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Project Summary

Industrial Waste Heat Recovery and the Potential for Emissions Reduction

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This report examines the applicability of conservation equipment to various industrial sectors, determines the net costs involved, and assesses the potential for conservation as a means of air pollution control. Predictions of the amount of waste heat available from U.S. industrial sources were made and a waste heat inventory was established. The inventory is segmented by industrial group, industry, process, and flue gas temperature. The waste heat recovery equipment analysis determined the costs and applications of a variety of waste heat recovery equipment. The analysis examined five major equipment types and their limitations. Cost functions were developed which used furnace flue gas flow rate and temperature, and air preheat temperature as inputs. A discussion of the major factors to be considered for the development of heat recovery equipment also is included. A discussion on the availability and development of high temperature burners and the effects of high preheat temperature on ancillary equipment is included. High preheat temperatures result in higher flame temperatures and correspondingly higher NO_x emissions. This issue also has been addressed in this report. Volume 1 describes study methodology and findings. Volumes 2 through 10 tabulate stack gas waste heat inventories for all the industrial processes studied.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The 10-volume final report summarized herein examines the applicability of waste-heat conservation equipment and techniques to various industrial sectors. The documents detail potential waste heat recovery (WHR) from several recovery techniques and the effects of waste heat recovery on air pollutant emissions.

The study encompassed five component tasks which were to:

1) Establish a waste heat inventory.
2) Identify feasible waste heat recovery technologies.
3) Determine factors limiting waste heat recovery from furnaces, ovens, and kilns.
4) Determine compatibility of WHR and available burner design.
5) Determine the effect of WHR devices on sulfur dioxide (SO_2), particulate (TSP), and nitrogen oxide (NO_x) emissions.

Volume 1 of the final report presents all the analyses and conclusions for these five components. Computer printouts from a detailed waste heat inventory (described below) are presented in Volumes 2 through 10 of the final report.

Approach

To determine the amount of waste heat available from flue gases, a waste heat inventory was established. The inventory was based on the U.S. Environmental Protection Agency's (EPA) National Emissions Data System (NEDS) for 1974. NEDS, which incorporates data from both large and small industrial sources, was analyzed and irrelevant data points removed. From theoretical thermodynamic calculations, heat content of flue gases was determined. Flue gas heat loss was tabulated and ranked by flue gas temperature to permit identification of heat sources. The waste heat content of flue gases was estimated at 16°C (60°F) and 150°C (300°F). In the subsequent analyses, only waste heat in the 150°C range was considered to be feasibly recoverable.

On the basis of temperature data from the waste heat inventory, various types of WHR equipment were identified. They are described in detail in the final report and include: recuperators and regenerators for furnaces, economizers for boilers, and tubular convection sections and air preheaters for tube-still heaters. Economic and technical information for each type is presented in the final report, as are the models used to estimate the waste heat recovery efficiency of each.

The study determines the limitations of WHR and identifies factors which affect its use in furnaces, ovens, and kilns. Such units have a high potential for waste heat recovery; however, because they vary greatly in design from site-to-site, analysis was limited to identification of general design and operating factors (e.g., typical operating temperature ranges), and discussion of how those factors might affect a decision to install WHR equipment.

The study also presents data on the effect of combustion air preheat (CAP) on burners. A variety of flame shapes and burner sizes are described, and potential applications CAP are identified.

Finally, the study presents analyses of how WHR might affect emissions of SO_2, TSP, and NO_x. The emphasis here is on modeling the changes that might be caused by combustion air preheating in gas furnaces. Calculations were performed to determine reductions in gas consumption (and thus SO_2 and TSP emissions) as preheat temperatures are increased. A simple computerized reaction kinetics model was developed to determine how thermal NO_x concentrations might increase as preheat temperatures are increased.

Findings

Waste Heat Inventory

Based on the waste heat inventory developed from the NEDS file, approximately 14.9 EJ (14.1 quads) of energy is being released per year from all non-evaporative emissions sources. It was calculated that 1.6 EJ (1.5 quads) of this heat is available for recovery from stack gases, i.e., gas at temperatures higher than 150°C.

Stack gas waste heat available from each of over a thousand industrial processes is tabulated by 56°C (100°F) temperature increments and shown in histogram form in Volumes 2 through 10 of the report. Processes are identified by their NEDS Source Classification Code (SCC). SCCs beginning with 1 are boilers; 2 are internal combustion devices; and 3 are industrial processes, with 3-90 entries classified by process fuel. A listing of processes by SCC is provided in Appendix H of Volume 1 of the final reports. The computer printouts are presented in numerical order from SCC 1-01-001-01 to 3-99-999-99 and are divided into the nine volumes according to the schedule in Table 1.

Table 1. *Division of Stack Gas Waste Heat Inventory into Volumes 2 to 10 of Report*

Volume Number	*SCCs* Covered*
2	*1-01-001-01 to 1-02-007-03*
3	*1-02-007-04 to 2-03-999-98*
4	*2-04-001-01 to 3-01-025-05*
5	*3-01-025-10 to 3-02-013-01*
6	*3-02-014-01 to 3-04-002-03*
7	*3-04-002-04 to 3-05-010-03*
8	*3-05-010-99 to 3-06-010-01*
9	*3-06-011-01 to 3-90-005-33*
10	*3-90-005-99 to 3-90-008-99*

**EPA's National Emissions Data System Source Classification Codes*

Each SCC is divided into two groups: sources with and without pollution control equipment. If an SCC has entries in only one of the groups, i.e., with or without control equipment, then only that group is shown. The total SCC is presented in the same format.

The top left hand corner of each page of inventory output gives the SCC number and is followed immediately by a brief description of the SCC. The top line indicates whether the information concerns entries with pollution control equipment, without equipment, or the total SCC.

The entry SIC = 0 indicates that the SCC has not been further subdivided by Standard Industrial Classification (SIC). However, if a four-digit number is given, the output includes the SCC entries also in the four-digit SIC. TOT RECS indicates the total number of records that were processed for the waste heat calculation for that section of the SCC. If SIC does not equal zero, TOT RECS will refer to the number of records in the total SCC, rather than the SIC subdivision of the SCC.

The first calculation results are given by temperature range. The flue gas heat content, given in Btu's, is entered in the appropriate one hundred degree range according to the flue gas exit temperature. The totals for the six different waste heat levels are given at the bottom of each column. The second page of the printout shows results tabulated by two-digit SIC's. The totals again appear at the bottom of each column. Finally, a histogram of the expected 60°F waste heat calculation is shown. This histogram allows a more comprehensive analysis of the relative significance of the waste heat content of the various flue gases. Each "H" on the histograms represents 1×10^{11} Btu's and the exact heat value is given in the column directly to the left of the histograms. Any range with a heat value over ten trillion Btu's will extend off the histogram scale and will not be reflected accurately.

For example, SCC 3-04-001-03 identifies aluminum reverberatory furnaces. The stack gas waste heat inventory is tabulated in 100°F (55.6°C) increments in Table 2. Maximum, minimum, and expected waste heat available in each temperature increment are presented in Btu's with respect to 60°F (16°C) and 300°F (149°C). Totals over the whole stack gas temperature range are provided at the bottom of each column. In the top half of Figure 1, the information is broken down by two-digit SIC. In the bottom half of this figure, the expected available waste heat with respect to 60°F (16°C) is presented in histogram form.

In Volume 1, discussions are also provided of the waste heat obtainable from several SCCs that offer high energy recovery potential. These are metallurgical coke byproduct ovens (SCC 3-03-003-01), basic oxygen furnaces (3-03-009-03), finish/soaking pits (3-03-009-11), open hearth steel furnaces (3-03-009-01 and 3-03-009-02), aluminum reverberatory furnaces (3-04-001-03), gas-fired dry cement kilns (3-05-006-04), furnaces for soda lime glass manufacturing processes (3-05-014-01), and natural gas-fired brick kilns (3-90-006-06).

Since a given industrial process may be in use by several different manufacturers, the computer printouts also break out stack gas waste heat content for each SCC by two-digit Standard Industrial Code (SIC). Those SICs that are covered are shown in Table 1.

A national waste heat inventory, presenting cumulative waste heat content for each two-digit SIC is presented in Volume 1 of the final report. Figure 2 shows cumulative available waste heat by SIC.

The waste heat inventory indicates that the largest waste heat producer is utilities (SIC 49), but only 0.5 EJ of the 6.1 EJ they

Table 2. *Waste Heat Output (Btus) — Aluminum Open Smelter Reverberator Furnace*

Temp	*Maximum 60 Deg*	*Expected 60 Deg*	*Minimum 60 Deg*	*Maximum 300 Deg*	*Expected 300 Deg*	*Minimum 300 Deg*
0.- 100.	.910E 11	.854E 11	.696E 11	.0	.0	.0
101.- 200.	.628E 13	.502E 13	.138E 13	.0	.0	.0
201.- 300.	.181E 13	.138E 13	.536E 12	.0	.0	.0
301.- 400.	.187E 13	.144E 13	.786E 12	.478E 11	.453E 11	.386E 11
401.- 500.	.265E 12	.209E 12	.821E 11	.334E 11	.318E 11	.199E 11
501.- 600.	.745E 12	.603E 12	.389E 12	.169E 12	.161E 12	.147E 12
601.- 700.	.205E 13	.168E 13	.108E 13	.555E 12	.528E 12	.471E 12
701.- 800.	.478E 12	.395E 12	.269E 12	.152E 12	.144E 12	.132E 12
801.- 900.	.295E 12	.247E 12	.175E 12	.113E 12	.107E 12	.979E 11
901.-1000.	.102E 13	.857E 12	.527E 12	.409E 12	.389E 12	.305E 12
1001.-1100.	.0	.0	.0	.0	.0	.0
1101.-1200.	.263E 12	.225E 12	.165E 12	.123E 12	.117E 12	.106E 12
1201.-1300.	.333E 12	.285E 12	.212E 12	.162E 12	.154E 12	.140E 12
1301.-1400.	.176E 12	.152E 12	.0	.938E 11	.891E 11	.0
1401.-1500.	.104E 13	.901E 12	.322E 12	.583E 12	.554E 12	.233E 12
1501.-1600.	.0	.0	.0	.0	.0	.0
1601.-1700.	.668E 13	.585E 13	.320E 11	.399E 13	.379E 13	.231E 11
1701.-1800.	.119E 13	.105E 13	.677E 12	.733E 12	696E 12	.486E 12
1801.-1900.	.0	.0	.0	.0	.0	.0
1901.-2000.	.364E 12	.323E 12	.258E 12	.237E 12	.225E 12	.184E 12
2001.-2100.	.0	.0	.0	.0	.0	.0
2101.-2200.	.0	.0	.0	.0	.0	.0
2201.-2300.	.0	.0	.0	.0	.0	.0
2301.-2400.	.0	.0	.0	.0	.0	.0
2401.-2500.	.0	.0	.0	.0	.0	.0
2501.-2600.	.0	.0	.0	.0	.0	.0
2601.-2700.	.0	.0	.0	.0	.0	.0
2701.-2800.	.0	.0	.0	.0	.0	.0
2801.-2900.	.0	.0	.0	.0	.0	.0
2901.-3000.	.0	.0	.0	.0	.0	.0
33	.223E 14	.185E 14	.652E 13	.688E 13	.654E 13	.236E 13
34	.924E 12	.811E 12	.377E 12	.610E 11	.579E 11	.0
35	.665E 10	.579E 10	.445E 10	.374E 10	.356E 10	.323E 10
36	.105E 12	.918E 11	.196E 10	.610E 11	.579E 11	.0
37	.906E 11	.761E 11	.513E 11	.268E 11	.255E 11	.233E 11
50	.470E 11	.370E 11	.0	.529E 10	.503E 10	.0
99	.147E 13	.118E 13	.0	.366E 12	.348E 12	.0
Total Btus:	.250E 14	.207E 14	.696E 13	.740E 13	.703E 13	.238E 13

discharge is available for waste heat recovery, while 1.1 EJ is available from manufacturers.

The best WHR potential is in: (1) refining (SIC 29), (2) stone, clay, and glass manufacturing (SIC 32), (3) primary metals (SIC 33), and (4) fabricated metals (SIC 34).

Recovery Techniques

Recuperators and regenerators are the two best combustion air preheat technologies for furnaces. They generally employ proven techniques for saving energy, and the necessary equipment is available from numerous manufacturers. The most efficient recovery method for boilers is economizers, a technology that is also widely available. For petroleum refining furnaces, convection sections that heat hydrocarbon liquids and air preheat technologies are most cost-effective and meet the technical constraints (e.g., space limitations) of this industry. These latter two WHR technologies are also the best ones to use for tube-still heaters.

Unfavorable economics limit market penetration of many types of heat recovery equipment, with equipment marketability being strong only when there is a desire for fuel savings or lower production cost. In the past, cost of maintaining production capacity has been a detriment to WHR installation, since the equipment provides an additional set of operation and maintenance problems. However, rising fuel costs and increased energy shortages are now making WHR more economically attractive.

Waste Heat Recovery on Furnaces

Doubling the combustion air temperature in furnaces by using WHR will roughly double fuel savings; however, equipment costs are likely to more than double.

If the flue gas temperature for a furnace is under 540°C (1000°F), recuperation is of interest only in continuous 24 hour-a-day furnace operations. For intermittent batch operations, a 650 to 760°C (1200-1400°F) flue gas temperature is usually a practical minimum. However, in many cases waste heat recovery in furnaces is an economically marginal investment if flue gas temperatures are lower than 820°C (1500°F).

Compatibility of Burners and Waste Heat Recovery

Ordinary burners require modifications if they are to use air that is preheated above 400°C (750°F). The greater the preheat, the more modification is needed in both design and construction materials. However, modifications in a combustion system cost only a fraction of the total cost of the WHR system.

It is generally more difficult, as well as more expensive, to operate high-temperature equipment than it is to operate ambient air systems. The addition of a temperature control requirement to the combustion system monitoring places another complex dimension into control of the fuel/air ratio. This continues to be an impediment to the use

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CC 30400103--ALUMINUM OPE SMELTING-REVERBERATO--TOTAL SCC  -SIC =    0 -TOT RECS =    319

EMP RANGE   COUNT

                              ------------------------------------------------------------------------------
   0.- 100.   .854E 11   !H
 101.- 200.   .502E 13   !HHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
 201.- 300.   .138E 13   !HHHHHHHHHHHHH
 301.- 400.   .144E 13   !HHHHHHHHHHHHHH
 401.- 500.   .209E 12   !HH
 501.- 600.   .603E 12   !HHHHHH
 601.- 700.   .168E 13   !HHHHHHHHHHHHHHHH
 701.- 800.   .395E 12   !HHH
 801.- 900.   .247E 12   !HH
 901.-1000.   .857E 12   !HHHHHHHH
1001.-1100.   .0         !
1101.-1200.   .225E 12   !HH
1201.-1300.   .285E 12   !HH
1301.-1400.   .152E 12   !H
1401.-1500.   .901E 12   !HHHHHHHHH
1501.-1600.   .0         !
1601.-1700.   .585E 13   !HHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
1701.-1800.   .105E 13   !HHHHHHHHHH
1801.-1900.   .0         !
1901.-2000.   .323E 12   !HHH
2001.-2100.   .0         !
2101.-2200.   .0         !
2201.-2300.   .0         !
2301.-2400.   .0         !
2401.-2500.   .0         !
2501.-2600.   .0         !
2601.-2700.   .0         !
2701.-2800.   .0         !
2801.-2900.   .0         !
2901.-3000.   .0         !
                         0--------10--------20--------30--------40--------50--------60--------70------
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Available Energy (10^{13} Btu)

Figure 1. *Waste heat output - aluminum open smelting reverberator furnace.*

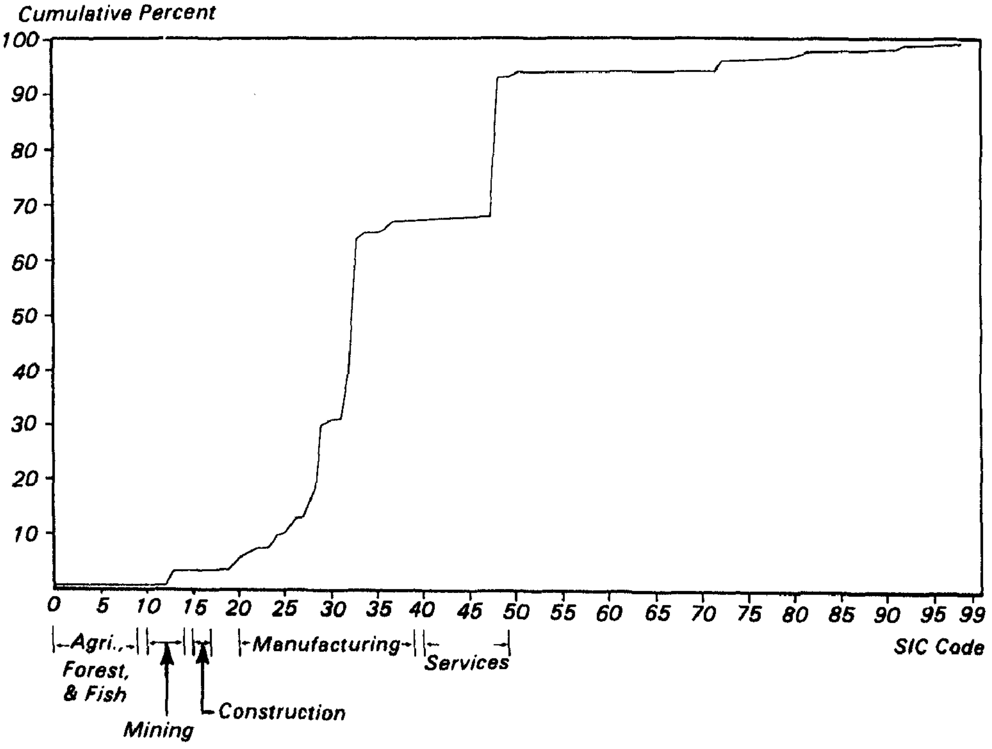

Figure 2. *National cumulative available waste heat by Standard Industrial Code (SIC).*

of WHR for energy conservation.

Emission Impacts

Sulfur dioxide and particulate emissions will be reduced as a result of reduced fuel consumption associated with waste heat recovery. In the case of combustion air preheat in gas furnaces, reductions of up to 20 percent in emissions of these pollutants are projected when preheated air temperatures are on the order of 540°C (1000°F).

There is little effect of combustion air preheat on fuel NO_x formation; other studies have found that a decrease in fuel NO_x occurs with increase in combustion air temperature and reduced fuel consumption. This decrease is usually small in absolute magnitude compared to changes in thermal NO_x with combustion air temperature.

There is only a gradual increase in thermal NO_x with increasing flame temperature up to 1790°C (3250°F). Above this flame temperature, thermal NO_x formation increases rapidly and approximately linearly with temperature up to about 1950°C (3550°F), where it reaches a maximum. However, most furnaces and boilers do not operate at air preheat temperatures that result in such high flame temperatures. Combustion air temperatures must be well above 450°C for flame temperatures of 1790°C to be reached. Therefore, it is not expected that the increases arising from combustion air preheat will generally cause occurrences of NO_x emission increases of over 100 ppm.

The Project Report was prepared by Energy and Environmental Analysis, Inc., Arlington, VA 22209; the Project Summary was prepared by ***Benjamin L. Blaney*** *(also the EPA Project Officer, see below) of the Industrial Environmental Research Laboratory, Cincinnati, OH 45268.*

The complete report consists of 10 volumes, entitled "Industrial Waste Heat Recovery and the Potential for Emission Reduction," (Order No. PB 84 152 339; Cost: $315.00 for the 10 volume set)

"Volume 1. Main Report," (Order No. PB 84-152 347; Cost: $22.00)
"Volume 2. Standard Classification Codes 1-01-001-01 to 1-02-007-03," (Order No. PB 84-152 354; Cost: $37.00)
"Volume 3. Standard Classification Codes 1-02-007-04 to 2-03-999-98," (Order No. PB 84-152 362; Cost: $38.50)
"Volume 4. Standard Classification Codes 2-04-001-01 to 3-01-025-05," (Order No. PB 84-152 370; Cost: $38.50)
"Volume 5. Standard Classification Codes 3-01-025-10 to 3-02-013-01," (Order No. PB 84-152 388; Cost: $38.50)
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"Volume 10. Standard Classification Codes 3-90-005-99 to 3-90-008-99," (Order No. PB 84-152 438; Cost: $37.00)

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