

ORNL/Sub--86-22044

DE91 000546

ORNL/Sub/86-22044

INDUSTRIAL OPERATING EXPERIENCE OF
THE GTE CERAMIC RECUPERATOR

Subcontract No. 86X22044C

Jeffrey M. Gonzalez
John L. Ferri
GTE Products Corporation
Towanda, PA

and

Wilfred J. Rebello
PAR Enterprises, Inc.
Fairfax, VA

Date Published - June 1990

Prepared for the:
DOE Office of Industrial Technologies
ED 01 12 00 0

and for the:

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285

operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract DE-AC05-84OR21400

MASTER

sb
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE OF CONTENTS

LIST OF FIGURES	v
LIST OF TABLES	vii
EXECUTIVE SUMMARY	ix
ABSTRACT	1
1. INTRODUCTION	1
2. INDUSTRIAL APPLICATIONS OF THE GTE RECUPERATOR	3
2.1 The GTE Recuperator System Design	3
2.2 Survey of Industrial Users	7
2.3 Common Problem Areas	12
2.3.1 Burner Problems	12
2.3.2 Combustion Control Problems	14
2.3.3 Recuperator Plugging	16
2.3.4 Corrosive Attack	17
3. COMPARATIVE ANALYSIS OF THE RECUPERATOR	
APPLICATIONS	20
3.1 Oil/Gas Consumption for Industrial Process Heat	20
3.2 Furnace Population	23
4. CASE STUDIES	26
4.1 Overview	26
4.1.1 Quality Assurance Measures	27
4.1.2 Post Mortem Analysis Techniques	28
4.2 Tunnel Kiln	32
4.3 Slot Forge Furnace	38
4.4 Lead Wire Annealing Furnace	43
5. CONCLUSIONS AND RECOMMENDATIONS	46
6. REFERENCES	49
APPENDIX I. List of Recuperator Users Contacted by Phone	51
APPENDIX II. List of Recuperator Users not Contacted	59

LIST OF FIGURES

Figure 1	GTE Ceramic Recuperator Matrix	4
Figure 2	Housed GTE Recuperator with Cutaway Section	5
Figure 3	Typical Thermal Performance of GTE Ceramic Recuperator	6
Figure 4	GTE Ceramic Recuperator Flow Arrangement	29
Figure 5	R1500 Recuperators on the Bickley Roller Hearth Tunnel Kiln At Saxonburg Ceramics	33
Figure 6	R1500 Recuperator Exhaust Inlet After 15 months of Operation at Saxonburg Ceramics	34
Figure 7	R1500 Recuperator Exhaust Outlet After 15 months of Operation at Saxonburg Ceramics	35
Figure 8	Phase Diagram Showing the Cordierite Phase Field in the Presence of a Sodium Compound	37
Figure 9	Side Wall of Dana Slot Forge Reheat Furnace Showing Burner-Recuperator Location and Gravel Hearth	39
Figure 10	R1500 Recuperator Exhaust Inlet After 5 months of Operation on Dana's Slot Forge Reheat Furnace	40
Figure 11	Air-Side and Exhaust-Side Passage Extracted From the Center Section of a GTE Recuperator Removed from a Dana Corporation Slot Forge Reheat Furnace	41
Figure 12	Fused Gravel Removed from a Dana Corporation Slot Forge Reheat Furnace After a 24-h soak at 2450°F	42
Figure 13	Exhaust Inlet of R1500 Recuperator Removed from Lead Wire Annealing Furnace at American Spring Wire Company	44
Figure 14	Exhaust Inlet of R1500 Recuperator Exposed to 200-g of NaOH at 2500°F for 24-h on GTE's Recuperator Test Furnace	46

LIST OF TABLES

Table 1	List of Recuperator Users Contacted by Phone	8
Table 2	List of Recuperator Users Not Contacted	10
Table 3	GTE Industrial Furnaces/Recuperators	11
Table 4	Recuperator Performance by Operating Range	13
Table 5	Recuperator Performance by Size	13
Table 6	Comparative Analysis of the GTE Ceramic Recuperator Applications	21
Table 7	Oil & Gas Consumption for Direct Process Heat for GTE Targeted Industries	22
Table 8	Furnace Energy Consumption/Population	24
Table 9	GTE Recuperator Nominal Air Flow Ratings	28
Table 10	Elements Sought and Detection Limits During Spectrographic Qualitative Analysis	31
Table 11	Spectrographic Qualitative Analysis of Samples from Saxonburg Ceramics	36
Table 12	Spectrographic Qualitative Analysis of Fired and Unfired Gravel from Dana's Slot Forge Furnace	42
Table 13	Spectrographic Qualitative Analysis of Sample from American Spring Wire Company	45

EXECUTIVE SUMMARY

GTE Products Corporation, under a jointly funded program with the U.S. Department of Energy (DOE), developed a compact ceramic high temperature recuperator that could recover heat from relatively clean exhaust gases at temperatures up to of 2500°F. The DOE program was very successful in that it allowed GTE to improve the technical and economic characteristics of the recuperator and stimulate industrial acceptance of the recuperator as an energy-saving technology.

The success of the DOE Program was measured by the fact that from January 1981 to December 1984, 561 recuperators were installed by GTE on new or retrofitted furnaces. One objective of this contract was to conduct a telephone survey of the industrial plants that use the recuperator to determine their operating experience, present status, and common problems, and thus to complete the historical picture.

The ceramic matrix material is made of cordierite, a magnesium aluminum silicate, in 10-in.cubes, 12-in.cubes, and 12- x 12- x 18-in. units that are rated at 0.6, 1.0, and 1.5 million Btu/h respectively. The exhaust gases from the furnace flow straight through the recuperator, while the air to be heated makes three passes. This arrangement allows air to be heated to 1300°F with exhaust gas temperatures of 2400°F. The three pass arrangement is counterflow with respect to the exhaust flow path. The design helps minimize temperature-induced stresses in the cordierite material, thus improving the reliability of the unit.

The thrust of the marketing effort was in the metal processing industries. This focus appears to be correct in view of the energy consumption and number of furnaces in these industries. The durability of the recuperators is indicated by their survival rate. Among 561 units installed on 165 new or retrofitted furnaces in 89 plants, 405 units (72%) were operating after 4 years. There are 117 units (21%) that are not in use either because of failure, poor business climate, or plant shutdown. The combined energy saving of the present operating units is estimated to be about 0.5×10^{12} Btu/year.

The reliability of the recuperated furnace is high in the lower temperature applications. Most of the recuperators (87%) installed on furnaces operating at 2000°F and below were operational through June 1988, while only 57% were being used on furnaces operating above 2000°F. Regarding recuperator size, the smallest unit seems to be more reliable. Of the three sizes of recuperators installed, 89% of the small 10-in.cubes, 72% of the intermediate 12-in.cubes and only 56% of the large units were operational. Possibly the large units are more severely stressed during operation or flaws may develop during the fabrication process.

The initial problems with hot air burners and combustion controls were solved by GTE

and the burner manufacturers. The current problems are recuperator plugging and corrosive attack by alkali compounds, both of which depend on the specific application. In most cases, plugged recuperators could be cleaned with an air lance during normal shutdown and reused. The alkali compounds appear to form lower temperature eutectics with the cordierite material, and if the furnace operating temperatures exceeded the softening point of the eutectic, failure occurred.

Sources of alkali compounds are fluxes used in aluminum remelt furnaces or pottery kilns, topping compounds used on steel ingots, and effluents from organic materials (trace concentrations) generated over extended periods of operation (16,000 hours). This study confirmed the effect of temperature on the life cycle of the recuperator. At temperatures above 2150°F life cycles can be reduced to weeks if the concentration of a reactive contaminant is high. A reduction of the alkali concentration (process modification), and/or reduction of the exhaust inlet temperature below 2100°F is required for successful application of the GTE ceramic recuperator. Injection of a sufficient quantity of ambient air into the exhaust gas stream before it enters the recuperator is one method utilized to maximize the life cycle of the ceramic. The reduced exhaust inlet temperature reduces the reaction rate of the contaminant. The recuperator efficiency is reduced only nominally. The decrease in exhaust inlet temperature and the increase in mass flow rate balance each other, resulting in negligible loss in preheat air temperature. The exhaust gas-flow inducement device (eductor) can generally accommodate the increased volume of exhaust gases, usually less than 10%. A combustion system designer must include ceramic matrix replacement costs based upon reduced life cycles into a projects economic feasibility analysis. Since there is no easy solution to alkali attack, applications generating large amounts of alkali should be avoided.

About 48,000 furnaces were identified that were similar to those in the 89 plants where the recuperators were installed. Based on the industrial users experience with this recuperator, the following industries are potential markets: metal heat treating, aluminum foundries, steel mills, steel forging, and structural clay products. Because of contaminated exhaust gas streams, the following applications should be avoided: tunnel kilns in the pottery and related industries, ladle preheaters in the ferrous and nonferrous industries, remelt and kettle furnaces in the secondary nonferrous industries and reheat/forge furnaces processing steel ingots with topping compounds.

ABSTRACT

GTE Products Corporation, under a jointly funded program with the U.S. Department of Energy (DOE), developed a compact ceramic high temperature recuperator that could recover heat from relatively clean exhaust gases at temperatures up to 2500°F. The DOE program was very successful in that it allowed GTE to improve the technical and economic characteristics of the recuperator and stimulate industrial acceptance of the recuperator as an energy-saving technology. The success of the DOE Program was measured by the fact that from January 1981 to December 1984, 561 recuperators were installed by GTE on new or retrofitted furnaces. One objective of this contract was to conduct a telephone survey of the industrial plants that use the recuperator to determine their operating experience, present status, and common problems, and thus to complete the historical picture. Additionally, recuperators were returned to GTE after operating on industrial furnaces, and a "post mortem" analysis was undertaken with a goal of identifying the potential reason(s) for premature failure of the ceramic matrix. When contamination of the matrix was evident, historical data and spectrographic analysis were used to identify the type of contaminant, and its source. This effort has shown the type of degradation that occurs and has identified system design techniques that can be used to maximize the ceramic recuperator life cycle.

1. INTRODUCTION

GTE Products Corporation began development of ceramic heat exchangers in 1973. This activity resulted in a high-temperature compact cross-flow recuperator made of cordierite which functions well in relatively clean exhaust gases at temperatures up to 2500°F. Part of the development work, which was jointly funded by DOE and GTE under Contract EX-76-C-01-2612 began in October 1976. A final report¹ published by DOE in August 1980 described development and field testing.

In August 1980, the DOE and GTE started a cooperative program titled a Technology Acceleration Program for High Temperature Recuperators (TAPHTR)². The primary goals of the cooperative agreement were to test, install, and collect baseline and operating data for 175 industrial applications of the high-temperature recuperator. The specific tasks of this program were to accurately assess the industrial high-temperature process requirements; to improve the technical and economic characteristics of the recuperator; to stimulate the industrial acceptance of the recuperator for waste heat recovery; and, by saving energy and increasing productivity, to further DOE's Office of Industrial Programs industrial conservation efforts.

During the TAPHTR program, 175 recuperators were installed on 38 furnaces in 30

industrial plants. With the exception of six newly designed furnaces, the furnaces were retrofitted with recuperators. These furnaces were operated at temperatures ranging from 1600°F to 2500°F and air preheat temperatures of 700°F to 1300°F were obtained. Four furnaces were fired by #2 fuel oil, one by #4 fuel oil, and the others with natural gas. Preheated air burners were manufactured by Eclipse Inc., Hauck Manufacturing Company, North American Manufacturing Co., and Selas Corporation. The combustion control systems which regulate temperature and fuel:air ratio were modified to accommodate the preheated air from the recuperator. Both pneumatic pressure and mass-flow controls as well as electronic control systems were used.

The TAPHTR program was successful in that it provided the following benefits to the host sites:

- Fuel savings of 12% to 61% made the retrofits economically attractive.
- Productivity increases resulted because of higher product throughputs, lower furnace reheat times, and, in the case of batch furnaces, more cycles per shift.
- In some cases, materials savings resulted from decreased scale formation.

The TAPHTR program also revealed system problems, some of which were solved during the course of the program or soon after. These were as follows.

- Inherent leakage around the seals could be tolerated provided fuel-rich conditions did not exist in the furnace.
- The initial hot air burners deposited carbon and had flame instability, but these were later corrected by the burner companies.
- Combustion controls on the cold-air side were not adequate to prevent excess gas conditions in the furnace. This was corrected after the TAPHTR program by development of a simple but novel hot-air side control system.
- In some cases, plugging of the compact recuperator passages necessitated the use of an on-line or periodic air-lance cleaning system.
- Some furnaces produce alkali or lead-based materials that can degrade the

magnesium aluminum silicate recuperator at temperatures above 2100°F. Many furnaces, originally categorized as producing clean exhaust, volatilize these materials as a result of the specific process or the furnace design. Degradation of the ceramic can often be eliminated or reduced by careful system design; however, experience has shown that subtle process or system design changes can produce greatly different exhaust gas constituents.

- A recuperator capable of withstanding the attack of common contaminants (alkali compounds) could accelerate the market acceptability of the ceramic heat exchanger, because a more confident estimate of life cycle could be offered for various applications.

The success of the DOE/GTE TAPHTR program is indicated by the fact that between January 1981, when the first DOE installation was started, and December 1984, about 560 recuperators were sold by GTE on new or retrofitted furnaces. Since the start of the DOE TAPHTR program, about 1200 recuperators were sold as either new or replacement units. A telephone survey was made of the industrial plants that installed the ceramic recuperator to determine their operating experience, present status, and common problems, and thus to complete the historical perspective of the recuperator. This report details the results of the telephone survey of the industrial users and provides some comparative analysis of the ceramic recuperator applications.

2. INDUSTRIAL APPLICATIONS OF THE GTE RECUPERATOR

2.1 THE GTE RECUPERATOR SYSTEM DESIGN

Ceramic recuperators are manufactured in three sizes: a 10 x 10 x 10 in. ceramic core with a recommended capacity of 0.6 million Btu/h, a 12 x 12 x 12 in. core with a capacity of 1.0 million Btu/h and a 12 x 12 x 18 in. core with a recommended capacity of 1.5 million Btu/h. The ceramic cores are constructed of cordierite, a magnesium aluminum silicate (MAS), which was selected because of ease of fabrication, relatively low thermal expansion, good thermal shock resistance, and certain corrosion-resistant characteristics. The recuperator is manufactured by bonding extruded MAS ribbed-sheets with a cordierite ceramic bonding material. The sheets and ribs are arranged to form a cross-flow heat exchanger (Figure 1). The ceramic core unit and resilient refractory seal are contained in a metallic housing. The unit is under a

slight compression from a spring assembly. A key feature of current recuperators is that the preheat air makes three passes in the recuperator while the exhaust gas passes through once. The air side passes are made possible by baffles in the metal housing (Figure 2). The areas of each pass are selected to optimize the heat transfer for a given pressure drop³. Figure 3 shows the typical performance of a model R1000 (12 x 12 x 12 in.) recuperator. The triple-pass recuperator provides higher preheated air temperatures than the earlier single-pass model. An added advantage of the triple-pass recuperator is that the maximum temperature difference between the exhaust gases and the preheated air is reduced. Temperature-induced stresses are therefore lower, thus increasing the reliability of the recuperator.

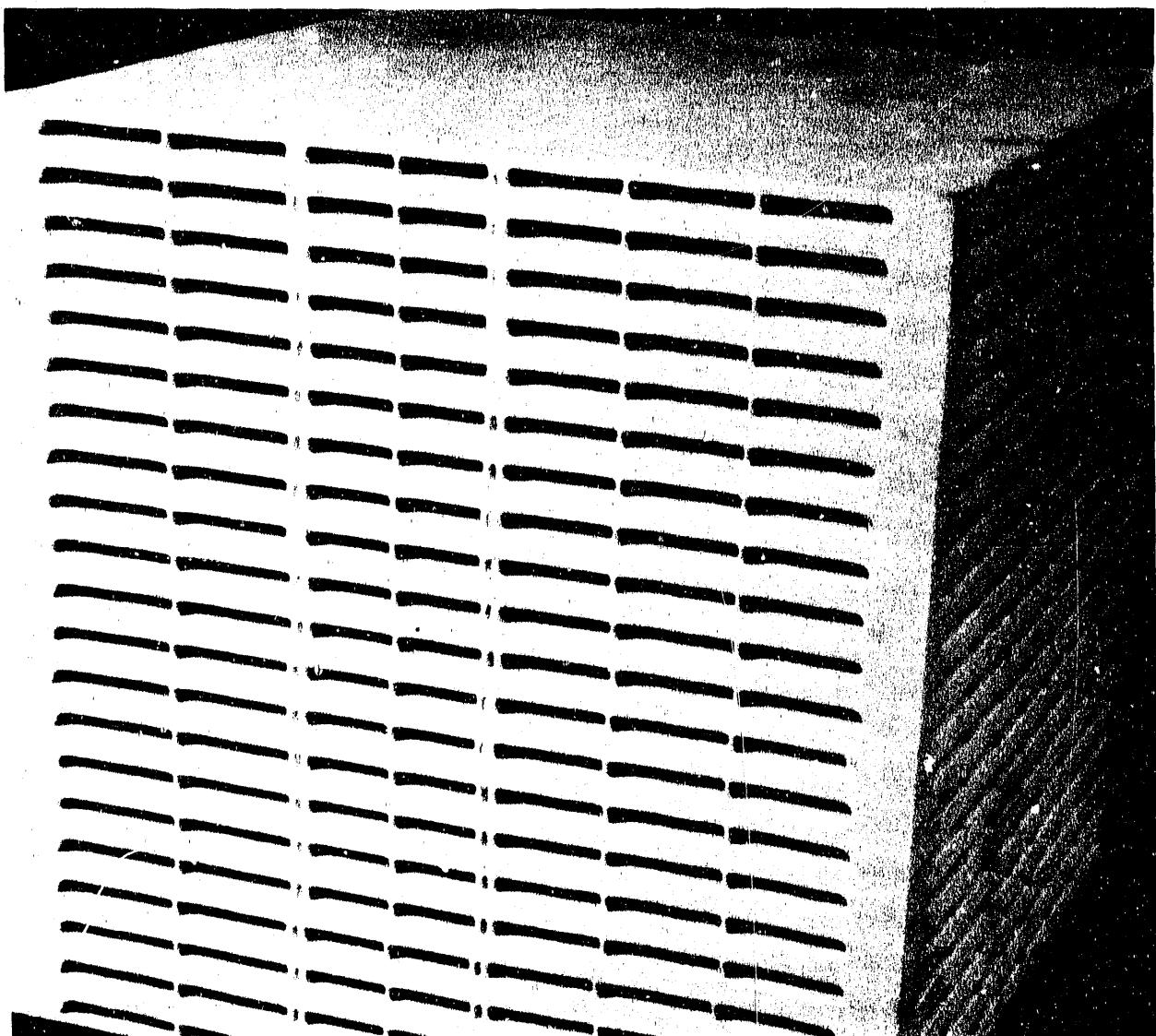


Figure 1
GTE Ceramic Recuperator Matrix

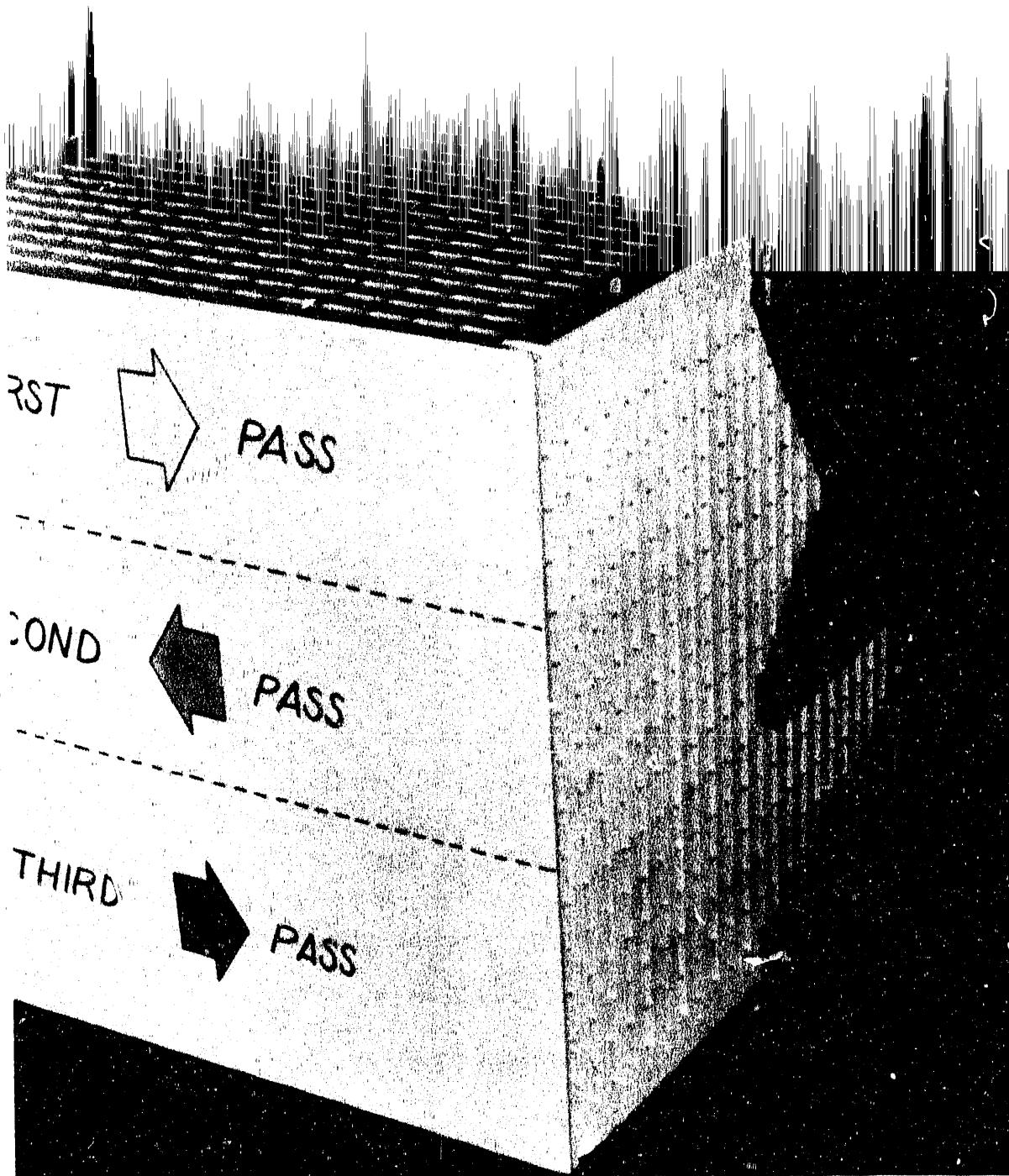


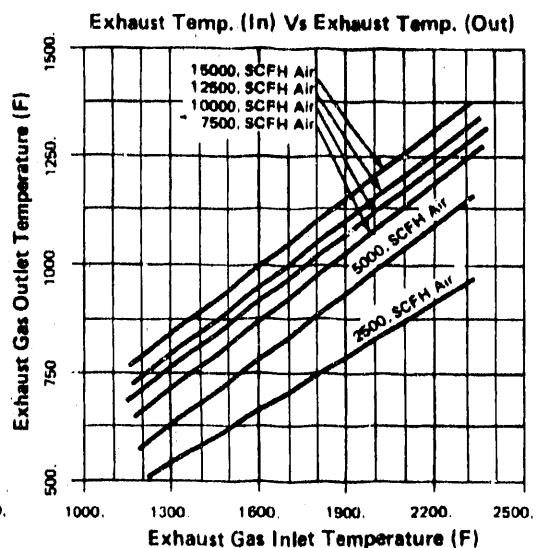
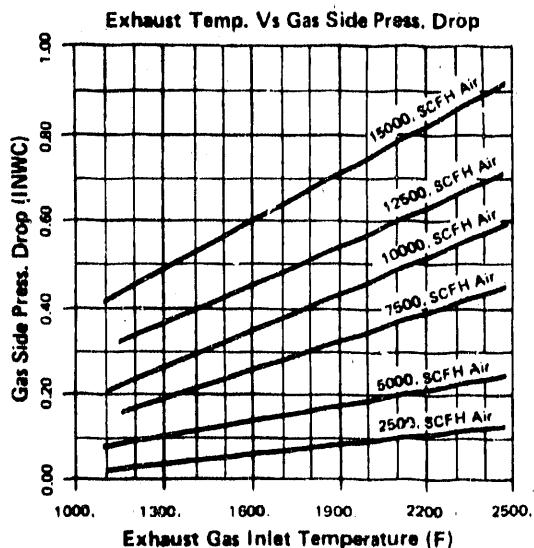
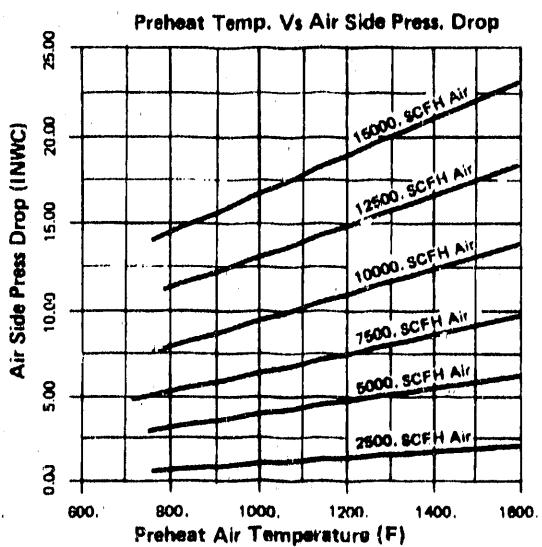
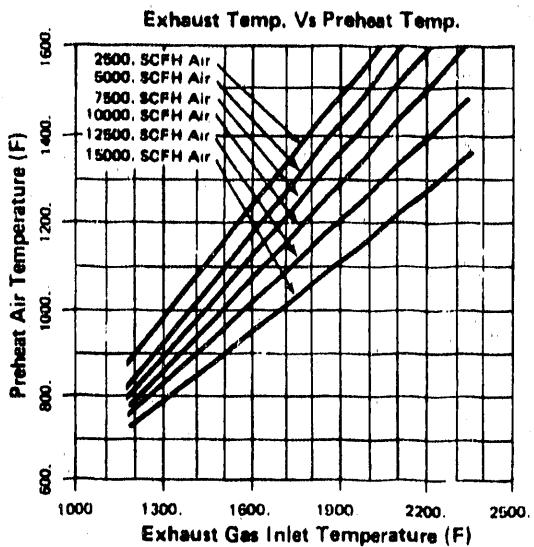
Figure 2
Housed GTE Recuperator with Cutaway Section

GTE 1500TPXA

- Product Code: 8163228
- Air Hole Size: .125" x .680"
- Exhaust Hole Size: .200" x .680"
- Flow Ratio = $0.917 \pm 5\% = \frac{\text{Air Flow}}{\text{Exhaust Flow}}$

Example:

1/4 mm BTU Burner using 10% excess air.
 Air Flow = 16500 SCFH
 Gas Flow = 1500 SCFH
 Exhaust Flow = 18000 SCFH
 Preheated Air Temp. at 2000°F Exhaust = 1050°F
 Pressure Drop Exhaust .77" H₂O Column
 Pressure Drop Air 20" H₂O Column



SYLVANIA Chemicals/
Metals **GTE**

Figure 3
Typical Thermal Performance of GTE Ceramic Recuperator

Since the TAPHTR program ended in 1982, the techniques for production, firing, and encasement of the ceramic cube in the metallic housing have been improved, which have resulted in a more reliable product. Another improvement in the recuperator system is related to the method of controlling the air:fuel ratio to the burner. The common methods of mass flow control, if applied to the cold-air side, do not compensate for changes in recuperator leakage and, if applied to the hot preheated air side, do not account for variations in the preheated air temperature. In case the recuperator leaks, the cold-side control would not correct the air:fuel ratio and the furnace could run fuel rich, if the leakage was large. In the case of controls applied to the preheated air, as the preheated air temperature increases, the air:fuel ratio decreases and fuel rich conditions could result depending on the air:fuel ratio established at system calibration. In the patented GTE temperature compensator⁴, a bimetallic strip in the preheated air stream compensates the pressure signal which controls the fuel flow, thus preventing a fuel-rich condition. This simple, relatively inexpensive device is now offered as part of the standard recuperator package.

2.2 SURVEY OF INDUSTRIAL USERS

The survey of industrial users of the GTE ceramic recuperator was based on a listing of companies in the United States and Canada provided by GTE. Seventy-two companies were contacted by phone and the present status as well as furnace/recuperator information were noted. These are presented in Table 1 and includes summary remarks regarding the industrial users experience and problems encountered. Seventeen industrial users were not traced either because they were not in business or had been acquired by another company. These 17 companies had no known telephone numbers and are listed in Table 2. The information listed in Table 2 is based on GTE records and contacts. In some cases the recuperators were scrapped prior to the companies close of business and have been noted as such. In the remaining cases the current status is unknown.

From the total of 89 industrial companies in the United States and Canada, 561 recuperators were installed on 165 new or retrofitted furnaces. Hot Work in the United Kingdom purchased 53 recuperators for installation, but their status is not known. In addition, 35 recuperators were purchased by various Japanese companies and their status is likewise not known at this time. A listing of the furnace types and number of recuperators are presented in Table 3. Of the total 571 new recuperators, 415 or 72% are still operating and 117 are not in use at present either because of failure, poor performance, or plant shutdown. The box-type furnace used either

Table 1
List of Recuperator Users Contacted by Phone

COMPANY	FURNACE TYPE	TEMP	REC. SIZE	REC #	PREHEAT
Ajax X-Ray	Potmelter	2150	0.6	1	1100
Ajax X-Ray	Potmelter	2200	0.6	1	1150
ALCAN	Ladle Preheater	1800	1.0	1	1000
Alfred Heller Heat Treating Co.	Muffle Heat Treat	2100	1.5	2	
AmCast Ind.Corp. (Dayton Malleable)					
American Spring Wire	Lead Potmelter	2300	1.5	2	1050
B&R Industries Inc.	Aluminum Potmelter	2000	0.6	1	750
Bay City Forge	Box Forge	2250	1.5	8	1200
Berkley Forge	Slot forge	2400	1.5	2	
Brampton Foundry	Potmelter	2300	0.6	1	600
Brown Engineering	Fume Incin	1200	1.5	1	200
Bucyrus Erie Co.	Heat treat	1800	0.6	12	1000
Buffalo Metal Casting	Aluminum Potmelter	2200	1.0	1	1000
Callen Mfg. Corp.	Al. remelt furnace	2200	1.5	2	1000
Carpenter Die	Pot Melters	2000	0.6	8	1000
CERTECH Inc.	Periodic Kilns	2200	0.6	2	1000
Compton Forge	Box forge	2250	1.5	4	
Conroe Forge & Mfg.	Pusher Furnace	2200	1.5	4	1100
Coulter Steel & Forge Co.	Box Forge	2200	0.6	2	1150
Crucible Steel	Box Reheat	2200	1.5	2	1050
Eastern Alloys	Kettle Fumace	2200	1.5	2	
Empire Steel Casting	Anneal.	2000	1.0	2	1000
Endicott Forging & Mfg.	Slot Forge	2350	1.5	4	1300
Finkl & Sons Inc.	Box Forge	2300	1.5	2	1200
GTE	9 Rotary Calcines	1800	1.5	6	1000
GTE			0.6	23	
GTE	9 Tube Furnaces	1500	1.5	8	1200
GTE			1.0	23	800
GTE	4 Tube Furnaces	2100	0.6	40	800
Gudgeon Bros.	Aluminum Potmelter	2200	0.6	1	900
Gulfco	Boxforge	2450	1.5	8	1150
Gulfco	Boxforge	2450	1.5	8	1150
Gulfco	Boxforge	2450	1.5	6	1150
Hammond & Irving	Box Heat Treat	2200	1.5	4	1100
Hammond & Irving	Box Heat Treat	2200	1.5	2	1100
Harnischfeger Co.	Pusher Furnace	2000	1.5	4	1150
Hayes Dana Co.	Carbottom	2300	1.5	8	1200
Hayes Dana Co.	Slot Forge	2300	1.5	2	1200
Howmedica Inc.	Pusher Type Mold Heater	2000	1.5	2	800
Howmet Turbine Co.	Pusher Reheat	2200	1.5	1	1240
Howmet Turbine Co.			1.0	2	
Howmet Turbine Co.	Furn.# 2	2250	1.5	1	1200
Howmet Turbine Co.			1.0	2	
Howmet Turbine	Pusher Die Reheat #1	2300	1.5	1	1190
Howmet Turbine			1.0	2	
Howmet Turbine	Furn.# 2	2300	1.5	1	1180
Howmet Turbine			1.0	2	
Kentucky Forge	Slot forge	2500	0.6	2	1200
Kleen Air	Ladle Heat	2200	1.5	1	1100
Krone Diecasting Co.	Reverb. Furnace	2200	1.0		
Ladish Company	Box Heat Ti	1800	0.6	8	850
Lebanon Steel Foundry	Carbottom Heat Treat	1800	1.5	6	850
Littler Diecast Corp.	Al. Pot Holding Furnace	2000	1.0	1	800
Maynard Steel Casting	Car bottom Heat Treat	1650	1.0	12	850
McInnes Steel	Boxforge	2250	1.5	4	1210
McWilliams Forge	Box Forge	2100	1.5	3	1160

Table 1
List of Recuperator Users Contacted by Phone

COMPANY	FURNACE TYPE	TEMP	REC. SIZE	REC #	PREHEAT
McWilliams Forge	Rotary Hearth	2300	1.5	8	1200
Mercury Marine	Al. Reverb	2000	1.5	2	1000
Milwaukee Forge	Carbottom Annealing	1550	1.0	10	800
Missouri Steel Castings			1.0	4	
Monroe Forge	Box Forge	2150	1.5	2	1220
Monroe Forge	Box Forge	2150	0.6	2	1050
Monroe Forge	Box Forge	2150	1.0	2	1000
Monroe Forge	Box Forge	2150	1.0	2	1000
National Forge	Carbottom Heat Treat	2350	1.5	8	1175
Norfolk & Western Rly. Co.	Carbottom Heat Treat	1800	1.0	7	1000
North Vernon Forge	Slot forge	2500	1.5	2	1200
Oregon Metallurgical	Slot Forge	2500	1.5	2	1200
Oregon Metallurgical	Heat Treat	2200	0.6	14	1100
Oregon Metallurgical	Box Forge	2200	0.6	12	1100
Pfizer Company	Vacuum Retort	2200	0.6	5	1150
Pfizer Company	Vacuum Retort	2200	0.6	5	1150
Pfizer Company	Vacuum Retort	2200	0.6	5	1150
Pfizer Company		2200	0.6	5	1150
Pfizer Company	Indirect Fired Calciners (8)	1900	1.5	32	1200
Pfizer Company	Muffle	1800	1.0	2	600
Pfizer Company	Annealing	2100	0.6	6	800
Pfizer Company	Annealing	2100	0.6	6	800
Pratt & Whitney	Box Heat Treat	2100	0.6	5	1150
Precision Cast Parts Corp.	Mold Preheating (10)	1900	1.5	20	900
Puget Sound		2400	1.5	1	1200
Salt Fleet Aluminum Co.	Aluminum Pot Melters	2000	0.6	1	900
Salt Fleet Aluminum Co.		2000	0.6	1	900
Saxonburg Ceramics Inc.	Rolls/Kiln	1800	1.5	2	1000
Schmitt Forge	Slot Forge	2250	1.5	2	1120
Scott Forge	Box Forge	2350	1.5	2	1100
Sherwood Medical	Heat Treat	1890	1.5	2	1000
Sherwood Medical			1.5	2	1000
Special Metals	Heat Treat	1800	1.5	6	1100
Special Metals	Reheat	2000	1.5	4	1200
Special Metals	Batch Annealing Furnace	1800	1.5	2	1100
Special Metals	Forge	2350	1.0	10	1100
Standard Steel Co.	Forge Reheat	2300	1.5	6	1100
Stanley Tools	Slot forge	2200	1.0	1	1000
Stanley Works	Lead Pot Melter	2050	0.6	8	950
Timet Corp.	Box Forge	1800	0.6	8	950
Trent Tube Co.	Annealing Furnace	1800	1.0	3	
TRW form Stanley Spring	Slot forge	1900	0.6	4	
Viking Metallurgical Corp.	Box Forge	2250	1.0	2	1200
Viking Metallurgical Corp.	Box Forge	2250	1.0	2	1200
Viking Metallurgical Corp.	Box Forge	2250	1.0	4	1200
Viking Metallurgical Corp.	Box Forge	2250	1.0	5	1200
Willard Industries Inc.	Solder Pots	1800	0.6	3	600
Willard Industries Inc.	(5 total)		0.6	1	700
Willard Industries Inc.			0.6	1	800
X-TEK Inc.	Retort Pit	1800	0.6	12	1000
X-TEK Inc.	Retort Pit		0.6	12	1000
X-TEK Inc.	Retort Pit		0.6	12	1000

Table 2
List of Recuperator Users Not Contacted

COMPANY	TYPE	TEMPERATURE F	SIZE MMBTU/HR	NUMBER OF RECUPERATORS	TEMP F
Alteck	Box Reheat	2200	1.5	6	1200
AMAX Speciality	Box Forge	2300	1.0	5	1200
Bethlehem Steel	Rotary Forge	2350	1.5	8	1250
Cape Ann Forge	Box Forge	2350	1.5	4	1250
Cedarbrook Eng.	Al Reverb.	2200	1.5	1	1100
Cooper Ind.	Slot Forge	2450	1.5	2	1200
Crescent Tool	Slot Forge	2400	1.5	2	1250
DANA	Slot Forge	2400	1.5	12	1250
ICE		1800	0.6	1	
Inland Steel	Annealing	1800	0.6	1	
Janney Cylinder			1.0	2	
Metamold	Reverb.	1400	1.0	2	800
National Lead	Lead Melter	1800	1.5	1	1000
O'Hara	Lead Melter	1800	1.5	2	1000
Pyronics	Forge	2200	1.0	1	
Rockwell	Slot Forge	2350	0.6	2	1000
WFI	Box Forge (2)	2200	0.6	3	
WFI	Heat Treat (2)	1950	1.5	3	
England				43	
Japan				35	

Table 3
GTE Industrial Furnaces/Recuperators

Furnace Type	Number of Furnaces	Number of Recuperators			Status Unknown
		Operational	Not in Use		
1 Box Forge/Reheat/Heat Treat.	43	104	61	13	
2 Slot Forges	18	17	22	0	
3 Aluminum Pot Melters	16	14	2	0	
4 Mold/Die Reheat Furnaces	15	34	0	0	
5 Indirect Tube-type Reduction Furnaces	13	71	0	0	
6 Rotary Calciners	9	29	0	0	
7 Retorts	9	44	0	0	
8 Carbottom Forge/Heat Treat.	7	43	8	12	
9 Aluminum Reverberatory	5	0	7	1	
10 Solder Pots	5	5	0	0	
11 Annealing	4	5	1	1	
12 Muffle	4	14	2	0	
13 Lead Melters/Heat Treat.	4	10	2	0	
14 Pusher	2	14	4	0	
15 Rotary Hearth	2	8	0	8	
16 Ladle Preheaters	2	0	2	0	
17 Clay/Pottery Kilns	2	2	2	0	
18 Misc.	5	1	4	4	
TOTALS	165	415	117	39	

for forging, reheating, or heat-treating metals was the most common type that GTE selected for heat recovery, accounting for 26% of the furnaces. One hundred seventy-eight recuperators were installed on these box furnaces, of which 104 or 58% are still operational. The slot forge furnaces were the next popular category with 18 furnaces outfitted with 39 recuperators of which only 43% are in operation. None of the aluminum reverberatory furnaces or ladle preheaters are currently recuperated. However, the success rate on pot melters, tube furnaces, rotary , retorts, and heat-treating furnaces was high.

If one considered the performance of the recuperators based on their operating temperature, shown in Table 4, one finds that 87% of those installed on furnaces at 2000°F and below are still operating, while only 57% of those installed at temperatures above 2000°F are still operating. The recuperator performance based on size is shown in Table 5. GTE manufactured the recuperators in three sizes, 0.6, 1.0, and 1.5 million Btu/h and these are 10 x 10 x 10 in., 12 x 12 x 12 in., and 12 x 12 x 18 in., respectively. Eighty-nine percent of the small units are still operating, while 78% of the medium size units were operational and only 57% of the larger units were still operating.

2.3 COMMON PROBLEM AREAS

The early installations suffered from two problems that were unrelated to the recuperator but nevertheless part of the recuperation system. One problem was with the burners and the other was with the control system. However, after a year's experience with recuperation, both the burner companies and GTE were able to benefit from these experiences and the necessary modifications were successful. There were two problems that could be traced to the recuperator; these were attack from corrosive elements in the exhaust gases and plugging from particulate matter. These problems will be described here based on conversations with the industrial users and GTE engineers.

2.3.1 BURNER PROBLEMS

The burners for the combustion of the natural gas and oil with the preheated air were provided by Eclipse Inc., Hauck Manufacturing Co., North American Manufacturing Co., and Selas Corporation.

For preheat air temperatures of less than 600°F, room-temperature burners were used and seemed to work satisfactorily. The initial hot-air burners designed for temperatures of 800°F and above were simple modifications of the room-temperature burners and some problems

Table 4
Recuperator Performance By Operating Range

	<u>>2000F</u>	<u>< 2000F</u>	<u>Totals</u>
Operating	159	256	415
Not in Use	93	24	117
Unknown	25	14	39
Totals	277	294	571

Table 5
Recuperator Performance by Size

Size MM Btu/h	0.6	1.0	1.5	Totals
Operating	182	92	141	415
Not in Use	6	19	92	117
Unknown	17	7	15	39
Totals	205	118	248	571

developed. One problem resulted from the cracking of the natural gas because of heating from the preheated air. This resulted in carbon and soot deposition. The alloy steel gas supply tube was surrounded by the preheated air which caused the cracking of the gas. This was later modified by design changes, and insulation was provided to keep the natural gas from attaining temperatures of above 600°F.

Another problem with the early burners was flame instability and flash back, particularly at low-fire conditions. The early hot-air burner designs had failed to account for the increased flame velocity due to the higher temperature air and natural gas. At low-fire conditions, flash back would occur into the alloy steel gas supply tube and tube failure resulted. These problems were eventually corrected and burners available today are working satisfactorily with preheat temperatures in excess of 1200°F.

2.3.2 COMBUSTION CONTROL PROBLEMS

The provision of adequate air:fuel ratio controls as well as furnace pressure control are very important parts of the recuperation system. In most applications, the excess air is maintained at about 10%. Higher amounts of excess air, which may be required in certain applications to obtain higher convective heat transfer rates in the furnace, would result in more fuel being used. In applications such as forging, excess air may be kept at about 5% to prevent excessive scaling of the work piece which results in loss of material as well as shorter life of the forging dies. When a furnace is recuperated by preheating the combustion air, the penalty in fuel usage when using higher excess air rates is not as severe in terms of available heat⁵ as with an unrecuperated furnace. Nevertheless, furnace operators continue to maintain low excess air rates on most of their furnaces.

The most common method of controlling a furnace without recuperation is to balance the gas pressure with the air pressure with a pressure balancing regulator. Since the mass flow rate of the air is a function of pressure and temperature and the temperature of the unrecuperated air stream is reasonably constant, the air:fuel ratio is maintained reasonably constant. In a recuperated furnace, the combustion air temperature can vary from ambient at start-up to about 1200°F at high-fire operation. In this case, the control techniques commonly used are mass flow control where the fuel pressure is proportional to the mass flow of air or cross-connected control where the fuel pressure is proportional to the air pressure. With either technique, the fuel can be controlled by the air stream from upstream of the recuperator (cold side) or downstream of the recuperator (hot side). Electronic mass flow controls may also be used but these are difficult to justify economically because of their cost and resultant longer paybacks.

When controls are set at low excess air rates, and some leakage around the seals occurs, the cold-side mass flow control cannot compensate for this and less air is supplied to the burner with the possibility that fuel-rich conditions may prevail in the burner and furnace. When this happens, combustion will take place at the point of leakage at the seals resulting in excessive temperatures being attained in the area of the leak and subsequent damage to the cordierite material. Often the area of the matrix near the leak may soften, melt, or be stressed enough that cracks form and the leakage increases. The ceramic matrix continues to deteriorate until leakage becomes excessive and the matrix must be replaced. If the hot-side mass flow control is used, the control system must operate effectively because as the temperature of the air increases, the air:fuel ratio decreases and the stoichiometry shifts to the richer side.

Operation of the furnace under fuel-rich conditions should be avoided. However, it is not uncommon to notice flames coming out of the exhaust side of the recuperator or eductor on top of the furnace. Sometimes when this happens, the furnace operators continue to operate the furnace under fuel-rich conditions in order to save the load in the furnace. The recuperators are considered expendable in these cases and are sometimes removed or replaced if the leakage becomes excessive. The pressure-compensated device⁴ that GTE offers as standard equipment effectively maintains proper stoichiometric conditions in the furnace.

The pressure in a furnace chamber is usually maintained slightly above atmospheric so that a small volume of combustion products would leak out of the chamber. Below-atmospheric operation is avoided because that would draw cold outside air into the furnace, resulting in more fuel usage as well as poor temperature distribution in the furnace cavity. When a furnace is recuperated, the additional pressure drop in the recuperator exhaust passages could result in more combustion products escaping through cracks in the furnace. As deposits collect in the exhaust passages, the exhaust side pressure drop in the recuperator increases and less combustion products flow through the recuperator, resulting in lower air preheats and more fuel consumption. This can be easily avoided by using exhaust fans or eductors on top of the recuperator exhaust to control the furnace cavity pressure and maintain the exhaust flow through the recuperator. On most of the systems sold by GTE, eductors and pressure controls are commonly used. The one furnace type where pressure control is very critical is the slot forge furnace where exhaust coming out of the slot is to be avoided to protect the operator. Recuperated slot forge furnaces present more difficulties in mass flow and pressure controls and the lower retrofit success rate bears this out.

2.3.3 RECUPERATOR PLUGGING

The GTE recuperator is very compact, and the exhaust gas passage sizes are usually 0.200 x 0.680 in., but could be as low as 0.125 x 0.680 in. before the green matrix is fired. After firing, the product passage sizes are somewhat smaller because of shrinkage. Because of its compact nature, the GTE ceramic recuperator is ideally suited for processes that have clean exhaust gas streams. Processes where the exhaust stream is particulate laden should be avoided as the particulates would tend to plug the exhaust gas passages. This unit could not be used in processes fired by pulverized coal.

Certain types of particulate plugging can be corrected by periodic cleaning by means of a soot blower or an air-lance system. The latter has been used effectively by some industrial users. There are other types of particulates, which may be close to their softening point that are tacky and build up into a deposit that cannot be easily removed by an air lance. These type of deposits create a problem and cleaning by means of a chisel or by ramming a welding rod through, as a few users did, most often cracks the ceramic matrix. These types of applications are not compatible with the GTE recuperator. High-temperature processes in which a material is vaporized and carried through with the exhaust gases should also be avoided because that material would condense in the recuperator and plug it. An example of this type of plugging could be a glass tank exhaust stream. GTE's experience indicated that there were several processes, first thought to be clean, that resulted in plugging problems. A few of the experiences of plugging are discussed below. When existing furnaces need relining, it is now becoming the normal practice to reline the furnaces with fiber because of its better insulating properties. After continuous use some of the fiber is carried by the exhaust gases and is deposited in the recuperator. Two industrial users (Nos. 10 and 55) experienced some plugging problems, but these were easily resolved by cleaning the recuperators during normal shutdown.

Indirect natural gas-fired tube furnaces are clean operations that suit the compact GTE recuperator. However, the tubes oxidize and deteriorate with use and occasionally fail. When failure occurs the powders treated in the tubes end up in the furnace and subsequently in the recuperator. Most often these deposits can be easily removed and the recuperators reused. Typical examples are the GTE tube furnaces for tungsten and molybdenum reduction (No. 24) and the Pfizer (No. 52) furnaces for reduction of red iron oxide. In the latter case, the iron oxide seemed to have made the cordierite very brittle and cracks formed which resulted in more leakage of air into the exhaust gas stream. The increased leakage could lead to fuel-rich conditions in the furnace if not monitored and corrected.

This type of plugging also was experienced by Pfizer (No. 51) in the productions of

calcium metal in retort furnaces. After extended use, the retorts could fail spilling the contents into the furnace. The calcium that then deposits in the recuperator corrodes the cordierite material. The recuperators last for about 18 months in this application, but Pfizer is very satisfied with the paybacks and, as a result of the first DOE project, have eight furnaces equipped with the GTE recuperators.

Molybdc oxide plugging was experienced by several plants. Molybdenum oxidizes very rapidly at high temperatures. In fact, when a billet of molybdenum is heated in a furnace, yellow dust escapes through the exhaust or through the furnace door when it is opened. If a high moly-alloy steel is being heated for forging (Nos. 23, 62, 63) over a period of time, the recuperator would get plugged with the oxide. They would have to be cleaned periodically. Often, in the preheating of molds and dies, these molds are set down in metal trays which are then introduced into a pusher furnace. Howmet Turbine (Nos. 32,33) experienced moly-oxide plugging on their die reheat furnaces which was traced to the alloy steel trays that held the investment dies. This problem was easily solved by using trays made from alloy steels that contained less molybdenum.

The only kettle furnace application was a zinc kettle at Eastern Alloys in New York (No. 20). The zinc oxide that plugged the recuperator could not be removed easily. It was also not established whether the zinc would corrode the cordierite material.

Two ladle preheaters were recuperated, one for aluminum (No. 2) and one for steel (No. 35). In both cases, the recuperators plugged up with dross and other material from the ladle. Ladle preheaters, therefore, are not a good application for the GTE recuperator.

2.3.4 CORROSIVE ATTACK

One application that GTE has concentrated on is alloy steel forging furnaces. These are mostly box-type furnaces that operate at between 2250°F and 2350°F depending on the type of alloy being worked. Most of the furnaces were natural gas fired and the exhaust gases were expected to be clean. However, at ten plants (Nos. 7, 16, 23, 29, 41, 42, 47, 60, 76 and 87) problems arose with the leaking recuperators causing the preheat air temperatures to drop. As the leaks got gradually worse, the furnaces would run fuel-rich and then the recuperators rapidly deteriorated. In the beginning, it was thought that the recuperators may have been faulty or that the furnace operators had run the furnace at fuel-rich conditions, causing the recuperators to crack. What was puzzling was that there were several plants where similar box forge furnaces were operating satisfactorily with the same fuel and at the same temperatures. Initially, the problem recuperators were replaced, but replaced matrices soon suffered the same

fate.

GTE analyzed several of the failed recuperators in the laboratory and found traces of sodium and potassium. The source of the sodium and potassium was traced to the ingots that were processed through the furnace. All of the furnaces at the ten plants processed raw ingots either continuously or on occasion. When molten steel is poured into an ingot, salts of sodium, potassium, calcium, etc., are placed on the top of the ingot. These are referred to as topping compounds. When these raw ingots are reheated in the recuperated furnace, the alkali deposits in the cordierite matrix and corrosive attack begins. The alkali metals form lower temperature eutectics with cordierite, resulting in softening and cracking of the matrix. Scott Forge (No. 60), a large progressive forge shop outside Chicago, installed five sets of the GTE recuperators on one of their forge furnaces, all of which failed. They sent a failed matrix to an independent laboratory and found that 2100°F eutectics were formed. With exhaust gases at 2350°F, it is easy to understand why the recuperators failed. Scott Forge installed 6 sets of Hague International's SiC tubular recuperator on a furnace, all of which failed due to alkali attack. Because of their interest in conservation, they then installed Hot Works metal units and all four failed relatively quickly. They concluded that it was not economical to recuperate furnaces that processed raw ingots containing topping compounds.

Several of the forge shops tried cutting off the tops of these ingots but could not completely get rid of the alkali metals, and the cordierite matrix failed. One plant that is satisfied with their fuel savings but would like longer recuperator life is Hawker Siddeley (No. 29) in Nova Scotia, Canada. This plant is supplied with hot ingots shipped in insulated containers, therefore they are unable to cut off the tops. Their furnaces are oil-fired and their paybacks (with 50% savings) are less than a year. Their engineer would continue to replace the failed cubes as long as it was economical to do so. In the case of Cape Ann Forge (No. 76), the plant is located by the seashore and salt in the air may have further contributed to the cube failure.

McWilliams Forge (No. 42) operates a box forge to reheat copper for forging into aircraft parts. The furnace has three recuperators. While the copper is being reheated, charcoal is thrown into the the back of the furnace probably to prevent the formation of copper oxide. However, the two recuperators closest to the back of the furnace failed and their replacements failed as well. It was found that the charcoal contained potassium which was the cause of the failure.

None of the recuperators on the Aluminum Remelt furnace (No.13) or Aluminum Reverberatory furnaces (Nos. 36, 43, 77 and 84) are in operation because of attack by sodium. Callen Mfg. Corp. in North Lake, Illinois uses a white powder called "Smokeless Flux" for

fluxing in their remelt furnace. Some of the powder deposited in the recuperator and could not be removed by an air lance. The flux may also have contained some sodium which could have attacked the cordierite, since the exhaust gases entered the recuperator at 2200°F. The aluminum reverberatory furnace recuperators were failures as well because of the fluxing agents used. It soon became evident that aluminum remelt/reverberatory exhaust gases are dirty gases and these applications are not suitable for the GTE recuperator.

The metal lead may also be considered a poor application with respect to attack on cordierite. Two lead melters (Nos. 85 and 86) operating at 1800°F were recuperated. In both cases, the recuperators plugged and were destroyed. The other two lead operations were annealing furnaces where steel spring wire (No. 5) and steel bailing straps (No 66) are tempered. In both these plants the operations are similar although furnace temperatures are 2300°F and about 2000°F to 2100°F, respectively. Both furnaces are still operating, but the recuperators have done better on the furnace operating at the lower temperature. Large stainless steel pots, 4 ft wide and 12 ft long, contain the molten lead at 1600°F for tempering steel and are supported at the bottom by piers made of firebrick. The natural gas burners fire low and the exhaust gases blow by the steel pot. Multiple straps, at least 14, and wires continuously pass through the lead. Molten lead falling on the firebrick forms a eutectic that destroys the brick rapidly. The brickwork on these furnaces is rebuilt every 6 to 12 months at American Spring Wire but lasts longer at Stanley Works.

There are three distinct problems with the recuperators. First, if the lead on occasion falls into the combustion chamber, it vaporizes and deposits in the recuperator, causing some plugging. The second problem relates to the firebrick which contains some potassium and sodium that is released in firing the brick and deposits in the ceramic matrix. Regular replacement of the fire-brick would hasten the demise of the ceramic matrix. Finally, it is possible that the lead and cordierite form lower melting eutectics that may soften or crack the matrix. If lead can cause the firebrick to deteriorate that fast, it surely must have an affect on the cordierite. It is possible that the eutectics formed with lead could soften at temperatures as low as 2200 or 2300°F. The fact that American Spring Wire operates at 2300°F while Stanley Works operates between 2000 and 2100°F may explain why the former's recuperators have to be replaced more often. It would appear that American Spring Wire should operate the furnace at a lower temperature unless this would adversely affect their production. It would appear that applications involving molten lead are not the best for the GTE recuperator.

3. COMPARATIVE ANALYSIS OF THE GTE RECUPERATOR APPLICATIONS

The 89 plants presented in Tables 1 and 2 have been categorized into their respective Standard Industrial Classification (SIC) codes and presented in Table 6 together with information on specific process energy (oil and gas only) consumption and furnace population. These two items will be discussed further in this section.

3.1 Oil/Gas Consumption for Industrial Process Heat

In assessing the impact that the GTE recuperator has made in terms of energy savings potential, one must consider the energy used for process heat by the various types of industries in which the recuperator was installed. The energy use data in Table 6 were obtained by PAR Enterprises from several sources⁶⁻¹¹. In using energy data from the various sources, one must be cautious and recognize that differences exist in the absolute values, but the numbers can be useful for impact analysis and indicating trends and directions to be pursued. The energy values in Table 6 were not authenticated; and differences between the values were not reconciled among the various sources, as this was considered outside the scope of this work. The Census of Manufacturers⁷ data is widely used and the EPA NEDS data base⁹ has useful information on energy, unit processes and equipment, collected from 34,000 plants in the United States.

In evaluating the furnace energy consumption for an aluminum remelt furnace, for example, one may start with the Census figures for fuels and electric energy consumed and subtract the electric energy, fuels used for feedstock purposes, for generating steam, for space heating and for non-process heating use. PAR Enterprises, Inc., performed such a task for GTE Products Corporation in 1982 and determined the oil and gas consumption for the major 4-digit industries. The entire listing from that study is presented in Appendix A. Those industries in which the recuperator was installed are listed in Table 7.

As can be seen from Tables 6 and 7, GTE has targeted the metals industries except for two installations in the Structural Clay and Pottery Products area. In terms of energy consumption, that decision was probably correct because the metals processing industries are quite energy intensive. Another reason for selecting these industries was probably the relative cleanliness of the exhaust streams which are primarily fueled by natural gas and oil. However, what was initially thought to be clean streams in the pottery kilns, aluminum remelt furnaces, and steel forging furnaces, in reality were corrosive streams that contained sodium and potassium which corroded both metals as well as ceramics. Nevertheless, most of the

Table 6
Comparative Analysis of the GTE Ceramic Recuperator Applications

SIC	Industry	Oil/Gas Energy Use in SIC (Energy Use in Furnace Type) Trillion BTU/Yr	Furnace Type	Furnace Population in Present GTE Applications	GTE Furnace Retrofit	Potential # of GTE Units based on 1 MM BTU/hr/unit	% of GTE Units Sold	Operating Remarks
325	Structural Clay Products	88.0(46.0)	Periodic Kiln	2574	1	7500	2	100 There are also tunnel and shuttle kilns.
326	Pottery	18.3(5.4)	Tunnel Kiln	270	1	900	2	0 Uses Feldspar as a flux.
331	Blast Furnace & Basic Steel Pro.	219(78.5)	Box Retort	365	3	9000	12	17 Installation problem: Plugging
332	Ferrous/Nonferrous Foundries	48.0(10.0)	Ladle Preheaters	667	2	667	2	0 Plugging with dress and fines from ladle. Poor Application
336	Steel Investment Foundries	2.3(2.3)	Investment Die Kilns	220	15	400	34	100 Experience to date - Good, but low total energy usage
3324	Primary Al	96.5(1.0)	Al Holding Furnace	272	1	1000	1	100
3334	Primary Non-ferrous Metals N.E.C.	19.0()	Reduction Tube Furnace/Calciners & Retorts	30		132	100	Large number of installations but low total energy usage
3341	Secondary Aluminum	28.6()	Reverbatory	242	5		8	0 Because of fluxes used: Poor application
3341	Secondary Lead	28.6(0.5)	Lead Ranchers	45	2	45	2	0 Lead appears to attack cordierite
3341	Secondary Zinc	28.6()	Kettle Furnace	87	1		2	0 ZnO ₂ plugged unit
3361	Al Foundries	24.5()	Pot Melter	16		11300	16	87 This appears to be a good application
3369	Nonferrous Foundries NEC	5.5(1)	Solder Pots	11300	5		5	100 Small Application: Similar to SIC 3361
3398	Metal Heat Treating	32.0(16.0)	Annealing Box, Car Bottom, Pit, Pot, Etc.	28800	26	12000	125	76 Lower temperatures (1400-1800F) increase chances of successful insulation
3462	Ferrous and Non-ferrous Forging	48.0(38.0)	Box, Slot, Rotary Hearth, Car-bottom & Pusher	3530	54	8000	212	55 Temperatures very (2200-2400F). Slot forges operate at top end and difficult to retrofit: Should pursue box forges not processing raw ingot
Misc.				3			6	0
Total				48372	165	50812	561	

Table 7
Oil & Gas Consumption for Direct Process
Heat for GTE Targeted Industries

National Rank	Standard Industrial Code	Industry	Energy Consumption (Trillion Btu/yr)
3	3312	Blast Furnaces and Steel Mills	688.2
11	3251	Brick and Structural Clay Tile	50.4
14	3321	Gray Iron Foundries	41.2
17	3462	Iron and Steel Forgings	36.6
23	3341	Secondary Nonferrous Metals	27.4
30	3361	Aluminum Foundries	20.7
31	3325	Steel Foundries, NEC	19.3
37	3255	Clay Refractories	16.8
42	3317	Steel Pipes and Tubes	13.6
48	3398	Metal Heat Treating	11.9
49	3259	Structural Clay Products, NEC	11.5
55	3322	Malleable Iron Foundries	8.4
61	3261	Vitreous Plumbing Fixtures	6.4
67	3313	Electrometallurgical Products	4.7
70	3264	Porcelain Electrical Suppliers	4.0
73	3369	Nonferrous Foundries, NEC	3.9
77	3463	Nonferrous Forgings	3.1
80	3269	Pottery Products, NEC	2.8
85	3262	Vitreous China Food Utensils	2.0
87	3362	Brass Bronze, Copper Foundries	1.9
89	3324	Steel Investment Foundries	1.5
91	3263	Fine Earthenware Food Utensils	1.4
97	3315	Steel Wire and Related Products	1.0
102	3334	Primary Aluminum	0.8

applications were suitable to the particular ceramic material, as evidenced by the 72% success rate in all the United States and Canadian installations.

Besides the metal industries, there are several other industries where the GTE recuperator could be applied. These industries are large energy consumers and use furnaces/reactors/heaters that are fueled by natural gas or oil and produce relatively clean exhausts at high enough temperatures to justify economical recuperation. Chemicals and Allied Products (SIC 28) are large energy consumers that have reactors, reformers, and fired heaters with exhausts suitable for the GTE recuperator. The same may be said about Petroleum Refining (SIC 29). In the Stone, Clay and Glass Industries (SIC 32), one would have to be more selective in the applications because of dirty exhaust gas streams. For example, structural clay products (SIC 326) may have cleaner exhaust streams than pottery products (SIC 326) which would use potentially damaging fluxing agents. Exhausts from glass tanks and cement kilns would not be suitable for the GTE recuperator because of corrosive compounds and particulates.

Thus, the chemicals and petroleum refining industries appear to have possibilities for using the GTE recuperator. The reason why GTE did not pursue these opportunities has been because we lacked the infrastructure needed to successfully market and support the product in this segment. In marketing the "Super Recuper", GTE relied solely on the burner manufacturers to sell their product to the industrial consumer. This worked very well in the metals industries where the burner companies were supplying combustion equipment to small foundries and forge shops .

However, the burner companies do not have the same relationship with the large plant operations, such as refineries and chemical plants. Most of these plants are technically sophisticated and have their own combustion department, and most of them fabricate their own furnaces and reactors. This may have been one reason why the petroleum and chemical industries were not targeted for recuperation.

The other group that GTE relied on to market the recuperator was the furnace manufacturers who could have promoted use of the technology. However, because of the poor business climate in the metals area, few, if any new furnaces were sold and furnace manufacturers were lucky to have survived financially.

3.2 FURNACE POPULATION

In 1981, PAR Enterprises, Inc. had conducted a survey of industrial furnace equipment¹² that provided some estimates of furnace types and population compiled from the published literature. Table 8 shows the number of furnaces that generate clean exhaust gases and

Table 8
Furnace Energy Consumption/Population¹²

	Energy Consumption Trillion-Btu/yr	Furnace Population
Clean Exhausts	1,144	145,800
Dirty Exhausts	1,687	14,500
Electric Furnaces	303	31,500
Totals	3,134	191,800

contaminated exhaust gases. The contaminated gases and energy consumption were primarily based on the EPA NEDS data base⁹ and are defined as gases containing large amounts of particulates or corrosive elements. The NEDS data base was based on information supplied by 34,000 plants in the United States, and information on contaminants in exhaust streams may not have been supplied for obvious reasons.

Further, natural gas-fired systems were usually taken as clean exhausts; whereas, one now considers soaking pits, aluminum remelt furnaces, and even box forge furnaces to have dirty exhausts because of corrosive elements such as sodium and potassium salts. Therefore, the information provided in Table 8 should not be used without further investigation. It is interesting to note that furnaces that produce clean exhausts greatly outnumber those with dirty exhausts but that energy used in the latter is more than that used in the clean operation. The furnace study¹² also indicated that only 30% of the furnaces producing clean exhausts were recuperated, while 70% of those producing contaminated exhausts were being recuperated. These numbers indicate that there are large potential markets for the GTE ceramic recuperator.

Referring to the furnace population figures in Table 6, it would appear to be more fruitful to pursue SIC 325 rather than 326 not only because of a larger number of furnaces available and larger potential for energy savings, but also because of cleaner exhausts in the case of the structural clay products as compared with pottery products.

In the blast furnace and steel products industry (SIC 331), oil and gas use amounted to about 897 trillion Btu/year. Most of this, or about 688 trillion, was used in SIC 3312. Here, the iron ore reduction and steel refining operations do not have opportunities for this type of recuperator. At one time there may have been at least 1800 soaking pits using about 120 trillion Btu, but this is not an application for the GTE recuperator because these are large furnaces that process raw ingots with topping compounds. However, reheating slabs, blooms, billets, and bars, if selectively chosen, could offer opportunities for the ceramic recuperator. There are 365 box-type reheat furnaces but there are also 589 pusher-type furnaces in this operation that GTE had not attempted to retrofit.

The SIC 331 includes a number of operations that appear to have excellent possibilities for the GTE recuperator. These are annealing and heat-treating operations involving 4535 furnaces (not included in SIC 3389) in the steel mill that consumes about 111 trillion Btu/year. These are listed in Table 9 and appear to be clean, low-temperature processes quite suitable for the GTE recuperator.

The iron and steel foundries (SIC 332) and nonferrous foundries (SIC 336) have been well sought out by GTE. Mold and die reheating furnaces have been successful retrofits as have been aluminum pot melters. These are relatively clean operations. However, ladle preheaters are to be avoided because of plugging problems. There were, however, several types of furnaces that GTE did not retrofit. There were 115 open hearth furnaces, 1737 reverberatory, and 190 rotary furnaces, all operating from 1200 to 2900°F; 3700 diecast holding furnaces operating at 1200°F+; and 220 investment cast holding furnaces operating at over 2000°F. In addition, there are about 1400 radiant and direct heat treat furnaces that operate at up to 1700°F that are not included in SIC 3398. The primary and secondary nonferrous metals do not appear to be good applications for the GTE recuperator either because of the small energy consumption or dirty exhausts. Aluminum remelt furnaces, lead melters, and zinc kettles have dirty exhaust streams that attack the cordierite recuperator material.

SIC 3339, primary nonferrous metals had a number of applications, most of which were in GTE's Towanda facility. These were indirect type, lower operating temperature furnaces for reducing tungsten and molybdenum compounds. The SIC energy consumption is low and there are not many plants in the United States that have these types of operations. One cannot deny, however, that GTE has saved energy and some of those furnaces are still operating with the original recuperators.

The nonferrous metals rolling and drawing operations (SIC 335) use about 126 trillion Btu/year of purchased fuels. This area was not addressed by GTE. There are smelting, holding, heating and annealing/heat treating operations in this SIC with an estimated 4,475 furnaces.

The metal heat treating industry, SIC 3398, appears to be a potentially profitable area for GTE to market much more extensively. There are a number of annealing/normalizing, hardening, tempering, carburizing, and other operations that are relatively low-tempeature operations with clean exhausts ideally suited for the GTE recuperator. However, there are many small furnaces and batch-type operations. For instance, there are an estimated 38,400 batch-type annealing/normalizing furnaces alone. These batch type of furnaces have not been considered in the furnace population count of Table 6 because the hours of operation are not known and therefore it could not be determined whether the economics would be attractive.

GTE appears to have concentrated the most in the steel forging industries. There were about 960 forge shops in 1980 but the recent business climate has been poor and a number of companies have closed their operations. While the alloy steel forge furnaces consume a large quantity of energy, they operate at very high temperatures between 2250 and 2400°F. At these temperatures, elements like sodium, potassium and calcium that originate either from the load (topping compounds) or from newly installed refractory could corrode the ceramic recuperator. Of the 212 units installed in these furnaces, only 56% are currently operating. Therefore, GTE needs to be more selective in these retrofits.

4. CASE STUDIES

4.1 OVERVIEW

GTE has developed procedures to evaluate a recuperator returned for refurbishing. These procedures were established to gather feedback to the recuperator designer, the manufacturing department and the system designers that specify the ceramic recuperator. Recuperators returned to GTE have generally been operated until complete system failure occurred. Complete system failure is defined as the inability to obtain required process temperatures and/or required product throughput. The recuperator, once destroyed, leaks a quantity of combustion air that is so large that the preheated-air temperature, volume and pressure are below the levels required for proper operation. A degraded ceramic recuperator is generally exposed to excess fuel conditions in its last stages of operation. The excess fuel in the exhaust stream mixes with the leaking combustion air and combustion takes place inside of the recuperator. The potential to generate extremely high temperatures within the recuperator from this combustion was thought to be the cause for the melting of the face of the ceramic matrix often found on matrix elements returned for rebuild. Another possibility was the formation of a low temperature eutectic from reaction of the cordierite ceramic reacting

with alkali metals often present in the glassy face of the ceramic. To fully understand the mode of failure of the ceramic matrix, ceramic recuperators were removed from service prior to failure during this contract effort. This allowed the investigation to proceed before some of the evidence was destroyed during the final stages of failure (excess fuel). This unique opportunity gave insight into the long term degradation of the ceramic.

4.1.1 QUALITY ASSURANCE MEASURES

The following procedures are followed prior to assembly of a ceramic matrix:

- The matrix is inspected for geometric tolerances
- The matrix must not contain visible cracks
- The matrix is tested for leakage and structural integrity, it
 - must leak < 5% of the nominal air flow rating at 1 psi
 - must survive a 5 psi pressure to the exhaust-side
 - must survive a 5 psi pressure to the preheat-side
- Leakage must not be concentrated in one area (which would indicate an internal crack)
- The unit is assembled and housed and must leak < 5% of its nominal air flow rating at 1 psi

The housed recuperator test procedure requires that the preheat-air outlet be sealed off. The combustion air inlet is then attached to a 2 psi blower. A valve vented to the room is used to adjust the pressure actually delivered to the assembled matrix. The pressure in the first pass of the recuperator is monitored, and the flow into the recuperator is determined, by calculating the pressure drop across an orifice plate upstream of the recuperator. Percentage values are determined by the ratio of actual leakage to nominal air flow for each pressure. The recuperator ratings are listed in Table 9. Generally, a recuperator system must operate at a pressure of 0.5 psi under high-fire conditions. This pressure is determined by the burner's specifications.

The ceramic matrix is sealed into the refractory lined metallic housing with a high temperature gasket (Figure 2). The gasket overlaps a 0.75 in. wide seal face on each of the corners of the ceramic cube. The seal face is formed by impregnating the ceramic with commercially available moldable aluminosilicate fiber. The moldable material is a slurry of 2600°F fiber suspended in a "water-glass" suspension (sodium-silicate). The sealed area reduces the effective heat transfer area of the recuperator. The area that is used to foster the multiple pass design is 0.5 in. high, and runs the entire width of the combustion air-inlet and combustion air-outlet faces of the recuperator. For example, the R0600 model is 10 x 10 x 10

Table 9
GTE Recuperator Nominal Air Flow Ratings

MODEL #	SIZE	Btu Rating	Nominal Air Flow Rating
R0600	10 x 10 x 10-in.	600,000-Btu/h	6,600-scfh
R1000	12 x 12 x 12-in.	1,000,000-Btu/h	11,000-scfh
R1500	12 x 12 x 18-in.	1,500,000-Btu/h	16,500-scfh

in, but the effective volume is 8.5 x 8.5 x 7.5 in.

The gasketed area then creates a .075 in. thick area without cross flow at the exhaust inlet section of the recuperator (dead area). This area generally operates at a temperature 200 to 500°F cooler than the exhaust gas temperature. The temperature of the ceramic in the area of cross flow is approximately equal to the average of the exhaust gases, and the combustion-air preheat-temperature. This unused area plays a critical role in the life cycle of the recuperator. The exhaust gases often contain contaminants that condense on the cooler ceramic. This ceramic reacts with the alkali materials and forms glassy materials that in time may seal off the exhaust inlet of the recuperator, rendering it useless. The concentration of contaminant is reduced in the "dead zone" by the cooled ceramic, and the area of crossflow is protected by the exhaust inlet dead area. This is illustrated in Figure 4.

4.1.2 POST MORTEM ANALYSIS TECHNIQUES

A "post mortem" analysis generally is as follows:

- Collect any residue or deposits loosely bound to the exhaust inlet and outlet
- Photograph and/or describe the housed matrix
- Leak test the housed matrix in a dead head test to determine the leakage flow at 0.25, 0.5, and 1 psi
- Remove the combustion air-inlet assembly and inspect for cracks and delamination of the ceramic
- Photograph and/or record findings
- Collect any debris, and analyze (qualitative emission spectrography) if not identifiable

- Remove the matrix and pressure test it if intact (generally the unit is delaminated and/or melted, and must be removed in sections)
- Photograph the matrix as it is sectioned, and identify “white cells”, cracking patterns, and corrosion patterns (if any)

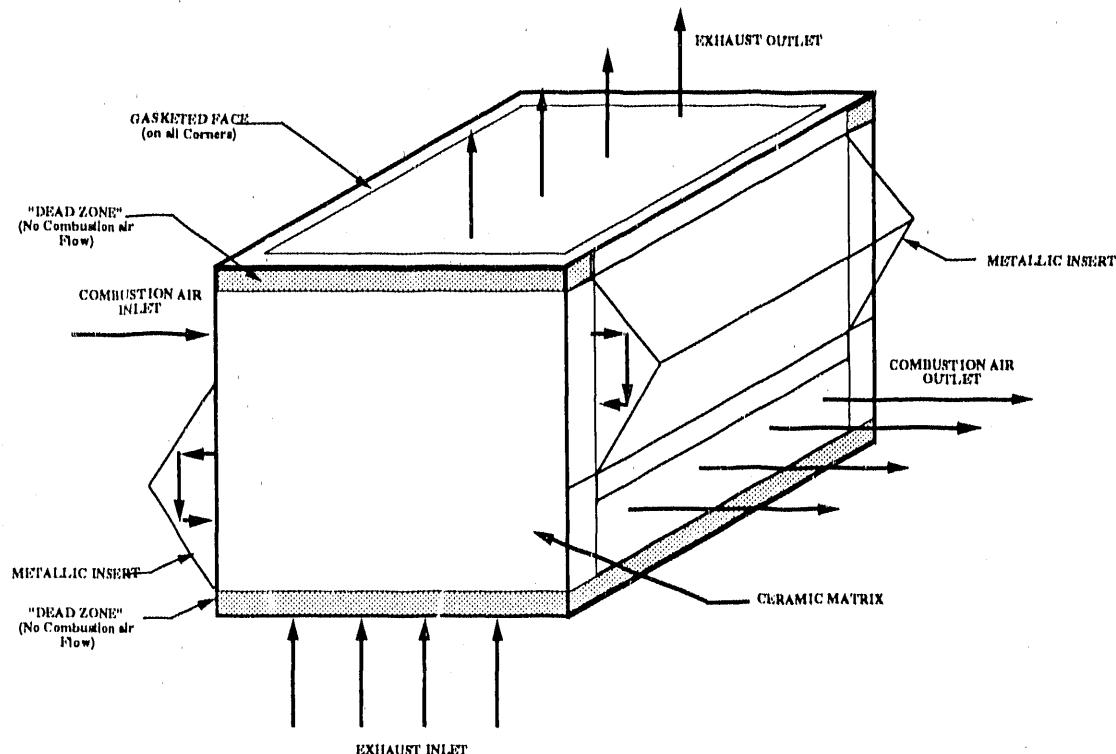


Figure 4
GTE Ceramic Recuperator Flow Arrangement

“White cells” are exhaust-gas passages that are still the color of an unused ceramic matrix. After use, regardless of the degree of cleanliness, temperature, or fuel type used on the application, the ceramic becomes darkened. A “white cell” is evidence of a crack that was present prior to recuperator operation. The cell fails to discolor because no exhaust gases ever pass through a cell with a crack. The pressure of the air in the combustion air channels (1 to 20 osi, depending upon input rate and system design) is significantly higher than the pressure in the exhaust gas channels (0.05 -0.15 osi). The higher pressure combustion air travels into the cracked exhaust channel, and then is directed towards the exhaust inlet and outlet section of the recuperator, where it mixes with the exhaust gases. These cells, when found, are

generally few in number (<5). A large number of cells (cracks) would be screened by the leakage and pressure tests. Cracks found in the area of a "white cell" of an operating recuperator are generally long, straight hairline cracks. They are barely visible at ambient temperature. Hairline cracks form during the cooling portion of the firing cycle. Experience has shown that cracks that form early in the sintering process always result in irregular shape cracking patterns distinguished by a large gap (.010-in.) in the center section. A crack this large would be cause for failure of the leakage tests. Most ceramic matrix elements have a leakage value of 1-2%, and much (or all) of this value is associated with the leakage about the gasketed seals of the leak test apparatus or along the outside edges or the recuperator.

With this knowledge in mind, a postmortem that finds cracks other than those associated with "white cells" must assume significant thermal stresses were placed on the ceramic matrix, outside of those it was designed to tolerate, or that the ceramic is no longer capable of withstanding thermal stresses. A condition that results in cracking from thermal stress can cause failure of the multiple pass system. This would cause ambient air to impinge on cells heated to temperatures close to the exhaust gas inlet temperature. These failures are rare, and a simple inspection of the metallic inserts (warping) will confirm if the multiple pass design was compromised. The more common reason for crack formation is the chemical degradation of the ceramic. Conversion of the cordierite ceramic to glass, and/or a mixture of other ceramics such as mullite or spinel has been observed when gross cracking of the ceramic matrix is observed.

This analysis was preformed for virtually every ceramic recuperator refurbished at GTE since the outset of this contract effort. The historical data obtained from this effort, and the information obtained by removing recuperators prior to failure confirms that failures are generally proceeding at a slow rate if trace contaminants are present in an exhaust stream. The rate is proportional to concentration and temperature. The fact that the units generally experience an excess fuel excursion prior to complete failure is due to degradation of the matrix. The degradation of the matrix may become more extreme during the excess fuel excursion, but the failure is generally not a result of the excess-fuel condition simply caused by control system failure. This finding was directly responsible for GTE's decision to specify that system designs must anticipate potential corrosion problems on applications typically thought to be clean. Even standard refractory brick has been shown to volatilize alkali contaminants.

Table 10 details the elements sought in a typical qualitative analysis. Additionally, the table lists the detection ranges reported for each element sought.

Table 10
Elements Sought and Detection Limits
During Spectrographic Qualitative Analysis

CHEMICAL SYMBOL	CHEMICAL NAME	REPORT SYMBOL	REPORT RANGE
Ag	Silver	V+	10-100%
Al	Aluminum	S+	5-50%
As	Arsenic	S	1-10%
B	Boron	ST+	0.5-5%
Ba	Barium	ST	0.1-1.0%
Be	Beryllium	T+	0.05-0.5%
Bi	Bismuth	T	0.01-0.1%
Ca	Calcium	FT+	50-500ppm
Cd	Cadmium	FT	10-100ppm
Co	Cobalt	VF+	5-50ppm
Cr	Chrome	VF	1-10ppm
Cu	Copper	VVF+	0.5-5ppm
Fe	Iron	VVF	<1ppm
Ge	Germanium	—	not detected
K	Potassium	—	
Li	Lithium	—	
Mg	Magnesium	—	
Mn	Manganese	—	
Mo	Molybdenum	—	
Na	Sodium	—	
Ni	Nickel	—	
P	Phosphorus	—	
Pb	Lead	—	
Sb	Antimony	—	
Si	Silver	—	
Sn	Tin	—	
Ta	Tantalum	—	
Th	Thorium	—	
Ti	Titanium	—	
V	Vanadium	—	
W	Tungsten	—	
Zn	Zinc	—	
Zr	Zirconium	—	

4.2 TUNNEL KILN (Saxonburg Technical Ceramics - Saxonburg, Pennsylvania.)

Figure 5 shows the two R1500 ceramic recuperators on the Bickley roller hearth tunnel kiln at Saxonburg ceramics. The furnace is 40 ft long. The operator is loading alumina setters that are used to transport alumina substrate through the furnace. Cycle times range between 1.7 and 2.7 hours. Recuperators are located on the preheated air zone of the furnace. The exhaust inlet temperature ranges between 2000 and 2300°F. Combustion air is preheated to the 1200 to 1400°F range and is then ducted to burners in the hot zone. The hot zone operated at temperatures between 2800 and 2900°F at 10% excess air. Natural gas is the only fuel used. Exhaust gas mass flow rates are approximately 30% greater than the combustion air mass flow rate. This results in the unusually high preheated-air temperature, and means that the ceramic matrix operates hotter than usual.

Figure 6 shows the exhaust inlet of a recuperator after 15 months of service. Figure 7 shows the exhaust outlet of the same recuperator. The glassy-melted appearance on the inlet side and the powder coating on the exhaust outlet were sampled for spectrographic analysis. Leakage rates, and exhaust side pressure drop reduced the performance of the recuperator to the point that furnace temperature could not be maintained. Leakage rates were approximately 35% at 16-osi. Eight samples were submitted for spectrographic analysis. The results are listed in Table 11.

Approximately 85% of the free flow area of the exhaust inlet was covered with a brown, glassy-like material. The inside of the matrix was covered with a brown, fibrous and/or powdered material. The matrix was cracked, and a partial delamination occurred on one of the recuperators (2 units were investigated). The major contaminants are identified in Table 11. The most important information is the composition of the glassy material (icicle) on the exhaust inlet section. The amount of alkali contrasts dramatically with the amount found in the ceramic matrix before operation (.01-.1%), an increase of 10 to 50 times. Although phosphorus is present in the exhaust outlet, it does not appear to react with the ceramic, and it deposits in the cooler exhaust outlet sections of the recuperator (dew point must be in the range of 900°F).

Sampling of the refractory brick and the mortar was undertaken in an effort to determine the potential of these materials as a source. Table 11 clearly indicates they are not potent candidates. The following is a list of possible sources of contaminant:

- The furnace refractory (one time exposure from initial burnout).
- The refractory mortar used (one time exposure from initial burnout).
- The NaOH wash utilized when changing the ceramic pins used to secure the ceramic rollers.
- A sintering aid in the SiC rollers (one time exposure from initial burnout).



Figure 5
R1500 Recuperators on the Bickley Roller
Hearth Tunnel Kiln at Saxonburg Ceramics



Figure 6
R1500 Recuperator Exhaust Inlet After
15 Months of Operation at Saxonburg Ceramics



Figure 7
R1500 Recuperator Exhaust Outlet After
15 Months of Operation at Saxonburg Ceramics

Table 11
Spectrographic Qualitative Analysis
of Samples from Saxonburg Ceramics

Sample Description	Al	Cr	K	Li	Na	P	Pb	Si	Ti
Grey-brown material hanging down from the Recuperator exhaust inlet	VS	T	S	ST	S	T	—	VS	ST
Residue from exhaust outlet of housing	S	ST	S+	S	VS	S	S+	S+	T+
Sample from cool end of preheat -zone roller	VS	T+	S	S+	S	—	—	S+	ST
Sample from hot-zone mortar (outer layer found on fire brick)	VS	T	—	—	T	—	—	S+	FT
Sample from hot-zone mortar (outer layer found on fire brick)	VS	T	—	—	T+	—	FT	S+	T+
Sample from cool end of hot-zone roller	VS	FT	ST	—	ST	—	VF+	VS	ST
Grey "icicle hanging from exhaust inlet"	S	S	—	ST	ST	V+	T+	ST	T
Green powder in exhaust outlet section	S	S	—	ST	ST	VS	FT+	S+	ST
Grey-green residue found 4-in. into the exhaust inlet channel	VS	T	S	ST	S	T	—	VS	ST

- Alkali compounds in trace quantities in the organic binder used in product (substrate).
- A deflocculant similar to Calgon (sodium hexameta-phosphate).
- A material that should not have passed thru the kiln.
- A material contained in the refractory setter used for the transport of ware through the kiln.
- Trace alkali in the alumina substrate being sintered.

Because the recuperators failed again, in another 15 months, the sources considered to be start up related were eliminated. Analysis of the organic binder showed that it does decompose and vaporize gases containing large amounts of alkali and phosphate. Further investigation showed that the quantity of product fired in the furnace each month produces a few pounds of alkali per month. The recuperator acts as a collector, as the vapor condenses on the cooler surface of the recuperator. Reactions then proceed, as the crystalline ceramic is converted to a glassy material. Figure 8 shows a phase diagram illustrating how the addition of sodium to cordierite reduces the melting temperature of cordierite. From right to left in the cordierite phase field, as the amount of sodium increases, the melting point steadily decreases. This diagram does not represent the phases present in the corroding core, but the diagram gives the general trend of the reaction of cordierite with an alkali.

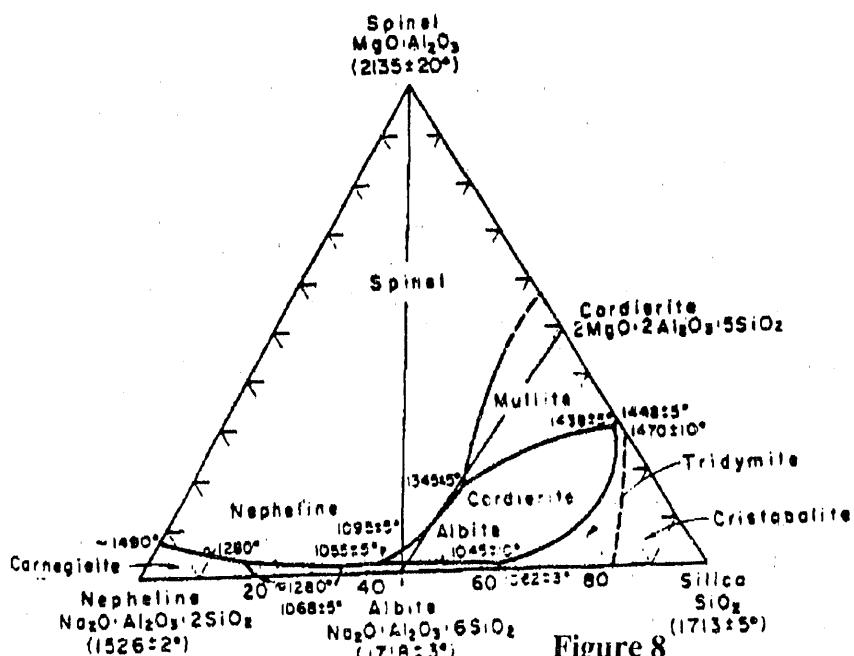


FIG. 2024.—System Na_2O -
 $\text{Al}_2\text{O}_3\text{-}2\text{SiO}_4\text{-MgO}\text{-}\text{Al}_2\text{O}_3\text{-SiO}_4$.
 J. P. Schairer and H. S.
 Voder, Jr., Carnegie Inst. Wash-
 ington, Yearbook, 57, 211 (1958).

Figure 8
 Phase Diagram Showing the Cordierite
 Phase Field in the Presence of a Sodium Compound

The removal of recuperators prior to complete failure produced identical results in terms of corrosive analysis. Softening of the outer extremities of the exhaust inlet face was apparent, however the degradation was limited to the "dead zone" of the exhaust inlet. Once the reaction proceeds to the area where combustion air flow exists dramatic increases in leakage rates occur rapidly.

Scaling of the ceramic was also observed during the post mortem analysis. A 0.002-in. thick section would separate from the matrix after exposure to the alkali. The newly exposed surface would then be exposed. Another scale section would form, then separate. The wall thickness of the ceramic recuperator matrix is only 0.050-in. This process helps to explain how the base of the ceramic becomes filled in (Figure 6). The continuing spalling, coupled with continuous contamination and exposure eventually leads to the blockage illustrated.

Recommendations made to maximize recuperator life were the reduction of exhaust inlet temperatures to 2000°F or below, and the substitution of organics with a lower level of alkali. Life cycles are currently approximately 2 - 2.5 years.

4.3 SLOT FORGE FURNACE (Dana Corporation - Lansing, Michigan)

The slot forge furnace at Dana utilizes two R1500 recuperators. The exhaust gases pass directly into the recuperator mounted on the side walls of the furnace. A burner is mounted directly to the recuperator. A burner-recuperator pair is mounted on each side of the furnace, and directly oppose each other. Figure 9 shows the arrangement of the recuperator on the fiber-lined furnace side wall. The hearth of the furnace is No. 2B stone (gravel).

The purpose of the gravel is to absorb any molten metal and/or scale that is generated during forge reheat operations. This practice is common on uncontrolled slot forge reheat furnaces. The operator only monitors the surface temperature of the steel (optically), and begins forging as soon as the bar obtains the required temperature (2300°F range). The furnace may operate at temperatures well above 2800°F in an attempt to rapidly achieve working temperatures. This process often resulted in the formation of molten steel. The recuperated furnace had a temperature limitation of 2450°F due to the recuperator. The gravel hearth was specified by the furnace designer to accommodate the scale created by the operation. The hearth is changed routinely (7-14 days).

Slot forge furnaces are started daily at 5:00 AM, and forging should begin within 2 hours. Exhaust gas inlet temperatures approach 2300°F within 3 minutes. The relatively low thermal mass of the fiber-lined furnace makes the rapid heat-up possible.

Figure 10 shows the exhaust inlet of a recuperator removed from service at Dana. The

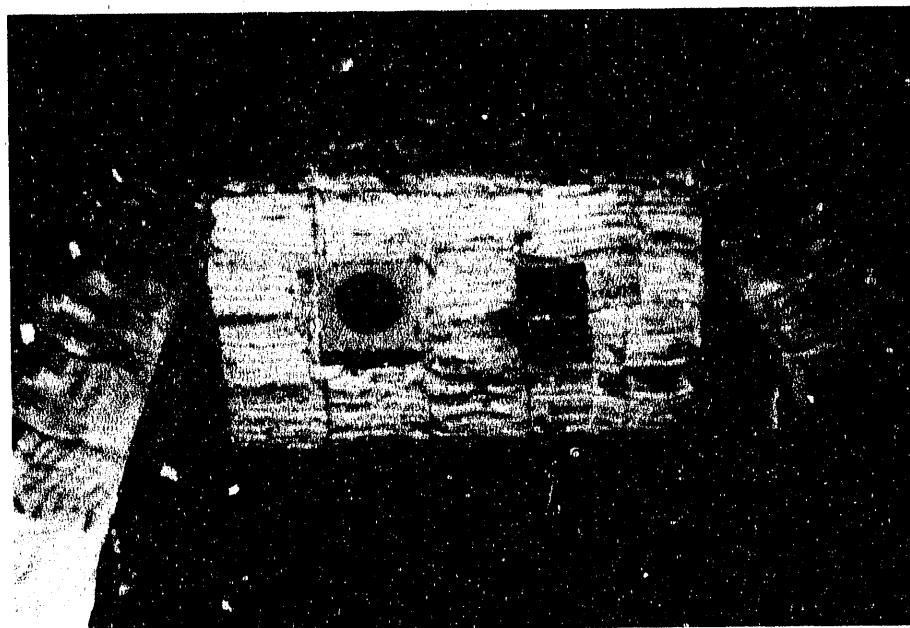


Figure 9
Side Wall of Dana Slot Forge Reheat Furnace
Showing Burner-Recuperator Location and Gravel Hearth
(viewed with crown removed)

matrix is covered with a black and brown coating. Preliminary indications are that iron and carbon are present.

Figure 11 shows the faces of air side and exhaust side passages located in the center of the recuperator. The arrows indicate the fluid flow directions. The cracking patterns are most severe in the hottest section of the recuperator (combustion air outlet). Here the ceramic is hottest, and most likely to react with contaminants. This matrix was leaking 40% when removed from service, but preheat air temperatures were still in the 1100°F range. Complete failure (inability to reheat the load in the required time) would have occurred shortly.

The spectrographic analysis showed the presence of sodium, potassium and iron in concentrations greater than 5%. The source for the sodium was determined to be the gravel. The source for the iron was the steel scale formed during forge reheating. Gravel was fired at GTE to 2450°F for a 24-h period at 10% excess air conditions. Figure 12 shows the fused residue of the gravel. Table 12 contrasts the compositions of the raw gravel and fired gravel. The table shows that the alkali fluxes are present in both the raw and fired gravel, but not in the same quantities as in the raw gravel. At furnace temperatures, these elements volatilize from the gravel and deposit (condense) and react with the cordierite.

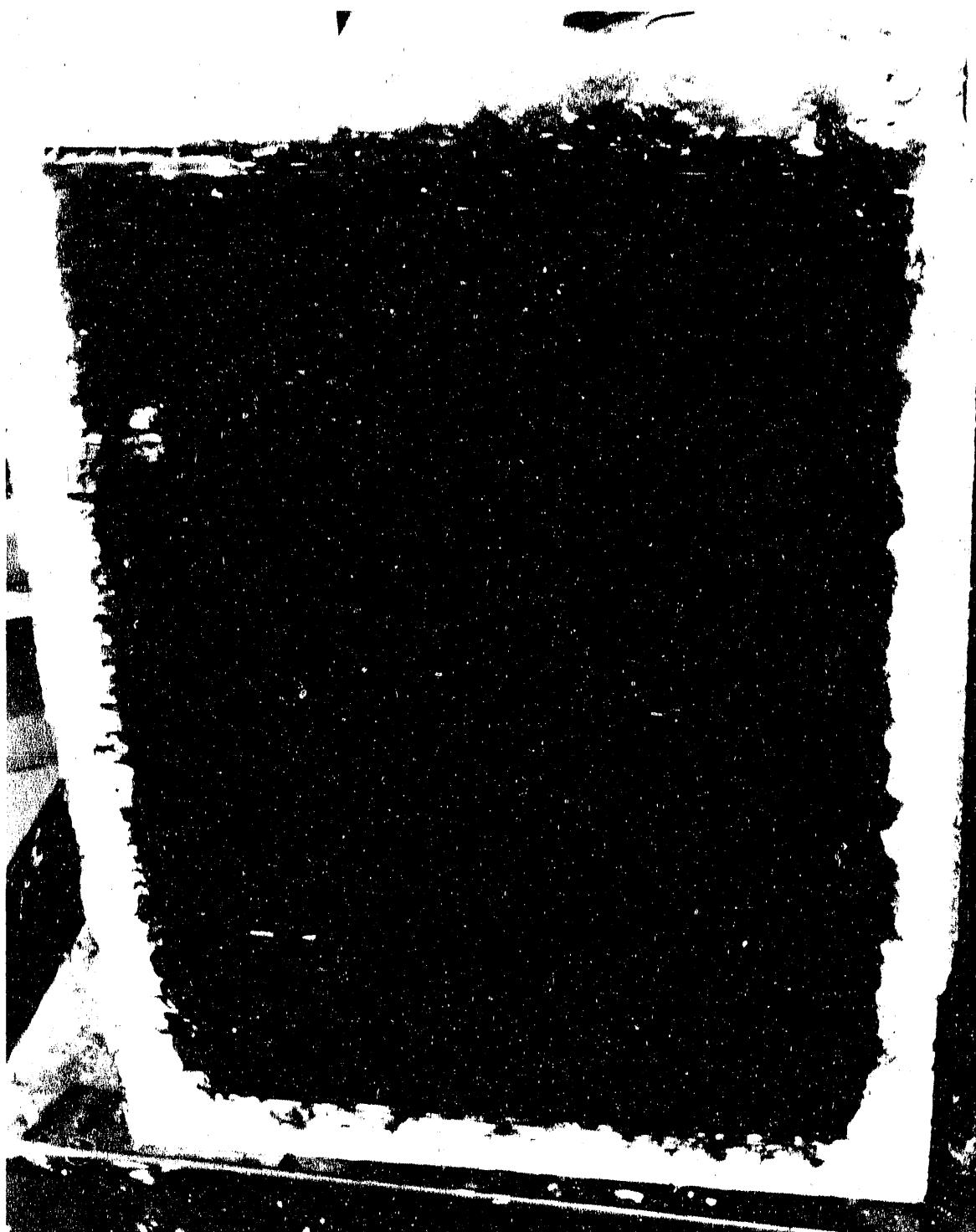


Figure 10
R1500 Recuperator Exhaust Inlet After 5 Months
of Operation on Dana's Slot Forge Reheat Furnace

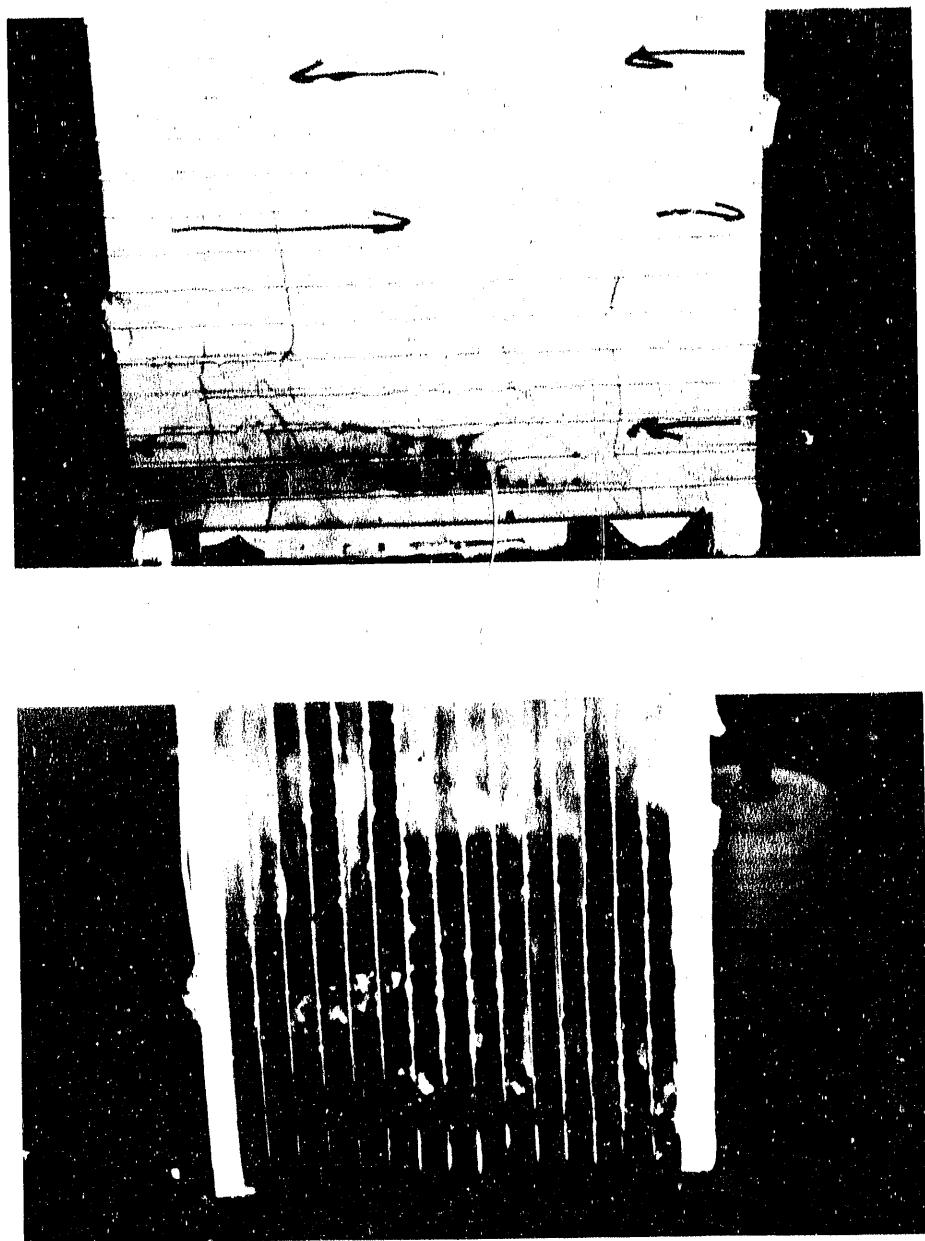


Figure 11
Air-Side and Exhaust-Side Passage
Extracted from the Center Section of a GTE Recuperator
Removed from a Dana Corporation Slot Forge Reheat Furnace

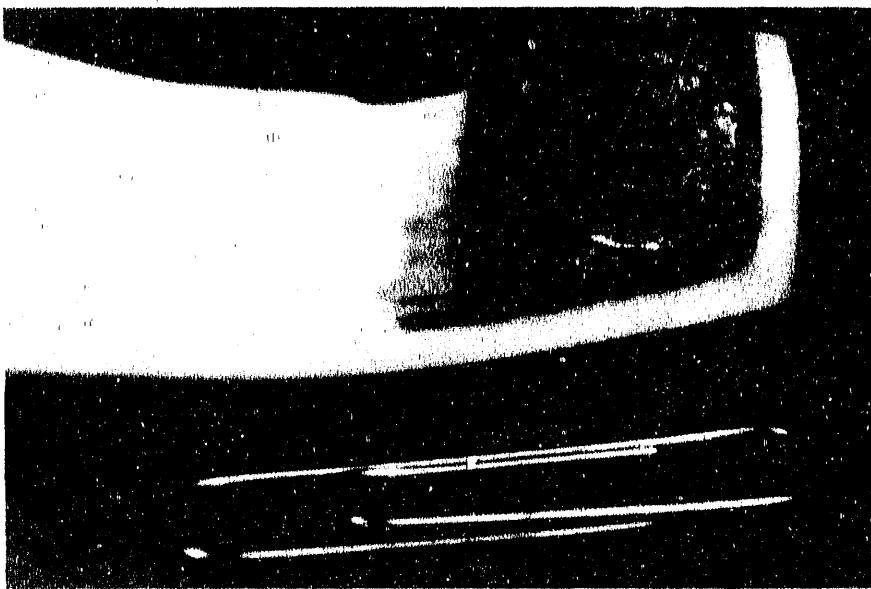


Figure 12
Fused Gravel Removed from a Dana Corporation
Slot Forge Reheat Furnace After a 24-h soak at 2450°F

Table 12
Spectrographic Qualitative Analysis
of Fired and Unfired Gravel from Dana's Slot Forge Furnace

Sample Description	Al	Ca	Fe	K	Li	Mg	Mn	Na	Pb	Si
Raw Gravel	T	VS	ST	ST	FT+	VS	ST	T	VF+	ST
Gravel fired to 2450°F (24-h)	T	VS	ST	VF+	VF+	VS	T+	VF	—	ST

The recommendation to replace the gravel refractory hearth with a high temperature castable refractory increased the life cycle from 4 weeks to 6-8 months. This increase made the recuperator life cycle acceptable from an economic perspective. Another design flaw was the placement of the recuperator on the side of the furnace. The exhaust gases traveled horizontally through the recuperator. A design modification was made that called for an

exhaust flue to be mounted on the furnace side wall. The flue's function was to transition the exhaust flow so that it passed vertically through the recuperator. This eliminated the metallic scale that often stuck to the side of the exhaust inlet of the recuperator, as the scale would settle out in the right angle section of the exhaust flue.

4.4 LEAD WIRE ANNEALING FURNACE (Am. Spring Wire - Cleveland, Ohio)

The furnace at American Spring Wire Company has a R1500 recuperator on each of two zones. Each recuperator is connected to four hot-air burners. The lead bath temperature is controlled automatically by adjusting the mass flow rate of the combustion air to each recuperator. The high fire input is adjusted to a 30% excess air rate. A spring loaded gas pressure regulator is loaded by an impulse line from the cold side of the recuperator. The regulator is adjusted to trim gas flow at a rate greater than the reduction in air flow. The net result is that the low fire input rate (4:1 flow turndown) operates at a 100% excess air firing rate. This control scheme offers a thermal turndown of greater than 20:1. The variable excess air mode of temperature control insures that thermal uniformity in the combustion chamber is maximized (maximum convection). The thermal input rate during annealing operations approaches the maximum thermal input rate of 2.5 million Btu/h, at 30% excess air.

The exhaust outlet from each recuperator is connected to a common manifold, and attached to a high-temperature exhaust fan. Exhaust flow through each recuperator unit is constant, however, the combustion air flow rate through each unit varies according to demand. The zone 2 control sensor measures the lead melt temperature at the exit end of the wire bath. The heat required to maintain the zone 2 temperature is less than that required by the zone 1 unit. The zone 1 combustion system must supply energy to recover the losses imparted when the ambient wire enters the retort. This recuperator generally operates at or near its high-fire rating.

Actual measurements show the exhaust inlet temperatures to be in the 2200 to 2300°F range. If we look at the combustion air flow entering each recuperator as cooling air, it becomes apparent that the unit with the greater combustion air mass flow rate will operate with the lowest mean temperature. The unbalanced combustion air flow makes the zone 2 recuperator run hotter at American Spring Wire. The fact that the preheated air temperatures from the zone 1 recuperator are cooler by 200 to 400°F confirms that the recuperators have different mean temperatures as a result of the mass flow imbalance. The zone 2 recuperator failed, while the zone 1 recuperator did not. The exhaust inlet of the zone 2 unit has melting on 50% of the face while the zone one unit had only a few areas that were melted. Figure 13 shows the exhaust inlet of the zone 2 recuperator.

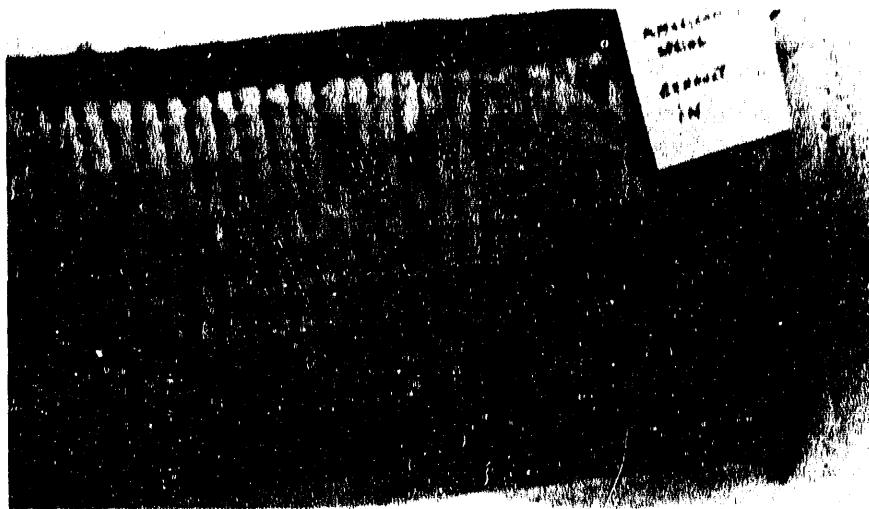


Figure 13
**Exhaust Inlet of R1500 Recuperator Removed from Lead
Wire Annealing Furnace at American Spring Wire Company**

Table 13 shows the results of a spectrographic analysis of various samples taken from American Spring Wire's annealing furnace. "Coke breeze" is the material on the top of the lead bath. Recuperator 2 was removed due to failure after 6 months of operation, and was replaced by recuperator 3. After a second failure (3 months of operation), both recuperators failed and were replaced (recuperator 1 and 3). This failure occurred soon after the lead pot was replaced (it failed). Recuperator 4 and 5 were operated for 1 year and removed after unit 5 failed (zone 2). Unit 5 was in excellent condition and was inspected and placed back on the furnace.

Both alkali and lead played a role in the failure of the recuperators at American Spring Wire (ASW). Lead enters the exhaust gas stream after it vaporizes in the combustion chamber. Molten lead from the exit portion of the pot (carried by the wire) drips onto the hot refractory, then migrates through the refractory and into the chamber. Another method that the lead enters the recuperator can be due to the leaking of a ruptured pot. The source of the alkali is believed to be from the castable refractory or the fiber board insulation used on the furnace.

A test was run on GTE's test furnace to simulate the conditions at American Spring Wire. A 200 gram sample of NaOH was placed directly below the exhaust inlet of an R1500 recuperator. The furnace was operated for 24-h at 2500°F. Flow rates and stoichiometric conditions were selected to simulate operation at ASW. The surface of the matrix was similar to that shown in Figure 13 (Zone 2 from ASW). This confirms the effect of the alkali found on all the recuperators that have failed due to corrosive attack.

on all the recuperators that have failed due to corrosive attack.

Table 13
Spectrographic Qualitative Analysis of
Samples from American Spring Wire Company

Sample Description	Al	Cr	K	Li	Na	P	Pb	Si	Ti
Material from the exhaust inlet of cube 2, Zone 2 (A)	ST+	ST+	VS	S+	VS	VS	VS	VS	ST
Material from center of exhaust cells of cube 1, Zone 1 (J)	ST+	T+	ST	T+	ST	ST	VS	ST+	T
Material from the exhaust inlet of cube 3, zone 2 (F)	VS	T+	S	ST	S	S	VS	VS	ST+
Material from center of exhaust cells of cube 3, zone 2 (H)	ST	T	ST	FT+	S	S+	VS	S+	ST
Sample of lead from annealer (L)	FT	VF+	VF+	—	VF+	—	VS	VF	VF
Sample of "coke breeze" (M) (Iron and zinc concentration is ST+)	ST+	FT	T	VF+	FT+	—	ST	S	ST
Material from center of exhaust cells of cube 4, zone 1	ST+	ST+	ST	ST	T	S+	S+	T	ST

Life cycles were extended to over 1 year by implementing the suggestions based upon results of the data shown in Table 13 (unit 4 and 5). These procedures were implemented when possible at American Spring Wire:

- Run the combustion air flow rates constant, and control temperature via regulation of the gas flow rate only. This will tend to balance the mass flow rates through the recuperators. Expected results are a more uniform life cycle for the zone 1 and zone 2 recuperator, and a corresponding reduction in maintenance costs.
- Burn the refractory out with the exhaust bypassing the recuperators after a pot failure. This will volatilize any lead contained in the refractory and avoid

contamination of the recuperators. Additionally any alkali that vaporizes from the castable refractory will avoid the recuperator.

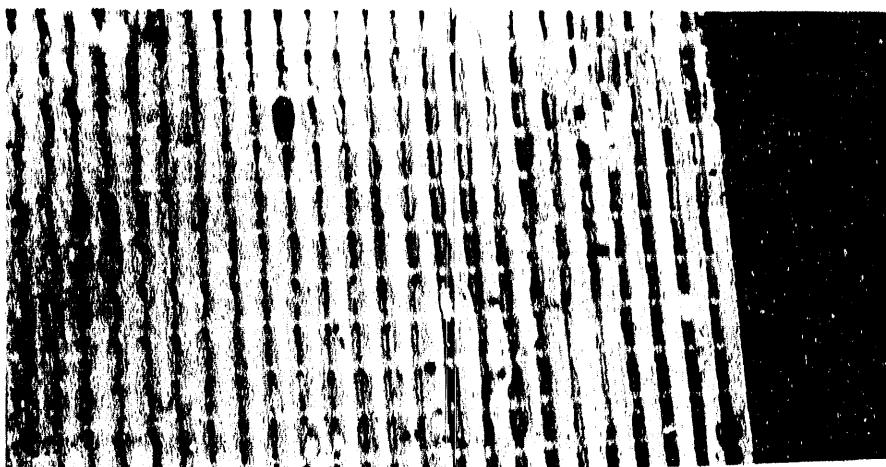


Figure 14

**Exhaust Inlet of R1500 Recuperator Exposed to 200-g of NaOH
at 2500°F for 24-h on GTE's Recuperator Test Furnace.**

5. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions may be drawn from GTE's experience with the ceramic recuperator.

- The thrust of the applications appear to be in the metal processing industries. This focus appears to be the correct one in view of the number of furnaces in these industries and potential for sales of their recuperators.
- The GTE ceramic recuperator is a success story as attested by the fact that, out of the 561 units installed on 165 new or retrofitted furnaces in 89 United States and Canadian plants, 405 or 72% are currently operating, while 117 or 21% are not in use either because of failure, poor performance, or plant shutdown. The status of the rest is unknown because those plants could not be contacted either because they declared bankruptcy or were taken over by other companies.
- The combined energy savings from the 405 units presently operating may be estimated at about 0.5 trillion Btu annually. In addition to energy savings productivity increases and material savings have also benefited the industrial users.

- The recuperators were installed on furnaces operating from 1400 to 2500°F and preheated air temperatures varied from 600 to 1300°F. Of those recuperators installed on furnaces operating at 2000°F and below, 87% are currently operating, while of those installed on furnaces operating at greater than 2000°F, only 57% are currently operating.
- Of the three sizes of recuperators installed, 89% of the 10 in. cube units, 77% of the 12 in. cube units, and only 56% of the large units are presently operating. This fact is not just coincidental, and it is possible that the larger units are more severely stressed in operation. Another reason for the higher failure rate on the large units may relate to the extrusion and firing of the raw ceramic during recuperator production.
- Four types of problems have been experienced since the initial DOE project, two of which relate to the recuperated system and two to the specific application. The system-related problems were experienced initially and involved inadequate hot-air burners and air:fuel ratio controls. These were corrected by the burner manufacturers and GTE, and the current burners and control systems are operating effectively.
- The recuperator is a plate-fin unit that is very compact, with plate spacings as small as 0.125-in. It therefore should be used in clean exhaust environments without particulates that could plug the recuperator. The other problem, plugging and corrosive attack by alkali, depend on the contaminants in the exhaust gas stream of the particular furnace.
- Plugging of the recuperator with fiber from the furnace lining can be corrected by cleaning during normal shutdown. Most plugging problems resulting from oxides deposited in the recuperator from indirect reduction furnaces could be resolved by cleaning with an air lance. Applications where vapors in the exhaust gases could condense in the recuperator, such as lead melting furnaces and glass tanks, should be avoided. Applications where the deposits are sticky and buildup occurs over time are difficult to clean without damaging the recuperator and should be avoided.
- The cordierite material of construction is susceptible to corrosion attack from

elements such as sodium, potassium, calcium, and other alkali and alkaline earth compounds. These alkali form lower temperature melting eutectics with the cordierite and failure will result if the furnace operating temperature exceeds the softening temperature of the eutectic, which has been measured to be as low as 2100°F in some cases. Nonferrous metals, such as lead and zinc, have also been found to attack the cordierite material.

- Sources of alkali are fluxing agents used in aluminum remelt/reverberatory furnaces and topping compounds used on steel ingots reheated in steel reheat and forging furnaces. The operating temperatures of these furnaces range from 2200-2400°F, which could exceed the softening temperature of the specific eutectic formation; therefore, recuperator failure would likely result in these applications. They should therefore be avoided.
- In marketing the ceramic recuperator, GTE has correctly targeted the metals industries. Except for two installations in the clay industry, all installations were in the metal processing industries. In these industries a total of about 48,000 furnaces were identified as having potential for recuperation.
- The historical data obtained from this effort, and the information obtained by removing recuperators prior to failure confirms that failures are generally proceeding at a slow rate if trace contaminants are present in an exhaust stream. The rate is proportional to concentration and temperature. The fact that the units generally experience an excess fuel excursion prior to complete failure is due to degradation of the matrix. The degradation of the matrix may become more extreme during the excess fuel excursion, but the failure is generally not a result of the excess-fuel condition simply caused by control system failure.
- Based on experience, industries that need to be pursued are (in order of preference):
 - metal heat treating (SIC 3398)
 - aluminum foundries (SIC 3361)
 - steel mills (SIC 331)
 - steel forging (SIC 3462), and
 - structural clay products (SIC 325)

- Based on the users experience, GTE should avoid the following furnace applications because of corrosive elements in the exhaust gases:
 - tunnel kilns in the pottery and related industries
 - ladle preheaters in ferrous and nonferrous industries
 - remelt and kettle furnaces in the secondary non-ferrous industries, and
 - reheat/forge furnaces processing raw ingots
- There is considerable potential in the metals industries where GTE has not retrofitted a furnace. There are about 4535 heat treat and annealing furnaces in SIC 331 that are suitable for the ceramic recuperator. In ferrous and nonferrous foundries (SIC 332 and 336) there are 5960 types of furnaces that could be retrofitted. In metal rolling and drawing operations (SIC 335), there are an estimated 4475 furnaces for smelting, holding, heating and heat treating. All of these furnace applications should be actively pursued.

6. REFERENCES

1. Cleveland J.J., et al, Ceramic Heat Recuperators for Industrial Heat Recovery, Final Report , No. DOE/EC/02162, August 1980.
2. Dorazio, R.E., et al, The GTE Ceramic Recuperator for High Temperature Waste Heat Recovery, 1984 Industrial Energy Conservation Technology Conference, Houston, TX, April 15-18, 1984.
3. Ally, M.R., et al, Optimization of Multi-pass Crossflow Heat Exchangers for Waste Heat Recovery Applications, 1984 National Heat Transfer Conference, Niagara Falls, N.Y., August 5-8, 1984.
4. Ferri, J.L., Temperature Compensated Air/Fuel Ratio Control on a Recuperated Furnace, 1983 Industrial Energy Conservation Technology Conference, Houston, TX, April 17-26, 1983.
5. Gonzalez J.M., and W. J. Rebello, Furnace Controls using High Temperature Preheated Combustion Air, 1981 Industrial Energy Conservation Technology Conference, Houston, TX., April 26-29, 1981.
6. Dorazio, R. E., et al, Technology Acceleration Program for the GTE Ceramic High Temperature Recuperator, Final Report, Contract No. DE-FC01-80CS 40330, January 1983.

7. U.S. Department of Commerce, Annual Census of Manufacturers, Fuels and Electric Energy Consumed, 1977 and 1982.
8. U.S. Department of Energy, End Use Energy Consumption Data Base.
9. U.S. Environmental Protection Agency, National Emissions Data System (NEDS) Data Base.
10. Oak Ridge Associated Universities, Industrial Energy Use Data Book, 1980.
11. Wilfert, G.L. et al, Characterization of Industrial Process Waste Heat and Input Heat Streams, Report #PNL-4912, May 1984.
12. Canete, D.W., and J.J. Crowell, Survey of Industrial Furnace Equipment, Final Report prepared for Battelle Pacific Northwest Laboratories under Contract # B-B4161-A-Z, December 1981.

Appendix I
List of Recuperator Users Contacted By Phone

COMPANY	LOCATION	PRODUCTS	FURNACE TYPE	TEMP F	HOURS RECUPERATOR	FREHEAT SIZE	START NUM	F DATE	STATUS	REMARKS	
Ajax X-Ray	Sayre, PA	Al/Bronze Casting Al/Bronze Casting	Potmelter Potmelter	2150 2200	2000 0.6	1	1100 1150	02/81 03/82	Operational Operational	The first recuperator was a single pass unit. Experience has been excellent.	
ALCAN	Oswego, NY	Al Sheets & Plates	Ladle Preheater	1800	8600	1.0	1	1000	05/82	Not in Use	The recuperators have had a problem with plugging with aluminum fines and dross from the ladle. Required cleaning caused delays. Not in use since 1985.
Alfred Heller Heat Treating Co.	Clifton, NJ	Machinery Parts	Muffle Heat Treat	2100	2000	1.5	2	11/82	Not in Use	The furnace is not in use because of the present business climate but is still in the plant.	
AmCast Ind Corp. (Dayton Malleable)	Cedartburg, WI								Unknown	Company changed ownership three years ago. Furnace does not exist at this point but may have been shipped to Wheel Tek, Freemont, In.	
American Spring Wire	Bedford Heights, OH	Spring Wire	Lead Potmelter	2300	8000	1.5	2	10/80	07/83	Oper-Rebuilt	The ladle has only 3 months to a year because of lead attack. Na & K from the new brick attack the recuperator. They have replaced 4 or 5 recuperators to date. Present units were put in about July 1986.
B&R Industries Inc.	Piscataway, NJ	Precision Aluminum Castings	Al Potmelter	2000	2000	0.6	1	7/90	03/82	Oper-Rebuilt	Recuperator has just been removed in 1987 because of excessive leakage and is to be replaced. Experience has been very good with 43% savings.
Bay City Forge	Erie, PA	Alloy Steel Forgings	Box Forge	2250	3425	1.5	8	12/00	10/82	Not in Use	Topping compounds corroded recuperator causing leakage and fuel rich operation. Poor pressure control at hi-fire caused burn out in furnace roof. Repair was delayed because of cost and budget considerations.
Berkley Forge	Berkley, CA	Alloy Steel Forging	Slot forge	2400		1.5	2	11/82	Not in Use	Recuperators failed after a month. They started leaking and the furnace ran fuel rich, resulting in flames in the unit with melting in spots. The customer was unhappy and the recuperators were removed.	

Appendix I (cont.)
List of Recuperator Users Contacted By Phone

COMPANY	LOCATION	PRODUCTS	FURNACE TYPE	TEMP F	HOURS RECUPERATOR OF PREHEAT F	SIZE NUM.	START DATE	STATUS	REMARKS
Brampton Foundry	Brampton, Ontario Canada	Aluminum Foundry	Potmetter	2300	2000	0.6 1	600	01/60	Not in Use
									Single pass unit was used till it failed and was never replaced. Present personnel do not know the history.
Brown Engineering	Seattle, WA		Furn Incin	1200	2000	1.5 1	200		Not in Use
									Fiber in the furnaces plugged both units and preheat dropped. They were removed and never replaced.
Bucyrus Erie Co.	Milwaukee, WI	Heavy Equip. Parts	Heat treat	1800	8000	0.6 12	1000	09/81	Unknown
									Several calls were not returned but after the DOE project was completed the recuperators were operating satisfactorily.
Buffalo Metal Casting	Buffalo, NY	Al Casting	Al Potmetter	2200	2000	1.0 1	1000	06/83	Not in Use
									The recuperator never worked right and was scrapped a long time ago.
Calien Mfg. Corp.	North Lake, IL	Aluminum Parts	Al reheat furnace	2200	6000	1.5 2	1000	06/83	Not in Use
									They use a white 'Smokeless Flux' for fluxing. A white powder would deposit in the recuperator. Air lanceing did not help. They were discarded soon after installation.
Carpenter Die	Burlington, Ont. Canada	Aluminum Casting	Pot Metters	2000	8000	0.6 8	1000	07/81	Operational
									Their experience has been good. There were two failures but these were due to accidents.
CERT TECH Inc.	Woodridge, NJ	Ceramic Powders	Periodic Kilns	2200	8000	0.6 2	1000	07/83	Operational
									The original units are still operating on the furnace but the customer does not feel they are now saving much when compared to a similar furnace.
Compton Forge	LA, CA	Steel Forgings	Box forge	2250	6000	1.5 4			Not in Use
									Customer declined to talk about the recuperator.
Corrco Forge & Manufacturing	Corrco, TX	Steel Forgings	Pusher Furnace	2200	6000	1.5 4	1100	07/84	Operational
									The original recuperators burned out in 1986 and were replaced.
Coulter Steel & Forge Co.	Emeryville, CA	Alloy Steel Forgings	Box Forge	2200	6000	0.6 2	1150	04/84	Operational
									Original recuperators still running. The customer is happy.
Crucible Steel	Syracuse, NY	Alloy Steel	Box Reheat	2200	3000	1.5 2	1050	01/82	Operational
									The original recuperators are still operating though they are presently leaking and may be ready to be replaced. Early control problems corrected.

Appendix I (cont.)
List of Recuperator Users Contacted By Phone

COMPANY	LOCATION	PRODUCTS	FURNACE TYPE	TEMP F	HOURS RECUPERATOR	PREHEAT F	START DATE	STATUS	REMARKS
					SIZE	NUM			
Eastern Alloys	Maybrook, NY	Zinc Al Castings	Kettle Furnace	2200	6000	1.5	2	09/82	Not in Use
									The recuperators plugged up with zinc oxide resulting in longer times for melting. Cleaning was unsuccessful. They are not presently being used and the customer is unhappy.
Empire Steel Casting	Reading, PA		Anneal	2000	2000	1.0	2	1000	07/84
									This furnace is only run on the night shift presently but operating satisfactorily.
Endicott Forging & Manufacturing	Endicott, NY	Steel Forging	Slot Forge	2350	2000	1.5	4	1300	09/83
									Two recuperators were removed by GTE for testing and replaced. The customer is happy.
Frankl & Sons Inc.	Chicago, IL	Steel Forgings	Box Forge	2300	6000	1.5	2	1200	06/81
									Initially there was a problem with plugging with molybdenum oxide. After 4 weeks the face of the cables melted. Their experience was bad and they gave up on the recuperators.
GTE	Towanda, PA	Oxide Ore Reduction	9 Rotary Calcines	1800	8000	1.5	6	1000	08/81
		Tungsten Powder	9 Tube Furnaces	1500	8000	0.6	23	1200	09/81
		Molybdenum Powder	4 Tube Furnaces	2100	8000	1.5	8	800	09/81
									Operational
Gudgeon Bros.	London, Ontario Canada	Aluminum Castings	Al Formelter	2200	2000	0.6	1	900	02/84
									Original units are still operating very satisfactorily.
Gulfo	Beaumont, TX	Rolled Ring Forgings*	Boxforge	2450	6000	1.5	8	1150	01/82
			Boxforge	2450	6000	1.5	8	1150	01/82
			Boxforge	2450	6000	1.5	6	1150	01/82
									Operational
Hammond & Irving	Auburn, NY	Parts for Machine Tools	Box Heat Treat	2200	3000	1.5	4	1100	04/82
			Box Heat Treat	2200	3000	1.5	2	1100	11/83
									Operational
Harmschaffer Co.	Milwaukee, WI	Forgings for Heavy Equipment	Pusher Furnace	2000	6000	1.5	4	1150	04/82
									Not in Use
									The recuperators were in operation till 11/86 when the forge shop was closed.

Appendix I (cont.)
List of Recuperator Users Contacted By Phone

COMPANY	LOCATION	PRODUCTS	FURNACE TYPE	TEMP F	HOURS RECUPERATOR	PREHEAT F	START DATE	STATUS	REMARKS
				SIZE	NUM	F			
Hayes Dena Co.	Nova Scotia Canada	Large Steel Forgings	Carbonbox	2300	8000	1.5	8	1200	10/82 Oper-Rebuilt They receive hot ingots with topping compounds which ultimately corrode the recuperators. They have replaced the cubes 3 times in 5 years. However, they seem satisfied saving about 50% on their fuel oil bill.
Hayes Dena Co.	St. Catherine Ont. Canada	Auto Parts	Slot Forge	2300	2000	1.5	2	1200	09/83 Operational Their experience has not been so good, the recuperators have been replaced twice.
Howmedica Inc.	Rutherford, NJ	Orthopedic Implants	Pusher-Mold Heater	2000	2000	1.5	2	800	09/82 Operational The recuperators have been replaced once and they are satisfied.
Howmet Turbine	Dover, NJ	Gas Turbines Blades & Vanes	Pusher Reheat	2200	6000	1.5	1	1240	10/82 Oper-Rebuilt The original recuperators were replaced twice.
Howmet Turbine	Whitehall, MI	Turbine Blades & Vanes	Pusher Die Reheat #1	2300	6000	1.5	1	1190	03/82 Operational They experienced the identical problems as their older plant in Dover, NJ. The original furnace recuperators were replaced once in 1985.
		Turbine Blades & Vanes	Furn. #2	2300	6000	1.0	2	1180	03/83 Operational The newer furnace units were also changed once.
Kennedy Forge	Madisonville, KY		Slot forge	2500	4000	0.6	2	1200	Not in Use The recuperators were scrapped two years ago. From the beginning, they had trouble keeping the furnaces at 2500F, possibly because of poor pressure control or poor flow distribution through the recuperators.
Kleen Air	Portland, OR	Furnaces Ovens Kilns	Ladle Heat	2200		1.5	1	1100	Not in Use The recuperators constantly plugged up with material from the ladle and the retrofit was abandoned.
Krone Diecasting	Chicago, IL		Reverb. Furnace	2200		1.0			Not in Use They scrapped the furnace 4 years together with the recuperators as they went to a different type of furnace.
Ladish Company	Cynthiana, KY	Valve Bodies	Box Heat Treat	1800	4000	0.6	8	850	03/82 Operational The original recuperators are still operating but the furnace is now used sparingly because of low demand in the oil drilling industry.

Appendix I (cont.)
List of Recuperator Users Contacted By Phone

COMPANY	LOCATION	PRODUCTS	FURNACE TYPE	TEMP F	HOURS RECUPERATOR PREHEAT	START DATE	STATUS	REMARKS
				F	NUM	F		
Lebanon Steel Foundry	Lebanon, PA	Alloy Steel Castings	Carbonom. Heat Treat	1800	4000	1.5	6	850 01/81 Operational Original recuperators are still operating on the furnace though operation has slowed to eight hrs/day. There have been no problems.
Linitt Diecast Corp.	Albany, IN	Aluminum Casting	Al Pot Holding	2000	2000	1.0	1	800 05/83 Oper-Rebuilt They have had no problems. The original unit lasted till 3/87 and the replacement core is about to be installed.
Maynard Steel Casting	Milwaukee, WI	Steel Forgings	Carbonom. Heat Treat	1650	6000	1.0	12	850 06/85 Operational The original recuperators are still in operation with no problems reported.
McInnes Steel	Corry, PA	Alloy Steel Forgings	Box Forge	2250	6600	1.5	4	1210 01/81 Not in Use The recuperators were replaced after 9 months and again after 18 months because they began leaking. There were problems with the MARC system. Other problems were related to the use of raw ingots (Na & K) occasionally.
McWilliams Forge	Rockaway, NJ	Forgings for Turbine Ind.	Box Forge	2100	2000	1.5	3	1160 04/82 Not in Use The DOE recuperators have been removed from the furnace because of a problem with the back two. When heating copper, charcoal is thrown into the furnace at the back end. The charcoal contains (K) which corroded the back two recuperators.
Mercury Marine	Fon Du Lac, WI	Outboard Engine	Al Reverb	2000	8000	1.5	2	1000 12/83 Not in Use This application is not a good one because the flutes used in the aluminum recuperator furnace attack the conductive material.
Milwaukee Forge	Milwaukee, WI	Carbon Steel Forging	Carboms. Annealing	1550	2000	1.0	10	800 06/81 Operational Original units are still operating.
Missouri Steel Castings	Poplar, MO					1.0	4	Unknown Nobody in the plant seemed to know about the recuperators. It is possible that they never were installed.

Appendix I (cont.)
List of Recuperator Users Contacted By Phone

COMPANY	LOCATION	PRODUCTS	FURNACE TYPE	TEMP F	TEMP °C	HOURS RECUPERATOR	PREFHEAT	START DATE	STATUS	REMARKS
Monroe Forge	Rochester, NY	Alloy Steel Forgings	Box Forge	2150	2000	1.5	2	1220	08/81	Oper-Rebuilt Since the original DOE furnaces other furnaces have been equipped with recuperators. All the recuperators have been rebuilt once. Prefheat temperatures gradually decrease to about 700F. This disappoints the customer.
			Box Forge	2150	2000	0.6	2	1050	Oper-Rebuilt	
			Box Forge	2150	2000	1.0	2	1000	06/82	Oper-Rebuilt
			Box Forge	2150	2000	1.0	2	1000	06/82	Oper-Rebuilt
National Forge	Erie, PA	Large Forging for Military	Carbonmon Heat Treat	2350	7200	1.5	8	1175	04/82	Not in Use Three or four sets of recuperators were used until they were destroyed in about 6 months. Hot toppling compounds used corroded the carbonite and caused leakage resulting in fuel rich conditions in the recuperator. This lead to a meltdown. This furnace is not presently used.
Norfolk & Western Ry. Co.	Remote, VA	Alloy Steel Parts	Carbonmon Heat Treat	1800	6200	1.0	7	1000	11/81	Operational This furnace is still operating without problems.
North Vernon Forge	North Vernon, IN	Alloy Steel Forgings	Slot forge	2500	2000	1.5	2	1200	10/83	Operational These recuperators were installed on two furnaces at Dana, Lansing, MI, but Dana closed down and sold these furnaces to North Vernon Forge. They have just only recently. These units have just been put into service.
Metalurgical	Portland, OR		Heat Treat	2200	2000	0.6	14	1100	Operational	There have been a few problems, but the customer seems satisfied.
			Box Forge	2200	2000	0.6	12	1100		
Pfizer Company	Canastota, CT	Calcium metal & lime products for the steel & lead industries	Vacuum Retort	2200	5760	0.6	5	1150	07/81	Operational
			Vacuum Retort	2200	5760	0.6	5	1150	07/81	Oper-Rebuilt
			Vacuum Retort	2200	5760	0.6	5	1150	07/81	
Pfizer Company	Eaton, PA	Red Iron Oxide	Indirect Fired	1900		1.5	32	1200	01/81	Oper-Rebuilt
			Calciner (8)							
Pfizer Company	Wallingford, CT	Steel Coils & Strips	Muffle Annealing	1800	8760	1.0	2	600	07/81	Operational
			Annealing	2100	8760	0.6	6	800	07/84	Operational
			Annealing	2100	8760	0.6	6	800		

Appendix I (cont.)
List of Recuperator Users Contacted By Phone

COMPANY	LOCATION	PRODUCTS	FURNACE TYPE	TEMP F	HOURS RECUPERATOR	PREHEAT F	START DATE	STATUS	REMARKS
Pratt & Whitney	Hartford, CT	Aircraft Engine Parts	Box Heat Treat	2100	8400	0.6	5	1150	12/82 Unknown No date in the plant seems to know what happened to the furnace.
Precision Cast Parts Corp.	Portland, OR	Steel & Titanium Aircraft Parts	Mold Preheating (ten)	1900	8000	1.5	20	900	1984 Operational They have 10 mold preheaters equipped with 20 recuperators. They are very satisfied and plan to order 8 more units for their heat treat furnaces. The units must be cleaned periodically due to fibers that come from the furnace.
Project Sound Salt Fleet Aluminum Company	Kent, WA Hamilton, Ont., Canada	Forge Furnace Aluminum Castings	Al Fox Melters	2400	2000	1.5	1	1200	05/84 Not in Use Both recuperators are still operating without problems.
Saxonyburg Ceramics	Saxonyburg, PA	Technical Ceramics - Electronics	Rob/Kim	1800	8000	1.5	2	1000	07/79 Not in Use The original recuperators were operated at 2000F and worked up to July 1985 giving about 40% savings. The furnace was modified to operate at 1800F. They use Firedepar as a fuel. They have not replaced any recuperators.
Schmit Forge	Portland, OR	Steel Forging	Slot Forge	2250	2000	1.5	2	1120	10/82 Operational Original recuperators are still being used though they do not maintain the original pressures at high fire. Customer is pleased.
Scott Forge	Spring Grove, IL	Steel & Copper Forgings	Box Forge	2350	8000	1.5	2	1100	03/83 Not in Use The original GTE units lasted 6 months. They have replaced 5 sets of GTE units (10 total). They have been through 6 sets of Hager SIC units and 4 Hot work metal units. All furnaces have Hot top on the inputs.
Sherwood Medical	Waterbury, CT	Hypodermic Needles	Heat Treat	1890	8000	1.5	2	1000	09/81 Operational They have had no problems though only one furnace is running at present because business is slow.
Special Metals	New Hartford, NY	Alloy Steel Parts for Aerospace Industry	Heat Treat Refheat Batch Annealing	1850 2000 1800	5760 1.5 1.5	6 4 2	1100 1200 1100	07/81 07/81 12/81	Not in Use Not in Use Operational In the heat treat and reheat furnaces (both DOE projects), the recuperators plugged up with MoO ₃ . They were removed after 2 years and not replaced. The annealing furnace is operating.

Appendix I (cont.)
List of Recuperator Users Contacted By Phone

COMPANY	LOCATION	PRODUCTS	FURNACE TYPE	TEMP F	TEMP HOURS	RECUPERATOR F	PREHEAT SIZE	NUM F	START DATE	STATUS	REMARKS
Special Metals	Dunkirk, NY	Alloy Steel Parts for Aerospace Industry	Forge	2350	5760	1.0	10	1100	11/6/2	Not in Use	They have had plugging problems with molybodic molybide and are not used.
Standard Steel Co.	Burnham, PA	Titanium Parts	Forge Reheat	2300	2000	1.5	6	1100	04/6/2	Not in Use	Since the recuperators were bought, their business bottomed out and they were not installed on the furnace.
Stanley Tools	Shelbyville, TN	Rail Peen Hammers	Slot forge	2200	6000	1.0	1	1000	04/2/2	Oper-Rebuilt	The original recuperator was replaced 3/8/77. They are pleased with the operation.
Stanley Works	New Britain, CT	Steel Strip for Packaging	Lead Pot Melter	2050	4000	0.6	8	950	06/8/1	Operational	The lead pot melter is used for tempering steel strip. Furnace firebrick is regularly replaced due to lead attack from the lead. They are satisfied with the recuperators. Long life is obtained if the furnace temp. is kept <2100F.
Timet Corp.	Toronto, Ohio	Titanium Parts	Box Forge	1850	7200	0.6	8	950	08/6/2	Operational	The furnace and recuperators are operating satisfactorily.
Tremi Tube Co.	Milwaukee, WI	Annealing Furnace	1800		1.0	3				Operational	The chief engineer believes that the furnace is still in operation but did not know the details. The maintenance engineers did not return calls. This furnace is operable.
TRW Form. Stanley Spring	Harrisburg, PA	Steel Springs	Slot forge	1900		0.6	4		04/5/2	Operational	
Viking Metallurgical Corp.	Verdi, NV	Titanium & Aluminum Parts for Aircraft	Box Forge	2250	5000	1.0	2	1200	10/6/1	Operational	One of the original recuperators installed 10/81 was replaced in 1981 itself. They don't know the reason. Since then all the recuperators on the four furnaces are operating satisfactorily.
Willard Industries	Charlotte, NC	Solder Alloys	Solder Pots (5 total)	1800	2000	0.6	3	600	06/6/2	Operational	There have been no problems reported.
X-TEK Inc.	Cincinnati, Ohio	Wheels & Drives for Mining Ind.	Rotor Pit	1800	6500	0.6	12	1000	09/8/2	Operational	The furnace structure failed 12/85 and taken out of service. It was never repaired because business was slow. They plan to repair the furnace.
			Rotor Pit			0.6	12	1000	09/8/2	Operational	No reported problems with the recuperators.
			Rotor Pit			0.6	12	1000	09/8/2	Operational	

Appendix II
List of Recuperator Users Not Contacted

COMPANY	LOCATION	PRODUCTS	FURNACE TYPE	TEMP	HOURS REC	SIZE # REC	PREHEAT	START DATE	STATUS	REMARKS
Attack	Dunkirk, NY	Aircraft/Auto Steel Parts	Box Reheat	2200	4500	1.5	6	1200	2/62	Not in Use. There were problems with this installation and the recuperators were destroyed once. Their disposition is unknown and Attack is not listed.
AMAX Specialty	Florham Park, NJ	Alloy Forgings	Box Forge	2300	6000	1.0	5	1200	10/62	Unknown. There were some plugging and other problems at this host site. AMAX was sold to another company, and the finance operating status is unknown.
Bethlehem Steel	Bethlehem, PA	Steel	Rotary Forge	2350	8000	1.5	8	1250	5/62	Unknown. The recuperators had problems and the customer was not happy. The part where the furnace was located has been shut down.
Cape Ann Forge	Gloucester, MA	Steel Forgings	Box Forge	2350	5000	1.5	4	1250	4/62	Unknown. The recuperators performed poorly because of sodium attack possibly due to location on the shore. No telephone exists for Gloucester, MA. Their initial experience was bad due to sodium attack. There is no telephone listing for the plant.
Cedarcrook Eng.	Cedarcrook, IL	Aluminum Castings	Aluminum Revert.	2200	2000	1.5	1	1100	8/65	Unknown. The recuperators were plugged with problems and were removed from the furnace 5/64.
Cooper Ind.	Memphis, NC	Steel Forgings	Slot Forge	2450	2000	1.5	2	1200	5/62	Not in Use. The recuperators were bad in this DOE project and the recuperators were removed 1/63.
Crescent Tool	Immaculata, NY	Hand Tools	Slot Forge	2400	5000	1.5	2	1250	4/62	Not in Use. There was no listing for Crescent Tool.
DANA	Lansing, MI	Auto Parts	Slot Forge	2400	5000	1.5	12	1250	12/81 to 6/83	Not in Use. Closed down operations. Prior to shut down their experience was good on six of the furnaces. Two furnaces were sold to North Vernon Forge of IN.
ICE	Montreal, Canada Chicago, IL & Canada	Steel	Annealing Furnace	1800	0.6	1			12/61	Unknown. No telephone listing for the company.
Inland Steel				1800	0.6	1				The recuperator was a poor design and the recuperator failed and was never replaced.
Jenney Cylinder	Cedarcrook, IL	Aluminum	Revert. Furnace	1400	2000	1.0	2	800	3/61	Unknown. The company could not be located.
Mesomold										The recuperators were destroyed after 5 months of operation because of the flues used in the furnace.
National Lead	NJ		Lead Melter	1800	2000	1.5	1	1000		Not in Use. Their experience was bad. The recuperators plugged, and were destroyed and never replaced.
O'Hara	Houston, TX	Steel Parts	Lead Melter	1800	2000	1.5	2	1000	6/83	Not in Use.
Pyromics	Cleveland, Ohio		Forge	2200	5000	1.0	1	1000	1/80	Not in Use. The recuperator was destroyed.
Rockwell	Pittsburgh, PA	Steel Parts	Slot Forge	2350	6000	0.6	2	1000	3/80	The experience was bad. The recuperator was destroyed after repeated attack from sodium/potassium.
										The experience with the early recuperators was bad.

Appendix II (cont.)
List of Reciprocator Users Not Contacted

COMPANY	LOCATION	PRODUCTS	FURNACE TYPE	TEMP	HOURS REC	REC SIZE	PREHEAT	REC	START DATE	STATUS	REMARKS
WFI	Houston, TX		2 Box Forge 2 Heat Treat	2200 1950	8000 1.5	0.6 3	3 3		9/82 3/83	Oper. Oper.	In connection with Combustion Services of Houston, these are said to be operating. Hot Work purchased of these reciprocators for use in various applications.
England					43						
Japan					55						Various users. No record of use.

END

DATE FILMED

11/21/90

