709.3 million. In energy demand, the primary aluminum industry is ranked eighth among all industries. The industry consumed 2.5% of the total U.S. industries' demand of 12,738 trillion Btu.

7.2 Major U.S. Producers

The 12 U.S. producers in the primary aluminum industry are shown in Table 7.1.^(2,5) The top five represent 77.5% of the industry capacity. Some of the companies have foreign operations; however, all the listed capacities are for U.S. operations only.

7.3 Basic Process Description

The primary aluminum industry is dependent on bauxite ore which is formed by the weathering of aluminum-bearing ores.⁽⁶⁾ The ore is crushed, washed, and dried. Alumina is produced by chemically processing the bauxite to remove various metals, such as iron, titanium, etc., and to reduce the silica content. Almost all commercially produced alumina is obtained by the Bayer process which involves a caustic leach at elevated temperature and pressure, followed by separation of the resulting sodium aluminate solution and selective precipitation of the aluminum as the hydrated aluminum oxide ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$). Leaching temperatures range from 220°F to 550°F with corresponding pressures ranging from 60 to 1000 psi depending on the composition of the raw bauxite ore.

The primary aluminum is produced by electrolysis of alumina in a molten bath of natural or synthetic cryolite (sodium aluminum fluoride). In the electrolysis, the alumina must be purer than 99.5% Al_2O_3 . The resistance of the bath to the flow of electric current is sufficient to maintain the operating temperature at 930 to

TABLE 7.1

1978 MAJOR U.S. PRIMARY ALUMINUM PRODUCERS

<u>Company</u>	<u>Capacity Tons</u>	<u>Production Tons</u>	<u>Sales*</u> <u>Million Dollars</u>
Alcoa	1,700,000	1,779,000	4,052
Reynolds	975,000	954,700	1,674
Kaiser	724,000	710,000	1,830
Consolidated	352,000	458,000	743
Anaconda	300,000	275,600	597
Alumax	218,700	-	718**
Howmet	218,700	-	-
Martin Marietta	210,000	-	472
Revere	203,200	-	371
Noranda	142,700	-	-
National Aluminum	90,000	-	-
Southwire	90,000	-	-
Total	5,224,930		

NOTE: * Represents aluminum sales only, except as noted by **

** Includes other products

980°C. The electrolysis cells (a battery of cells is called a "potline") utilize direct current ranging from 65,000 to 150,000 amperes. The voltage drop across a single cell is 4.5 to 5.0 volts and across a potline, it may be 600 to 1000 volts. The cells are tapped periodically for the molten aluminum.

The molten metal may be sent directly to rolling, casting, or extrusion to manufacture commercial items. Or, if the mill schedule does not require immediate finished products, the melt will be cast into slabs and ingots. These raw metal items will then be held in storage. When production scheduling requires, the storage inventory will be released to melting furnaces. The primary aluminum is then remelted; alloy metals may be added according to specification. Then the melting furnace is tapped and the molten material is sent to rolling, casting, extrusion and other operations for finished products.

A representation of the industry is shown in Figure 7.1 highlighting the aluminum melting furnace.

7.4 Industry Waste Heat Production

The primary aluminum industry, while essentially a one product industry, has a wide diversity of operations, practices, and commercial products within the 12 producers. Also, with plants in 17 states, there are marketing differences as well as plant differences which affect many aspects of the operations. Therefore, the energy consumption and waste heat production can only be generalized for the industry. When applied to a specific plant, the energy aspects must be evaluated as "typical" and "possibly applicable".

7.4.1 Sources and Amounts

The latest year, 1977, for which information is available on consumption of purchased fuels and electric energy, the primary aluminum industry consumed 322.8 trillion Btu, valued at \$709.3 million, as reported by the Bureau of the Census.⁽⁴⁾ The Aluminum Association⁽⁵⁾ has reported that for year 1978, the industry used a total of 1001.6 trillion Btu. Although the energy consumptions quoted are for two different years, they are comparable since the industry for the years 1977 and 1978 was operating its primary aluminum plants at near capacity with no new facilities added during this period. The difference in the quoted energy consumption results from the industry having purchased approximately 32 percent of its required energy and obtaining the remainder from captive sources. Electric power constitutes 66% of the purchased energy and 68% of the total energy consumed, both purchased and captive. As an example, Alcoa in a fact booklet states that it "generates almost half of the electric power it uses in the U.S...."⁽⁸⁾

FIGURE 7.1
ALUMINUM PLANT FLOWSHEET*

*Casting, Rolling, Extrusion,
Wire, Forging, Tubing

The energy consumption situation is summarized in Table 7.2 for primary aluminum (SIC 3334).

TABLE 7.2

ENERGY CONSUMPTION-PRIMARY ALUMINUM PRODUCERS

<u>Energy Source</u>	<u>Purchased-1977 Trillion Btu</u>	<u>Total-1978 Trillion Btu</u>
Electric Power	214.2 (66%)	681.5 (68%)
Fuels (Natural Gas, Fuel Oil, Coal, and other hydrocarbons)	108.6 (34%)	320.1 (32%)
Totals	<u>322.8</u>	<u>1001.6</u>

The more interesting evaluation is to determine the allocation of energy between operations⁽⁷⁾ as shown in Table 7.3. Examining Table 7.3 indicates that the major fossil fuel energy consumption is in two plant operations: alumina production and furnaces -- melting, holding, casting, etc. The fossil fuel usage in the alumina operation is for heating purposes to maintain the chemical caustic leaching operation at elevated temperature. There is considerable waste heat generated, but it is unrecoverable. However, the situation is different in the furnace operations. In these operations, natural gas (mainly) and fuel oils are burned to melt and heat up aluminum. The combustion flue gases in this operation used to be vented to the atmosphere. In recent years, the industry's energy conservation program has concentrated on installing recuperators on these furnaces. Also, there has been a considerable amount of research and development work performed on furnace flue gas recuperation.^(9,10)

An interesting analysis of energy consumption per pound of product for every step of processing in the aluminum industry has been prepared by W. E. Stephens, Alumax, Inc.⁽¹¹⁾ This is shown in Table 7.4 and may be considered a typical generalization when compared to Table 7.3.

TABLE 7.3

ENERGY CONSUMPTION ACCORDING TO PLANT OPERATION

(Primary Aluminum Industry - 1978)

<u>Plant Operation</u>	<u>Electric Power Trillion BTU</u>	<u>Fuels Trillion BTU</u>	<u>Totals</u>	
			<u>Trillion BTU</u>	<u>%</u>
Bauxite	0.20	0.16	0.36	0.1
Alumina	12.1	101.0	113.1	11.2
Electrolytic Cell (Molten Metal)	600.0	101.9	701.9	70.1
Melting, etc. Furnaces	7.0	53.2	60.2	6.0
Mill Products	56.8	60.4	117.2	11.7
Other Fabrication	4.3	4.5	8.8	0.9
Totals	<u>680.4</u>	<u>321.2</u>	<u>1001.6</u>	<u>100.0</u>

TABLE 7.4
TYPICAL ENERGY CONSUMPTION ACCORDING TO OPERATION

<u>Plant Operation</u>	<u>BTU/LB Finished Aluminum</u>	
Bauxite & Alumina	18,200	(14%)
Molten Metal (Electrolysis)	84,500	(65%)
Melting, etc. Furnace	7,800	(6%)
Mill Products & Fabrication	<u>19,500</u>	<u>(15%)</u>
Totals	130,000	100%

Table 7.4 indicates where the fossil fuels energy is consumed, other than electric power. The industry is concentrating on reducing electrical power consumption since this constitutes the major area in which savings are possible. The fuel-fired furnaces are their second target for energy conservation.

There is relatively sparse information on the number of melting furnaces in the U. S. Although sources refuse to comment,⁽¹⁴⁾ there are some clues. In 1976, Alcoa had 90 melting furnaces at 11 plant locations.⁽¹²⁾ In that year, Alcoa had a primary aluminum capacity of 1.675 million tons, or 32.3% of total U. S. This indicates that there may have been a total of about 280 melting furnaces. Some industry sources speculate that a typical plant would have 7 to 15 melting, holding and casting furnaces. Therefore, in 1976, at 31 plants there may have been a total of 217 to 465 furnaces. Since the industry has not added more plant investment since 1976, it is reasonable to estimate that perhaps 280 melting furnaces exist in the U.S.

7.4.2 Current Recovery and Utilization

Within the last few years, the industry has added recuperators to the melting furnaces to recover some of the flue gas waste heat. The waste heat recovered is used to preheat the furnace combustion air to about 900°F. According to Refs. 11, 12, 13, melting furnaces range in capacity and operating details. The industry situation may be generalized by estimating a typical melting furnace operation, as follows:

- 100,000 lbs. aluminum charge
- Natural gas fuel

- Melt cycle time - 3 to 6 hours
- Furnace flue gas - up to 2300°F
- Recuperator exit hot gas - up to 1500°F
- Preheated air - 900 to 1000°F
- Furnace heat input - up to 30 million Btu/Hr
- 53% of heat input exits in stack flue gas
- 80% operation stream time (actually, much higher in recent years).

Various industry sources estimate the number of recuperators installed on melting furnaces to be about 40%. If waste heat was recovered from the flue gas between 2300°F and 1200°F, approximately 50% of the waste heat energy would be recovered for utilization. Therefore, a simplified calculation on potential waste heat recovered and utilized can be made as follows:

No. Furnaces	60% of 280 = 168
Recovered & Utilized Heat Per Furnace Per Hour	$0.5 \times 0.53 \times 30 \times 10^6 = 8.0 \times 10^6$ BTU/HR
No. Furnace Turns Annually (Assume 3 hrs. cycle and 0.75 Recharge Efficiency)	$0.8 \times 24 \times 365 \times 0.75 / 3 = 1752$
Potential Waste Heat Recovered & Utilized From Melting Furnaces	$168 \times 3 \times 8.0 \times 10^6 \times 1752 = 7.0$ Trillion BTU

According to Table 7.3, the melting furnaces consumed 53.2 trillion Btu annually of natural gas and fuel oil. The calculated 7.0 trillion Btu year recovered and utilized would represent a 13% fossil fuel saving in this plant operation, in addition to that currently saved by existing recuperators.

A secondary use for preheated air is to dry the "sows" in storage (1000 lb. aluminum ingots) by heating them to 300°F before charging to the melting furnaces.⁽¹⁵⁾ Other uses of preheated air are for drying and preheating scrap.⁽¹⁶⁾ Apparently, the industry is employing recuperator preheated air for a variety of plant and operation purposes.

7.5 Potential FWHR Applications

Waste heat recovery from the flue gas of the aluminum melting furnaces is considered a highly desirable potential application for the FWHR. The FWHR could be used to preheat air for fuel combustion in the furnace and for drying and preheating aluminum ingots and scrap before charging the melting furnaces. The FWHR could also be used to raise steam for in-plant electric power generation.

7.6 Technical and Economic Assessment

The proposed FWHR applications analyzed for the aluminum industry are as follows:

- (1) Steam/electric power generation with heat recovered from the flue gas of a melt furnace.
- (2) Preheating combustion air with heat recovered from the flue gas of a melt furnace.

The technical and economic assessment, provided in the following subsections, is based on the approach developed in Section 3.0.

7.6.1 Application #1: FWHR Using Flue Gas for Electric Power Generation

The proposed FWHR application, shown in Figure 7.2, consists of steam/electric power generation using waste heat recovered from the aluminum melt furnaces (capacity 90,000 lbs. per charge) flue gas.

Although the furnace capacity is stated in terms of a charge, its operation results in a continuous flow of flue gas. Since each plant generally has several melt furnaces, the flue gas should be able to be ducted to achieve a desired flow rate. The application analyzed uses a two-stage FWHR system with a waste gas stream of 10,000 SCFM.

Equipment required in addition to the two-stage FWHR system includes the balance of steam plant and auxiliary systems (e.g., turbine generator and associated equipment). The technical and economic analyses are summarized in Tables 7.5 and 7.6.

7.6.2 Application #2: FWHR Using Flue Gas for Air Preheating

The proposed FWHR application, shown in Figure 7.3, consists of combustion air preheating using waste heat recovered from the aluminum melt furnace flue gas. All conditions are assumed the same as in Application #1 except for the service characteristics.

FIGURE 7.2
FWHRs USING FLUE GAS FOR POWER GENERATION
(ALUMINUM INDUSTRY)

TABLE 7.5

TECHNICAL ASSESSMENT OF FWHRS IN ALUMINUM INDUSTRY
APPLICATION #1: FLUE GAS FROM MELT FURNACE FOR ELECTRIC POWER
(90,000 LBS CAPACITY)

WASTE GAS STREAM CHARACTERISTICS

Gas Temperature	2200°F
Flow Rate	10,000 SCFM
Heat Available	22.6 Million BTU/HR
Stack Gas Temperature	350°F
Corrosive Species	Not Available
Condensible Species	Not Available

SERVICE/APPLICATION CHARACTERISTICS

Type	Electric Power Generation
Steam	600 PSIG; 650°F

ENERGY CONSERVATION POTENTIAL

Fan Power	100 HP (80 KW)
Energy Resource Expended	850,000 BTU/HR
Energy Recovered	1,760 KW
Net Energy Conservation	1,680 KW
Energy Conservation Parameter (Z) *	22

POTENTIAL TECHNICAL PROBLEMS

- Operation of two-staged bed system needs to be established.

*
Z>6 Considered Highly Favorable Energy Conservation

TABLE 7.6

ECONOMIC ASSESSMENT OF FWHRs IN ALUMINUM INDUSTRY
APPLICATION #1: FLUE GAS FROM MELT FURNACE FOR ELECTRIC POWER
(90,000 LBS CAPACITY)

FWHRs COSTS

FWHR Unit *	\$197,100
Balance of Steam Plant	112,700
Auxiliary Systems	390,800
Total Equipment	<u>\$700,600</u>
Installation Cost	<u>\$350,300</u>
Total Installed Cost	<u>\$1,050,900</u>

OPERATING COSTS (ANNUAL)

Electric Power (Fan Power)	\$28,800
Maintenance (Scheduled & Repair)	105,100
Total Operating	<u>\$133,900</u>

SAVINGS FROM CONSERVATION

Savings Per Year	\$633,600
Net Savings Per Year	\$499,700
Payback Period	2.1 Years

*Based on two stage system; cost for high temperature stage is assumed to be 20% greater to allow for expensive structural materials.

FIGURE 7.3
FWHRs USING FLUE GAS FOR
COMBUSTION AIR PREHEATING
(ALUMINUM INDUSTRY)

The proposed application requires a two-stage FWHR with a capacity of 10,000 SCFM to preheat combustion air to 1000°F. It is assumed that all the recovered heat is used to preheat the needed combustion air. The technical and economic analyses are summarized in Tables 7.7 and 7.8.

7.6.3 Summary of FWHR Applications in Aluminum Industry

The two applications analyzed appear to be technically and economically feasible. Combustion air preheating application would require a less complex system with less equipment than the power generation application.

Although the FWHR applications appear to be economically viable, the potential problem areas -- corrosion, erosion, fouling -- need to be resolved at the design stage. The performance of the FWHR system also needs to be established over a long period of continuous operation.

7.7 Summary of Industry Comments

7.7.1 Industry Comments

Telephone interviews were held with Alcoa, Reynolds Metals, and Kaiser Aluminum (the top three producers) and the Aluminum Association, Washington, D.C. (the trade association).

There was some sensitivity exhibited by the industry in discussing waste energy conservation. The industry, as a whole, is engaged in various development programs to reduce energy consumption, mainly electric power. Through the Aluminum Association, the industry is holding periodic workshops where there is an exchange of industrial information on energy conservation developments. The workshop papers issued in the 1976 and 1979 meetings indicate that a major topic is recuperating the waste heat in the stack gas from the melting furnace. It is obvious that the aluminum industry is receptive to new technology and equipment for waste heat recovery and utilization.

Alcoa noted in a telephone conversation that they had made a paper study of a FWHR for a melting furnace and had concluded that the economics were not satisfactory, i.e., payout period and ROI did not meet the Alcoa standard for capital investment.

7.7.2 Industry Receptivity

The aluminum industry was somewhat interested in a demonstration program project, but their comment was generally restrained. The restrained attitude may be due to the fact that the major producers claim that they are vigorously pursuing possibilities and developments in (a) reduction of energy consumption and (b) waste heat energy recovery and utilization.

TABLE 7.7

TECHNICAL ASSESSMENT OF FWHRs IN ALUMINUM INDUSTRY
APPLICATION #2: FLUE GAS FROM MELT FURNACE FOR COMBUSTION AIR PREHEATING
(90,000 LBS CAPACITY)

WASTE GAS STREAM CHARACTERISTICS

Gas Temperature	2200°F
Flow Rate	10,000 SCFM
Heat Available	20 Million BTU/HR
Stack Gas Temperature	500°F
Corrosive Species	Not Available
Condensible Species	Not Available

SERVICE/APPLICATION CHARACTERISTICS

Type	Combustion Air Preheating (70°F to 1000°F)
------	---

ENERGY CONSERVATION POTENTIAL

Fan Power	100 HP (80 KW)
Energy Resource Expended	850,000 BTU/HR
Energy Recovered	20 Million BTU/HR
Net Energy Conservation	19 Million BTU/HR
Energy Conservation Parameter (Z)*	24

POTENTIAL TECHNICAL PROBLEMS

- Operation of two-staged bed system needs to be established.

*Z > 6 Considered Highly Favorable Energy Conservation

TABLE 7.8

ECONOMIC ASSESSMENT OF FWHRs IN ALUMINUM INDUSTRY
APPLICATION #2: FLUE GAS FROM MELT FURNACE FOR COMBUSTION AIR PREHEATING
(90,000 LBS CAPACITY)

FWHRs COSTS

FWHR Unit*	\$295,700
Balance of Steam Plant	None
Auxiliary Systems	None
Total Equipment	<u>\$295,700</u>
Installation Cost	\$147,900
Total Installed Cost	<u>\$443,600</u>

OPERATING COSTS (ANNUAL)

Electric Power (Fan Power)	\$28,800
Maintenance (Scheduled & Repair)	44,400
Total Operating	<u>\$73,200</u>

SAVINGS FROM CONSERVATION

Savings Per Year	\$253,400 (Natural Gas at \$2/ Million BTU)
Net Savings Per Year	\$180,200
Payback Period	2.5 Years

*Two stage FWHRs air preheating unit assumed to cost 50% more than steam generation unit for Application #1.

REFERENCES - ALUMINUM INDUSTRY

1. "1977 Census of Manufactures - Primary Aluminum SIC 3334," Preliminary Report, June 1978 Bureau of Census, Washington, D.C.
2. "Aluminum Statistical Review - 1978," August 1979, Aluminum Assoc., Washington, D.C., p. 34-35.
3. "Aluminum," Chemical Week, Jan. 31, 1979, p. 29-30.
4. "Annual Survey of Manufactures, 1977 - Fuels and Electric Energy Consumed," MC77-SR-4-(P), May 1979, Bureau of Census, Washington, D.C.
5. Corporate Annual Reports - 1978.
6. "Mineral Facts and Problems," Bulletin 667, 1975 Edition, p. 37-66, Bureau of Mines, Washington, D.C.
7. "Energy Conservation and the Aluminum Industry," June 1979, Aluminum Association, Washington, D.C.
8. "Facts about Alcoa," p. 6, October 1979, Aluminum Company of America, Pittsburgh, Pa.
9. "Aluminum Industry Energy Conservation Workshop Papers," May 1976, Aluminum Association, Washington, D. C.
10. "Aluminum Industry Energy Conservation Workshop IV Papers," June 1979, Aluminum Association, Washington, D. C.
11. Stephens, W. E., "Aluminum Industry Energy Conservation Workshop Papers," Paper No. 13, May 1976.
12. Hartley, C. F., "Aluminum Industry Energy Conservation Workshop Papers," Paper No. 6, May 1976.
13. Nowak, T. A., "Aluminum Industry Energy Conservation Workshop IV Papers," Paper No. 10, June 1979.
14. Primary Aluminum Producers. Telephone Interviews, October through December, 1979.

15. Stauffer, W. O., "Aluminum Industry Energy Conservation Workshop IV Papers," Paper #14, June 1979.
16. Ahrens, A. C., "Aluminum Industry Energy Conservation Workshop IV Papers," Paper #15, June 1979.

8.0 HEAVY CRUDE OIL INDUSTRY

8.1 Significance of Industry in U.S. Economy

200,000 B/D of heavy crude oil are currently produced in southern California by steam injection. In 1979, U.S. crude production averaged 6.5 million B/D. The heavy oil production was about 3.0% of the U.S. domestic supply. The 1978 DOE management plan was to develop 500,000 B/D of California heavy oil by 1985, to which could be added another 200,000 B/D by 1985 developed from other heavy oil reservoirs in states such as Texas and Louisiana. Heavy oil reserves have been discovered in a total of nine states. Current international events affecting oil imports indicate that increased development of heavy crude oil production by steam injection will go well beyond the most recent goal of 700,000 B/D nationally by 1985^(1,2).

The potential recoverable by steam enhanced oil recovery (EOR) is 5.45 billion barrels assuming the lifted crude is not burned as fuel for EOR. Assuming that heavy oil production could be developed to a million B/D rate, this could amount to about 1.2% of the current domestic production and last for about 15 years.

8.2 Major U.S. Producers

The major corporations active in California heavy crude oil production by steam injection are shown in Table 8.1, as taken from industry sources.⁽¹⁾

8.3 Basic Process Description

A significant amount of crude oil remains in the geologic reservoir after the energy originally pressurizing the reservoir has been dissipated in crude production. This stage is called primary recovery. Then, the secondary recovery stage is commenced in which fluids such as natural gas and water ("water flooding") are used to supplement the natural displacement forces in the reservoir in order to drive the crude oil from the rock strata into the well and to the surface.

Secondary recovery processes are responsible currently for perhaps 50% of domestic crude oil production. The American Petroleum Institute (API) estimates that approximately two-thirds of the U.S. petroleum crude discovered will be left in the geologic rock strata reservoirs following completion of primary and secondary recovery stages. Enhanced Oil Recovery (EOR) is defined as the additional recovery of oil from the petroleum reservoir beyond that which can be economically recovered by conventional primary and secondary stage methods.

TABLE 8.1

CURRENT MAJOR CORPORATIONS ACTIVE IN CALIFORNIA STEAM EOR

<u>Company</u>	<u>Daily Production Capacity</u> <u>(Barrels/Day)</u>
Getty	75,000
Shell	30,000
Chanslor Western (Santa Fe)	28,000
Mobil	25,000
Tenneco	5,000
McCullough	2,000
Gulf	2,000
Arco	2,000
Occidental	1,000
Chevron	Not Available
All others	<u>50,000</u>
TOTAL	220,000

Thermal EOR is the most advanced tertiary stage recovery process because of active field experience. Thermal processes add heat to the geologic reservoir to reduce the petroleum viscosity or to vaporize fractions of it. The petroleum is made more mobile within the pores of the rock strata so that it can be effectively driven to the producing wells.

Steam injection is currently the most advanced EOR process and has the largest number of commercial projects in operation. It has been successfully used in southern California since the middle 1960s. It occurs in two phases:

- Steam stimulation of the producing wells
- Steam drive from steam injected into wells to increase production from nearby producing wells.

The steam is produced by a generator in the immediate area of the producing wells.

Two companies dominate the steam generator equipment manufacture and sales in the U.S., namely: C-E Natco (subsidiary of Combustion Engineering Corporation) and Struthers Thermo-Flood Corporation (subsidiary of Struthers Wells Corporation).

Generator units range in heat input capacity from 10 to 250 million Btu/hour. The most popular sizes are 25 to 50 million Btu/hour. The 50 MM Btu/hour unit is currently the most popular and widely purchased. The steam is provided normally at about 900 psig and 80% quality, although there is a wide range of equipment in the field delivering up to 1500 psig saturated steam, depending on petroleum reservoir conditions.

The steam generators are direct-fired by usually burning some of the crude oil lifted from the petroleum reservoir by steam injection. As a rule-of-thumb, for every three barrels of heavy crude lifted, one barrel is burned as fuel to provide the steam. In a few cases, natural gas may be burned but this is becoming more unusual with time. The boiler feedwater (BFW) comes from local wells or is recovered by treatment from the crude oil-steam condensate mixture lifted in production. The generator is equipped with an economizer section in the short stack to recover thermal energy in the flue gas. The BFW is preheated in the economizer section. The furnace combustion products enter the economizer at about 1500°F. C-E Natco preheats their BFW near to the saturated steam condition (e.g., 533°F for 900 psig operation). C-E Natco uses some of the steam generated to aid in preheating the BFW. Struthers prefers to preheat the BFW

only up to 430°F. Both vendors do not preheat their fuel or combustion air. The stack flue gas exits to the atmosphere between 350°F to 700°F. The economizer section suffers fouling due to burning the crude oil. The economizer is cleaned at the end of a six week cycle because the exit stack gas temperature rises from 350°F to 700°F due to fouling.

The popular 50 million Btu/hour steam generator (shown in Figure 8.1), as supplied by Struthers, has the following performance specifications:

● Absorbed Heat Duty	50 million Btu/hr
● Crude Fuel Oil (130,000 Btu/gal)	9405 GPD (224 BPD)
● Boiler Feedwater	96 GPM (48,000 lbs/hr)
● Steam Delivered	900 psig, 80% quality
● Crude Oil Lifted, Gross	28,215 GPD (672 BPD)

8.4 Industry Waste Heat Production

8.4.1 Sources and Amount

The steam generator is normally fired by heavy crude oil. Approximately one-third of the heavy crude produced by steam injection is used as fuel, i.e., for every three barrels of crude lifted from the reservoir, one barrel is consumed as fuel. The generator stack is equipped with an economizer section which extracts heat from the flue gas at about 1550°F and preheats the boiler feedwater (BFW). The stack emits to the atmosphere a flue gas in the range of 350°F to 700°F. During a six weeks cycle, the stack economizer section gradually fouls up due to soot particulates resulting from combustion of the heavy crude oil. This fouling causes the gas temperature to rise from 350°F (initially clean economizer section) to 700°F. At this point, the section is cleaned to restore the thermal efficiency for preheating the BFW.

SOURCE: Struthers Wells Co.
Catalog

FIGURE 8.1
STEAM GENERATOR FOR HEAVY CRUDE OIL RECOVERY

Assuming an average stack gas temperature of 500°F during the cycle period, the potential available waste heat for recovery is in the range of 500°F down to 200°F. Assuming a typical flue gas resulting from combustion of heavy crude oil, the amount of waste heat available in the range from 500°F to 200°F will be approximately 80 Btu/lb of flue gas. A typical steam generator⁽³⁾ developing 900 psig, 80% quality steam with a capacity of 50 million Btu/hr will consume about 75,000 lbs/day of fuel oil. This will result in a daily flue gas flow of about 1.4 million lbs. Therefore, the potential available heat will be approximately 109 million Btu/day.

Currently, there are about 1,000 steam generator units in field operations. The units range in size from 10 to 250 million Btu/hour capacity. The most popular unit sizes are 25 and 50 million Btu/hour, but the industry is now buying mainly the 50 million Btu/hour unit. A rough estimate is that the industry is currently sending to the atmosphere on a daily basis about 80 billion Btu/day.

8.4.2 Current Recovery and Utilization

The two manufacturers are furnishing steam generator units with economizer sections that are recovering the flue gas waste heat in the range of 1500°F down to an average emission temperature of 500°F. They claim fuel efficiencies of 80% to 91%. Equipment previously manufactured restricted the cooling of the waste heat to about 500°F because of the SO_x content of the flue gas. The heavy crude oil has a sulfur content in the area of 1.0 to 1.5%, but it can be higher. In order to avoid equipment deterioration, the manufacturers have allowed the flue gas to vent to the atmosphere above 350°F to avoid moist SO_x condensate. At this time, one of the manufacturers is offering a plastic coated convection section in the economizer which it is claimed will permit flue gas to be cooled to 150°F.

8.5 Potential FWHR Applications

The potential applications for waste heat recovery are the preheating of the boiler feedwater (BFW) or the combustion air. The BFW supply comes from two sources:

- Site wells at a temperature of about 70°F
- Recycled water recovered from crude oil-steam condensate separators after the crude has been lifted to the surface. This water is at a temperature of about 170°F.

The FWHR application is possible at one of two points in the generator:

- Replacement of the economizer section and therefore processing a flue gas at 1500°F.
- Addition to the flue gas stack and handling the current emission at 500°F.

The southern California heavy oil industry is currently under state environmental compliance orders to retrofit SO_x scrubbers to existing operations. The state is attempting also to enforce NO_x requirements. In regard to the SO_x scrubber operation, a cooler flue gas will result in more efficient performance of the scrubber.

In August 1979, the federal government deregulated price control for heavy crude oil production, 16° API gravity or heavier. It has been estimated that the sales rate of new steam generator units will be about 300 units annually in the period 1980-1985, now that there is a greater price incentive for heavy crude oil producers.

8.6 Technical and Economic Assessment

The proposed FWHR applications analyzed for heavy crude oil recovery include the following:

- (1) Boiler feedwater heating with heat recovered from the flue gas stream from a boiler producing steam for heavy crude oil recovery.
- (2) Preheating combustion air with heat recovered from the flue gas stream from a boiler producing steam for heavy crude oil recovery.

The technical and economic assessments are provided in the following subsections; these analyses are based on the approach developed in Section 3.0.

8.6.1 Application #1: FWHR Using Flue Gas for Boiler Feed-Water Heating

The proposed FWHR application involves recovery of heat from flue gas to heat boiler feedwater for a 50 million Btu/hr steam generator as shown in Figure 8.2.

The proposed application requires a FWHR system and the ducting as required. The technical and economic analyses of the proposed FWHR applications are provided in Tables 8.2 and 8.3.

FIGURE 8.2
FWHRs FOR BOILER FEEDWATER HEATING
(HEAVY CRUDE OIL RECOVERY)

TABLE 8.2

TECHNICAL ASSESSMENT OF FWHRs IN HEAVY CRUDE OIL RECOVERY
APPLICATION #1 - BOILER FEEDWATER HEATING
(50 MM BTU/HR BOILER)

WASTE GAS STREAM CHARACTERISTICS

Gas Temperature (Average)	400°F
Flow Rate	12,000 SCFM
Heat Available	2.75 Million BTU/HR
Stack Gas Temperature	200°F
Corrosive Species	SO ₂ , H ₂ SO ₄
Condensible Species	H ₂ SO ₄ , H ₂ O

SERVICE/APPLICATION CHARACTERISTICS

Type	BFW Heating (70°F to 150°F)
------	-----------------------------

ENERGY CONSERVATION POTENTIAL

Fan Power	40 HP
Energy Resource Expended	340,000 BTU/HR
Energy Recovered	2.75 Million BTU/HR; Crude Oil Savings - 12 BPD
Net Energy Conservation	Crude Oil Savings - 10 BPD
Energy Conservation Parameter (Z) *	8.1

POTENTIAL TECHNICAL PROBLEMS

- Corrosion and erosion of heat transfer surfaces and downstream equipment
- Fouling of downstream equipment
- Distributor design to achieve required quality of fluidization, particularly with condensing species.

*Z > 6 Considered Highly Favorable Energy Conservation

TABLE 8.3

ECONOMIC ASSESSMENT OF FWHRs IN HEAVY CRUDE OIL RECOVERY
APPLICATION #1 - BOILER FEEDWATER HEATING
(50 MM BTU/HR BOILER)

FWHRs COSTS

FWHR Unit	\$93,200
Balance of Steam Plant	Negligible
Auxiliary Systems	None
Total Equipment	<u>\$93,200</u>
Installation Cost	\$46,600
Total Installed Cost	<u>\$139,800</u>

OPERATING COSTS (ANNUAL)

Electric Power (Fan Power)	\$10,800
Maintenance (Scheduled & Repair)	\$14,000
Total Operating	<u>\$24,800</u>

SAVINGS FROM CONSERVATION

Savings Per Year (Crude Oil at \$16/BBL)	\$57,600
Net Savings Per Year	\$32,800
Payback Period	4.3 Years

ECONOMIC CONSIDERATIONS

- Impact of structural materials selected for FWHRs equipment on the equipment cost
- Impact of environmental regulations
- Price ceiling on crude oil

8.6.2 Application #2: FWHRs Using Flue Gas for Combustion Air Preheating

The proposed FWHRs application involves recovery of heat from the fuel gas for combustion air preheating as shown in Figure 8.3.

This application requires a FWHR system and the ducting as required. The technical and economic analyses are summarized in Tables 8.4 and 8.5.

8.6.3 Summary of FWHRs Applications in Heavy Crude Oil Recovery

The potential applications include boiler feedwater heating and combustion air preheating. The boiler feedwater heating application satisfies the technical criterion set to screen the candidate industries while an analysis of the combustion air preheat application indicates that the proposed system is not technically highly favorable. Although the boiler feedwater heating application seems attractive, the large size of the FWHRs (approximately 150 ft² nominal bed size) may be a limiting factor in some applications.

Corrosion, erosion, ash fouling, and the design of the air distributor are potential problem areas that must be considered in the design of the proposed FWHR system.

At the assumed price of heavy crude oil (\$16/BBL), the combustion air preheating application is not economically feasible.

8.7 Summary of Industry Comments

Getty Oil Company is the largest operator in the southern California heavy crude oil production and the most advanced technically in the use of thermal enhanced oil recovery (EOR) by steam injection. Their attitude towards FWHRs is simply that if the equipment vendors offer it and guarantee the new thermal efficiency, they will buy the equipment.

Two companies dominate the steam generator equipment manufacture and sales in the U.S., namely: C-E Natco (subsidiary of Combustion Engineering Corporation) and Struthers Thermo-Flood Corporation (subsidiary of Struthers Wells Corporation). Their steam generators are similar in design and performance. But, there are proprietary technology differences for competitive reasons. The heavy crude oil industry, which relies currently on steam injection, buys their field equipment equally from both vendors.

Struthers Thermo-Flood Corporation and C-E Natco are interested in fabricating FWHR units for retrofit to existing crude oil production units and for including integral units in new customer orders.

FIGURE 8.3
FWHRS FOR AIR PREHEATING
(HEAVY CRUDE OIL RECOVERY)

TABLE 8.4

TECHNICAL ASSESSMENT OF FWHRs IN HEAVY CRUDE OIL RECOVERY
APPLICATION #2 - COMBUSTION AIR PREHEATING
(50 MM BTU/HR BOILER)

WASTE GAS STREAM CHARACTERISTICS

Gas Temperature	400°F
Flow Rate	12,000 SCFM
Heat Available	2.75 Million BTU/HR
Stack Gas Temperature	200°F
Corrosive Species	SO ₂ , H ₂ SO ₄
Condensible Species	H ₂ O, H ₂ SO ₄

SERVICE/APPLICATION CHARACTERISTICS

Type	Combustion Air Preheating (70°F to 180°F)
------	--

ENERGY CONSERVATION POTENTIAL

Fan Power	40 HP
Energy Resource Expended	340,000 BTU/HR
Energy Recovered	0.96 Million BTU/HR; Crude Oil Savings - 4 BPD
Net Energy Conservation	Crude Oil Savings - 2.6 BPD
Energy Conservation Parameters (Z)*	2.8

POTENTIAL TECHNICAL PROBLEMS

- Corrosion and erosion of heat transfer surfaces and downstream equipment
- Fouling of downstream equipment
- Distributor design to achieve required quality of fluidization, particularly with condensing species.

*Z > 6 Considered Highly Favorable Energy Conservation

TABLE 8.5

ECONOMIC ASSESSMENT OF FWHRs IN HEAVY CRUDE OIL RECOVERY
APPLICATION #2 - COMBUSTION AIR PREHEATING
(50 MM BTU/HR BOILER)

FWHRs COSTS

FWHR Unit	\$93,200
Balance of Steam Plant	Negligible
Auxiliary Systems	None
Total Equipment	<u>\$93,200</u>
Installation Cost	<u>\$46,600</u>
Total Installed Cost	\$139,800

OPERATING COSTS (ANNUAL)

Electric Power (Fan Power)	\$10,800
Maintenance (Scheduled & Repair)	\$14,000
Total Operating	<u>\$24,800</u>

SAVINGS FROM CONSERVATION

Savings Per Year (Crude Oil at \$16/BBL)	\$23,000
Net Savings Per Year	None
Payback Period	N/A

ECONOMIC CONSIDERATIONS

- Not Economically Feasible

The equipment industry and the heavy crude oil operators gave the impression that they were strongly interested in FWHRs if there is a motivating force, such as a subsidized demonstration program.

REFERENCES - HEAVY CRUDE OIL INDUSTRY

1. Noran, D., "Oil & Gas Journal, March 27, 1978, p. 130 133.
2. "Enhanced Oil Recovery," National Petroleum Council, U.S. Dept. of Interior, Dec. 1976.
3. "Enhanced Oil Recovery Steam Generators," Struthers Thermo-Flood Corp., Winfield, Kansas, (1979).

Note: Sales brochure by division of Struthers Wells Corp.

9.0 PETROLEUM REFINING INDUSTRY

9.1 Significance of Industry In U.S. Economy

The petroleum refining industry (SIC 2911) in 1977 consisted of 349 plants, employing about 103,000 people. In 1977, the industry sales were \$91.83 billion or 6.8% of all manufactures.^(1,2) The industry ranked sixth among all U.S. industries. As of January 1979, petroleum refineries were located in 41 states and had a crude oil capacity of 17.2 million barrels/calendar day or 18.1 million barrels/stream day.⁽³⁾

In 1976, the petroleum refining industry consumed purchased fuels and electric energy to the amount of 1,218 trillion Btu, costing \$1.947 billion. In that year, the industry ranked second in energy consumption among all U.S. industries and consumed 9.6% of the 12,625 trillion Btu purchase by all industries.⁽⁴⁾

The petroleum refining industry purchases approximately one-half of its energy requirements; the remainder comes from internal generation of fuels, such as refinery gas, petroleum coke, residual fuel oil, and distillate. Also, some natural gas is captive, being produced along with domestic crude oil production. In 1976, the petroleum refining industry consumed both purchased and internally generated energy equal to 2.73 quads or approximately 3.6% of all U.S. energy consumption. In 1978, the industry's total consumption was estimated at 3.0 quads or about 4% of all U.S. consumption.^(5,6)

9.2 Major U.S. Producers

As of January 1979, the petroleum refining industry consisted of 289 refinery plants in 41 states. The total refinery crude oil capacity was 17.2 million barrels per calendar day.⁽³⁾ The top 52 companies had 91% of the industry capacity.⁽⁵⁾

The major U.S. producers are usually involved in many different commercial activities. Some are multi-national; others are conglomerates; and some are mainly importers of finished products or are importers of finished products plus being operators of domestic refineries. Therefore, ranking the major companies on their domestic refinery operations is somewhat difficult. Table 9.1 ranks the top 15 companies on the basis of their domestic refinery crude oil capacity.^(3,7,8) The total revenue column refers to all revenue from all sources and activities.

The top 15 U.S. producers, as ranked by refinery crude capacity, have 64% of the capacity and own 28% of the total number of U.S. refineries.

TABLE 9.1

1978 MAJOR U.S. PETROLEUM REFINERS-TOP 15

<u>Rank</u>	<u>Name</u>	<u>Refinery Crude Cap. Barrels/Calendar Day</u>	<u>No. Refineries</u>	<u>Total Revenue Million Dollars</u>
1	Exxon	1,574,000	5	64,886
2	Std. Oil Indiana	1,202,000	10	14,962
3	Shell Oil	1,151,000	8	11,063
4	Std. Oil Calif.	1,122,000	11	24,106
5	Texaco	1,051,000	9	29,124
6	Mobil	891,000	7	37,331
7	Gulf Oil	845,000	5	20,097
8	Atl. Richfield	815,000	4	12,985
9	Sun Co.	484,000	4	7,525
10	Std. Oil (Ohio)	452,000	3	5,198
11	Continental Oil	305,000	5	9,455
12	Phillips	302,000	5	6,998
13	Cities Service	291,000	1	4,661
14	Ashland Oil	289,000	2	5,166
15	Union Oil Calif.	228,000	3	5,955
Total Top 15		11,022,000	82	

9.3 Basic Process Description

The balancing of product yields from refineries with specific market demands has required processes for the conversion of petroleum hydrocarbons of one molecular weight range and/or structure into some other weight range and/or structure. These processes increased the total plant yield by adding to the commercial products obtained directly by distillation of the crude oil. One such process is fluid catalytic cracking (FCC) which is used mainly to create gasoline, C3 and C4 olefins, and isobutane primarily by the selective decomposition of heavy distillates. FCC was introduced during World War II and progressively displaced the earlier thermal-cracking processes to a large extent.

The fluid catalytic cracking unit (FCC) in the petroleum refinery has been selected as the plant operation currently having potential for waste heat recovery. A flowsheet of the FCC process is shown in Figure 9.1.

A typical FCC unit consists of (1) reactor, (2) regenerator, (3) main fractionator, (4) air blower or compressor, (5) spent catalyst stripper, (6) catalyst recovery equipment and (7) gas recovery unit. The feedstock is a gas oil fraction from prior distillation of the crude. The preheated feedstock is mixed with a controlled stream of hot, regenerated catalyst. The resulting mixture of vaporized oil and catalyst ascends in the riser to the reactor at a velocity such that the catalyst particles are suspended more or less discretely in a dilute phase. Significant cracking of the gas oil occurs in the riser. Upon reaching the reactor, the linear velocity of the hydrocarbon vapors is reduced to the extent that the catalyst settles out to form a dense phase bed. The remainder of the process conversion occurs as the hydrocarbon vapors pass through the dense bed.

Above the dense bed in the reactor is another dilute phase of suspended fine catalyst particles, most of which are separated from the cracked hydrocarbon vapors by cyclone separators. The separated particles are returned to the dense phase bed of the reactor through a dip leg. The cracked vapors, carrying a minor amount of catalyst fines, go to the main fractionator where they are distilled into several products. A portion of the fractionator bottoms is sent to a settler to recover the catalyst fines which are then passed back to the reactor. The spent catalyst, which is the dense bed in the reactor, descends by gravity into a stripper where hydrocarbon vapors adsorbed on catalyst particles are removed by a counter-current flow of steam.

The stripped catalyst descends through a control valve into a regenerator kiln where the catalyst deposit (mainly carbon from

FIGURE 9.1
FLUID CATALYTIC CRACKING FLOWSHEET
(PETROLEUM REFINING)

hydrocarbon degradation during cracking) is burned-off. The carbon coating must be burned-off to restore activity to the catalyst. In a typical operation, between 5 to 7% of the feedstock oil ends up as a carbon deposit on the catalyst particles. The burned-off catalyst is then recycled through the riser to the reactor.

Air is introduced into the regenerator at a pressure up to 40 psig. The regenerator kiln operates up to 1400°F to burn off the carbon. The hot flue gas (up to 1400°F) is the product of controlled combustion such that the composition is about 10% CO, 10% CO₂, and the remainder is nitrogen and steam resulting from combustion of hydrocarbons in the carbon deposit and humidity introduced in the combustion air. The hot flue gas at about 1400°F and 40 psig is currently handled in the following ways:

- 10% of FCC units vent the hot flue gas to the atmosphere after passage through a scrubber or electrostatic precipitator (ESP).
- 10% of FCC units send the hot flue gas through a cyclone separator and then to a hot gas expander to recover the pressure and thermal energies and convert them into shaft work. The expander shaft powers the air compressor that supplies combustion air to the regenerator kiln. The expander exhaust which has undergone a 250 to 300°F cooling in expansion is sent to the atmosphere at about 1100°F and 2 to 3 psig.
- 80% of the FCC units send the 1400°F and 40 psig flue gas through a waste heat boiler to generate steam for plant operation requirements. Half of these units (about 40% of all FCC units) are equipped with CO combustion chamber. The CO combustion is maintained by a small stream of refinery reformer hydrogen. The combustion increases the temperature and thermal energy of the flue gas stream and, in turn, increases the waste heat boiler steam generation capacity.

In recent years there have been suggestions to add the waste heat boiler to the expander exhaust and capture the thermal energy in the 1100°F exhaust flue gas.

9.4 Industry Waste Heat Production

9.4.1 Sources and Amounts

There are two significant sources of waste heat in the petroleum refining industry:

- Hot flue gases from process heaters and furnaces
- Hot process gases and liquids which are presently cooled to safe operation temperatures by cooling water or air.

As a result of telephone interviews with the industry and equipment vendors, the following statements may be made:

- The petroleum refining industry is embarked on a continuing waste heat energy conservation program.
- Hot flue gases are being controlled and conserved by extensive use of waste heat boilers and recuperators.
- Hot process gases and liquids are being matched more closely with colder streams so that waste heat is recycled into the process.
- The industry considers that a potential application exists for waste heat recovery in processing the hot flue gas from the FCC regenerator kiln.

As of January 1, 1979, there were 142 FCC units in 41 states.⁽³⁾ Table 9.2 indicates the geographical distribution and total state capacity. Capacity is reported as barrels per stream day (BSD) which can be derived as equal to fresh feedstock per calendar day divided by 0.90 which is assumed to be current operational stream time. Note that state ranking is according to FCC total fresh feed capacity. The top 10 states have 99 units (70% of all U.S. FCC facilities) and 4.6 million barrels/stream day of fresh feed capacity (93% of the U.S. capacity).

A typical FCC regenerator kiln operation may be specified by the industry practice parameters presented in Table 9.3.^(13,14) Note that "old" units refer to FCC units engineered and/or constructed more than eight years ago. There are 113 FCC units between 11,000 and 184,000 B/SD. The median size unit is approximately 33,000 B/SD if the 29 FCC units under 10,000 B/SD are eliminated.

A simplified calculation of the potential waste heat available can be developed on the basis of the following assumptions:

- Waste heat in regenerator flue gas can be recovered in range of 1400°F down to 500°F
- FCC unit operates 320 days/year
- 40% of all FCC units will be retrofitted with waste recovery units (including those with expanders)

TABLE 9.2

FLUID CATALYTIC CRACKING UNITS IN U.S.
(1979 Geographical Distribution & Capacity)

<u>Rank</u>	<u>States</u>	<u>No. Refineries</u>	<u>No. FCC Units</u>	<u>FCC Fresh Feed Cap. Thousand Barrels/Stream Day</u>
1	Texas	54	30	1,422
2	Louisiana	25	9	568
3	California	39	14	516
4	Illinois	12	9	442
5	Indiana	8	4	442
6	New Jersey	4	4	237
7	Pennsylvania	10	4	219
8	Ohio	7	6	206
9	Oklahoma	12	10	194
10	Kansas	11	9	162
11	Washington	8	3	95
12	Mississippi	6	2	72
13	Kentucky	4	2	65
14	Wyoming	13	7	62
15	Delaware	1	1	62
16	Utah	8	7	56
17	Montana	6	4	48
18	Michigan	6	2	42
19	All Other States	55	15	75
	Totals	289	142	4,985

TABLE 9.3

TYPICAL FCC REGENERATOR OPERATION PARAMETERS

<u>PARAMETERS</u>	<u>AMOUNTS</u>
Median Capacity Fresh Feed	33,000 B/D
Fresh Feed Density	25° API
Carbon on Spent Catalyst	
Old FCC Units	7% Wt.
New FCC Units	5% Wt.
Regenerator Flue Gas Composition	
Old FCC Units	10% CO, 10% CO ₂ , Remainder N ₂
New FCC Units	About 20% CO ₂ , Remainder N ₂
Regenerator Flue Gas Temperature	
Old FCC Units	1250°F
New FCC Units	1400°F
Regenerator Flue Gas Pressure	25 to 40 PSIG
Regenerator Combustion Air	
Old FCC Units	10 Lbs. Air/Lb. Carbon
New FCC Units	14 lbs. Air/Lb. Carbon

- Credit is not taken for CO combustion chamber prior to WHB
- Flue gas composition is 10% CO, 10% CO₂, and remainder N₂
- Inclusion of a hot gas expander will use a portion of the available thermal energy. However, the potential Btus available will be the same for the total system, whether it be expander plus waste heat recovery, or waste heat recovery alone.

The calculation is outlined below:

FCC Unit Size	33,000 B/D
40% of Total No. Avg. Units For Retrofit	$0.4 \times 113 = 45$
Flue Gas Flow/FCC Unit by Vendor Estimate	5000 Lbs/Min. or 7.2×10^6 Lbs/Day
Flue Gas Heat Content, 1400°F to 500°F	245 BTU/Lb
Annual Days of Operation	320
Potential Available Waste Heat for Recovery & Utilization	$45 \times 320 \times 7.2 \times 10^6 \times 245 =$ 25 Trillion BTU

It has been roughly estimated that the petroleum refining industry in 1978 consumed about 3.0 quads, as shown in Table 9.4.(5,6)

TABLE 9.4

1979 PETROLEUM REFINING ENERGY REQUIREMENTS

<u>Energy Source</u>	<u>Quads (10^{15} BTUs)</u>
Purchased Electricity	0.1
Purchased Fuels	1.1
Captive Sources	<u>1.8</u>
Total Energy Consumed	3.0

Therefore, the potential available heat that can be recovered from the FCC regenerator kiln operation and utilized is 0.8% of the industry requirements.

9.4.2 Current Recovery and Utilization

Some 80% of the FCC regenerator kiln units are equipped with a waste heat boiler on the flue gas exit to generate steam for in-plant use. Half of these units, or 40% of the total, are equipped with a CO combustion chamber prior to the waste heat boiler to burn the flue gas to increase the heat content.

About 10% of the FCC regenerator kiln units are equipped with a hot gas expander to process the flue gas exit at 1400°F and 40 psig. The hot gas expansion develops shaft power for the regenerator centrifugal air compressor supplying combustion air. No information is available on how many expanders exhaust their cooled gas (about 1100°F) to a waste heat boiler. Industry indications are that few, if any units, have such a configuration, i.e., the 1100°F expander exhaust is vented to the atmosphere.

About 10% of all FCC units have neither a waste heat boiler or a hot gas expander. The 1250°F to 1400°F flue gas is vented to the atmosphere.

9.5 Potential FWHRS Applications

There are four potential applications for the FWHRS in the petroleum FCC process.

- Retrofit FWHRS to FCC units which are now venting the regenerator flue gas directly to the atmosphere
- Retrofit FWHRS to FCC units which have a hot gas expander exhausting its 1100°F gas directly to the atmosphere
- Retrofitting a combination of a hot gas expander and FWHRS to either (a) FCC units that have no waste heat recovery, or (b) replacing units having only a waste heat boiler with the new combination
- Replacing waste heat boilers in FCC units by retrofitting FWHRS.

The last application requires comment. Current waste heat boilers require soot blowers to keep the tubular passages clear. There is considerable carbon soot carry-over from the regenerator combustion. This is troublesome to the refinery operator. The EPA stack

regulations permit emission of only a maximum of 1.0 lbs. particulates per 1000 lbs. carbon burned-off. Efficient operation of soot blowers requires good plant maintenance. The refinery operators would like a better arrangement because soot accumulations reduce heat transfer efficiency and may result in sudden ejections of particulates which can cause emission problems. The FWHRs technology and equipment might be a satisfactory solution to the waste heat boiler problem.

There are two outstanding plant operation problems to FWHRs applications. First, there is the space problem. Everyone contacted was concerned about the cost of retrofitting a FWHRs in the limited space available to the waste heat boiler. Secondly, there is a potential explosion problem with waste heat boilers which have a CO combustion chamber upstream. Since explosions have occurred, the industry is wary about retrofitting new technology and equipment in this type of plant configuration.

9.6 Technical and Economic Assessment

The proposed FWHRs application analyzed for the petroleum refining industry involves heat recovery from a fluid catalytic cracking (FCC) regenerator off-gas to heat boiler feedwater.

The technical and economic assessment is provided in the following section; these analyses are based on the approach developed in Section 3.0.

9.6.1 Applications #1 & #2: FWHRs Using FCC Regenerator Off-Gas

The proposed FWHRs application, shown in Figure 9.2, uses heat recovered from the off-gas of a FCC regenerator to generate steam. It is assumed that the off-gas is expanded through a hot gas expander before being ducted to the FWHRs for heat recovery. The expander is only installed on approximately 10 percent of the FCC regenerator units, although greater use is expected in the future. If the hot gas expander is not installed, the FWHRs can be used to recover the additional thermal energy from the off-gas.

The proposed application requires an FWHRs as well as the balance of steam plant. The technical and economic assessments presented in Tables 9.5, 9.6, and 9.7 were performed for the following plant conditions:

Application #1 - New balance of steam plant required.

Application #2 - Existing balance of steam plant assumed adequate.

FIGURE 9.2
FWHRS USING FCC REGENERATOR FLUE GAS
(PETROLEUM REFINING)

TABLE 9.5

TECHNICAL ASSESSMENT OF FWHRs IN PETROLEUM REFINING INDUSTRY
APPLICATION #1 & #2 - OFF-GAS FROM FCC REGENERATOR
(NEW BOP EQUIPMENT)

WASTE GAS STREAM CHARACTERISTICS

Gas Temperature	1000°F
Flow Rate	60,000 SCFM
Heat Available	42.3 Million BTU/HR
Stack Gas Temperature	400°F
Corrosive Species	SO ₂ , HC
Condensible Species	H ₂ O
Other Species	C ₂ , CO, H ₂

SERVICE/APPLICATION CHARACTERISTICS

Type	Low Pressure Steam; 350°F
------	---------------------------

ENERGY CONSERVATION POTENTIAL

Fan Power	260 HP
Energy Resources Expended	2.3 Million BTU/HR
Energy Recovery	42.3 Million BTU/HR
Net Energy Conservation	40 Million BTU/HR (7.1 BPD Crude Oil)
Energy Conservation Parameter (Z)*	19

POTENTIAL TECHNICAL PROBLEMS

Minimization of combustion hazard potential.

*Z > 6 Considered Highly Favorable Energy Conservation

TABLE 9.6

ECONOMIC ASSESSMENT OF FWHRs IN PETROLEUM REFINING INDUSTRY
 APPLICATION #1 - OFF-GAS FROM FCC REGENERATOR
 (NEW BOP EQUIPMENT)

FWHR COSTS

FWHR Unit	\$466,200 (37,000 PPH Capacity)
Balance of Steam Plant	256,000
Auxiliary Systems	None
Total Equipment	<u>\$722,200</u>
Installation Cost	<u>\$361,100</u>
Total Installed Cost	<u>\$1,083,300</u>

OPERATING COSTS (ANNUAL)

Electric Power (Fan Power)	\$70,900
Maintenance (Scheduled & Repair)	108,300
Total Operating	<u>\$179,200</u>

SAVINGS FROM CONSERVATION

Savings Per Year	\$1,218,200 (Crude Oil at \$4/Million BTU)
Net Savings Per Year	\$1,039,000
Payback Period	1.1 Years

ECONOMIC CONSIDERATIONS

- Economically attractive especially considering future price increases in crude oil.

TABLE 9.7

ECONOMIC ASSESSMENT OF FWHRs IN PETROLEUM REFINING INDUSTRY
APPLICATION #2 - OFF-GAS FROM FCC REGENERATOR
(EXISTING BOP EQUIPMENT)

FWHRs COSTS

FWHR Unit	\$466,200 (37,000 PPH Capacity)
Balance of Steam Plant	Existing
Auxiliary Systems	None
Total Equipment	<u>\$466,200</u>
Installation Cost	<u>\$233,100</u>
Total Installed Cost	<u>\$699,300</u>

OPERATING COSTS (ANNUAL)

Electric Power (Fan Power)	\$70,900
Maintenance (Scheduled & Repair)	69,900
Total Operating	<u>\$140,800</u>

SAVINGS FROM CONSERVATION

Savings Per Year	\$1,218,200 (Crude Oil at \$4/Million BTU)
Net Savings Per Year	\$1,077,400
Payback Period	0.6 Years

ECONOMIC CONSIDERATIONS

- Economically attractive especially considering future price increases in crude oil.

9.6.2 Summary of FWHRs Applications in Petroleum Refining Industry

The two FWHRs applications analyzed in the petroleum refining industry appear to be technically and economically feasible with a potential to achieve significant savings in energy. The estimated payback period is short for both applications (approximately one year or less). The FWHRs application in the petroleum industry is likely to become more economically attractive in the future because of the expected increases in crude oil prices.

9.7 Summary of Industry Comments

9.7.1 Industry Comments

The following companies were interviewed on the subject of waste heat recovery and utilization in petroleum refining:

- Petroleum Refinery Companies

- Exxon Corporation
 - Mobil Corporation
 - Standard Oil of California
 - Phillips Petroleum Corporation

- Engineer-Contractors & Equipment Vendors

- Pullman-Kellogg
 - UOP Inc. (Procon Inc.)

The industry reaction regarding waste heat recovery and utilization was reserved. The companies claimed that they are progressively solving their problems of reduction of energy consumption and improving waste heat conservation and utilization. However, they were open-minded about demonstration program projects on new technology and equipment. But, all of them observed that if FWHRs worked and the economics were satisfactory, they would be inclined to spend their own money to install such units and avoid demonstration programs. Nevertheless, they indicated a willingness to consider demonstration programs with cost-sharing if the negotiated terms and conditions were satisfactory. One consideration, emphasized above all in evaluating the FWHRs application, was that the costs and economics of the FWHRs application must be evaluated according to the financial and cost accounting standards and procedures of their corporate business.

The engineer-contractors and equipment vendors were also reserved. They required more information on the commercialization of FWHRs before considering it as (1) an alternative to the waste heat boiler, or (2) connecting it to the hot gas expander. They indicated a willingness to cooperate in a demonstration program, but were concerned about cost-sharing.

9.7.2 Industry Receptivity

As noted in Section 9.7.1, both industry and the engineer-contractors/equipment vendors are interested but somewhat reserved. In this industry, it appears likely that much more FWHRs data must be made available that indicates that the technology and equipment is ready for large-scale commercialization.

REFERENCES - PETROLEUM REFINING INDUSTRY

1. "1977 Census of Manufactures - Petroleum Refining SIC 2911," Preliminary Report, July 1979, Bureau of Census, Washington, D.C.
2. "Statistical Abstract of the U.S. 1978," 99th Annual Edition, Table No. 1419, p. 816-817; Table 1322, p. 765, Bureau of the Census, Washington, D.C.
3. "Annual Refining Survey," Oil and Gas Journal, March 26, 1979, p. 122-153.
4. "Annual Survey of Manufactures 1976 - Fuels and Electric Energy Consumed," M76 (AS)-4.1, Bureau of Census, Washington, D.C.
5. American Petroleum Institute, Statistical Dept., Washington, D.C. Telephone interview.
6. "1979 HPI Market Data," p. 27, Hydrocarbon Processing, August 1978, Houston, Texas.
7. Corporate Annual Reports - 1978.
8. "Chemical Week 300," Chemical Week, April 25, 1979, p. 28-45, McGraw-Hill, New York, N. Y.
9. "Chemical Technology," Vol. IV, p. 47-49 (1972), Barnes & Noble Division, Harper & Row, New York, N.Y.
10. "Chemical and Process Technology Encyclopedia," D. M. Considine, Editor, p. 505-509, McGraw-Hill Book Co., New York, N. Y.
11. "Study of Inplant Electric Power Generation in the Chemical, Petroleum Refining and Paper and Pulp Industries," Report No. TE5429-97-76, FEA Contract No. CO-04-50224-00, Section 4.2, pgs. 4-23 to 4-55, ThermoElectron Corp. (1976).
12. "Basic Process Data on the Potential for Low Level Waste Heat Recovery in the Petroleum Refining and Selected Chemical Industries of the West South Central U.S.," Report No. HCP/M5056, Section 3, p. 25-74 (July 1978).
13. Petroleum Refinery Companies. Private Interviews.
14. Equipment Vendors and Engineer-Contractors to Petroleum Refiners. Private Interviews.

10.0 CHEMICAL INDUSTRY

10.1 Significance of Industry in U.S. Economy

The chemical industry consists of about 12,000 plants owned by 200 major companies in the business whose 1978 sales ranged from \$100 million to over \$10 billion. The companies have a wide diversity of operations and products, e.g., some are purely chemical; others produce non-chemical as well as chemical products; some are conglomerates which produce many different non-related products; and many of the majors are multi-national with great complexity of chemical and non-chemical operations.⁽¹⁾

Most of the chemical operations are confidential and detailed information on specific industrial situations is not readily available. Although there are most likely many operations with waste heat energy losses, information is lacking on the specific industrial locations. Generally, the most likely sources of waste heat energy available is in the manufacture of certain inorganic chemicals which are categorized as "commodity" chemicals because of their relatively large product volume sales. These chemicals have relatively high temperature levels in some of their process manufacturing steps. The phosphate fertilizer industry is typical of this waste heat energy situation.

The chemical industry group, SIC 28, is ranked fourth among all U.S. manufacturing industries.⁽²⁾ The latest information available (1976) indicates the industry shipped \$104.1 billion or 8.7% of all manufactured products. In 1976, this industry group ranked first in consumption of purchased fuels and electric energy, having consumed 3,017 trillion Btu or 24% of the total U.S. industrial purchased energy.⁽³⁾ A breakdown of the industry group by major segment is shown in Table 10.1.

In SIC 287, "Agricultural Chemicals", the industry group talked freely about one problem area, namely, that large amounts of waste heat are being thrown away in the phosphate rock calcining process. Therefore, this industry was selected to analyze in this study.

10.2 Major U.S. Producers

The calcining of phosphate rock is a precursor to two segments of the phosphate industry:

- Defluorinated phosphate rock for animal feed supplement

TABLE 10.1

1976 CHEMICAL INDUSTRY GROUP
PRODUCTS VALUE & ENERGY CONSUMPTION

<u>SIC No.</u>	<u>Industry</u>	<u>Products Shipped Million Dollars</u>	<u>Purchased Energy Consumption Trillion BTU</u>
281	Indust. Inorganic Chem.	11,611	713
282	Plastic Materials, Synthetics	17,156	398
283	Drugs	13,016	63
284	Soap, Cleaners, Toilet Goods	14,741	49
285	Paints & Allied Products	5,931	15
286	Indust. Organic Chem.	25,685	1,277
287	Agricultural Chemicals	9,195	397
289	Miscellaneous Chem. Prod.	6,803	105
	Totals	104,138	3,017

- Nodulized rock for electric furnace production of elemental phosphorus which is used to produce high purity phosphoric acid for the chemical and food industries and ferroalloy for the steel industry.

The defluorinated phosphate rock producers are listed in Table 10.2, based on data derived from various sources.(4,5,6,7)

TABLE 10.2

DEFLUORINATED PHOSPHATE ROCK PRODUCERS

<u>Company</u>	<u>Location</u>	<u>Phosphate Rock Capacity Tons/Year</u>
IMC Corp.	Mulberry, Fla.	150,000
Occidental Pet.	White Sands, Fla.	90,000
Borden Chem.	Plant City, Fla.	90,000 (est.)

In the latest period of the industry fertilizer year, July 1, 1978 to June 30, 1979, the three producers processed about 222,000 tons of rock.

The nodulized rock-electric furnace phosphorus producers are listed in Table 10.3 based on data from various sources.(4,5,6,7) During the latest industry fertilizer year, the eight producers nodulized about 5 million tons of phosphate rock in nine kilns. Except for Stauffer's Tennessee operation, which has two kilns, all the other producers operated single kilns.

10.3 Basic Process Description

Phosphate rock is mined mainly in Florida, North Carolina, and Tennessee. The rock is processed to manufacture mainly phosphate fertilizer. Other products are animal feed supplement; elemental phosphorus from which high purity phosphoric acid is made as a precursor to the manufacture of chemicals, detergents, food additives; and ferrophosphorus for the steel industry.

The phosphate rock mine production in 1976 is shown in Table 10.4.(3)

TABLE 10.3

NODULIZED ROCK-ELECTRIC FURNACE PHOSPHORUS PRODUCERS

<u>Company</u>	<u>Location</u>	<u>Phosphate Rock Capacity Tons/Year</u>
FMC Corp.	Pocatello, Idaho	1,500,000
Monsanto	Soda Springs, Idaho	1,000,000
Monsanto	Columbia, Tenn.	1,000,000
Stauffer	Silver Bow, Montana	570,000
Stauffer	Mount Pleasant, Tenn.	300,000
Stauffer	Tarpon Springs, Florida	330,000
Hooker (Occidental)	Columbia, Tenn.	500,000
Mobil Chemical	Tarpon Springs, Florida	31,000
Total Rock Capacity		5,231,000

TABLE 10.4

U.S. PRODUCTION OF PHOSPHATE ROCK-1976

<u>State</u>	<u>Mine Production-Million Tons</u>	
	<u>Rock</u>	<u>P₂O₅</u>
Florida, North Carolina	174.0	20.5
Tennessee	4.0	0.8
Idaho & Other Western States	<u>9.7</u>	<u>2.2</u>
Totals	187.5	23.5

Approximately 222,000 tons of phosphate rock (0.1% of total) were mined in fertilizer year 1978-79 to be calcined to produce defluorinated rock for animal supplement feed. The rock is crushed to size and wet with dilute phosphoric acid. The rock is charged continuously to a rotary kiln or a fluid-bed calciner. Natural gas or fuel oil is burned. The combustion gas products pass over or through the pulverized rock and remove the fluoride component in gaseous state. The hot exit gas passes through a water scrubber to remove the gaseous hydrogen fluoride and dust particulates and is vented to the atmosphere. The defluorinated rock process is shown in Figure 10.1.

Approximately 5 million tons of phosphate rock or 2.7% of total mined in the fertilizer year 1978-79 were calcined to produce nodulized phosphate rock for the electric furnace phosphorus industry. The rock passes through a rotary kiln or traveling grate and is calcined by counter-current hot gas from the combustion of rich carbon monoxide gas. This gas is produced in the operation of the electric furnace wherein a charge of rock, silica, and coke undergo an electrochemical reaction. The carbon monoxide rich gas (93%) results from the consumption of the coke and the graphite electrodes. The kiln exit gas is water-scrubbed to remove fluoride and sulfur components and is vented to the atmosphere. The nodulizing rock process is shown in Figure 10.2.

10.4 Industry Waste Heat Production

10.4.1 Sources and Amounts

The three defluorinated rock producers vent the hot stack gas directly to the atmosphere after passing through a water scrubber.

FIGURE 10.1
DEFLUORINATED ROCK PROCESS FOR
ANIMAL FEED PHOSPHORUS SUPPLEMENT

FIGURE 10.2
NODULIZING PHOSPHATE ROCK PROCESS FOR
ELECTRIC FURNACE PHOSPHORUS

IMC burns No. 6 fuel oil; Occidental and Borden burn natural gas. Typical operations for natural gas and fuel oil processes are outlined in Table 10.5 based on telephone interviews.⁽⁷⁾

It should be noted that the exit gas flow, temperature, and corrosive components are only rough estimates and that detail differences are due to different plant operation practices. A rough estimate indicates that about 0.1 trillion Btu/Year are vented to the stack and lost in the water scrubbers of the three producers.

The five producers of nodulized rock have a total of nine kilns. There are various plant practices among the several producers which make it difficult to define a standard or typical plant. Table 10.6 compares two of the largest operations in the U.S.⁽⁷⁾

These two phosphate rock industry segments are losing about 1.0 trillion Btu/Year in waste heat energy through their calcining and nodulizing operation stacks. In year 1976, SIC 287 "Agricultural Chemicals" consumed 397 trillion Btu of purchased energy (See Table 10.1) The phosphatic fertilizer industry segment, SIC 2874, consumed 67 trillion Btu. Therefore, the estimated stack gas waste energy potentially recoverable represents about 1.5% of the phosphate fertilizer industry consumption.

10.4.2 Current Waste Heat Recovery and Utilization

There is limited current recovery or utilization of the waste heat energy in the phosphate rock calcining industry. Several electric furnace companies have from time to time made studies on recovery and utilization of the waste heat from the nodulizing operation.⁽⁷⁾ One company is known to have mounted a waste heat boiler on the stack gas to produce 75 psig steam. This steam is used to keep the storage phosphorous product in a molten state.

10.5 Potential FWHRS Applications

Recovered waste heat energy may be applied in two ways:

- Producing steam for turbine generator in-plant electric power
- Preheating air for various plant drying and preheat processes.

The waste heat recovery in the nodulizing rock process can contribute needed electric power to the electric furnace operation for elemental phosphorus. The energy input required by an electric furnace is of the order of 12,000 kWh per ton of elemental phosphorus produced. As a rough estimate, the largest U.S. nodulizing plant can process 1.5 million tons/year of phosphate rock which, after further

TABLE 10.5
TYPICAL DEFLUORINATED ROCK CALCINING

	<u>Plant No. 1</u>	<u>Plant No. 2</u>
Fuel	Natural Gas	Fuel Oil
Equipment	Fluid Bed Calciner (2)	Rotary Kiln (2)
Rock Feed, Total	90,000 Tons/Yr	150,000 Tons/Yr
Plant Operation	Continuous	Continuous
Stream Time	80%	80%
<u>Exit Gas</u> (Before Scrubbing):		
Temperature	2200°F	1000°F
Flow	20,000 SCFM	22,100 ACFM
Corrosive Components	Fluoride, Dust (400 Lbs/Hr)	1% HF, <1% Sticky Dust

TABLE 10.6
NODULIZED PHOSPHATE ROCK OPERATIONS

	<u>Plant No. 1</u>	<u>Plant No. 2</u>
Fuel	CO Furnace Gas	CO Furnace Gas
Equipment	Rotary Kiln	Traveling Grate
Rock Feed, Total	1 Million Tons/Yr	1 Million Tons/Yr
Exit Nodulized Rock Temp.	1400 ^o F	1400 ^o F
Plant Operation	Continuous	Continuous
Stream Time	80%	80%
<u>Exit Gas (Before Scrubbing):</u>		
Temperature	1022 ^o F	1022 ^o F
Flow	Not Available	140,000 ACFM
Dust Load	Not Available	450 Lbs/Hr
Corrosive Components	Not Available	HF, SO ₂

processing, will give about 145,000 tons/year elemental phosphorus. This will require about 1.7 billion kWh/year or a plant demand capacity of 250,000 KW. The defluorinated rock industry can also utilize electric power for general plant operation needs.

Both defluorination and nodulizing operations can utilize preheated air for drying and preheating the phosphate rock before charging to the kiln or calciner. At least one of the electric furnace operators uses a nodulizing kiln stack gas waste heat boiler to produce 75 psig steam to keep storage phosphorous in a molten state.

10.6 Technical and Economic Assessment

The proposed FWHRs applications analyzed for the chemical phosphate rock industry are as follows:

- (1) Steam/electric power generation with heat recovered from the flue gas stream of a nodulized rock kiln.
- (2) Drying and preheating phosphate rock with heat recovered from the flue gas stream of a fluidized bed calciner.

The technical and economic assessment of these potential applications is provided in the following subsections; these analyses are based on the approach developed in Section 3.0.

10.6.1 Application #1: FWHRs Using Flue Gas from Nodulizing Rock Kiln

The proposed application involves steam/power generation using a two-stage FWHR system to recover heat from a nodulizing rock calciner kiln (capacity of 1.5 million tons/year phosphate rock) as shown in Figure 10.3. The proposed application requires an FWHR system (capacity of 50,000 SCFM waste gas stream) as well as the balance of steam plant, steam turbine-generator and associated electrical equipment.

The technical and economic analyses of the proposed application are provided in Tables 10.7 and 10.8.

10.6.2 Application #2: FWHRs Using Flue Gas from Fluidized-Bed Calciner

The proposed application shown in Figure 10.4 uses the FWHRs for drying and preheating the phosphate rock with the flue gas from a fluid-bed calciner. The fluidized-bed preheater/dryer is sized to handle a gas stream of 20,000 SCFM. No additional equipment is required other than ducting and solids handling equipment. The technical and economic analyses are summarized in Tables 10.9 and 10.10.

FIGURE 10.3
FWHRs FOR NODULIZING KILN
(CHEMICAL INDUSTRY)

TABLE 10.7

TECHNICAL ASSESSMENT OF FWHRs IN CHEMICAL INDUSTRY
APPLICATION #1 - NODULIZING ROCK CALCINER
(5,000 TONS/DAY)

WASTE GAS STREAM CHARACTERISTICS

Gas Temperature	1000°F
Flow Rate	50,000 SCFM
Heat Available	38 Million BTU/HR
Stack Gas Temperature	350°F
Corrosive Species	SO _x , HF, HCl
Condensible Species	H ₂ SO ₄ , HCl

SERVICE/APPLICATION CHARACTERISTICS

Type	Electric Power Generation
Steam	600 PSIG; 650°F

ENERGY CONSERVATION POTENTIAL

Fan Power	500 HP (370 KW)
Energy Resource Expended	4.3 Million BTU/HR
Energy Recovered	2,960 KW
Net Energy Conservation	*2,590 KW
Energy Conservation Parameter (Z)	8

POTENTIAL TECHNICAL PROBLEMS

- Operation of a two-stage bed system needs to be established.

* Z > 6 Considered Highly Favorable Energy Conservation

TABLE 10.8

ECONOMIC ASSESSMENT OF FWHRs IN CHEMICAL INDUSTRY
APPLICATION #1 - NODULIZING ROCK CALCINER
(5,000 TONS/DAY)

FWHRs COSTS

FWHR Unit	\$777,000
Balance of Steam Plant	189,500
Auxiliary Systems	<u>None</u>
Total Equipment	\$966,500
Installation Cost	<u>\$483,300</u>
Total Installed Cost	\$1,449,800

OPERATING COSTS (ANNUAL)

Electric Power (Fan Power)	\$135,000
Maintenance (Scheduled & Repair)	<u>145,000</u>
Total Operating	\$280,000

SAVINGS FROM CONSERVATION

Savings Per Year	\$1,065,600
Net Savings Per Year	\$ 785,600
Payback Period	1.9 Years

FIGURE 10.4
FWHRS FOR DRYING AND PREHEATING ROCK
(CHEMICAL INDUSTRY)

TABLE 10.9

TECHNICAL ASSESSMENT OF FWHRs IN CHEMICAL INDUSTRY
APPLICATION #2 - DEFLUORINATED ROCK KILN

WASTE GAS STREAM CHARACTERISTICS

Gas Temperature	2200°F
Flow Rate	20,000 SCFM
Heat Available	41.6 Million BTU/HR
Stack Gas Temperature	500°F
Corrosive Species	HF, Dust
Condensible Species	H ₂ O

SERVICE/APPLICATION CHARACTERISTICS

Type	Drying & Preheating Rock
Rock Throughput	150,000 LBS/HR

ENERGY CONSERVATION POTENTIAL

Fan Power	194 HP (150 KW)
Energy Resource Expended	1.6 Million BTU/HR
Energy Recovered	41.6 Million BTU/HR
Net Energy Conservation	40 Million BTU/HR
	(≈1 Million FT ³ /DAY Natural Gas)
Energy Conservation Parameter (Z)*	26

POTENTIAL TECHNICAL PROBLEMS

- Condensation of undesirable species in the phosphate rock feed
- Corrosion and erosion

* Z > 6 Considered Highly Favorable Energy Conservation

TABLE 10.10

ECONOMIC ASSESSMENT OF FWHRs IN CHEMICAL INDUSTRY
APPLICATION #2 - DEFLUORINATED ROCK KILN

FWHRs COSTS

FWHR Unit*	\$215,000
Balance of Steam Plant	None
Auxiliary Systems**	<u>Negligible</u>
Total Equipment	\$215,100
Installation Cost	<u>\$107,600</u>
Total Installed Cost	<u>\$322,700</u>

OPERATING COSTS (ANNUAL)

Electric Power (Fan Power)	\$ 54,000
Maintenance (Scheduled & Repair)	<u>32,300</u>
Total Operating	\$ 86,300

SAVINGS FROM CONSERVATION

Savings Per Year	\$576,000 (Natural Gas at \$2/Million BTU)
Net Savings Per Year	\$489,700
Payback Period	0.7 Years

ECONOMIC CONSIDERATIONS

*Cost of fluidized-bed dryer/preheater is expected to be much less than the FWHR equipment assumed here because of the absence of heat exchange surfaces.

**Auxiliary equipment for solids feeding, withdrawal and handling is usually available in plant; incremental cost for this equipment assumed negligible.

10.6.3 Summary of FWHRs Applications in Chemical (Phosphate Rock) Industry

The chemical industry is very diverse with various potential waste heat sources for heat recovery. However, these waste streams are usually dust laden, corrosive and/or noxious. The applications with inherent potential for heat recovery from hot corrosive dust laden gas streams provide an opportunity to take advantage of the unique operation and performance characteristics of the FWHRs.

The two applications analyzed are potentially viable, both technically and economically. Although the potential problem areas (e.g., corrosion, erosion, distributor plate design, optimization) need to be resolved by an engineering/commercial demonstration, it appears that the fluidized-bed dryer/heater application is more attractive than the steam/electric power generation application, essentially because of the minimal initial cost of fluidized-bed dryer/heater system.

10.7 Summary of Industry Comments

The following corporations were contacted by telephone for their viewpoints on waste heat recovery and utilization:

IMC Corp.	Defluorinated Rock
Occidental Petroleum	Defluorinated Rock
Borden Chemical	Defluorinated Rock
FMA Corp.	Nodulized Rock
Monsanto	Nodulized Rock

Uniformly, the companies were interested in waste heat recovery and utilization. The three companies engaged in defluorinated rock operations were equally interested in steam production for in-plant electric power and in preheated air for drying and preheat operations. The two major companies in nodulized rock-electric furnace operations were interested in electric power generation but not too impressed by this utilization because it would have only a minor impact on their relatively huge electrical demands. They indicated stronger interest in preheating the rock charge to the nodulizing kiln.

All companies indicated that new technology waste heat recovery applications would be mainly evaluated on economic basis, i.e., capital investment required and payout time or ROI. Apparently, their current energy costs have not reached the point where the dollar value of Btus saved becomes the determinant for application of waste heat recovery systems.

REFERENCES-CHEMICAL INDUSTRY

1. "Chemical Week 300", Chemical Week, April 25, 1979, p. 28-45
2. "Statistical Abstract of the U.S.-1978", 99th Annual Edition, Table No. 1419, Bureau of Census, U.S. Dept. of Commerce
3. "Annual Survey of Manufactures-1976: Fuels and Electric Energy Consumed", M76(AS)-4.1, Table C, pg. 7, Bureau of Census, U.S. Dept. of Commerce.
4. TVA, National Fertilizer Development Center Muscle Shoals, Alabama. Private communication
5. Bureau of Mines, Washington, D.C. Private communication.
6. "Minerals Yearbook 1976", Vol. 1, p. 1101-1110, Bureau of Mines, Washington, D.C.
7. Operating Companies. Private telephone communications
8. "Phosphatic Fertilizers", Technical Bulletin No. 8, 2nd. Ed., p. 56-57, (1966), The Sulphur Institute, Washington, D.C.

11.0 STUDY RESULTS

11.1 Characteristics of Potential FWHRs Applications

Applications in six industries were examined with the objective that the recovered waste heat energy could be practically utilized within the plant to fulfill an actual need which would reduce overall consumption of energy. The applications were analyzed based on literature research and telephone interviews with management personnel of the various industries. Table 11.1 summarizes the evaluations of an FWHRs application to a single plant unit within a typical size industry plant.

The steel industry offers the greatest quantity of waste heat available for recovery from a single plant unit, namely, the reheat furnace flue gas which ranges from 74.4 to 140.4 million Btu/hour. The cement industry presented two plant opportunities: the preheater bypass gas at 27.4 million Btu/hour and the kiln exhaust gas at 60.8 million Btu/hour. The petroleum refinery contains a special situation wherein the fluid catalytic cracking (FCC) regenerator discharges a flue gas which contains 42.3 million Btu/hour available for recovery. Within the chemical industry, the phosphate fertilizer industry operates kilns and calciners which emit flue gases ranging in available heat from 38 to 41.6 million Btu/hour for recovery. The melting furnace in an aluminum plant offers a similar magnitude heat recovery opportunity of 20.0 to 22.6 million Btu/hour.

The maximum size FWHRs unit sold in the U.S. by Granco is 20 million Btu/hour. The applications evaluated (see Table 11.1) were for plant situations ranging from 1.0 to 7 times greater, with the exception of the heavy crude oil industry which was somewhat smaller.

The waste gas streams available for heat recovery were flue gases from furnaces or boilers and off-gases or exhaust gases from kiln or calciners. These plant waste heat sources are expected because the nature of the plant equipment produces relatively large amounts of waste gas at elevated temperatures which do not readily lend themselves to simple heat conservation methods. The basic conventional approach has been to employ waste heat boilers or recuperators. In the past, there has not been a widespread thorough application of these units for a variety of reasons, both technical and economic.

The waste heat recovery service applications, indicated in Table 11.1, are electric power generation, combustion air preheating, boiler feedwater heating, and drying. These applications were in accord with industry suggestions on the preferable usage of the waste heat

TABLE 11.1

CHARACTERISTICS OF POTENTIAL FWERS APPLICATIONS

INDUSTRY (Nominal Plant Size)	WASTE ENERGY STREAM	WASTE HEAT STREAM CHARACTERISTICS			SERVICE APPLICATION	TYPE ENERGY SAVED
		Gas Temperature (Inlet/Exit)	Flow Rate Thru FWERS (Thousand SCFM)	Heat Available For Recovery (Million BTU/HR)		
CEMENT Application #1 (1700 Tons/Day)	Preheater- Bypass Gas	1900°F/700°F	20	27.4	Electric Power Generation	Electric Power
	Kiln Exhaust Gas	1000°F/350°F	80	60.8	Electric Power Generation	Electric Power
STEEL Application #1 (250 Tons/Hr)	Flue Gas from Reheat Furnace With Recuperator	1400°F/350°F	60	74.4	Electric Power Generation	Electric Power
	Flue Gas from Reheat Furnace Without Recuperator	2300°F/350°F	60	140.4	Electric Power Generation	Electric Power
ALUMINUM Application #1 (90,000 Lbs. Cap)	Flue Gas from Melt Furnace	2200°F/550°F	10	22.6	Electric Power Generation	Electric Power
	Flue Gas from Melt Furnace	2200°F/500°F	10	20.0	Combustion Air Preheating	Natural Gas
HEAVY CRUDE OIL Application #1 (50 MM Btu/Hr)	Flue Gas from Boiler	400°F/200°F	12	2.8	Boiler Feedwater Heating	Heavy Crude Oil
	Flue Gas from Boiler	400°F/200°F	12	2.8	Combustion Air Preheating	Heavy Crude Oil
PETROLEUM REFINING Applications #1 & #2 (33,000 Bbl/Day)	Off-gas from FCC Regenerator	1000°F/400°F	60	42.3	Steam Generation	Crude Oil
CHEMICAL Application #1 (5,000 Tons/Day)	Flue Gas from Nodulizing Rock Calciner	1000°F/350°F	50	38	Electric Power Generation	Electric Power
	Flue Gas from DeFluorinated Rock Kiln	2200°F/500°F	20	41.6	Drying and Preheating Rock	Natural Gas

recovered. These usages will save a wide variety of fossil or fossil-derived energies consumed in plant operations, including electric power, natural gas and crude or distillate fuel oil.

The temperature ranges of the waste gas streams of the six industries analyzed are indicative of most industrial processes with unutilized waste heat streams. The FWHRs temperature levels, shown in Table 11.1, have a hot waste gas entering in the range of 400°F to 2300°F, and an exiting cooled gas range of 200°F to 700°F. The cooled exit gas temperature depends on the service applications and is oriented to the needs of the particular plant, i.e., it is plant and process specific. The opportunity for the FWHRs to operate within the widest hot-cold temperature range available is most important. It allows for utilization flexibility and it improves the ability of the FWHRs to compete on better terms with the waste heat boiler and recuperator which enjoy a marked advantage in their ability to operate on significantly closer temperature approach on the hot and cold ends.

11.2 Technical and Economic Assessments

The technical and economic assessments are summarized in Table 11.2 for each of the six industries. In the technical assessments, the net energy conserved for each application was determined based on the difference between the energy recovered and the energy expended to recover the waste heat. An energy conservation parameter, Z, is defined to provide a measure of technical practicality of the FWHRs for a specific application. This factor is defined as the ratio of the energy recovered to the energy (resource) expended to recover the waste heat. The major result of the technical assessments is:

- Each application analyzed has a favorable ratio (ranges from 2.8 to 26) of energy recovered to energy expended for the recovery. Other than application #2 in the heavy crude oil recovery industry, these ratios were in the highly favorable range (i.e. greater than 6). Therefore, the identified FWHRs applications have the potential for considerable energy savings.

In the economic assessments, the equipment installed cost and the annual operating cost were estimated for each application. The annual dollar savings were determined based on the net energy conserved and an assumed cost for the specific energy resource saved. The annual net savings were determined based on the difference between the annual energy cost savings and the annual operating costs. These costs were used to determine simple payback periods for each FWHR application. The major result of the economic assessments is:

TABLE 11.2

SUMMARY OF TECHNICAL AND ECONOMIC ASSESSMENT

INDUSTRY	NET ENERGY CONSERVED	ENERGY CONSERVATION PARAMETER(Z) ^a	TOTAL INSTALLED COST (Thousands of \$)	ANNUAL OPERATING COSTS (Thousands of \$)	ANNUAL NET SAVINGS (Thousands of \$)	SIMPLE PAYBACK PERIOD (Years)	COMMENTS
CEMENT							
Application #1	2,550 KW	24	1,184	150	619	1.9	Heavy Particulates Load
Application #2	4,595 KW	19	3,399	467	1,329	3.2	Heavy Particulates Load
STEEL							
Application #1	5,350 KW	13	4,129	575	1,625	2.5	
Application #2	10,500 KW	24	6,364	799	3,141	2.0	High Temperature Gas Stream
ALUMINUM							
Application #1	1,680 KW	22	1,051	134	500	2.1	High Temperature Gas Stream
Application #2	19 MM BTU/HR	24	444	73	180	2.5	High Temperature Gas Stream
HEAVY CRUDE OIL							
Application #1	10 BBL/LAY	8.1	140	25	33	4.3	
Application #2	2.6 BBL/DAY	2.8	140	25	None	-	Not Economically Feasible
PETROLEUM REFINING							
Application #1	40 MM BTU/HR	19	1,083	179	1,039	1.1	New BOP Equipment Acquired
Application #2	40 MM BTU/HR	19	699	141	1,077	0.6	Uses Existing BOP Equipment
CHEMICAL							
Application #1	2,590 KW	8	1,450	280	786	1.9	Particulates Laden Gas Stream
Application #2	40 MM BTU/HR	25	321	86	490	0.7	Particulates Laden High Temperature Gas Stream

^aZ = Energy Recovered/Energy(Resource) Expended For Recovery

- Simple payback periods ranged from 0.6 to 4.3 years for each industrial application, except application #2 in the heavy crude oil recovery. This application (combustion air preheating) did not provide a net savings from the value of energy conserved. The payback periods for the economically feasible applications are within the usual corporate plant accounting and financial standards. Therefore, the use of the FWHR technology should meet the usual economic criteria imposed by corporations in evaluating capital investment.

Table 11.2 shows a capital investment range of \$140,000 to \$6,364,000 for the various industrial applications considered, and an annual operating cost ranging from \$25,000 to \$799,000. These sums of money are relatively small compared to the range of annual net savings of energy expressed in dollars - \$33,000 to \$3,144,000. This satisfactory relation between FWHR capital investment/operating cost and annual net savings is expressed by the good range of short payback periods.

In appraising the results summarized in Table 11.2, it should be noted that the economics of the FWHRs have not been compared with the conventional waste heat boiler and recuperator systems. The cost and economic data summarized in Table 11.2 indicate that the FWHRs applications considered are reasonable and in accord with corporate standards. The energy conservation parameter column indicates a highly favorable ratio for the FWHRs. It should be noted that waste heat boilers and recuperators possibly have lower pressure drops, thus requiring a lower amount of fan/blower electric power. Although conventional heat recovery equipment may have a more favorable energy conservation parameter, plant and process specific conditions would have to be analyzed to determine the most suitable system for waste heat recovery and utilization.

Although the potential applications for FWHRs appear to be very attractive from the energy recovery and economic standpoint, design studies, including possibly additional R&D, may be required for some of these applications.

Currently, the FWHR systems available commercially are small, single stage units with inert beds to recover heat from relatively non-corrosive gas streams at temperatures up to 1800°F. Since the technology is emerging, it may be assumed that the designs are not optimized. Moreover, the performance data have not been well established. Consequently, the following FWHR system parameters need to be analyzed for the potential applications identified in this study:

- Design of distributor plate to minimize pressure drop while achieving an adequate quality of fluidization
- Selection of structural materials and design approaches for heat exchangers and other internals
- Design and operation of multi-stage FWHRs.

In addition to these factors that are common to almost all applications, some applications require additional attention. The application of FWHR systems in a high temperature waste gas stream environment (i.e., greater than 1800°F) may result in structural material problems, especially for the gas distributor plate. Proposed applications in the steel, aluminum, and chemical industries expose the FWHRs to temperatures that are higher than the current design of commercial units (1800°F). If the high temperature creates a major design problem for the FWHRs in these applications, the waste gas stream temperature could be reduced by bleeding in atmospheric air, although net energy recovered would be decreased. The corrosive components (e.g., HF, HCl, alkali compounds, H₂SO₄, SO₂) in the waste gas stream will also require special consideration in the design of the FWHRs, especially at the high temperatures. The application of FWHRs using a sorbent bed material could minimize the impact of corrosive components on downstream emission control equipment and reduce environmental emissions. This possible advantage of FWHRs was not analyzed for the applications identified in this study.

11.3 Waste Heat Recovery and Utilization Potential for FWHRs

The summary of the waste heat recovery for the six industries is shown in Table 11.3. The potential waste heat that can be recovered and utilized in FWHRs applications is estimated to be 242 trillion Btu annually. This amount is equivalent fossil fuel saving is equal to 41.7 million barrels of distillate fuel oil or 213 BCF of natural gas. The significance of this waste energy recovery and utilization for six industries is that it is equivalent to 6.4 days of crude oil imports or 2.9 days of total crude runs to refinery stills at current operation levels in the U.S. petroleum refining industry.

The potential savings in energy were based on an evaluation of each industry which took into consideration the following factors:

- Recovery of waste heat and its practical utilization in typical process plants for each specific industry analyzed
- Estimation of the number of plant units in each industry that could be retrofitted with FWHRs units

TABLE 11.3

WASTE HEAT RECOVERY AND UTILIZATION POTENTIAL FOR FWHRs

(SUMMARY FOR SIX INDUSTRIES)

<u>INDUSTRY</u>	<u>WASTE HEAT SOURCE</u>	<u>WASTE STREAM</u>	<u>ANNUAL RECOVERED HEAT</u> (Trillion Btu)	<u>ANNUAL EQUIVALENT FUEL SAVING</u>	
				<u>Dist. Oil</u> (Million Bbls)	<u>or</u> <u>Nat. Gas</u> (BCF)
CEMENT	Preheater By-Pass	Flue Gas	12	2.1	12
"	Dry Process Kiln	Exhaust Gas	35	6.0	35
STEEL	Reheat Furnace	Flue Gas	96	16.5	96
"	Coke Oven Battery	Flue Gas	5	0.9	5
"	Dry Quench Coke (New Technology)	Inert Recycle Gas	32	5.5	32
ALUMINUM	Melting Furnace	Flue Gas	7	1.2	7
HEAVY CRUDE OIL	Steam Generator	Flue Gas	29	5.0	-
PETROLEUM REFINING	FCC Regenerator	Flue Gas	25	4.3	25
CHEMICAL	Phosphate Rock Kiln	Exit Gas	1	0.2	1
TOTALS			242	41.7	213

NOTE: One Barrel Distillate Oil = 5,824,000 Btu

One SCF Natural Gas = 1,000 Btu

- Estimation of realistic operation stream time based on current industry operation levels
- Assumption that there would be a widespread application of FWHRs, or other waste heat recovery technology, within each industry, in a relatively short period of time so that the maximum recovery of waste heat within each industry would be realized.

The industry receptivity to equipment innovation and their attitude toward a demonstration program, as determined by telephone interviews, influenced the selection of the six industries for application of FWHRs and impacted on the estimation of the potential energy savings. Industry receptivity was strong in the cement, chemical (phosphate), and heavy crude oil (equipment vendors) industries. The steel, petroleum refining and aluminum industries, while expressing strong interest, stated that their consideration of FWHR systems would have to be evaluated relative to their commitments to on-going energy conservation programs.

12.0 CONCLUSIONS AND RECOMMENDATIONS

12.1 Conclusions

The following conclusions are made based on this study:

- (1) Major U.S. industries, which have been identified in this study, are currently rejecting large amounts of waste heat in forms which can be readily recovered and utilized by employment of the fluidized-bed waste heat recovery technology.
- (2) Analysis of FWHRs for six industries indicates that applications are technically and economically feasible and that the plant applications have widespread utility within and outside the specific industries.
- (3) Potential waste energy of 242 trillion Btus annually available for recovery and utilization in the six industries analyzed justifies the federal government's promotion of applications of FWHRs and conventional waste heat recovery systems.
- (4) Processes in the six industries were found to be highly suitable for FWHRs application. The industries are ranked below according to energy savings, industry receptivity and diversity of applications to assist DOE in their decision regarding participation in a limited number of demonstration projects:

<u>Energy Savings</u>	<u>Industry Receptivity</u>	<u>Application Diversity</u>
Steel	Cement	Heavy Crude Oil (Boiler Flue Gas)
Cement	Chemical (Phosphate)	Steel/Aluminum (Furnace Flue Gas)
Heavy Crude Oil	Heavy Crude Oil (Vendors)	Cement/Chemical/ Petroleum Refining (Kiln Gas)
Petroleum Refining	Steel	
Aluminum	Petroleum Refining	
Chemical (Phosphate)	Aluminum	

- (5) Although the FWHR units are commercially available for relatively small industrial applications, the performance of this technology has not been thoroughly established. Technical and economic data on scale-up of this technology is needed for widespread commercial applications in the large industrial processes identified in this study.

Although this study focused on the application of FWHRs, the data presented on industry processes and waste heat streams are applicable to energy conservation programs involving other waste heat recovery technologies (e.g., conventional waste heat boilers and recuperators). The study results indicate there would be significant benefits to the nation in focusing a national program on these six industries in the plant operation areas identified in this study.

12.2 Recommendations

The following recommendations are offered based on this study:

- (1) Application of the FWHRs should be promoted in the six industries identified in this study, particularly the steel (furnace flue gas), cement (kiln gas) and the heavy crude oil (boiler flue gas) industries. A successful demonstration program of the FWHRs sponsored by the federal government should provide potential industrial users the confidence to use the fluidized-bed waste heat recovery system.
- (2) Research and development should be performed on advanced fluidized-bed waste heat recovery systems incorporating improved operational characteristics (i.e., active beds, larger capacities, different bed materials, and higher temperatures) to broaden their application in industry. The R&D efforts should emphasize making available technical and economic information necessary to enable equipment vendors to provide commercial FWHRs units with performance guarantees.
- (3) Industrial energy conservation programs employing waste heat recovery technologies in addition to FWHRs should be focused on the process waste heat streams in the six industries identified in this study.

APPENDIX A

FWHRS TECHNICAL AND ECONOMIC PARAMETERS

FIGURE A.1
SENSIBLE HEAT IN WASTE GAS STREAM

A-3

FIGURE A.2
HEAT AVAILABLE IN WASTE GAS STREAM

TABLE A.1
ESTIMATED SERVICE TEMPERATURE IN VARIOUS APPLICATIONS

Application	Thermal Fluids	Service Temperature, °F
Green House/Hot House for Growing Plants	Air, Flue Gas	70 - 90
Space Heating	Water, Air	120 - 140
Hot Water	Water	140 - 180
Combustion Air Preheating	Air	300 - 900
Boiler Feed Water Heating	Water	150 - 350
Drying	Flue Gas	250 - 600
Low Pressure Steam	Water/Steam	220 - 350
High Pressure Steam	Water/Steam	600 - 900

FIGURE A.3
PRESSURE DROP IN FLUIDIZED-BED

FIGURE A.4
FAN ENERGY REQUIRED

FIGURE A.5
RELATION BETWEEN FAN ENERGY
AND ENERGY AVAILABLE

TABLE A.2
SHALLOW-BED FWHR UNIT COSTS

Waste Gas		Cost For Types of Application (Dollars)			Duty, 10 ⁶ Btu/Hr		
Flow Rate, SCFM	Temp., °F	Hot Water	Steam	Thermal Fluid	Hot Water	Steam	Thermal Fluid
1000	1200	14,300	25,500	14,600	1.05	4.795	0.607
5000	1200	32,300	52,200	36,100	5.25	19.975	3.035
10,000	1200	53,300	77,700	61,700	10.5	79.95	6.07
1000	1800	15,100	26,300	16,500	1.79	11.38	1.2
5000	1800	36,500	54,300	41,400	8.95	56.90	6.0
10,000	1800	62,500	89,600	73,500	17.9	113.8	12.0

Source: John C. Bugai--Granco Equipment Company, Grand Rapids, MI. Telephone conversation-- November 6, 1979.

TABLE A.3
FWHR UNIT COSTS PER MILLION BTU/HR DUTY
(1979 DOLLARS)

Waste Gas		Equipment Cost, \$/Million Btu/Hr		
Flow Rate, SCFM	Temp. °F	Hot Water	Steam	Thermal Fluid
1,000	1200	13,619	32,075	24,053
5,000	1200	6,152	13,132	11,894
10,000	1200	5,076	9,773	10,164
1,000	1800	8,436	19,057	13,750
5,000	1800	4,089	7,870	6,900
10,000	1800	3,457	6,493	6,125
5,000	800	11,577	---	---
5,000	600	20,838	---	---

TABLE A.4
STEAM GENERATING PLANT COSTS^{*}
(1976 DOLLARS)

Component	\$ / KW			
	100,000 pph 10 MW	200,000 pph 20 MW	300,000 pph 30 MW	400,000 pph 40 MW
Steam Generator	51	49.5	48	47
Deaerator	1.5	1.5	1.2	1
Water Treatment	46	39	32	30
Boiler Feed Pump and Drives	1.4	1.4	1.4	1.4
Electrical Switch Gear	1.3	1.3	1.2	1.2
Chemical Treat- ment	0.5	0.5	0.5	0.5
Duct Work & Insulation	0.9	0.9	0.9	0.9

* Based on Burns & Roe, Inc. data as reported in RPA Report

TABLE A.5
POWER GENERATION EQUIPMENT COSTS*
(1976 DOLLARS)

Component	\$/KW		
	Capacity: 5MW	7.5 MW	15 MW
Steam Turbine Generator	216	163.2	121.5
Control Room and Electrical Switch- gear	29	24.5	20

* Based on Burns & Roe, Inc. data as reported in RPA Report

APPENDIX B

TECHNOLOGY STATUS

FLUIDIZED-BED WASTE HEAT RECOVERY

B.1 FWHR Technology Concepts

Fluidized-bed waste heat recovery (FWHR) is an emerging technology with several different design features. These design features make the FWHR system potentially suitable for a large variety of applications. The following classifications of the technology are made to account for some of its important design features:

Shallow/Deep Bed Systems: Shallow bed technology uses bed depths from 1.5 to 9 inches whereas deep bed systems may be operated with beds as deep as 4 feet. Shallow beds are operated at a relatively low fluidizing velocity (about 2 ft/sec) with a characteristic pressure drop across the bed ranging from 6 to 20 inches of water. The pressure drop across the deep beds could be as high as 60 to 90 inches of water.

Single/Multistage Systems: Fluidized-bed waste heat exchangers can be designed as single or multiple stage systems. Sometimes, it is advantageous to use one stage of fluidized bed and another stage of conventional heat exchanger.

Direct/Indirect Heat Exchanger Systems: Generally, FWHRs are indirect heat exchangers with submerged heat exchanger tube bundles carrying a thermal fluid (air, water/steam or a patented fluid such as dow-therm). However, in some instances a direct heat exchanger can be designed without the need for heat exchanger surfacing (e.g., fluidized-bed clinker cooler in cement manufacturing industry).

Active/Inert Bed Systems: FWHRs can be designed to recover heat from relatively non-corrosive gases using inert bed material. However, in some instances, suitable sorbents can be used as bed material to remove some noxious/corrosive gases; for example, calcined limestone can be used to remove SO₂ from flue gas streams. Although a significant potential exists for active bed systems, additional R&D work is required for their commercial application.

Atmospheric Pressure/Pressurized Operation: FWHRs are currently utilized exclusively for near-atmospheric pressure operation but the technology can be utilized for waste streams at elevated pressures. However, the pressurized FWHRs is not currently commercially available.

B.2 FWHR Equipment Available

Fluidized-bed heat exchanger technology using shallow beds was developed and commercialized by Stone-Platt Fluidfire Company in the United Kingdom. Granco Equipment Company, Grand Rapids, Michigan and Fennell Corporation, Harvey, Illinois are the U.S. licensees for the Stone-Platt Fluidfire technology. Apparently, Stone-Platt Fluidfire has employed FWHR technology in a wide range of applications including waste heat recovery from diesel engine exhaust aboard a diesel powered ship.

The FWHR equipment available in the U.S. consists of semi-custom built systems developed and manufactured by Granco Equipment Company, with a capacity range of 0.5 to 20 million Btu/hr.⁽¹⁾ The Granco-built equipment includes the complete heat exchanger unit with fan and controls. Granco Equipment Company has sold three FWHR units to industry*. However, these units are not yet operational.

The Granco Equipment Company offers semi-custom built units for recovery of heat from waste gases at temperatures up to 1800°F to produce hot water, to generate steam or to heat a patented thermal fluid. The service applications include process heating and process steam for various industries.

B.3 State of the Technology

The status of the fluidized-bed heat exchanger technology is summarized in Table B.1. The shallow bed system can be employed in various applications. The selection of a specific system depends on the particular industrial process/plant. The current technology status indicates that only shallow inert fluidized-bed waste heat recovery systems have been developed and commercialized for diverse applications.

B.3.1 Data Available on Shallow-Bed Systems

Shallow-bed heat exchanger technology was developed and commercialized by Stone-Platt Fluidfire Company in the U.K. Very limited technical data are available for the Stone-Platt Fluidfire waste heat exchanger technology.^(1,2,3) These data for a specific heat recovery unit are as follows:

Bed Material:	Alumina, Sand
Bed Depth (expanded):	2 - 3 in.

*Telephone conversation with J. Bugai, Granco Equipment Company, Grand Rapids, Michigan

TABLE B.1

STATE OF THE FLUIDIZED-BED (HEAT EXCHANGER) TECHNOLOGY

<u>Fluidized-Bed Concept</u>	<u>Status Of Development/Commercialization</u>
Shallow Bed, Single Stage	Commercially Available for FWHR up to 20×10^6 Btu/hr
Deep Bed, Single Stage	Technology Available; FWHR Systems Using This Technology are not Commercially Available
Shallow Bed, Multiple Stage	Not Yet Developed
Shallow Bed, Single Stage with Conventional Heat Exchanger	Feasible
Direct Heat Exchanger	Feasible (e.g., Fluidized-Bed Cement Clinker Cooler)
Indirect Heat Exchanger	Feasible (e.g. Stone-Platt Fluidfire System); Commercially Available up to 20 Million Btu/hr
Inert Bed System	Commercially Available
Active (Deep) Bed System	Extensively Used in Various Applications but not for Waste Heat Recovery
Active (Shallow) Bed System	Not Exploited and None Available
Atmospheric Pressure System	Commercially Available
Pressurized System	Feasible but Needs Further Development

Fluidization Velocity:	1 - 2 ft/sec.
Pressure Drop Across the Bed:	6 - 8 in. water
Bed Side Heat Transfer Coefficient:	40 Btu/ft ² -hr-°F
Heat Exchanger Tubes:	Finned Tubes (0.5 in. ID, 1.5 in. OD)

A small fluidfire heat exchanger has been investigated by the United Technologies Research Center (UTRC).⁽³⁾ The results are provided in Table B.2.

Stone-Platt Fluidfire has developed a graph,⁽¹⁾ shown in Figure B.1, to compute the potential heat recovery and nominal size of a FWHR system when the waste gas temperature is specified.

There is considerable amount of data available for deep bed systems. However, the applications now under consideration in general preclude the use of deep beds with large pressure drops and associated fan power requirements.

B.3.2 Limitations for Scale-Up

Scale-up of shallow-bed FWHR equipment would not necessarily present any unresolvable problems. Technically, a scale-up to four times the current throughput can be attempted without undue risks. In addition, a modular approach could extend the capacity without a need for further scale-up efforts.

B.3.3 Major Characteristics of Fluidized-Bed Systems

The relatively high pressure drop of a fluidized-bed is a major disadvantage. However, there are several advantages derived from the characteristics of fluidized-bed. These include the following:

- High heat transfer coefficient for submerged tubes
- Uniform bed temperature
- Bed/bed material characteristics.

High Heat Transfer Coefficient

The fluidized bed is in a turbulent state with bed material being continuously recirculated in the bed. This turbulent state provides an excellent means to transfer mass and heat resulting in good mixing

Source: Stone-Platt Fluidfire/Granco Equipment Company

FIGURE B.1
SIZE AND RATING OF FWHRs UNITS

TABLE B.2

SUMMARY OF UTRC TESTS ON STONE-PLATT
FLUIDFIRE SHALLOW BED HEAT EXCHANGER

Performance Specifications

Thermal Rating: 140,000 Btu/hr
Heat Source: Propane products of combustion
Gas Inlet Temperature: 436 °F
Gas Exhaust Temperature: 247 °F
Water Inlet Temperature: 160 °F
Water Outlet Temperature: 180 °F

Heat Exchanger Surface (Measured)

Tube and Fin Material: Copper, assumed thermal conductivity of
220 Btu/ft-hr-°F
Tube to Fin Attachment: Alloy bonded
Number of Tubes: 12 (in series/parallel combination)
Tube Outer Diameter: 0.715 in.
Tube Inner Diameter: 0.50 in.
Fin Outer Diameter: 1.375 in.
Fin Spacing: 73/10 in.
Fin Thickness: 0.025 in.
Outside Surface Area: 1.54 ft²/ft
Ratio Outside to Inside Area: 11.7
Total Surface Area in Bed: 50 ft²

Gas Flow Area (Measured)

Total Grate Area: 7.36 ft²
Active Distributor Area: 5.94 ft²
Tube Blockage: 1.78 ft²

Particle Properties (Measured)

Material: Alumina
Diameter: 0.026- 0.005 in. (by microscopic examination)
Density: 245 lb/ft³
Voidage of Poured Bed: 0.43

and heat transfer coefficients. Because of high heat transfer coefficients, the in-bed heat exchanger surface requirements are reduced, resulting in a more compact waste heat recovery unit.

Uniform Bed Temperature

The turbulent state of a fluidized-bed is also conducive to minimize temperature gradients in the bed. In the gas fluidized beds, the waste gas temperature is quickly reduced to the bed temperature with the temperature drop occurring within an approximate depth of three inches above the gas distributor plate. Beyond this short depth, the bed temperature remains uniform across the bed and is close to the exhaust gas temperature.

A uniform temperature across the bed is an attractive feature of the fluidized bed especially when the bed material is to serve as a sorbent. However, since the bed temperature is uniform and close to that of the exhaust gas, the thermal fluid cannot be heated to a temperature above that of the exhaust gas. In this respect, the fluidized-bed system is not as attractive as the counter-current heat exchanger system in which the thermal fluid can be heated to a relatively higher level of temperature. This inherent disadvantage of the FWHRs may necessitate the use of a multistage concept to achieve the necessary heat recovery while raising the thermal fluid temperature to the required level.

The fluidized-bed system also offers another advantage by its characteristic property of reducing the temperature of the hot gas stream to the temperature of the bed within a few inches of the bed depth; since the bed temperature is quickly lowered, the range of structural materials available to the designer is widened. Also, these structural materials are likely to perform adequately over a longer period of time, thus avoiding some of the current problems associated with high temperature recuperators.

Bed/Bed Material Characteristics

Both the bed and bed material characteristics of FWHRs provide attractive features. The presence of a bed, particularly the deeper beds, provides a thermal storage capability which is not present in the conventional tubular heat exchanger systems. Because of the inherent thermal storage capability, fluidized-bed systems could be designed to operate with intermittent streams. However, such systems are not available currently and would require additional R&D work for commercialization.

The turbulent nature of the fluidized-bed provides an excellent means for scrubbing of the submerged heat exchanger tubes. Because of this scrubbing, the in-bed heat exchanger tubes are anticipated to remain clean without fouling deposits. Because of the absence of fouling deposits, the heat exchanger efficiency remains high over a long period of time, thus reducing the equipment downtime.

Usually, the waste gas streams contain noxious and/or corrosive gases. Fluidized-beds provide an excellent opportunity to reduce pollutants while recovering heat. Depending on the noxious/corrosive species and the temperature, a suitable sorbent could be chosen to eliminate/minimize a pollutant. For example, SO_2 could be removed from the gas stream at a temperature of about 1500°F by using limestone as a sorbent material. Although such a potential advantage exists, sorbent fluidized-bed waste heat recovery systems are not available in the market. Further R&D work would be necessary to tap this potential advantage of fluidized-beds in various industrial applications.

B.3.4 Comparison of FWHR with Conventional Heat Exchangers

Figure B.2 provides a process schematic and temperature profile comparison between the FWHR and a conventional heat exchanger. A quantitative comparison of their design and performance characteristics is shown in Table B.3.

B.4 Design and Performance Considerations

The primary design considerations for the application of FWHRs are as follows:

- Optimization of the design to minimize fanpower without affecting the quality of fluidization
- Optimization of heat exchanger surface design
- Selection of structural materials for the heat exchanger surface internals and for the equipment down stream
- Selection of suitable bed material for each application.

The potential FWHRs performance as compared with conventional waste heat boilers is shown in Table B.4. The comparison is provided for the primary performance parameters of interest in applications of waste heat recovery systems.

B-10

CONVENTIONAL COUNTER CURRENT HEAT EXCHANGER
(NOTE: T_S can be smaller than T_{Fout})

FLUIDIZED BED WASTE HEAT EXCHANGER
(NOTE: T_{Fout} cannot be greater than T_S)

FIGURE B.2
COMPARISON OF FWHRs WITH CONVENTIONAL
HEAT EXCHANGER

TABLE B.3
COMPARISON OF SINGLE STAGE FWHR WITH
CONVENTIONAL HEAT EXCHANGERS

Aspect	Comparison of FWHR System With Conventional Systems
Space Requirement	Potentially Less
Floor Area	Greater
Heat Exchanger Surface	Less
Potential of Heat Exchanger Fouling	Less
Potential for Pollution Control By Sorbent Use (e.g., SO _x Sorption)	Greater
Potential for Operation With Intermittant Streams	Greater
Potential Service Temperature	Lower
Initial Cost	Higher; Likely to be Reduced With Manufacture of More Units
Pressure Drop	Greater

TABLE B.4

COMPARISON OF FWHR SYSTEM PERFORMANCE
WITH CONVENTIONAL WASTE HEAT BOILER

<u>Performance Parameter</u>	<u>Potential FWHR System Performance As Compared to Conventional Waste Heat Boiler</u>
Operability	About the Same
Efficiency	About the Same
Reliability	Better
Availability	Better
Maintainability	About the Same
Stability	Better
Environmental Compliance	Better
Safety	Better
Systems Compatibility With Industrial Plant/Process	Better

The availability of data relevant to the design and performance parameters for the FWHRs is limited. Current R&D programs^(3,4) dealing with the fluidized-bed technology are summarized in the following section.

B.5 Current FWHR Development Programs

B.5.1 U.S. Government Programs

FWHR Systems

- UTRC has completed an investigation of a small FWHR system (designed, fabricated and supplied by Stone-Platt Fluidfire, Ltd. of England) under a Department of Energy (DOE) contract. DOE Technical Monitor was Dr. William Thielbahr. UTRC Program Manager was Dr. Mikio Suo.
- DOE also has recently initiated a project with Aerojet to investigate the influence of bed material properties on the heat transfer characteristics of the fluidized bed and to develop optimization parameters.

Related Programs

- DOE has major programs related to the development and commercial implementation of fluidized-bed combustion technology. The data from the DOE/FBC Program could provide the basis for designing deep-bed, active/inert bed fluidized-bed waste heat exchangers to recover heat from waste streams.

B.5.2 U.S. Industry

Only two U.S. Corporations - Granco Equipment Company, Grand Rapids, Michigan and Fennell Corporation, Harvey, Illinois - are licensees of the Stone-Platt Fluidfire fluidized-bed technology to sell commercial units for various applications; Granco is directing their efforts at the waste heat exchanger and packaged fluidized-bed boiler market while Fennell Corporation specializes in heat treatment equipment.

Although the other U.S. vendors are not actively competing for the potential FWHRs market, several companies including the major boiler manufacturers - Babcock and Wilcox, Combustion Engineering, Foster Wheeler - are potentially capable of developing and marketing the technology. The U.S. companies have been actively involved in the development of the deep, active/inactive fluidized bed combustion

systems. The deep bed FWHR technology may be applicable to some industrial applications.

B.5.3 International Activity

Shallow-Bed Technology - The Stone-Platt Fluidfire Systems Limited developed the shallow-bed FWHR systems. Stone-Platt has employed the shallow-bed technology in various industrial applications including an application to recover heat from diesel engine exhaust aboard a ship.

Deep-bed Technology - Various organizations from the U.K., West Germany, Poland, Japan, Norway, Sweden, Australia and India have been involved in fluidized-bed technology. Various companies from the U.K. and West Germany have developed the technology to a commercial status. However, deep-bed technology is not likely to be a candidate technology for FWHR systems because of the large pressure drop associated with the deep-bed systems.

REFERENCES-APPENDIX B

1. Anonym, Technology Licensed by Stone - Platt of England for Fluidized Bed Heat Recovery and Coal Burning Package Systems, Fluidfire/Granco Equipment Company, Grand Rapids, MI
2. Virr, M. J., Industrial Coal Fired Fluidized Bed Boilers and Waste Heat Boilers, Stone-Platt-Fluidfire Limited, Dudley
3. Cole, W.E. and Suo, Mikio: Investigation of Waste Heat Recovery Utilizing Fluidized Bed Heat Exchangers, United Technologies Research Center, East Hartford, CT, Report R78-912942, November 1978
4. Thielbahr, W. and Perlsweig, Origin and Status of the DOE Heat Exchanger Technology Program to Improve Energy Conversion Efficiency, Department of Energy, Office of Fossil Energy Technology, February 1979