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RECUPERATIVE SYSTEM FOR HIGH AND ULTRA-HIGH TEMPERATURE FLUE GASES

Final Report

By
John G. Reitz
Kenneth J. Coeling
Arvind C. Thekdi

January 31, 1979

Work Performed Under Contract No. EC-77-C-07-1672

Technical Center—Thermal Systems
Midland-Ross Corporation
Toledo, Ohio

U. S. DEPARTMENT OF ENERGY

Division of Industrial Energy Conservation

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ABSTRACT

Advanced recuperative system technology for high and ultra-high temperature flue gases was investigated. Several high temperature recuperator system and component concepts were evolved and studied for the purpose of finding the schemes and designs that attain maximum fuel savings. The most promising concepts for industrial application were pre-engineered further to devise designs for adaptation to existing steel mills.

The principal effort was aimed at steel soaking pit applications. The concept which provides the highest air preheat temperatures and the largest fuel savings for soaking pit application utilizing basic state-of-the-art technology is a low air pressure ceramic recuperator operated in conjunction with a higher air pressure metallic recuperator. This concept has the additional advantage that higher air pressures can be attained at the burner than can be attained with an all ceramic recuperator. These higher air pressures are required for high momentum, high efficiency burner performance, resulting in improved productivity and additional fuel savings. The technical feasibility of applying this high temperature recuperation system to existing soaking pits was established.

I. EXECUTIVE SUMMARY

There are many industrial thermal processes in which very high temperature flue gases containing large amounts of heat are sent directly out of the stack. Rather than wasting all this heat energy, it can be harnessed to preheat the combustion air to a very high temperature. High temperature heat exchangers (recuperators) can be used to transfer the flue gas energy to preheat the combustion air. The fuel savings that can be realized are very large – up to 50%. Approximately .16 quads (10^{15} Btu) of energy are presently being used annually in steel soaking pits alone. Savings of .06 quads of energy could be attained if all existing pits were retrofitted with high temperature recuperation.

The U.S. Department of Energy (DOE) has been very much interested in finding and implementing improved methods of recuperation for the steel industry. Midland-Ross was selected as one of DOE's recuperator technology contractors with the specific assignment of developing a ceramic/metallic recuperation system for high temperature applications (particularly steel mill soaking pits). A ceramic/metallic recuperation system includes both a ceramic recuperator and a metallic recuperator. These two high temperature recuperators are used together in a favorable system arrangement to preheat the combustion air with the waste heat from the high temperature flue gases. The ceramic recuperator provides low pressure, ultra-high temperature preheated air to the burner, and the metallic recuperator provides preheated air at the high pressures needed for the high performance burner.

It is desirable to achieve temperatures 50 to 100% higher than present air preheat temperatures. Also, the amount of space available to fit these high temperature recuperators was found to be very restrictive. Thus, considerable technology development was needed to satisfy these difficult equipment requirements. Midland-Ross has effectively utilized its background technology in energy conservation in the development of concepts to achieve these operational goals.

Major conclusions from this high temperature recuperation system development program include the following:

1. Large fuel savings in industry through high temperature recuperation are viable.
2. The technical feasibility of applying high temperature dual recuperation systems to existing steel soaking pits was established.

3. Economic analysis indicates that retrofitting high temperature recuperators on steel soaking pits which have no existing air preheat is substantially more favorable than retrofitting soaking pits that have some air preheat.

4. In general, there is no existing commercial ceramic recuperator design which can be retrofitted in the available space near existing steel soaking pits, due to the large volume required by these designs to accomplish high heat recovery.

5. A compact and efficient ceramic recuperator module, which has the potential for building into multi-module units for high heat recovery, yet is compatible with minimum space availabilities, has been identified.

II. PROJECT SUMMARY

The purpose of this project was to develop and advance the technology for the ceramic (tile)/metallic recuperator concept. The principal application is for the recovery of up to 70% of the heat energy from ultra-high temperature steel soaking pit flue gases.

Requirements

In order to attain the very large fuel savings possible with this high temperature recuperator system there are some very difficult equipment requirements to satisfy. These requirements are:

a. High (up to 70%) energy recovery effectiveness.

b. Efficient combustion burner suitable for high temperature (up to 1500°F) preheated air.

c. Sufficiently compact recuperators to be suitable for retrofit application (to fit existing steel mill soaking pit installations).

d. Operation with a number of different fuels: natural gas, residual fuel oil, coke oven gas.

e. Economy of operation - low capital costs and maintenance costs.

Tasks

This ceramic (tile)/metallic recuperator development project (sponsored by DOE) was comprised of five major tasks. These tasks are summarized as follows:

1. Industry Survey and Requirements

An industrial survey was the starting point and basis for the technical work carried out on this project. The initial survey work in this program considered all industries and is described in Section V, Industry Survey. Thirteen industries were identified as viable candidates to benefit substantially from high temperature recuperation. Four industrial processes were identified as major areas for very large energy savings. They are: steel ingot heat, steel reheat furnaces, steel forging and glass melting.

At DOE's request, most of the survey work was focused on steel soaking pit applications. Results of this effort are described in Section IX, Demonstration Site Acquisition. The survey indicated that high temperature recuperation can conserve .06 quads of energy annually in steel soaking pits alone.

The two major problems identified for steel soaking pit applications were:

1. Very limited space for the recuperator system in existing soaking pit facilities.
2. The payback period was too long for some steel companies.

Preliminary economic analysis revealed that the steel soaking pits having no existing recuperation would generally have the shortest (and most favorable) payback period in retrofitting a high temperature recuperator system.

Of the 43 steel soaking pit installations surveyed, 10 were found to have no recuperation. It was further determined that the older style tile recuperator would not fit into the soaking pit area of any of these ten installations. This clearly focused the area of emphasis for the concept development work, a major reduction in the size of the tile recuperator.

This survey information also indicated the need for a second area of investigation in the concept development work. This was to find recuperator arrangements or schemes that could replace and fit into the confines of existing tile or ceramic recuperators without major field demolition and rebuilding capital costs.

2. Development of Concept

The industry survey thus defined the major objective for concept development work as follows: Find the materials and designs that will be compatible with the existing space and confines of soaking pit areas.

In conjunction with this major requirement it was necessary to optimize the entire recuperative system for minimum size and cost. The starting point for the concept was the determination of the proportions of combustion air to be preheated in the tile and the metallic recuperators. It was determined that an air split of 60/40 between the tile and the metallic recuperators best satisfied all the system requirements. (This included materials limitations at high temperatures as well as other factors explained in Section VI.)

Having selected an air split ratio it was possible to compare various tile (or ceramic) recuperator materials and conceptual designs on an equivalent basis. Direct size reduction of the existing surface (tile) recuperator was first investigated. Then a variety of other ceramic recuperator design concepts were investigated. The most promising concept found was based on a GTE Sylvania ceramic recuperator. Major changes to the recuperator were required to adapt this concept to the environment of a steel soaking pit. A modified recuperator design was conceived (Figure 6) which provides large enough flue gas passages to prevent plugging from carryover contamination in the soaking pit flue gases, yet it is considerably more compact than the tile recuperator.

Comparing the overall heat transfer coefficients on a volume basis, the coefficient for the compact ceramic recuperator concept design is calculated to be 20 Btu/Hr-°F-cubic foot, whereas the tile recuperator coefficient is 4 Btu/Hr-°F-cubic foot. This permits a significant size reduction.

3. Recuperator and Component Design

The operation of the ceramic/metallic recuperator concept is described in summary as follows:

Figure 2 shows an arrangement for a typical soaking pit with the addition of the proposed ceramic/metallic recuperation system. The ceramic recuperator receives high temperature flue gases in excess of 2000° F from a soaking pit and preheats secondary combustion air entering at ambient temperature. Flue gases are then passed on at about 1200° F to a metallic, high surface area exchanger. Primary combustion air is heated in this second recuperator. The primary and secondary combustion air streams are then mixed in a high momentum burner, with the primary air stream used to entrain the very high temperature secondary air. This technique results in operation of the ceramic recuperator in a near balanced pressure (the air pressure is within very few inches W.C. of the flue gas pressure), low leakage configuration, and results in a workable high efficiency energy conservation system.

Finally, each recuperator system has its own control system in order to gain maximum efficiency for each individual soaking pit. This will permit faster heatup and improved productivity, as well as the fuel savings to be realized with the incorporation of this system.

The system preliminary design approach used provides a method for designing for a variety of applications. However, to execute a meaningful design it was necessary to select a specific steel soaking pit installation, and to design the high temperature recuperative system for it. At the steel soaking pit installation selected there is no existing combustion air preheating.

The first design step was to establish the system design parameters. These are set forth in Figure 9 for both high fire and low fire conditions. The system was designed for a 20 MM Btu/Hr firing rate at high fire and a 60/40 air split between the ceramic recuperator and metallic recuperator. The current high fire condition in each pit is 30 MM Btu/Hr. A lower firing rate can be used because of increased efficiency.

A conceptual design layout was made for installing a ceramic/metallic recuperator system in each of two soaking pits. Pre-engineering of the following principal components and subsystems was carried out:

Ceramic Recuperator
Metallic Recuperator
High Temperature Integral Jet Pump/Burner
Control System
Flue Gas Exhauster
Combustion Air Blowers
Ducting and Flue Lines

Technical feasibility of adapting a high temperature ceramic/metallic recuperator system into the available space of an existing soaking pit was established.

The component which received the greatest engineering effort was the ceramic recuperator. A computer program was developed and written to relate heat transfer parameters, pressure drop parameters, dimensions, and a variety of recuperator configurations and arrangements. The selected design for this application was a four air-pass ceramic recuperator with 2" x 10" flue gas passages and 3/8" x 1" air passages. Its core dimensions are 10' long x 7' wide x 6 1/2' high.

The major engineering problem identified was that of sealing and fastening the multi-module, multi-air pass ceramic recuperator.

4. Ceramic Recuperator Design, Fabrication and Laboratory Test

Since the mechanical design of this ceramic recuperator was so critical to the entire project, a plan was devised and initiated to design, build and test a multi-module, multi-airpass test unit. This unit was designed to test the critical sealing and fastening features required of a full size ceramic recuperator.

Although the test unit is smaller than the full size recuperator, it has the full size flue gas and air passages. Laboratory preparation for the test was initiated and the individual ceramic modules were fabricated.

5. Demonstration Site Acquisition

In order to demonstrate this high temperature recuperator concept utilizing this very advanced technology, the United States Department of Energy offered to consider sharing the costs of designing, building and testing such a high temperature recuperator system. Consequently, Midland-Ross sought a steel company host site from among the many who could benefit from retrofitting this high temperature recuperator system into their existing steel soaking pit installation. This host would be required to share the costs of such a test demonstration. Midland-Ross carried out pre-engineering investigations and economic studies at several steel soaking pit installations. These studies have been in support of securing an agreement that would satisfy the requirements of all parties involved, for the purpose of acquiring a high temperature recuperator site for test demonstration.

A specific proposal to a steel company for a demonstration program is presented in Appendix B. They found the high temperature recuperator system proposed to be very attractive. They, therefore, requested that the steps toward an actual test demonstration be pursued. However, further technical discussions and negotiations were terminated until funding for the test demonstration work becomes available.

III. INTRODUCTION

Recent literature is replete with studies indicating the large amounts of energy that could potentially be saved in industry with recovery and use of waste process heat through high (air preheat temperatures up to 1600° F) and ultra-high (air preheat temperatures up to 2400° F) temperature recuperation. However, producing hardware to accomplish these large energy savings at affordable costs is quite another thing. Such hardware does not exist at the present time. Existing recuperator systems for high temperature flue gases have various defined limitations with respect to design operating temperature, material durability or overall system costs. (These limitations are presented at the end of this section.) On the other hand, recuperative systems which will provide these large energy savings may he a long way off in time and money. It is desirable to develop technology for this high and ultra-high temperature recuperation to attain the large energy savings, with the lowest cost in time and money. In addition, the equipment and construction costs must be affordable.

There is a high temperature recuperator system concept that can provide large energy savings with only a modest extension of current technology. This is the ceramic (tile)/recuperator concept. It is based on the same principle as the tile/metallic recuperator system sold commercially by the SURFACE DIVISION of Midland-Ross. This system has provided preheat temperatures in the range of 1000° F. Mechanical redesign of this system, including the combustion system, with some limited development could provide a more effective heat recovery system.

Research into high and ultra-high temperature recuperation was initiated by Midland-Ross in the mid 1970's by the development of an integral recuperator burner system for steel soaking pits. The system employed a unique low pressure cast tile ceramic recuperator coupled in tandem to a high pressure metallic recuperator. Based on the system advantages, the United States Department of Energy (DOE) in 1977 (then ERDA) indicated interest in sponsoring further development of the system for higher temperatures and subsequent industrial demonstration.

Phase I of this two-phase DOE funded program was an R&D project at the Midland-Ross Technical Center to develop and advance the ceramic (tile)/metallic recuperator system. Phase II of this program was to become the actual demonstration of the system. As discussed later, Phase II of the program has not been approved.

At the inception of the project, it was expected that some version of this SURFACE DIVISION "tile" recuperator would be used. However, as explained in Section VI (Concept Development), due to space limitations in existing steel soaking pits it was necessary to identify and advance a "ceramic" recuperator concept that would be far more compact.

Thus, in this report three kinds of ceramic (tile) recuperators are referred to:

1. Tile - This is the standard SURFACE DIVISION tile recuperator that SURFACE has been building for many years with clay tile.

2. Ceramic - To distinguish the SURFACE tile recuperator from the new recuperator work underway using a very promising thermally shock resistant ceramic material, the term "ceramic" is referred to in this report.

3. Ceramic - Other older recuperators, such as the Amsler-Morton ceramic recuperator, are referred to by name in this report.

   It is true, however, for all three of these recuperators that they are all ceramic, and they are all constructed from ceramic tiles. Thus, when referring to them in a system sense, either term - ceramic or tile - can be used to distinguish these non-metallic recuperators from the metallic recuperator.

Limitations of the various existing metallic or ceramic recuperator systems made it necessary to develop and advance the new ceramic/metallic concept. These limitations, summarized as follows, were considered in developing the new concept.

<u>Metallic Recuperators</u>

- Limit in air preheat temperatures attainable
- Require protection from over temperature flue gases
- Material corrosion
- Limited life

<u>Ceramic Recuperators</u>

- Excessive cracking of the ceramic
- Excessive gas leakage between air and flue passages
- High variability in fuel savings due to the above design/material problems

The scope of work carried out to advance the continued ceramic/metallic recuperator concept is presented in the following section.

IV. SCOPE OF WORK - PHASE I - HIGH AND ULTRA-HIGH TEMPERATURE RECUPERATION (HTR)

The scope of the work for Phase I of HTR is summarized by five distinct tasks as follows:

1. Industry survey and determination of recuperator requirements for high and ultra-high temperature processes.

2. Development of the tile/metallic concept for high temperature recuperation through analytical and experimental investigation of tile and metallic recuperator components.

3. Design investigation of high effectiveness tile/metallic recuperator and components for high and ultra-high temperature flue gases for general industrial application.

4. Design, fabricate and test in the laboratory a ceramic (tile) recuperator.

5. Obtain the agreement of a steel mill to provide the steel soaking pit facilities and to participate in a high temperature recuperator test demonstration (Phase II). This task was made a formal part of the project in May of 1978, subsequent to signing of the initial contract.

V. INDUSTRY SURVEY

A preliminary industrial survey was undertaken to identify possible applications for high temperature recuperation (HTR). This included the following survey steps:

1. Identify industrial processes that operate at ultra-high temperatures and have large total energy usage.

2. Obtain current energy usage practices and process information that relate to the application of high temperature recuperation.

3. Identify requirements for the use of high efficiency recuperators; i.e., materials, unit size, configuration and maintenance, in selected industrial process operations.

INDUSTRIAL PROCESS CANDIDATES FOR HIGH TEMPERATURE RECUPERATION

A preliminary list of industrial processes with very high flue gas temperatures and with large energy consumption was formulated, primarily from published literature. This list is presented in Table 1. The table was used to start screening the best candidate industrial processes for high temperature recuperation application.

The table shows that steel ingot heating, steel reheat furnaces, steel forging and glass melting consume the largest amounts of energy (approximately .16 quads, .28 quads, .05 quads, and .20 quads, respectively); in addition, the flue gas temperatures are quite high. Therefore, these industrial processes are identified as major areas for very large energy savings.

TABLE 1

PROCESS CHARACTERISTICS PERTINENT TO HTR

Process	Flue Gas Temp. (°F)	Annual Energy Consumption (10^9 Btu)
Aluminum Casting	2000–2800	21.2
Brass Melting	2000–2200	
Refractory Clay	2300–2500	21.9
Copper Melting	2100–2500	22.5
Copper Refining	2300–2600	10.1
Steel Normalizing	1700–1800	
Steel Forging	2000–2100	50,000
Steel Ingot Heating	2100–2400	160,000
Reheating Steel	2000–2200	281,000
Sintering (Metal Powder)	2000–2100	
Structural Clay	2800–3000	150,000
Continuous Casting	2000–2200	4,200
Glass Melting	2600–3000	Over 200,000

To further screen these various processes for high temperature recuperation application, more survey information was required. The type of information which was needed is listed as follows:

1. Type of furnace used
2. Operating temperature
3. Flue temperature
4. Energy required per ton
5. Total annual energy consumed
6. Potential energy savings
7. Current energy practices
8. Limitation in use of HTR
9. Constraints
10. Cycle effectiveness

Based on this accrued survey information, the results and conclusions for the processes that appeared to be the most promising for HTR application are discussed as follows:

STEEL FORGING

The East Ohio Gas Company sponsored a project to explore and investigate the opportunities and problems in applying high temperature recuperation to steel forging. This was done by setting up demonstration testing of high temperature recuperation on a forging furnace in an Ohio steel plant. The two problems that appeared to confront companies considering high temperature recuperation for forging furnaces at that time were:

1. The batch operations were frequently too small to justify HTR.
2. Space interferences around the forging furnace cause HTR retrofit to be very difficult.

Industry so far has generally been reluctant to incorporate high temperature recuperation in forging operations. Nevertheless, with adequate application engineering, it is believed that viable opportunities can be found for high temperature recuperation in steel forging operations.

REHEAT FURNACES

Considerable interest was found for steel reheat furnace recuperation. Several steel mills invited Surface Engineering and Midland-Ross to discuss the feasibility of recuperation for their large reheat furnaces. They could readily see the large energy losses they were having from lack of recuperation. The energy consumption on an individual furnace basis for these furnaces is large - 1/2 billion to one billion Btu per hour per furnace. This offers great potential for very large energy savings through high temperature recuperation. It is worthy of further application investigation in the near future.

GLASS MELTING

Regeneration is used for air preheating in the glass industry where large quantities of glass are melted. It saves much heat energy. Large glass melting operations do not generally appear to present good opportunities for high temperature recuperation because of the unfavorable economics compared to existing regeneration.

On the other hand, smaller glass melting operations sometimes referred to as "unit day batches", indicate good potential for high temperature recuperation. Typical day batches for glass melting require approximately 10 million Btu/ton at 10 to 60 tons per day. Therefore, with hundreds of small glass operations, there appears to be good opportunity for large energy savings through high temperature recuperation.

STEEL SOAKING PITS

Figure 1 summarizes the large energy savings and dollar savings potential found for HTR application in steel soaking pits. Potentially, there are approximately .06 quads of energy and 225 million dollars to be saved annually.

EARLY INDUSTRY SURVEY CONCLUSIONS

The two most frequent limitations in retrofitting a high temperature recuperator in an existing steel mill for any of these steel processes were found to be:

1. There was insufficient space available in which to fit the HTR equipment.

2. The payback period was too long (greater than 1½ to 3 years).

These two problems thus defined the work emphasis for this entire high temperature recuperator project.

Because time was a limiting factor on the project, it became apparent that one manufacturing process should be selected for further survey work. This preliminary survey work confirmed the potential for recuperation in steel soaking pits. In addition, DOE requested that survey work and other project efforts be concentrated on steel soaking pit recuperation. Therefore, steel soaking pit application feasibility investigative work comprised the principal portion of this survey and this project. The steel soaking pit survey work is presented in the first portion of Section IX (Demonstration Site Acquisition).

VI. DEVELOPMENT OF CONCEPT

1.0 System Concept Design

The high temperature recuperator concept developed for steel ingot soaking pit application is shown schematically in Figure 2. The flue gases from the soaking pit first pass through the ceramic (tile) recuperator and then through the metallic recuperator. The combustion air is passed in parallel through the two recuperators. Part of the combustion air is preheated in the metallic recuperator and part is preheated in the ceramic (tile) recuperator. The proportion of air (referred to here as air split) that is preheated in each recuperator and then mixed for combustion in the burner, has a major effect on the various temperatures.

1.1 Criteria and Approach

The principal criteria in developing a system concept that must be met for a high temperature tile/metallic recuperative system are summarized as follows:

1. Minimum size and space requirement
2. Maximum fuel savings
3. Minimum overall cost, and
4. Dependability and reliability of components and system.

Each of these criteria is essential for the following reasons:

1. Minimum system equipment size is necessary in order that it can be retrofitted into existing steel soaking pit installations.
2. Maximum fuel savings are the ultimate purpose of this program.
3. Steel companies can justify high temperature recuperation equipment only if the capital investment is low enough to permit an acceptable return on this investment.
4. Equipment must be reliable, and consistently do what it is supposed to do over a long period of time without incurring direct or indirect problems.

Specific values for these criteria can be developed for any specific application.

Many variables, which have a major effect in meeting the system concept criteria, are contained in the energy balance equations. The concept development approach used required taking an energy balance on the flue gas and the air for each of the two recuperators for various assumed recuperator air splits and recuperator characteristics. (Sample calculations are presented in Reference 1.)

The resulting temperatures affect other variables, such as pressure drops, recuperator size, materials and design. These, in turn, determine the ability to satisfy the criteria. Therefore, examination of these temperatures and their relationship to each other was carried out as described below.

1.2 Summary of Development Steps

The air mix temperature was systematically evaluated to determine the effect of various air splits. In summary, the concept was developed using the following steps:

1. The appropriate equations were derived to relate the following ceramic and metallic recuperator temperatures as a function of the air split between the two recuperators and various assumed recuperator thermal characteristics:

    - Flue gas in
    - Flue gas out
    - Air in
    - Air out

2. A computer analysis was used to quantify these relationships in the form of temperature curves. An example of these curves is presented in Figure 4. This example is described in summary in paragraph 1.4.

3. Based on optimum temperature relationships, a recuperator system specification was established as an initial reference design point.

    The following two additional steps were carried out at a later date to evolve a more specific system design (Section VIII).

4. Approximate recuperator physical characteristics required to provide the assumed thermal characteristics were determined.

5. The reference design point was altered as judged necessary to satisfy the system criteria of paragraph 1.1; and Step 4 was repeated.

1.3 Results

The resulting final air mix temperature, as a function of air split between the two recuperators based on the indicated system assumptions is presented in Figure 3. This is the parameter that determines fuel savings, which is the ultimate purpose of this program. This figure is discussed in the following section (1.4).

Air and flue gas temperatures, to and from the two recuperators, versus air split are presented in Figure 4. The parametric lines are for various temperature differences (ΔT's) between the flue gas inlet temperature and the air exit temperature from the given recuperator (metallic or ceramic). ΔT values of 100° F., 200° F. and 300° F. are shown.

Figure 4 is a very meaningful and useful graph for designing a tile/metallic recuperator system. Other temperature combinations were also considered in optimizing this recuperator system. Additional discussion is presented in paragraph 1.4.2 below.

1.4 Discussion – Design Considerations

1.4.1 Relationship of Air Mix Temperature Vs. Air Split Design Interpretation

The curve in Figure 3 shows in theory that the maximum air mix temperatures occur when only one recuperator is used, whether metallic only or ceramic only. However, this is impractical at the present time when recuperator materials are considered.

Figure 4 can be used to assist in determining the most favorable air split. The left side of the graph is not a practical area of operation because metallic recuperators cannot withstand the 1600° F or greater flue gas temperatures <u>and</u> high air preheat temperatures. Also, the right side of the graph is not a practical area of application because none of the ceramic recuperators in existence today have been proved to be capable of withstanding the combustion air pressures needed for effective burner control and turndown. Thus, in practice the ceramic/metallic recuperator concept will provide maximum fuel savings.

A jet pump is used to aspirate the low pressure air from the ceramic recuperator with the high pressure air from the metallic recuperator. For the jet pump to perform properly, a maximum of 65% of the air can be put through the ceramic recuperator (i.e., a 65/35 air split). On the other hand, if the air to the ceramic recuperator is too low, the metallic recuperator material temperature is driven too high, especially at low fire when higher recuperator temperature levels prevail. Therefore, the minimum air through the ceramic recuperator is about 35% depending upon the metallic recuperator materials, design and construction.

1.4.2 Recuperator Size and Cost

System design requires that a recuperator air split selection be made because recuperator size is a parameter to be minimized, particularly the ceramic (tile) recuperator.

Figure 4 presents recuperator air mix temperature for various combinations of recuperator ΔT's. The recuperator size is directly dependent on recuperator ΔT, and fuel savings are directly dependent on air mix temperature. From Figure 4, the trade-off relationships can be seen. Many graphs, such as Figure 4, were generated and are presented in Reference 1. For a particular application, it would only take one further step to convert these relationships into costs. Once the recuperator is designed, a capital cost can be determined. Fuel savings for a given air mix temperature and flue gas temperature can be determined. Direct cost comparisons can then be made.

The considerations presented in this section are necessary in the determination of the most favorable recuperator air split. It is concluded that the above system design approach can be used in determining the most favorable air split to the two recuperators for any given soaking pit application.

2.0 Ceramic (Tile) Recuperator Design

2.1 Criteria and Approach

The same design criteria for the recuperator system listed in Paragraph 1.1 apply to the ceramic (tile) recuperator. These design criteria are:

1. Minimum size and space requirement
2. Maximum fuel savings
3. Minimum overall cost, and
4. Dependability and reliability of components and system

Additional design requirements that must be applied to the ceramic (tile) recuperator are:

1. Maximum effective heat transfer per unit volume. It is essential to substantially reduce the recuperator size in order that it can be retrofitted into the limited space near existing ingot soaking pits.
2. Minimum air pressure drop and air pressure level. If the air pressure level is too high, the air leakage becomes unacceptably high as cracks in the ceramic and joints develop with time.
3. Minimum cracking, fracture, and air leakage. These are the most common and serious problems associated with ceramic (tile) recuperators.

Concept design analysis was undertaken to determine the following:

1. Heat transfer coefficient and factors affecting it in existing Surface Division tile recuperators at conditions identified for HTR. (These conditions are specified in Figure 9.)
2. Means of substantially improving heat transfer in this Surface tile recuperator and thereby reducing recuperator size.
3. Alternative concept approaches to optimize heat transfer and recuperator volume.

2.2 Results

The results of the recuperator heat transfer and pressure drop calculations are shown in Table 2 on the following page*. This table includes the overall heat transfer coefficient for the standard Surface Division tile recuperator in an existing soaking pit installation. It also includes overall heat transfer coefficient, pressure drop and volumes at HTR conditions for:

a. A standard Surface Division tile recuperator, and

b. An advanced compact ceramic recuperator conceptual design.

2.3 Surface Division Clay Tile Recuperator

The Surface Division tile recuperators (Figure 5) have been established as very dependable low leakage recuperators. This is accomplished by maintaining a low and nominally matched pressure level between the air side and the flue gas side of the recuperator so that little air leaks through cracks which develop in operation. Since these recuperators have proved to be dependable and effective, it was desirable to determine their efficiency by heat transfer analysis and their potential for size reduction.

Overall Heat Transfer Coefficient on an Existing Soaking Pit

The determination of the overall heat transfer coefficient (on a per tile basis) for the Surface Division low pressure clay tile recuperator was completed. The overall heat transfer coefficient was determined by two means for an existing soaking pit installation. The first method was to determine "U" from known soaking pit conditions - namely, known recuperator size, heat transferred and temperatures. The second method was by theoretical heat transfer analysis. Good agreement between the two methods was found as evidenced by the results (1.7 and 1.8 $\frac{\text{B.t.u.}}{\text{Hr-°F.-Ft}^{2}}$) previously presented in Table 2 for these two methods.

*These figures were for development of concept only. Although there are similarities they should not be confused with the application design case presented in Section VII. The differences are due to a 40/60% air split rather than a 60/40% air split.

TABLE 2

Tile Recuperator & Ceramic Recuperator
Heat Transfer Coefficient and Pressure Drop Performance

Classic Surface Division Clay Tile Recuperator

Overall Heat Transfer Coefficient on an Existing Steel Soaking Pit on Square Foot Basis

Theoretical Calculation	$U = 1.7 \frac{\text{B.t.u.}}{\text{Hr-°F.-Ft}^2}$
Field Data Basis	$U = 1.8 \frac{\text{B.t.u.}}{\text{Hr-°F.-Ft}^2}$

HTR Conditions

Calculation Extrapolation	$U = 1.5 \frac{\text{B.t.u.}}{\text{Hr-°F.-Ft}^2}$
Overall Heat Transfer on Volume Basis	$U = 4.1 \frac{\text{B.t.u.}}{\text{Hr-°F.-Cubic Ft.}}$
Recuperator Core Volume*	1580 Cubic Feet
Air Pressure Drop	$\Delta P = .1$ inch w.c.
Flue Gas Pressure Drop	$\Delta P = .02$ inch w.c.

Compact Ceramic Recuperator

Overall Heat Transfer Coefficient

Area Basis	$U = 2.7 \frac{\text{B.t.u.}}{\text{Hr-Ft}^2\text{-°F.}}$
Volume Basis	$U = 18.1 \frac{\text{B.t.u.}}{\text{Hr-°F.-Cubic Ft.}}$
Recuperator Core Volume*	385 Cubic Feet
Air Pressure Drop	$\Delta P = 6.0$ inch w.c.
Flue Gas Pressure Drop	$\Delta P = .03$ inch w.c.

*For original HTR reference design point (40% air to ceramic (tile) recuperator & 60% air to metallic recuperator)

2.4 Design Change Considerations

It was noted that the tile recuperator has several characteristics that contributed to poor heat transfer and large size. These are:

1. Poor air side heat transfer coefficient due to low air velocities.
2. Very large air side and flue gas side passages.
3. Thick walls.

Various design changes were considered to correct these deficiencies. The most noteworthy factor, an increase in air velocity, raises the air pressure level when large air velocities are introduced to improve the heat transfer coefficient. High air pressure in conjunction with any ceramic recuperator leaks has always eventually resulted in unacceptable recuperator performance. However, it was observed that new ceramic technology, applied with somewhat higher pressure drops and pressure levels than used in the Surface tile recuperator, may provide a much more compact and workable ceramic recuperator design. As a starting point a nominal air pressure drop of 6.0 inch w.c. was selected as a limit for design purposes.

Another factor noted at the time that would permit a more compact ceramic recuperator design was the thin walls in the ceramic recuperator that GTE Sylvania was developing. With this information and these considerations a much more compact recuperator was conceived. This very promising GTE ceramic recuperator is described in Section VII.

2.5 Advanced Compact Ceramic Recuperator Concept

The large carryover of particulate matter and other foreign matter in the flue gas from the soaking pit can cause a problem in plugging the recuperator flue gas passages if these passages are too small. The most favorable flue gas hole size depends on the type of application. However, considering a number of factors such as plugging, Δ P, minimum size, etc., for preliminary design purposes, it was judged that the flue gas hole sizes could be reduced from the Surface tile hole size.

It was found that a multi-pass recuperator is essential to obtain the high air preheat temperatures required. A simple cross flow heat exchanger will not provide the heat transfer effectiveness needed for this application. However, several air passes approach counterflow heat transfer performance for maximum effectiveness.

The design configuration shown in Figure 6 was conceived for performance analysis and for the purpose of presenting to ceramic supplier/fabricators for fabrication consideration and cost estimating. This is a four air-pass arrangement.

It should be noted that GTE recuperator material and the fabrication process have the potential for competitive costs. The physical design, including fabrication cost considerations are an important part of the recuperator development and design, including this initial conceptualization.

The thermal design is presented in Section VII, 3.0 and in Appendix A.

2.6 Other Ceramic Recuperator Design Concepts

Some initial consideration was given to other recuperator design concepts - for example, a cylindrical tile concept such as the one being developed by the British Steel Company. (Reference 4.) However, with the GTE Sylvania recuperator concept appearing to be very promising, further engineering effort was directed toward the design problems and opportunities associated with this concept.

3.0 Other System Concepts Considered

As stated previously the key to bringing high and ultra-high temperature recuperation to reality in existing steel soaking pit applications is finding means to utilize the very limited space available. The search for means to maximize fuel savings while minimizing capital investment included consideration of these concept arrangements:

3.1 "Piggyback" Metallic Recuperator

The "piggyback" concept was considered because it was noted that existing Surface Division tile/metallic recuperators in the field at least have the needed space for high temperature recuperator retrofit because the large tile recuperator is already there. The "piggyback" approach consists of adding a metallic recuperator to the existing tile/metallic recuperator and using it to preheat the combustion air prior to entering the tile recuperator. Thermal calculations (Reference 1) revealed that only a 150° F. air preheat temperature improvement over the rather modest existing air preheat temperature would result. The resulting fuel savings improvement was not enough to justify this concept. Thus, this concept arrangement was discarded.

3.2 Replacement of Tile Recuperator with Ceramic Recuperator

The replacement of the tile recuperator with the advanced compact ceramic recuperator was considered because of the space available in an installation where a large tile recuperator already exists. In this case a compact efficient ceramic recuperator having an overall heat transfer coefficient, "U", approximately four to five times that of the existing tile could provide much greater air preheat. Yet it could be installed within the envelope of the existing tile recuperator. Air preheat could be improved several hundred degrees. This approach is worthy of further pursuit in the future. The time for this project permitted development of only the ceramic (tile)/metallic recuperator concept.

3.3 Replacement of Older Style Ceramic Recuperator

The Amsler-Morton type ceramic recuperator has been found to eventually crack and leak, resulting in very large fuel losses. Air leakage has been extensive enough to force shutdown of soaking pits using this type of ceramic recuperator. Some steel companies report having simply by-passed this recuperator because they judge it is more trouble than it is worth. The compact, efficient ceramic recuperator now under development could be an excellent candidate, once developed and proved, to replace these recuperators. This is worthy of further technical pursuit.

3.4 HTR Using A Single Ceramic Recuperator

If or when ceramic recuperators can be advanced to the point that they can withstand higher air pressure levels, (approximately 15" to 20" w.c.), without air leakage, they would provide excellent high temperature recuperation. These combustion air pressures would be adequate for operation of a high momentum burner; and the air preheat temperatures could be as high or higher than the dual recuperator average air preheat temperature. This would result in greater fuel savings which is the purpose of this program. This single ceramic recuperator concept would also have great advantages in simplicity over the dual recuperator system.

With natural gas or #2 oil the flue gas passages in this ceramic recuperator could be kept small enough to attain a relatively compact single recuperator. The mechanical sealing problems at these pressure levels place this concept farther away in time. However, this concept has great potential. It should be pursued for other industrial recuperator applications as well.

4.0 Metallic Recuperator Sub Project

4.1 D.L.I.

4.1.1 Scope of Work

A subcontract was carried out by Des Champs Laboratories, Inc. for developing a compact high temperature metallic recuperator, as presented in Appendix C.

4.1.2 Concept

The Des Champs metallic recuperator concept is shown in Figure 7 as well as Appendix C. The design is based on the assumption that it can be made to be efficient and economical and should be reliable because it is made up of folded sheet metal. The flue gases are passed on one side of the sheet metal and the air on the other side in a counterflow arrangement. The ends of the sheet metal are sealed with a ceramic material. Considering the importance of a recuperator with minimum space requirements, the D.L.I. compact recuperator concept appears to have interesting potential.

4.2 Other Metallic Recuperator Sources

Inquiries on the capabilities and performance of metallic heat exchangers engineered and built by other companies were also made. For example, a multi-airpass shell and tube type metallic recuperator has shown good inherent design features (reference Figure 7). Thermal Transfer Corporation is a supplier of this type of heat exchanger. Another proven high temperature metallic recuperator is the Hazen. It utilizes a tube within a tube in which to pass and to preheat the air. Some of the design advantages of both of these metallic recuperators are:

1. The round tubes provide the inherently strong configuration needed at very high temperatures.
2. With the multi-pass arrangement heat transfer performance approaching counterflow efficiency can be obtained.
3. Tubes at the flue gas inlet, where the temperatures are the highest, can be made of a material with high temperature capability; and a less expensive tube material can be used for the remainder of the heat exchanger.
4. Plugging and cleaning problems are very minimal.
5. No dependence on ceramic seals.

VII. SYSTEM AND COMPONENT DESIGN

The HTR system and principal component preliminary engineering design was undertaken. They are described as follows:

1.0 Soaking Pit Application

The steel soaking pit installation discussed in Section IX was selected as the basis for designing a typical HTR system. None of the steel soaking pits at this installation has any recuperation or combustion air preheating. On-site inspection revealed that both a ceramic recuperator and a metallic recuperator could probably be installed in the space available. The ceramic recuperator can be installed within the existing building by opening up the flue line on the side away from the battery centerline. Note attached drawings D-4051-D and D-4052-D (Figures 8A and 8B). The metallic recuperator can be located just outside the building above the exhaust flue. (For a complete description see Appendix B.)

It was important to assure that the design approach used for this task presents the practicality and "concreteness" of a specific application, yet the flexibility and breadth to readily extend the basic design to other conditions or applications.

2.0 Design Parameters

2.1 Air Split

The study reported in the Concept Development Section VI was utilized to select the ceramic/metallic recuperator combustion air split. In selecting an air split between the two recuperators it was noted that a 60/40 air split provides as high an air preheat mix temperature as a 40/60 air split. To ease the very high temperature requirements on the metallic recuperator, and because there appears to be adequate space for a ceramic recuperator sized for 60% of the combustion air flow, a 60/40 air split was selected. Thus, utilizing the system design curves previously generated, a new system design point was defined. This point is presented in Figure 9.

2.2 High Fire Operation

The high fire thermal conditions are shown schematically in Figure 10. The ceramic recuperator delivers 1800° F. air and the metallic recuperator delivers 1000° F. air. The average combustion air preheat temperature is 1480° F.

2.3 Low Fire Operation

Having established a ceramic recuperator design (Section VII, 3.0), the low fire thermal conditions for the recuperator were then determined. These are presented schematically in Figure 11. The average combustion air preheat at low fire is 1700° F.

2.4 Other System Parameters

The component parameters follow from the basic system parameters presented in Figure 9. The component design requirements are presented in each of the following principal component sections, as appropriate.

3.0 Ceramic Recuperator – Thermal Design

Considerable effort went into the thermal analysis of the ceramic recuperator. The ceramic recuperator thermal design analysis is summarized in Appendix A.

A computer program was developed specifically to perform an optimization study. The air passage geometry and flue gas geometry which the computer optimization study indicated to be most advantageous for this application were determined. The recuperator design concept that was selected from the concepts considered is shown in Figure 12.

The sketch shown in Figure 12 presents this geometry. The design embodies 2" x 10" flue gas passages and 1" x 3/8" air passages. The outer core dimensions are 7' x 6 1/2' x 10'. The flue gases flow straight through the recuperator while the air flow has four passes. The predicted thermal performance this geometry will provide has already been presented as the design point (Figure 9). The air pressure drop is estimated to be 5" w.c. and the flue gas pressure drop approximately .01" w.c. The analytically predicted performance is good, although not as good as test data reported from other units tested. How good the actual thermal performance will be is yet to be determined. The tests planned at Midland-Ross on the ceramic test unit should provide the answer. These tests are discussed in Section IX.

4.0 Ceramic Recuperator - Mechanical Design

No one has yet built and operated compact ceramic recuperators on steel soaking pits that are free of very harmful cracking and leakage. Thus, the most crucial HTR system design requirement is the mechanical design of the sealing and fastening of a sizable, multi-module, multi-airpass, ceramic recuperator. The ceramic vendor is operating small single module ceramic recuperators in their production plants without apparent cracking. However, the requirements of the steel soaking pit application adds new dimensions to the problem.

The units under development and test by GTE Sylvania were manufactured as a single piece; whereas, the size necessary for a steel soaking pit will require several ceramic modules to be joined together. The seals between the ceramic modules must remain intact for the useful life of the recuperator. Another uncertainty with ceramic recuperators relates to air side seals. The multi-pass arrangement requires a flow containment that directs the air from pass to pass. The seal between the ceramic core and the flow containment is considered to be a potential source of trouble. The best method of making this seal (with acceptable durability) is not known at this time.

Both the ceramic module seals and the air side seals are complicated by thermal expansion. The ceramics have a small coefficient of thermal expansion (1.1×10^{-6} in/in °F.) but the large dimensions (8 and 10 feet) and high temperatures (up to 2300° F.) result in a 1/4 inch thermal expansion of the recuperator ceramic core. If the ceramic core is placed in a metal housing there could be a considerable differential expansion between the ceramic core and the housing. Temperature distribution and thermal expansion considerations will have to be an integral part of any seal evaluation.

These ceramic materials and single recuperator modules which have been under development by GTE Sylvania are presented as follows:

Material

Magnesium - Alumina - Silicate Ceramic - MAS-8400

Called - Cordierite

Temperature - good to 2650° F.

Cost - inexpensive

Other material information is presented in the GTE Technical Bulletins presented in Figures 13 and 14. The module matrix and assembly can also be seen in Figure 13.

5.0 Metallic Recuperator

The specifications for the metallic recuperator were developed and given to Des Champs Laboratories, Inc. They are shown in Table 3. As a basis for comparison to DLI, other commercially available metallic recuperators for this application have been found. As noted in Section VI, both Thermal Transfer and Hazen have metallic recuperators that may meet all the requirements of this application.

The design configurations of these three metallic recuperators are depicted in Figure 7. The physical configuration for each of the three are seen to be quite different. In brief these three design configurations are:

1. Thermal Transfer - shell and tube
2. Hazen - tube within a tube
3. DLI - folded sheet metal

TABLE 3

METALLIC RECUPERATOR SPECIFICATIONS

High Fire Design Point	**20 MM Btu/Hr/Pit**
Flue Gas Temp. In	1200° F.
Air Exit Temp.	1000° F.
Flue Gas Exit Temp.	900° F.
Air Temp. In	77° F.
Air Flow Rate	1520 s.c.f.m.
Flue Gas Flow Rate	4175 s.c.f.m.
Air Pressure	5 p.s.i. static
Air △ P	10 in. w.c.
Flue Gas Pressure	Atmospheric ± .1 in. w.c.
Flue Gas △ P	.25 in. w.c.
Low Fire Operating Conditions	
Flue Gas Temp. In	1500° F.
Air Exit Temp.	1300° F.
Air Pressure	5 p.s.i. static

For this application the Hazen or the Thermal Transfer metallic recuperator could be placed in the flue line with a straight-through path for the flue gases. They may have a maintenance advantage over the DLI recuperator in that they could be cleaned of flue gas carryover debris or plugging quite readily. Also, if some tubes become too corroded or damaged, they could be replaced without having to remove the whole unit.

It is not clear at the present time how the DLI recuperator would be cleaned or repaired. It is conceivable that the small flue gas passages with many obstructions would exhibit a tendency to plug. Quotations were obtained for the Des Champs recuperator and a comparable Thermal Transfer recuperator.

6.0 Combustion System and Controls

A burner and jet pump have been combined into an efficient integral unit for ceramic/metallic recuperator application. This integral jet pump/burner unit has been under development at Midland-Ross. It requires a unique control arrangement for this ceramic/metallic recuperator application. The control design has been developed (see Figure 15). It is summarized below. The reference control system is designed for both maximum productivity and efficiency. (There is a Midland-Ross patent application pending for the control system which was previously developed using Midland-Ross funding.)

The pit temperature is used to generate a signal that controls the cold air flow to the metallic recuperator. The ceramic recuperator air flow is slaved to the metallic recuperator air flow to give a constant flow ratio. The air flow to the two recuperators is summed and used to control the fuel flow.

Should the ceramic recuperator at some time begin to leak air into the flue gas stream, an auxiliary control system has been provided to maintain the proper air/fuel ratio. Uncompensated leakage would cause the combustion system to operate rich since the ceramic recuperator air is metered on the inlet side of the recuperator. A flue gas oxygen analyzer and current proportioning output controller will call for additional air supply to the ceramic inlet to compensate for the leakage and associated drop in flue gas oxygen concentration. This air will bypass the ceramic recuperator air metering orifice in order to avoid upsetting the fuel-following-air feature. Cold metering of the air has been selected as it avoids all of the problems associated with temperature compensation.

The new burner will be capable of utilizing average preheat temperatures up to 1800° F. At high fire conditions the combustion products will have high momentum to give efficient heat transfer in the pit. To accomplish this the air supplied through the metallic recuperator will be at about 5 p.s.i.g. and will be used as the primary air in a jet pump. The air supplied through the ceramic recuperator will be at low pressure and will be the secondary gas in the jet pump. The burner will be capable of concentrating the supplied heat at either end of the pit, controlled by the temperature differential. At the present state of development, in the low fire condition the burner can supply either high momentum combustion products utilizing medium temperature preheated combustion air, or low momentum combustion products utilizing ultra-high preheated combustion air. A choice was made to utilize the ultra-high temperature preheated air to maximize fuel utilization. In some applications it may be desirable to have high momentum to provide better heat transfer to the work.

7.0 Selection of Other Principal System Components

7.1 Flue Gas Exhausters

Flue Draft

The reference installation has one exhaust stack (120 ft. high) that serves four pits. For the design study it was assumed (consistent with the demonstration plan) that two of the four soaking pits will have high exhaust gas temperatures (no recuperation) and two soaking pits (with high temperature recuperation) will have low exhaust gas temperatures. Flue gas pressure drop and stack draft were calculated for a number of pit firing cases in order to determine if there is a case in which the available draft might not be sufficient. The results of the principal cases calculated are presented in Table 4. For the last case presented in the table, the available draft is only .37" w.c. This calculation is for an average high fire condition rather than for the time in the cycle with the coldest flue gas temperature. Thus, the stack draft would probably not be sufficient, and an exhauster would be required.

One exhauster would be used for two pits. It must be sized to handle dilution air that will be used to protect the metallic recuperators from a high temperature excursion. The principal specifications are:

1. Volume - 39,000 ACFM at 1200° F.
2. Draft - 3" w.c.
3. Temperature - 1200° F.

The two types of exhausters shown in Figure 16 will meet the requirements for this application. These are:

1. Centrifugal blower
2. Jet ejector

The jet ejector has a higher initial cost and requires more height to install than a fan. However, it is expected that it will require less maintenance and it will be able to withstand, for a short period of time, an over-temperature excursion that might occur if there is a fault in the combustion air system. A low temperature fan may not be able to withstand the temperature excursion without damage and the maintenance will be more difficult since moving parts are located in the flue gases. The first choice is to utilize an existing tall stack. The choice of a jet ejector or a centrifugal fan will depend upon the particular location. For the reference design a jet exhauster was selected, principally on the basis of maintenance and reliability.

TABLE 4

FLUE GAS DRAFT FOR VARIOUS COMBINATIONS OF SOAKING PITS AT HIGH FIRE CONDITIONS

Total No. Of Pits In Operation	No. Of Pits Without Recuperation	No. Of Pits With Recuperation	Ave. Flue Gas Temp. (° F.)	Total Theo. Draft ("w.c.)	Available Draft ("w.c.)
2	2	0	800	.89	.77
2	1	1	1460	1.10	.92
3	1	2	1625	1.14	.64
3	2	1	1270	1.06	.76
4	2	2	1460	1.10	.37

7.2 Air Blower

The basic requirements of the different types of air blowers that are used in the reference design are summarized as follows:

Blower Specification

Use	ΔP	Volume
Primary Air	5 psig	1700 scfm
Secondary Air	8" w.c.	6000 scfm
Dilution Air	4" w.c.	1500 scfm

8.0 Proposed Equipment and Services

The required equipment and services for installation of the HTR system at the reference location have been identified. They are presented in Appendix B.

9.0 Cost Estimate

A preliminary cost estimate for the two pit reference design has been completed and is summarized in Figure 17. It is noted that it is not final. It is a budget estimate. The estimated cost for this two pit application is:

Engineering ----------------------	$ 180,000
Equipment and Field Labor --------	$1,070,000
Total	$1,250,000

VIII CERAMIC RECUPERATOR LABORATORY TEST

1.0 Test Plan

To help resolve the uncertainty about ceramic recuperators and to obtain performance data that can be used for designing a steel soaking pit recuperator, a development test program was planned. The test plan was presented in Reference 2.

2.0 Test Modules

A test module was specified. Each module has overall dimensions of approximately 10" x 15" x 14" (Figure 18). There are four flue gas passages, each 3" x 10". This size was based on an earlier system recuperator specification. The air passages are 0.25" x 1". Four modules were planned for the test as shown in Figure 19. This arrangement requires all of the types of seals that will be required in a full size recuperator.

The tooling for this concept was built and the individual modules were fabricated.

3.0 Laboratory Test Apparatus

In the test the plan was to use the ceramic recuperator to represent a small segment of various locations in a full scale recuperator. This requires that the temperature of both the flue gas and the air be controlled. The required laboratory set-up for this was identified, using existing Midland-Ross equipment that can be modified for the purpose. The instrument scheme and the planned laboratory test apparatus are presented in Figures 20 and 21, respectively.

IX. DEMONSTRATION SITE ACQUISITION

As indicated in Section V, the two principal limitations in the application of high temperature recuperation to steel soaking pits were found to be:

1. Space constraint for the recuperator system in existing soaking pit facilities.
2. Payback period is inconsistent with corporate goals of some steel companies.

Therefore, resolution of these two problems was a principal part of all investigative work for most of the project.

1.0 Steel Company Contacts

Forty-five steel soaking pit installations were contacted by letter to promote HTR. (Installation is defined here as an entire steel company division complex of soaking pits. It includes from 8 to 64 steel soaking pits per installation.) The introduction of HTR included a questionnaire designed to obtain fuel usage and recuperator related information for use by Midland-Ross to identify the installations that could benefit most from HTR. Some of these data are not included in this report due to their identified confidential nature. A typical questionnaire is included in Figures 22A and 22B. Sufficient information for initial screening purposes was obtained from forty-three of the forty-five installations contacted.

2.0 Response From Steel Companies

2.1 Summary of Questionnaire Data

Pertinent data from these questionnaires are summarized as follows:

Number of steel soaking pit installations contacted	45
Number of installations that responded	43
Number of installations with no recuperation	10
Typical air preheat temperatures with recuperation	600° F. - 1000° F.

Typical flue gas temperature from soaking pit during soak	2000° F. - 2300° F.
Typical high fire rate per soaking pit	15-32 MM Btu/hr
Typical low fire rate per soaking pit	5 - 10 MM Btu/hr

As noted previously, the estimated potential annual fuel and dollar savings for soaking pit recuperation are presented in Figure 1.

2.2 Installations With No Air Preheat

Prior to making specific steel company contacts for the purpose of acquiring an HTR Demonstration Site, preliminary calculations were made to determine return on investment as a function of the principal factors that affect it. (On this project payback period was used as the measure of return on investment. It is later defined in Paragraph 3.0.) These calculations revealed in general, the steel soaking pit installations with no recuperation (no air preheat) have the greatest potential to justify the cost of high temperature recuperation equipment. The data on the ten installations with no recuperation are tabulated as follows:

A.	Number of soaking pit installations with no recuperation	10
B.	Number of soaking pit installations with room for large, low leakage tile recuperator and HTR system retrofit	0
C.	Number of installations with possible adequate room for advanced, highly compact, high efficiency high temperature ceramic recuperator and HTR system retrofit	8
D.	Number of installations with no interest or space for HTR	2

E.	Number of installations with no interest (with space) for HTR	1
F.	Number of installations with possible space and interest that were pursued immediately	4
G.	Number of installations remaining	3

Results of Midland-Ross efforts to solicit participation by one of the four companies (identified in Item F) with DOE and Midland-Ross in an HTR demonstration were as follows:

<u>Company #1</u> - (in Ohio) - This company could not justify the large capital investment for the extended payback period. They declined any participation. No further actions were taken.

<u>Company #2</u> - (Far West) - This company is interested in HTR. Their engineering is in basic agreement with the concept. For participation consideration an executive summary and preliminary design and installation concept were presented to their corporate management. Steps toward a formal decision of participation were started. However, further technical discussions and negotiations were terminated until funding for the test demonstration work becomes available.

<u>Company #3</u> - (South) - Interest was expressed by corporate officials based on a need to upgrade their facility - either by HTR or continuous casting. Their interest was at first oriented more toward continuous casting. However, they subsequently considered the following factors regarding HTR:

a. With a more advanced efficient and smaller ceramic recuperator the HTR can be retrofitted into their soaking pit installation.

b. With increasing fuel prices and lower installation costs than anticipated, the payback period may be short enough to justify HTR (2 to 3 years).

The responsible corporate official (President) requested a submittal of a proposal with re-examination of the capital costs for a two pit retrofit. One of their two-pit batteries would very readily lend itself to an HTR demonstration installation and test. This installation was investigated carefully. Note the technical proposal in Appendix A which was submitted to this company. This is discussed in Paragraph 4.0 of this section.

Company #4 - (Middle West) - No response on which to base further contact was made.

Relevant information on the three remaining installations (from the above summary tabulation - Item G) that have no existing recuperation is as follows:

Company #5 - (Midwest) - The kind and quantity of steel this company processes (stainless steel at less than 40% of the time in production) would not yield sufficient fuel savings to justify an HTR investment. Therefore, no further action was taken.

Company #6 - (West) - This company has expressed much interest in recuperation. They have been inclined toward installation of metallic recuperation only. However, if the advanced ceramic recuperator can be developed to use in an application such as they have, there could be HTR retrofit opportunities for many steel soaking pits at this installation.

Company #7 - (Southwest) - This company was receiving natural gas at below market price. Therefore, no immediate interest was exhibited at the time of inquiry.

2.3 Installations With Existing Recuperation

Payback calculations based on fuel savings (only) revealed that high existing air preheat temperature reduces the attractiveness for HTR investment. However, there are a number of factors or situations that can justify investment in an HTR system to obtain higher air preheat temperatures than currently achieved.

In addition to fuel savings there are:

1. Productivity improvement resulting either in increased capacity or cost savings, or both.
2. Replacement of faulty equipment that causes large fuel and/or productivity loss – for example, existing leaky ceramic recuperators that result in large fuel losses.

For these reasons some companies with existing recuperation were queried further; and solicitation of one company in particular was pursued. It was found that this company (also in Ohio) using Amsler-Morton ceramic recuperators, loses more fuel than they save by recuperation.

The cracks, fractures and leakage with these ceramic recuperators have become so extensive that these recuperators must be completely torn out and rebuilt every three years. However, the air leakage through the cracks and breaks in the tile becomes very large in much less than three years. The pit heat-up time soon becomes much slower. The net result is that more total fuel is used per heat (or per ton) because of insufficient air than if no recuperator was used to preheat the air. Many companies recognize this and simply by-pass this older type of ceramic recuperator.

Thus, although there are companies that are on record as already having recuperation, some are viable candidates for HTR recuperation (with equipment that works reliably).

3.0 Payback Analysis

The most common method of considering return on investment (ROI) in the steel industry is years of payback. It is defined simply as:

$$\text{Payback} = \frac{\text{Capital Investment}}{\text{Savings Per Year}}$$

General payback relationships were determined at the outset of this soaking pit demonstration site acquisition task. For a capital expenditure such as High Temperature Recuperation, the steel companies at the present time generally require a payback period of 1 1/2 to 3 years.

The calculation of payback periods for various HTR applications exhibit inherent imprecisions due to the level of accuracy of data obtained from industrial sources. Estimates of baseline data are based on individual assumptions, and therefore, can be controversial. Yet payback calculations are essential in justifying capital expenditures. Examples of payback calculation input assumptions that can vary considerably are:

1. Maximum acceptable payback period.
2. Projected cost of fuel or energy.
3. Productivity improvement.
4. Applicable productivity improvement savings.
5. Flue gas temperatures or air preheat temperatures.
6. Net savings.
7. Cost of HTR equipment, demolition, construction and engineering.

3.1 Payback Based On Fuel Savings

Payback analysis must be done for each specific site application. A sample payback data sheet for such a specific application is shown in Figure 23.

Payback analysis was made to assess the factors that would have the greatest effect on payback period. Using previously generated capital cost estimates as a base, payback periods were calculated for various firing rates under situations of retrofitting cold air pits and also for pits presently using preheating air at 800° F. Estimates were made assuming one, two, and four soaking pits based on fuel savings only. Savings for productivity improvement were not included. The results are shown on the graph in Figure 24. It can be noted that the payback period appears acceptable where there is no existing air preheat. If the existing air preheat is above 800° F., the payback period on fuel savings alone is poor.

3.2 Cost Savings From Increased Production

In addition to fuel cost savings, savings from improved productivity with application of HTR can be very large. A productivity increase of 15% to 20% can be expected from the combined effect of higher temperature gases, better convection from higher gas velocities, and better pit temperature uniformity from "front to back" pit temperature control. Productivity increases can reduce payback period as follows:

1. Number of pits requiring HTR retrofit.
2. Increased manufacturing capacity if the soaking pit is a production bottleneck.
3. Reduced labor and overhead.

For example, if the soaking pit is the limiting factor for production, savings from increased productivity can be greater than savings from reduced fuel requirements. Studies of one major steel company illustrated this.

4.0 Detailed Proposal To A Steel Company

One particular company having no existing recuperation (in the South) was selected for a more detailed proposal and design analysis (note Section VII). The favorable situation this company has, lends itself to being a good candidate for a demonstration site. With the advent of a more compact ceramic recuperator (compared to the tile recuperator) there is sufficient space to install the HTR system. The addition of a high temperature recuperation system to two of the four pits in group would permit direct comparison of the HTR system with the current non-recuperated system.

Considerable effort was expended on this project in evolving a workable HTR equipment design concept that can be adapted to the space available at this installation. The following three items comprised the technical portion of this proposal:

1. A preliminary design layout.
2. A definition of the equipment and field labor required.
3. A preliminary cost estimate.

A description of the equipment and services that were proposed to be supplied to this steel company is presented in Appendix B of this report. The cost estimate is presented in Figure 17.

Upon examination of this proposal this company was very much interested in hosting and participating in the demonstration of this high temperature recuperation system. At the present time, however, it appears that DOE funding for Phase II, HTR Test Demonstration, will be postponed for two years.

Economic Analysis

Payback calculations have been made for this application based on fuel savings only. As indicated above, there are other substantial potential savings resulting from the increased productivity possible with this high temperature recuperative system. Figure 23 presents the input assumptions and the resulting years of payback for this prospective demonstration site.

The payback for two different cases considered for this installation are:

Case 1 – Demonstration site at 25% participation – 2.0 years

Case 2 – Future HTR systems 100% funded by the steel company – 3.5 years

On final analysis for a specific application of the HTR, cost benefit resulting from increased productivity can be identified. This can be a major factor in reducing the payback period in the application of HTR.

5.0 Possible HTR Applications

Considerable benefit was derived from this Demonstration Site Acquisition Task in identifying application problems and opportunities as well. This task effort included applications analysis, preliminary sizing and layout, preliminary costing and proposal preparation.

Based on this work it became apparent that there is a need for a compact, highly efficient ceramic recuperator that can fit into relatively tight spaces. Such a recuperator would permit the following kinds of HTR retrofit applications in steel soaking pits:

1. This single ceramic recuperator unit could fit within the confines of existing tile recuperators with much higher recuperator performance at modest retrofit costs.

2. Retrofit to replace existing older style faulty and leaky ceramic recuperators with this advanced, more reliable unit, would be possible.

3. Retrofit of a complete HTR system, which incorporates the dual recuperator concept (as proposed in this program).

In addition, other kinds of steel processing could utilize this compact, highly efficient single ceramic recuperator. While contacting these numerous steel companies in this demonstration site acquisition task, considerable interest was expressed in recuperation for steel reheat furnaces as well as for soaking pit recuperation.

X. CONCLUSIONS

1. Large fuel savings in industry through high temperature recuperation are viable.

2. The classic tile recuperator is too large for retrofitting into a steel soaking pit which has no existing preheat.

3. For HTR steel soaking pit retrofit applications, an advanced compact ceramic recuperator is essential to fit in the limited space available. No such recuperator, which meets all the necessary application requirements, is available at the present time.

4. Considerable ceramic recuperator design/development and test work is needed to advance and prove a design which has no cracking and leaking, and is practicable for industrial use.

5. There are great fuel saving opportunities for adapting this compact, efficient ceramic recuperator to many other applications within and outside of the steel industry.

6. The technical feasibility of applying high temperature recuperation systems to existing steel soaking pits was established. It is based on the preliminary engineering, design layout, equipment definition and cost estimate for the reference design described herein.

7. Industry does not feel the concern at the present time of being sharply curtailed due to the energy shortage that was felt three years ago when this program was conceived. Therefore, a high temperature recuperation system must compete for investment funds solely on the basis of ROE.

8. Payback analysis indicates that HTR retrofit of steel soaking pits with no existing air preheat is much more favorable than retrofitting soaking pits with existing preheat.

LIST OF REFERENCES

1. J. G. Reitz, Midland-Ross Corp., Quarterly Progress Report, April to June, 1978, "Recuperator System for High and Ultra-High Temperature Flue Gases".

2. J. G. Reitz, Midland-Ross Corp., Quarterly Progress Report, July to September, 1978, "Recuperator System for High and Ultra-High Temperature Flue Gases".

3. V. J. Tennery, G. C. Wei, "Recuperator Materials Technology Assessment", ORNL/TM-6227, 1978.

4. F. W. Cleaver and W. R. Laws, "BSC's New High Pressure Ceramic Recuperator", Iron and Steel Engineer, Sept., 1977.

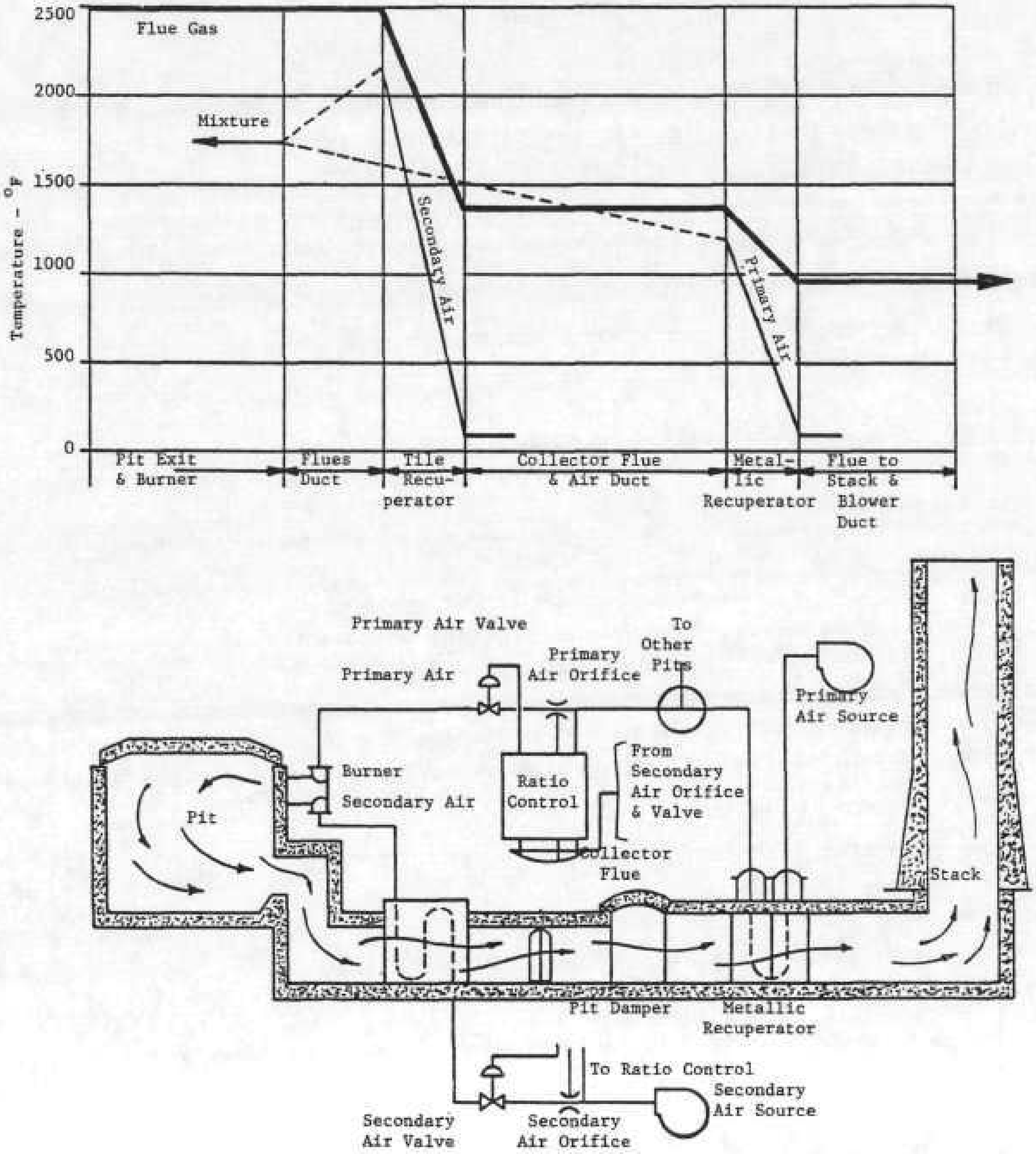
FIGURE 1

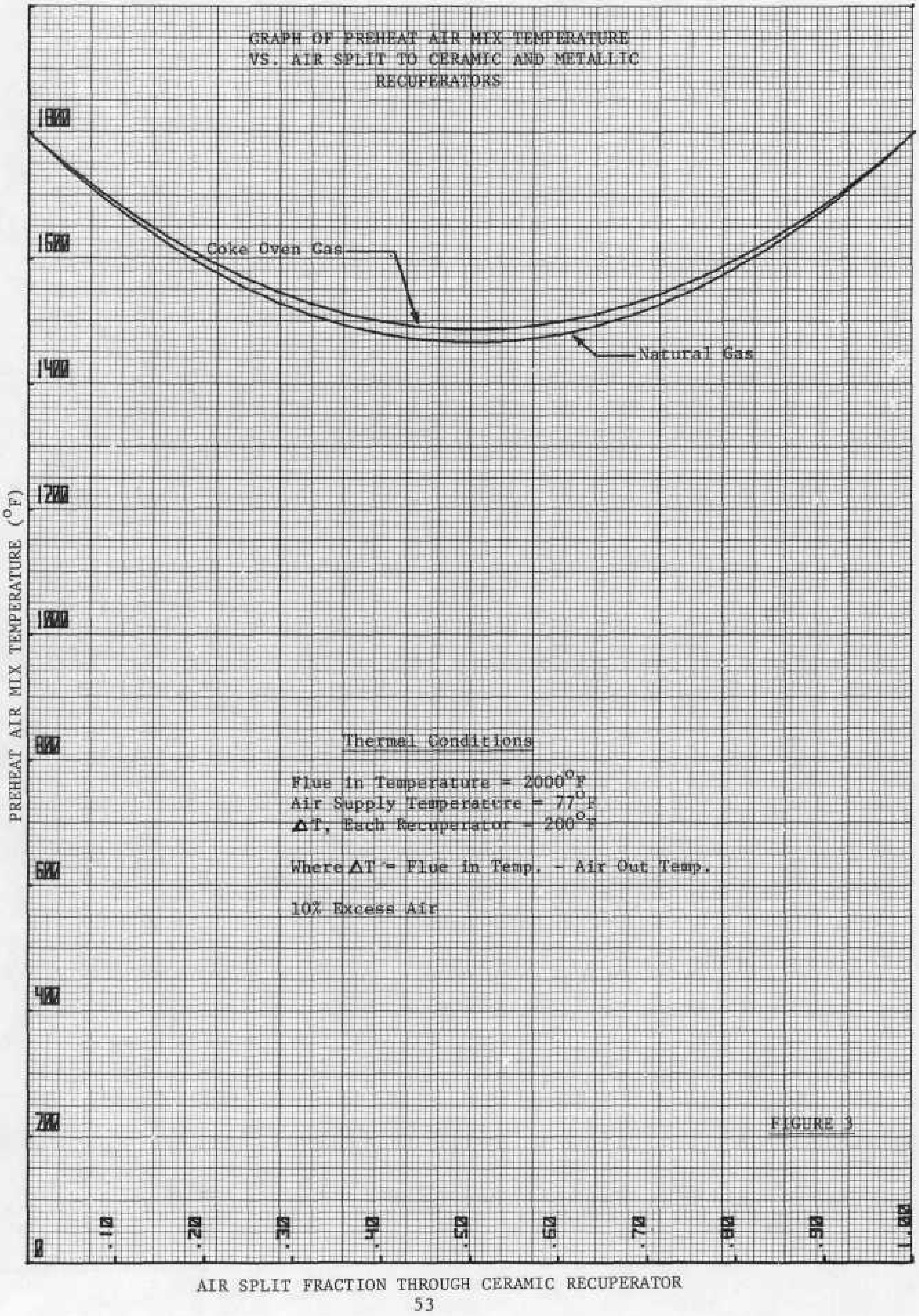
STEEL MILL SOAKING PIT RECUPERATION SURVEY

Steel Mill Soaking Pit Installations Surveyed (8 to 64 soaking pits at each installation)	43
Number of Installations with no Recuperation	10
Number of Installations with 500° F. (typical) Air Preheat	15
Number of Installations with 900° F. (typical) Air Preheat	18
Annual Energy Consumption - Current	.16 Quads/yr.
Energy Savings Anticipated Assuming Retrofit of All Existing Pits with High Temperature Recuperation	.06 Quads/yr.
Annual Fuel Savings Estimated by Early 1980's	$225 Million
Capital Investment	$800 Million

FIGURE 2

TILE-METALLIC RECUPERATION
PROPOSED SOAKING PIT ARRANGEMENT





GRAPH OF PREHEAT AIR MIX TEMPERATURE
VS. AIR SPLIT TO CERAMIC AND METALLIC
RECUPERATORS

Thermal Conditions

Flue in Temperature = 2000°F
Air Supply Temperature = 77°F
ΔT, Each Recuperator = 200°F

Where ΔT = Flue in Temp. - Air Out Temp.

10% Excess Air

FIGURE 3

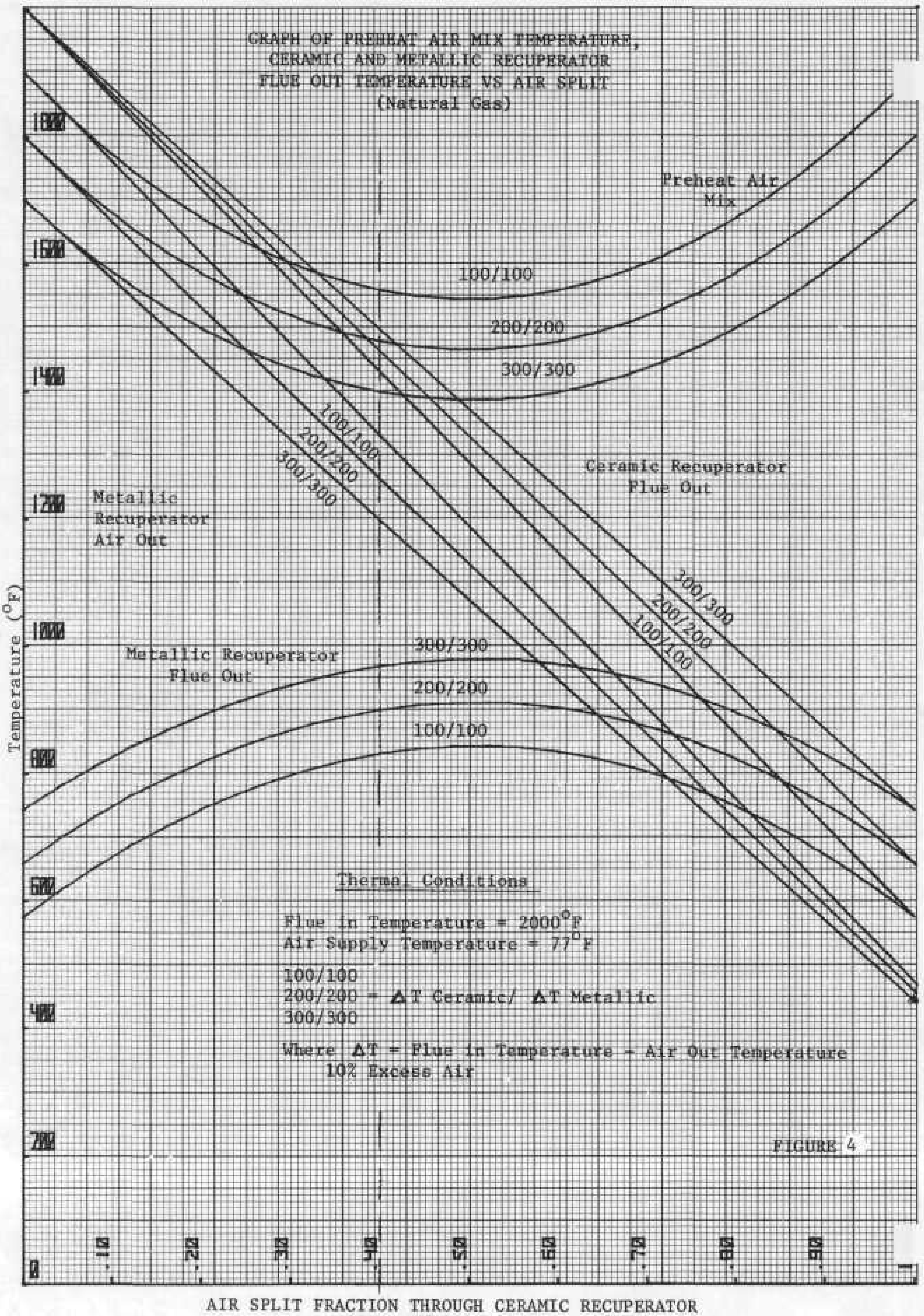
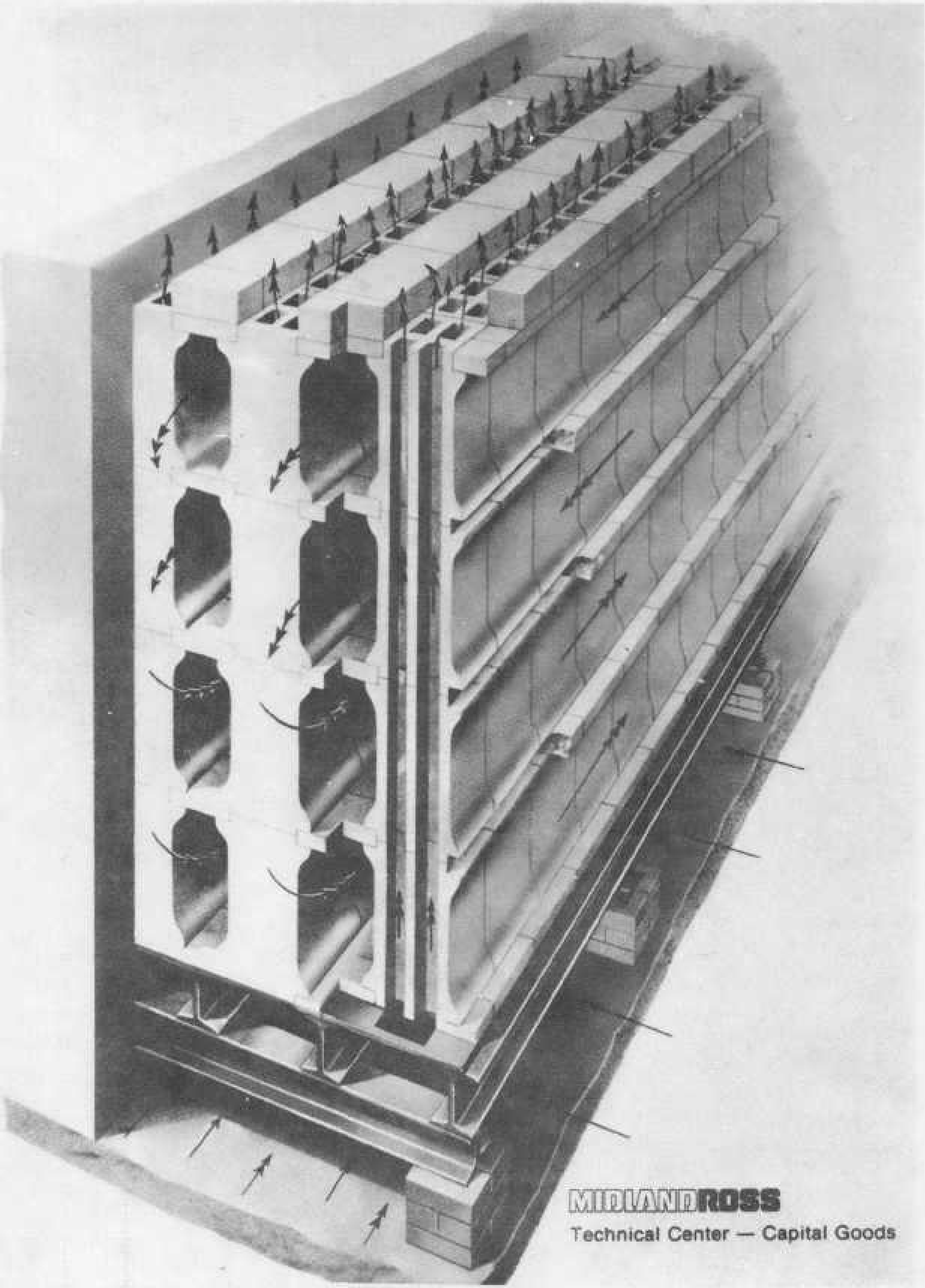

GRAPH OF PREHEAT AIR MIX TEMPERATURE,
CERAMIC AND METALLIC RECUPERATOR
FLUE OUT TEMPERATURE VS AIR SPLIT
(Natural Gas)
1800
1600
1400
1200
1000
800
600
400
200
0
Temperature (°F)
Preheat Air Mix
100/100
200/200
300/300
Metallic Recuperator Air Out
100/100
200/200
300/300
Ceramic Recuperator Flue Out
300/300
200/200
100/100
Metallic Recuperator Flue Out
300/300
200/200
100/100
Thermal Conditions
Flue in Temperature = 2000°F
Air Supply Temperature = 77°F
100/100
200/200 = ΔT Ceramic/ ΔT Metallic
300/300
Where ΔT = Flue in Temperature - Air Out Temperature
10% Excess Air
.10
.20
.30
.40
.50
.60
.70
.80
.90
1
AIR SPLIT FRACTION THROUGH CERAMIC RECUPERATOR

FIGURE 4

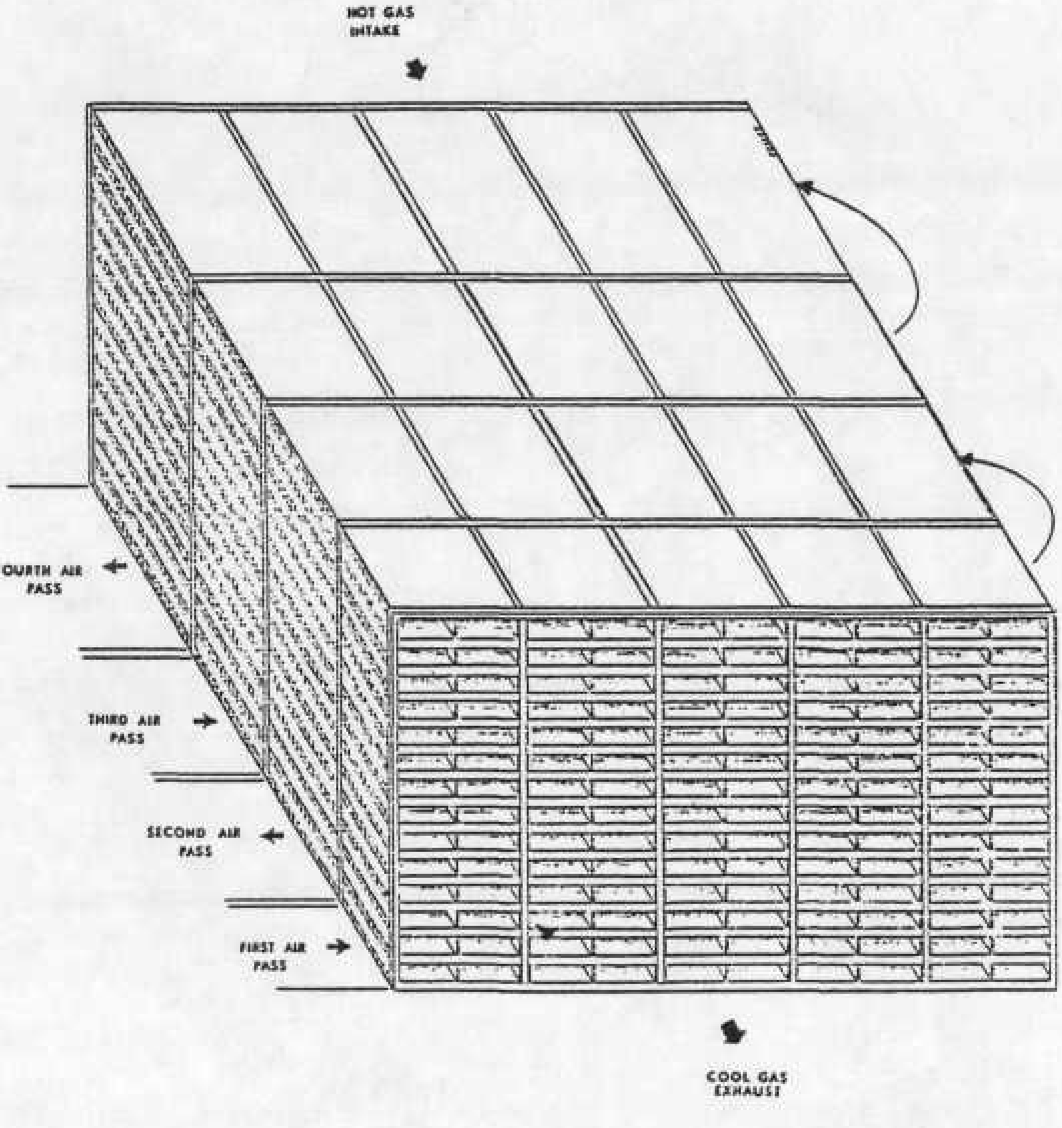
FIGURE 5



MIDLAND ROSS

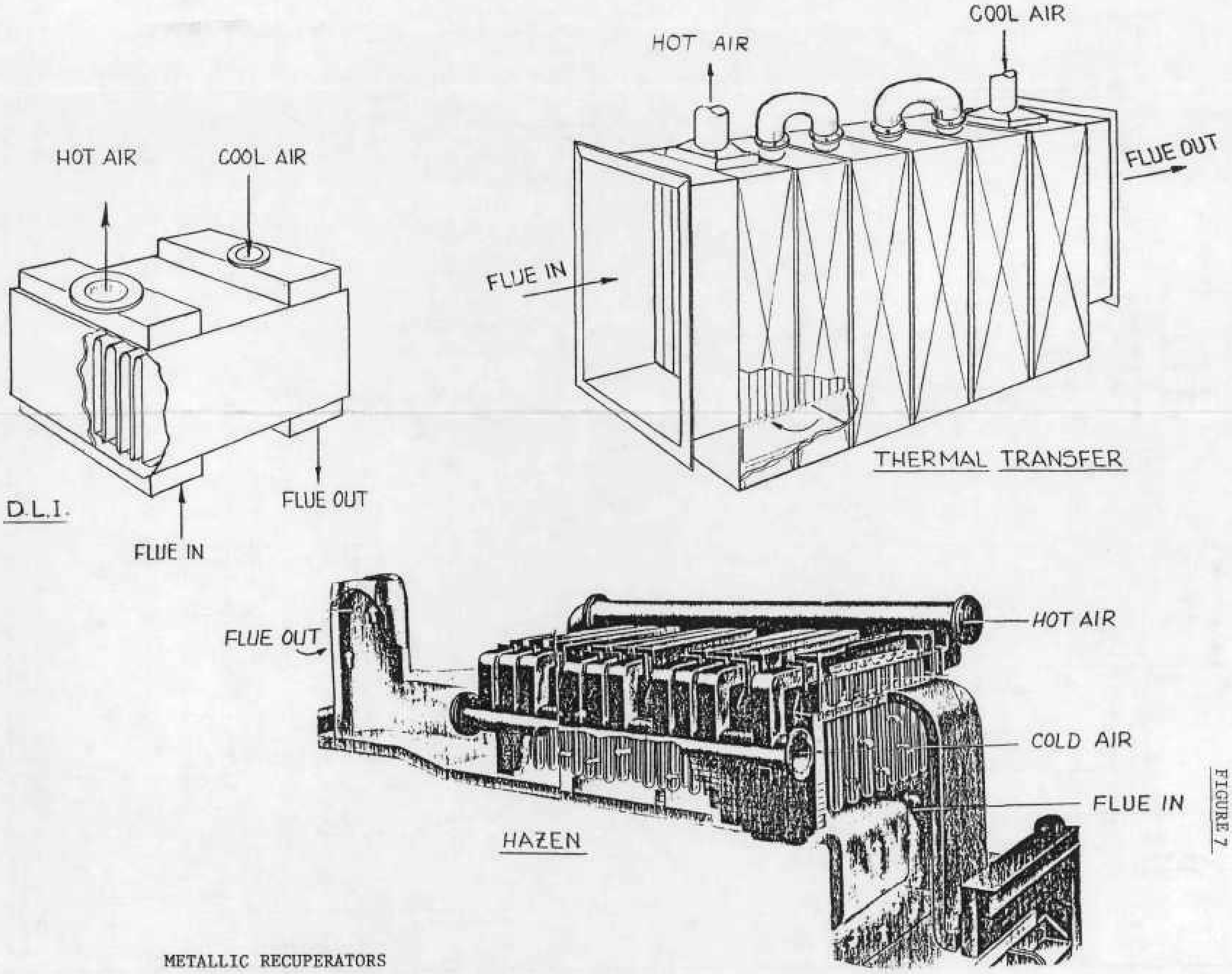
Technical Center — Capital Goods

FIGURE 6



MIDLAND-ROSS
Technical Center — [illegible]

CERAMIC RECUPERATOR CONCEPT



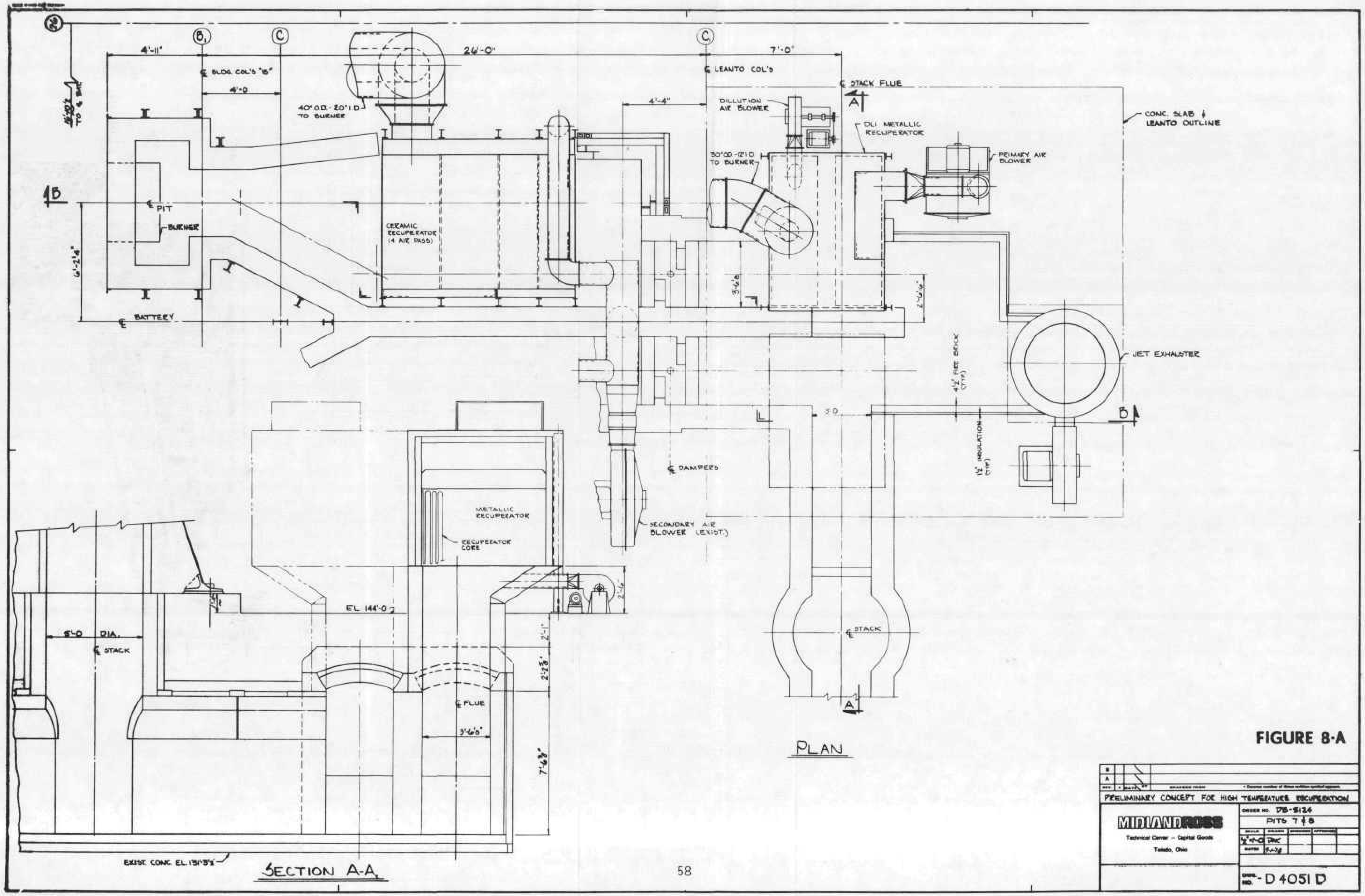
D.L.I.

THERMAL TRANSFER

HAZEN

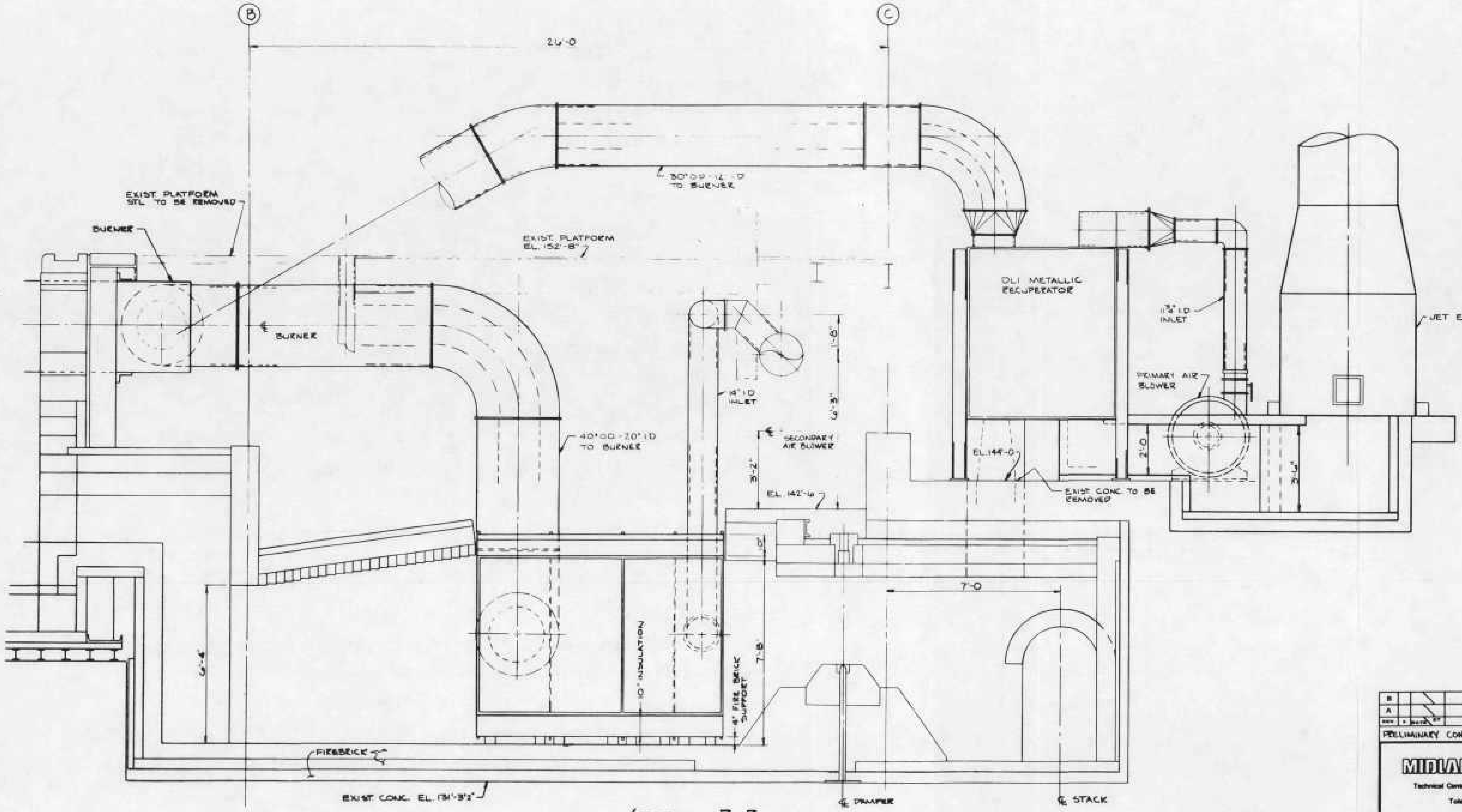
METALLIC RECUPERATORS

FIGURE 7



B₁
C
C₁
4'-11"
26'-0"
7'-0"
℄ BLDG. COL'S "B"
4'-0
℄ LEANTO COL'S
℄ STACK FLUE
40" O.D. - 20" I.D. TO BURNER
4'-4"
DILLUTION AIR BLOWER
A
DLI METALLIC RECUPERATOR
CONC. SLAB & LEANTO OUTLINE
30" OD - 12" I D TO BURNER
PRIMARY AIR BLOWER
B
℄ PIT
BURNER
CERAMIC RECUPERATOR (4 AIR PASS)
6'-2¼"
3'-6⅛
2'-4¼"
℄ BATTERY
JET EXHAUSTER
4½" FIRE BRICK (TYP.)
1½" INSULATION (TYP.)
3'-0
B
℄ DAMPERS
SECONDARY AIR BLOWER (EXIST.)
METALLIC RECUPERATOR
RECUPERATOR CORE
EL. 144'-0
2'-4"
2'-1"
2'-2⅝"
5'-0 DIA.
℄ STACK
℄ FLUE
3'-6⅛"
7'-6⅝"
℄ STACK
A
EXIST. CONC. EL. 131'-3½"
SECTION A-A₁
PLAN
B
A
PRELIMINARY CONCEPT FOR HIGH TEMPERATURE RECUPERATION
MIDLAND ROSS
Technical Center – Capital Goods
Toledo, Ohio
ORDER NO. 78-5124
PITS 7 & 8
½"=1'-0
PAC
DWG. NO. - D 4051 D

FIGURE 8-A



SECTION B-B

FIGURE 8·B

B
A
REV.

PRELIMINARY CONCEPT FOR HIGH TEMPERATURE RECUPERATION

MIDLAND ROSS
Technical Center – Capital Goods
Toledo, Ohio

ORDER NO. DB-5124
PITS 7 & 8
3/8"=1'-0" DWC
9-1-81

DWG. NO. - D 4052 D

FIGURE 9

HTR REFERENCE DESIGN POINT

High Fire		
Firing Rate		20MM Btu/Hr
Fuel		Natural Gas
Excess Air		10%
Air Split	Ceramic Recuperator	60%
	Metallic Recuperator	40%
Ceramic Recuperator		
Flue Gas Temperature In		2000°F
Air Temperature In		77°F
Air Temperature Out		1800°F
Flue Gas Temperature Out		1200°F
Air Flow Rate		2280 scfm
Flue Gas Flow Rate (Both recup.)		4180 scfm
Metallic Recuperator		
Flue Gas Temperature In		1200°F
Air Temperature In		77°F
Air Temperature Out		1000°F
Flue Gas Temperature Out		900°F
Air Flow Rate		1520 scfm
Low Fire		
Firing Rate		5MM Btu
Fuel, Excess Air, Air Split, Air Supply Temp. (Same as High Fire)		
Flue Gas Temperature In		2200°F
Air Flow Rate -	Ceramic Recuperator	570 scfm
	Metallic Recuperator	380 scfm
Flue Gas Flow Rate		1045 scfm

All other thermodynamic parameters are result of recuperator geometry and materials selected and the above selected values.

HTR REFERENCE DESIGN POINT

High Fire

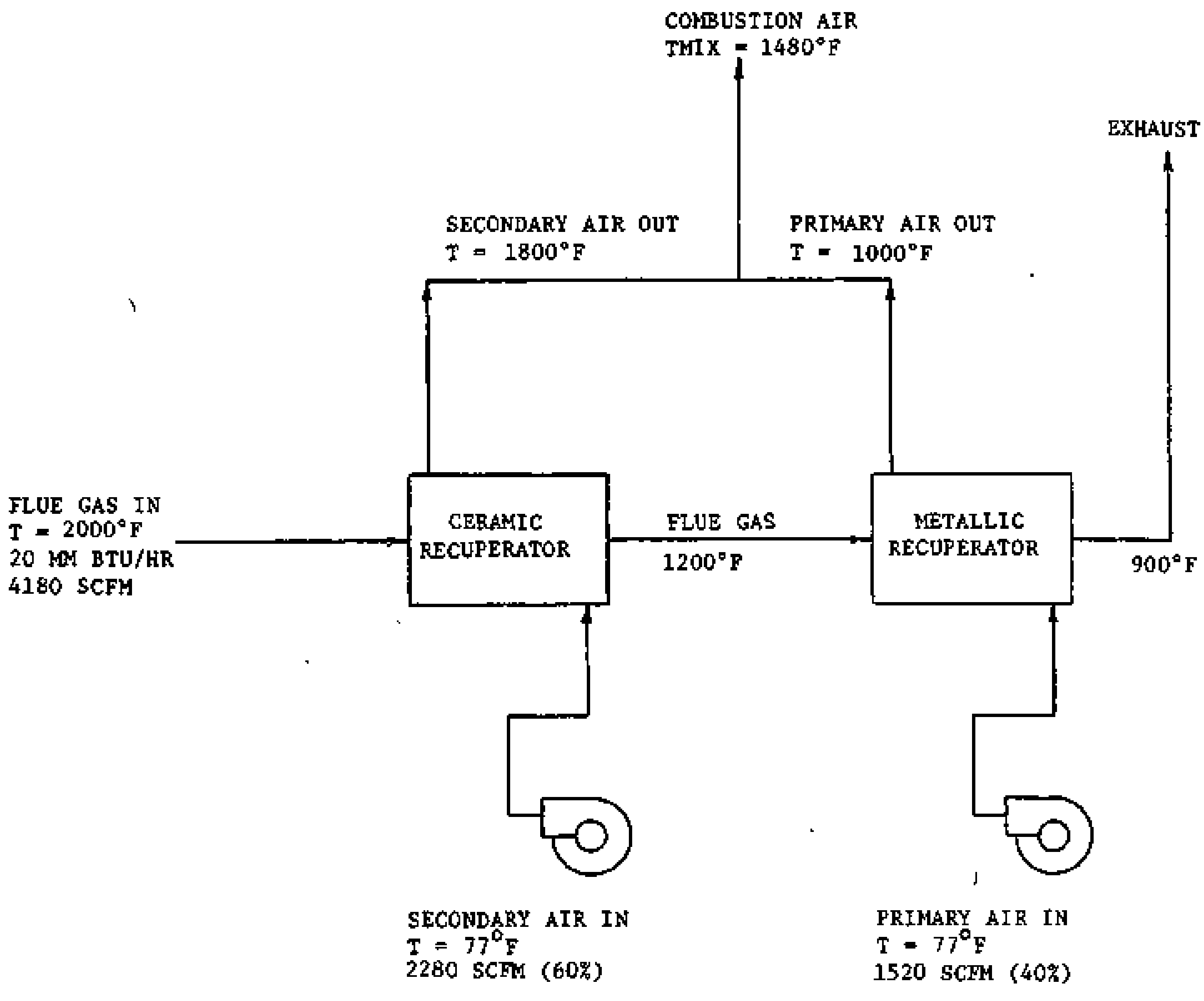


FIGURE 11

HTR REFERENCE DESIGN POINT

Low Fire

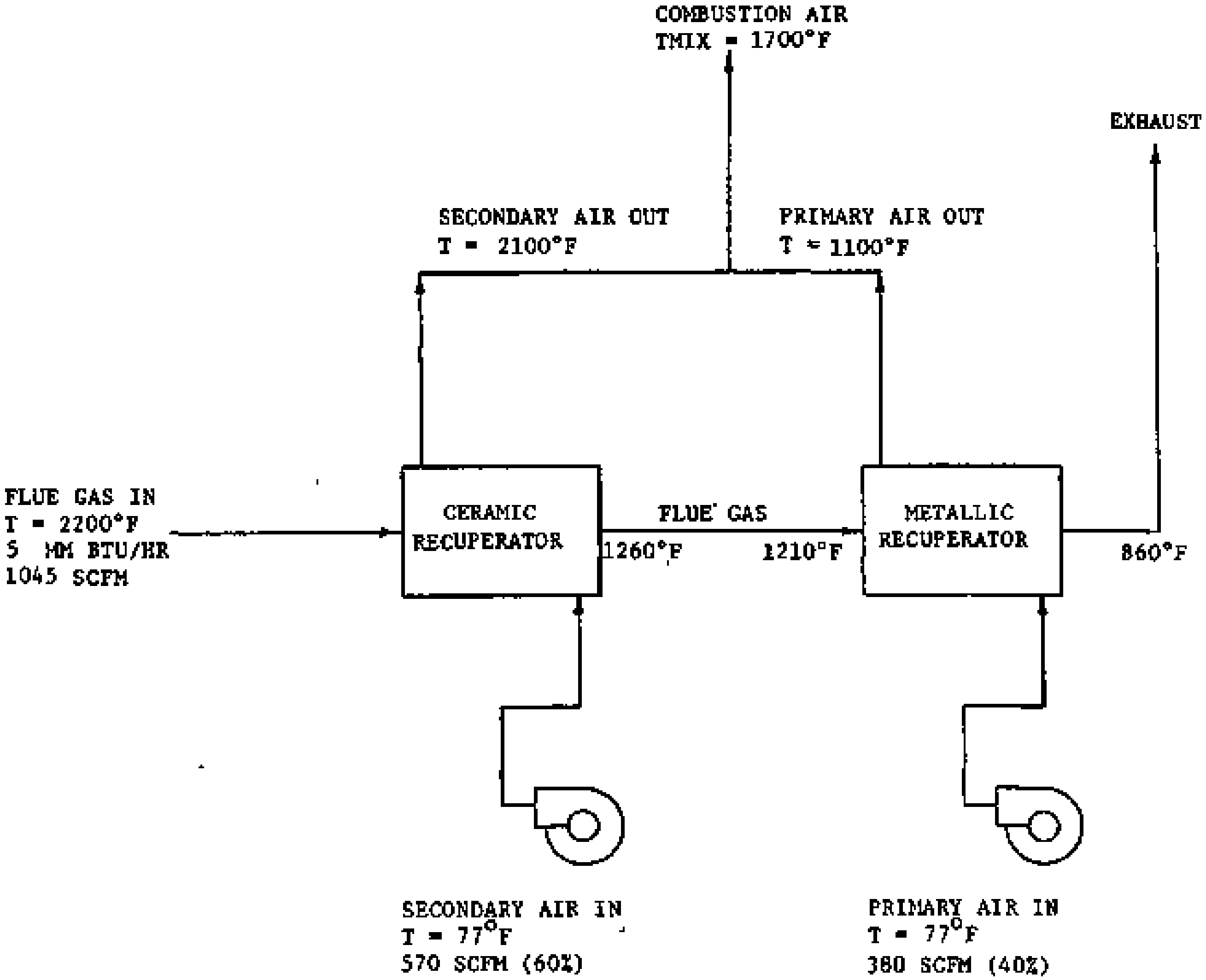
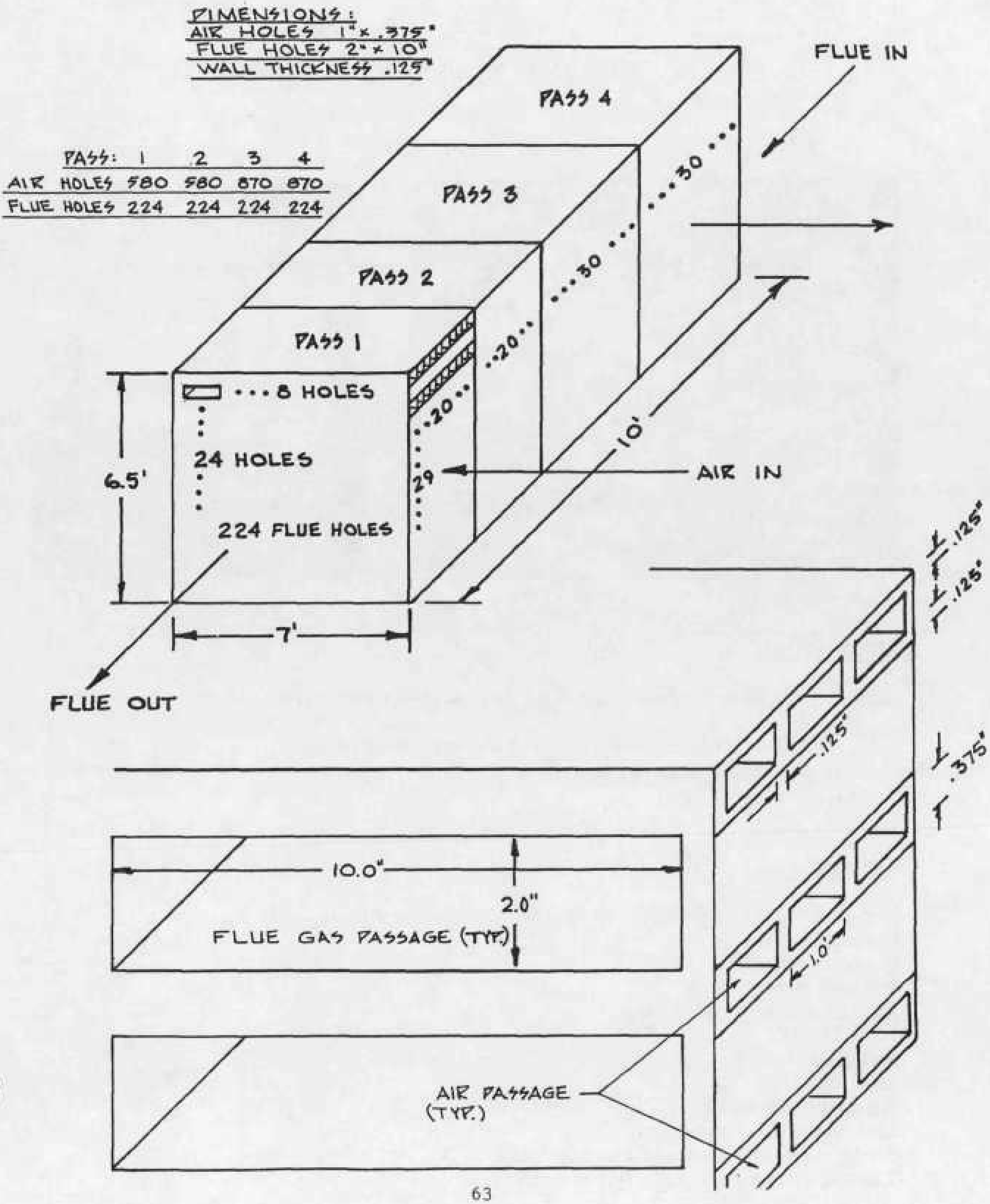


FIGURE 12

CERAMIC RECUPERATOR GEOMETRY



DIMENSIONS:
AIR HOLES 1" x .375"
FLUE HOLES 2" x 10"
WALL THICKNESS .125"

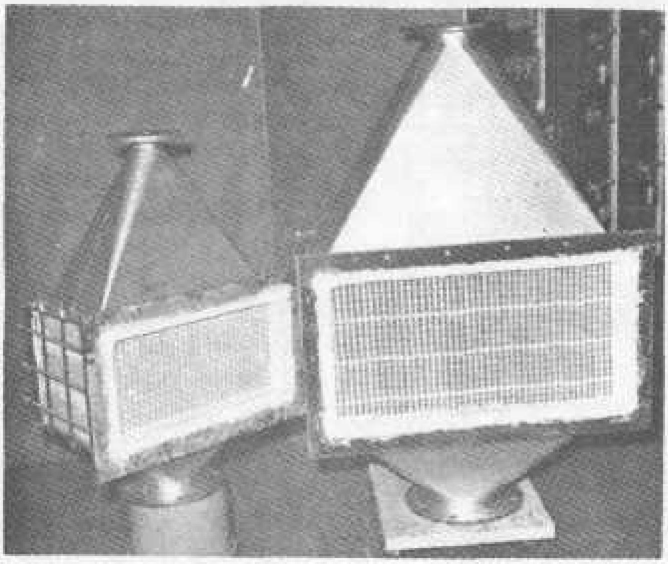
PASS:	1	2	3	4
AIR HOLES	580	580	870	870
FLUE HOLES	224	224	224	224

GTE SYLVANIA

CHEMICAL AND METALLURGICAL DIVISION
NEW PRODUCT DATA

FIGURE 13

CERAMIC RECUPERATORS FOR WASTE HEAT RECOVERY



APPLICATION

Recovery of "waste" exhaust heat from furnace stacks and recycling recovered heat to:

(1) Preheat the combustion air to high-temperature burners.
(2) Return the heat to the furnace, thereby reducing the quantity of fuel consumed.
(3) Heating of plant.

ADVANTAGES

High-temperature capability – can be used without cooling to 2700 °F.
Chemically inert.
Corrosion resistant.
Will not thermal shock.
High heat transfer efficiency.
Long life.
Distortion free.
Light weight.
Simple installation.
Less costly than exotic metals.
Safety - loss of power and loss of cooling air will not affect unit.
Thermal cycling does not affect material.

FIGURE 14

SIZE AND SHAPE CAPABILITY

Computer design model program enables optimization of variables for individual applications.

Standard module dimensions of 2 ft^3 and 6 ft^3. Virtually any size by ganging modules.

Wall Thicknesses: 0.040 to 0.060".

Hydraulic diameters from 0.015" to 1".

TECHNICAL SPECIFICATIONS

Material: Magnesium-Alumina-Silicate Ceramic - MAS-8400.

Passage Geometry: Rectangular.

Wall Thickness: 0.050".

Bulk Density:	Matrix	50 lbs/ft^3
	Material	137 lbs/ft^3

Modulus of Rupture (solid bars): 8000 psi.

Thermal Expansion: (0-800 °C) in./in./°C 2.0×10^{-6}.

Thermal Shock Resistance: Excellent.

Melting Point. 2750 °F.

CM-967 (2/78)

Precision Materials Group/Chemical & Metallurgical Division/Towanda, Pa.

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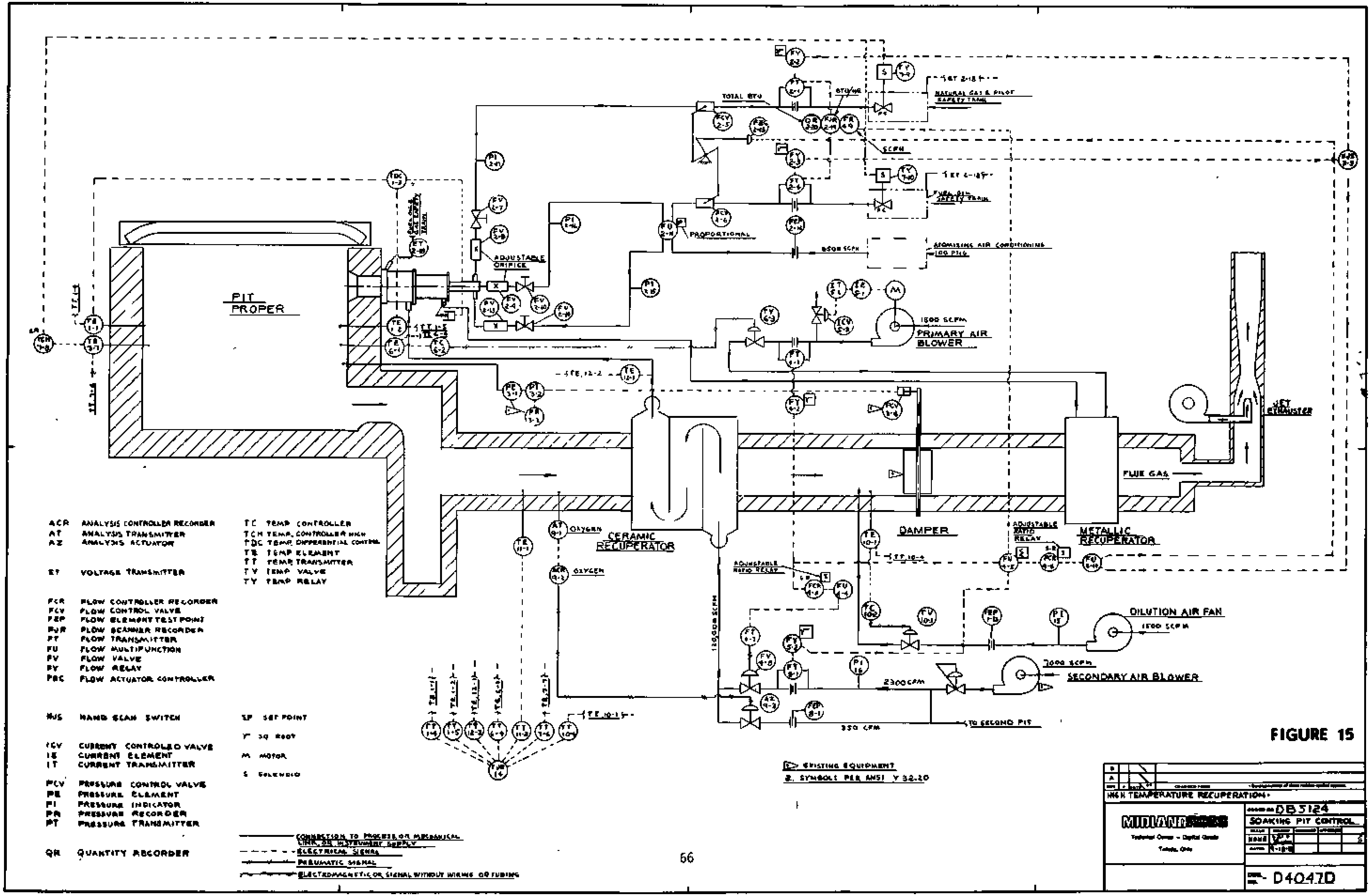
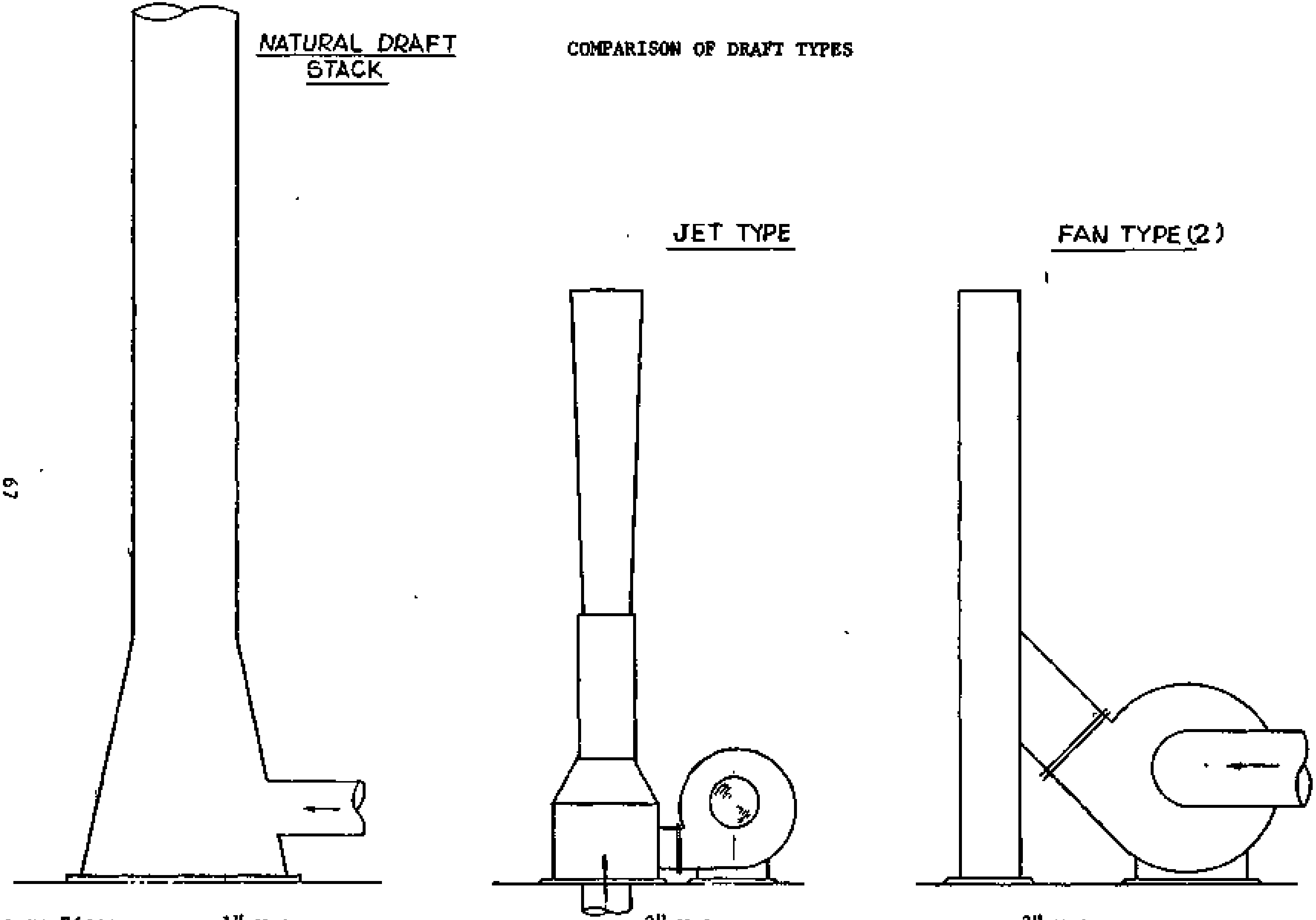

PIT PROPER
CERAMIC RECUPERATOR
DAMPER
METALLIC RECUPERATOR
FLUE GAS
JET EXHAUSTER
PRIMARY AIR BLOWER
1500 SCFM
DILUTION AIR FAN
1500 SCFM
SECONDARY AIR BLOWER
7000 SCFM
2300 CFM
350 CFM
TO SECOND PIT
12000 SCFM
OXYGEN
ADJUSTABLE ORIFICE
ADJUSTABLE RATIO RELAY
PROPORTIONAL
TOTAL BTU
BTU/HR
SCFH
NATURAL GAS & PILOT SAFETY TRAIN
SET 2-18
FUEL OIL SAFETY TRAIN
SET 4-18
ATOMIZING AIR CONDITIONING
100 PSIG
850 SCFH
TE, 12-2
TT 10-4
TT 10-1
M
S
EXISTING EQUIPMENT
2. SYMBOLS PER ANSI Y 32.20
ACR ANALYSIS CONTROLLER RECORDER
AT ANALYSIS TRANSMITTER
AZ ANALYSIS ACTUATOR
ET VOLTAGE TRANSMITTER
FCR FLOW CONTROLLER RECORDER
FCV FLOW CONTROL VALVE
FEP FLOW ELEMENT TEST POINT
FSR FLOW SCANNER RECORDER
FT FLOW TRANSMITTER
FU FLOW MULTIFUNCTION
FV FLOW VALVE
FY FLOW RELAY
FAC FLOW ACTUATOR CONTROLLER
HSS HAND SCAN SWITCH
ICV CURRENT CONTROLLED VALVE
IE CURRENT ELEMENT
IT CURRENT TRANSMITTER
PCV PRESSURE CONTROL VALVE
PE PRESSURE ELEMENT
PI PRESSURE INDICATOR
PR PRESSURE RECORDER
PT PRESSURE TRANSMITTER
QR QUANTITY RECORDER
TC TEMP CONTROLLER
TCH TEMP. CONTROLLER HIGH
TDC TEMP. DIFFERENTIAL CONTROL
TE TEMP ELEMENT
TT TEMP TRANSMITTER
TV TEMP VALVE
TY TEMP RELAY
SP SET POINT
√ SQ ROOT
M MOTOR
S SOLENOID
CONNECTION TO PROCESS OR MECHANICAL LINK, OR INSTRUMENT SUPPLY
ELECTRICAL SIGNAL
PNEUMATIC SIGNAL
ELECTROMAGNETIC OR SIGNAL WITHOUT WIRING OR TUBING
HIGH TEMPERATURE RECUPERATION
MIDLAND
Toledo, Ohio
DB 5124
SOAKING PIT CONTROL
D4047D

FIGURE 15

COMPARISON OF DRAFT TYPES



Pressure Rise:	1" w.c.	3" w.c.	3" w.c.
Horsepower:	0	60 HP	30 HP each
Cost:	(Existing)	$30,000	$14,000 each

FIGURE 16

FIGURE 17

PRELIMINARY COST ESTIMATE

Engineering	$ 133,930
Purchasing	350,900
Factory	192,352
Erection Supervision	83,293
Freight	15,000
Insurance	3,877
Subtotal w/o Field Labor	$ 779,352
BLS Escalation (10%)	$ 77,935
Erection Field Labor	175,335
Service Reserve (1.1%)	11,359
Total	$1,043,981
G & A	205,664
Total Contract Sales Price	$1,249,645

Conversion of two (2) Soaking Pits to Ceramic/Metallic Recuperation

Technical Center
9/20/78

Not to be used, typical only.

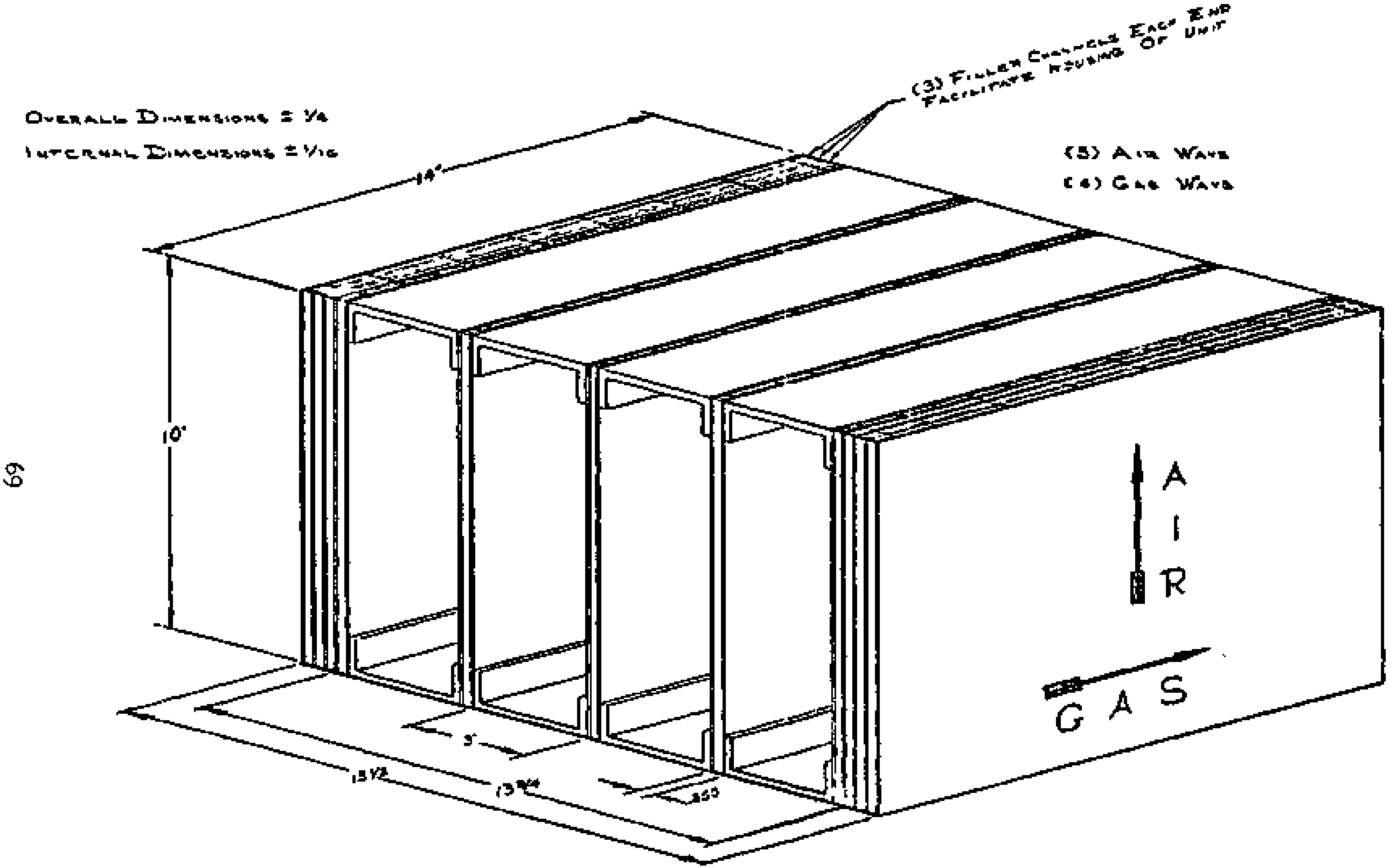
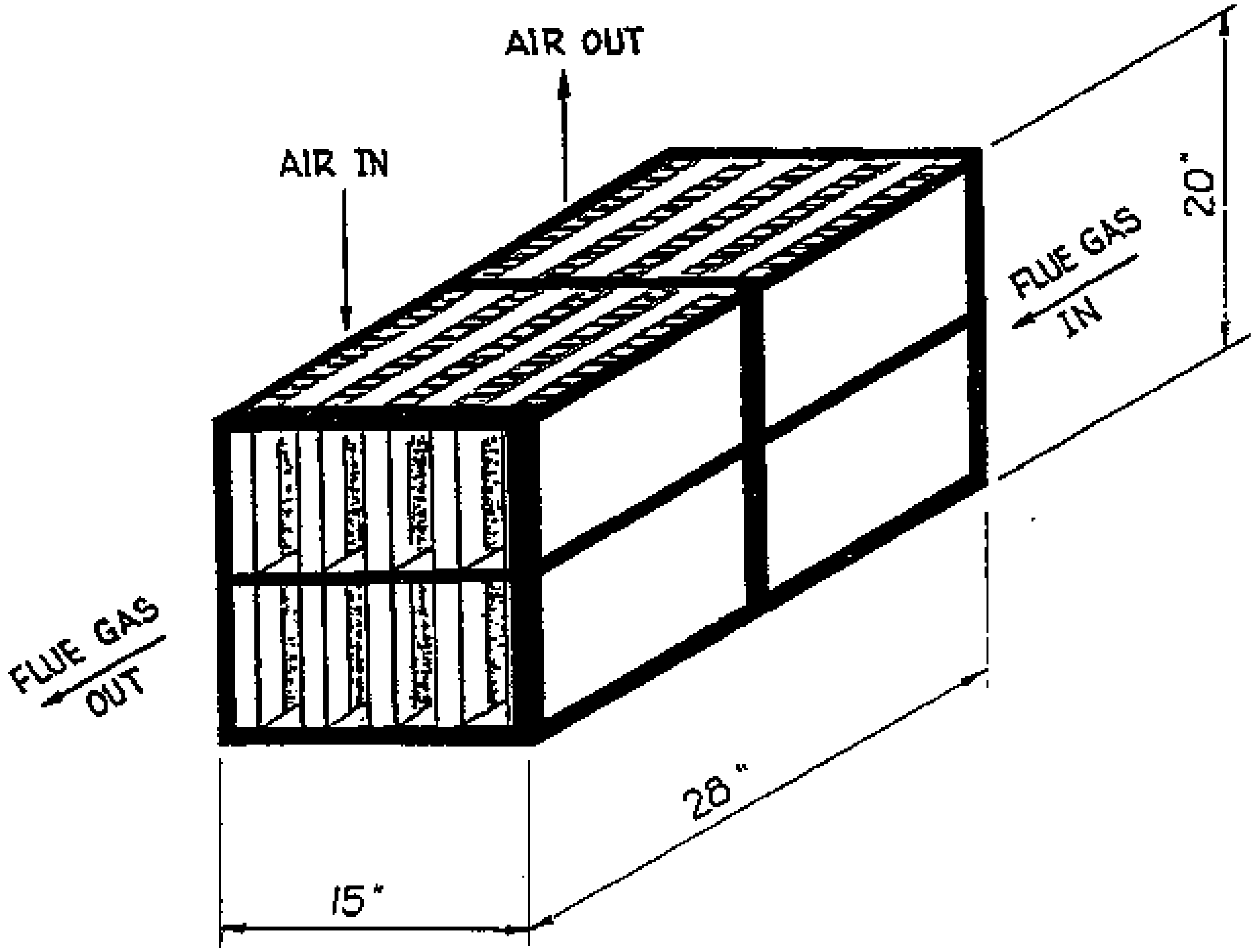


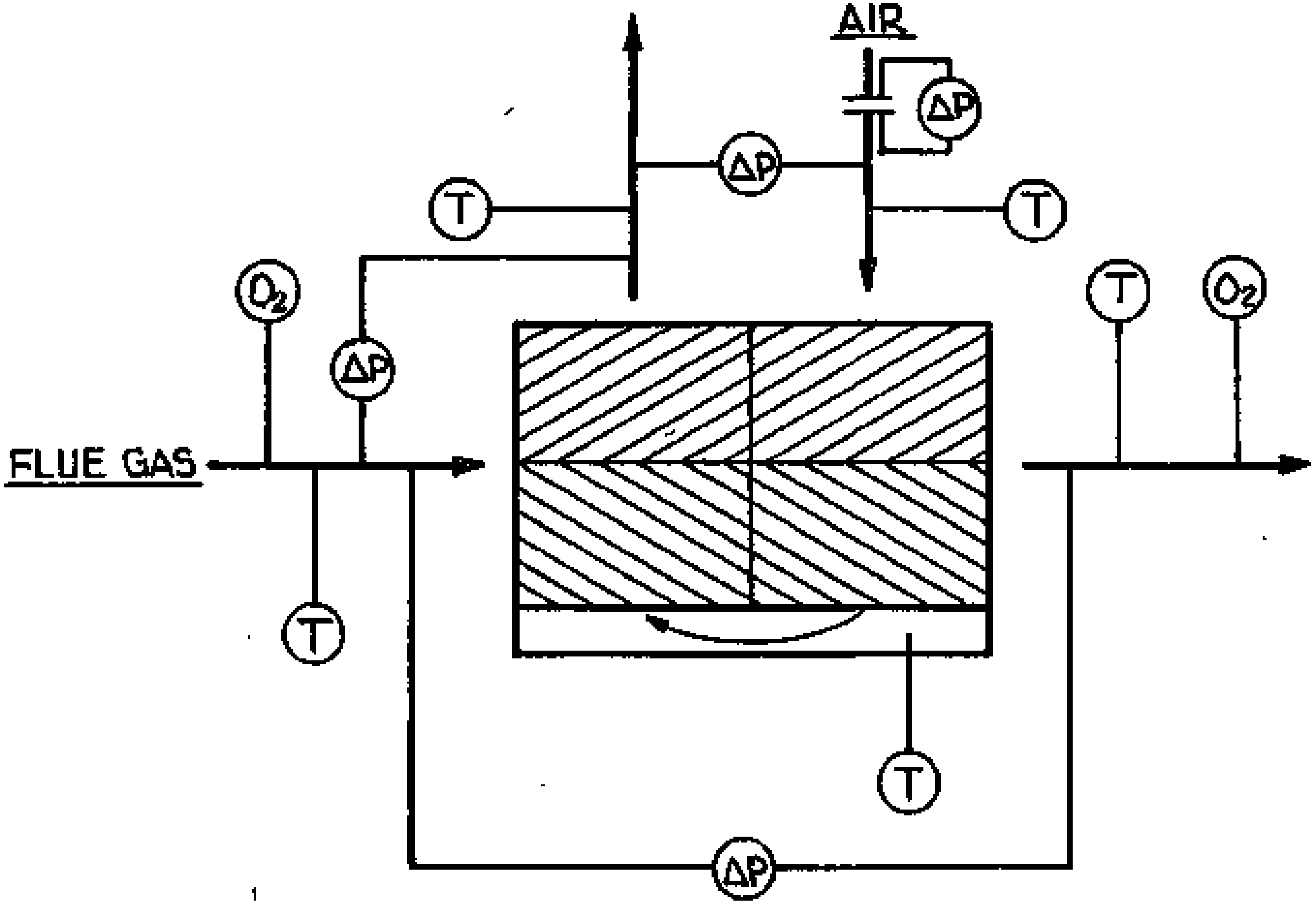
FIGURE 18

MIDLAND ROSS
CERAMIC RECUPERATOR
PROTOTYPE

FIGURE 19



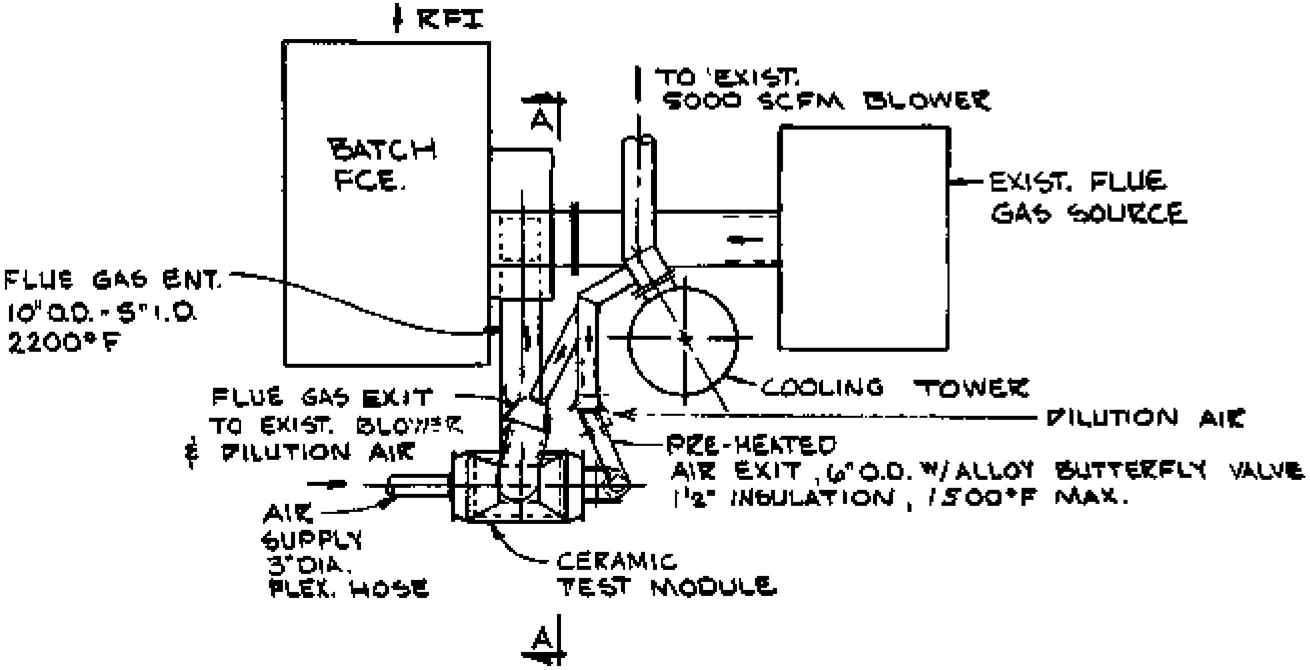
LABORATORY CERAMIC RECUPERATOR TEST ASSEMBLY CONCEPT

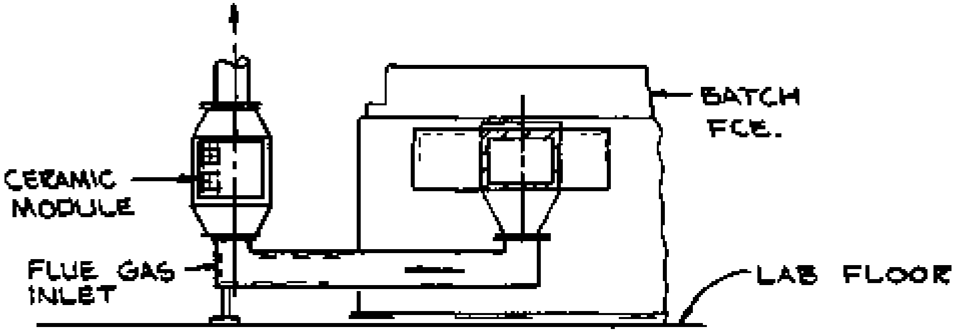


CERAMIC RECUPERATOR TEST INSTRUMENTATION

FIGURE 20

CERAMIC RECUPERATOR TEST APPARATUS PLAN CONCEPT





SECTION A-A

FIGURE 21

SAMPLE QUESTIONNAIRE

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FIGURE 22A

DEMONSTRATION SITE QUESTIONNAIRE
HIGH TEMPERATURE RECUPERATIVE SYSTEM

The information on these two sheets will be helpful in answering these three key questions relevant to applicability of a High Temperature Recuperative System installation.

1. Is adequate space available for installing a High Temperature Recuperator?
2. What are the potential energy savings?
3. What is the payback period?

Present Situation

Existing Recuperation: Tile NONE Metallic NONE

Nominal Air Preheat Temperature ambient

Flue Gas Temperature 2000° to 2200°F

Pit Btu Rating 30,000,000

Pit Actual Btu Usage: High Fire 30,000,000 Soak 10,000,000

Time Period: High Fire 2 hrs Soak 4 hrs

Estimated Process Energy Efficienty 2.2 MBTU/Ton

Total Annual Energy Consumed by Pits 551,570MM BTU/yr

Number of Pits 8 Number of Batteries 4

Present Use Factor 128 hr/wk

Primary Fuel Natural Gas Alternate Fuel #2 Fuel oil

Pit Capacity tons/heat 80

% Hot Tops 90 % Cold Ingots 10

Present Pit Condition ________

Present Recuperator Condition ________

Space Availability SUITABLE FOR ONE RECUPERATOR ONLY PER PIT

FIGURE 32.5

Future for Pits 10 year expected life remaining

Other Recuperator Retrofit Considerations and Constraints

ORIGINAL FLUE DESIGN ALLOWS FOR CONVENTIONAL METALLIC RECUPERATOR INSTALLATION

Alternate Solution to New Tile Recuperator Installation

USE TILE RECUPERATOR ONLY – 28% fuel savings

Productivity Increase

What value would you assign to a 5% production increase 62,300 /yr

10% production increase 116,100 /yr

20% production increase 212.850 /yr

Basis for Payback Calculations

Projected Fuel Costs present NAT. GAS $1.43/MBTU
#2 FUEL OIL $2.19/MBTU

Estimated % Fuel Savings

Other Possible Future Considerations
Ceramic Fibre Roof Insulation

Comments

Space conditions severely limit addition of two recuperators

Jack Reitz
Midland-Ross Corp./P.O. Box 985, Toledo, Ohio 43696/(419) 537-6235

HIGH TEMPERATURE RECUPERATOR

DATA SHEET

FIGURE 23

Company ______________________ Number of Pits 2

Input

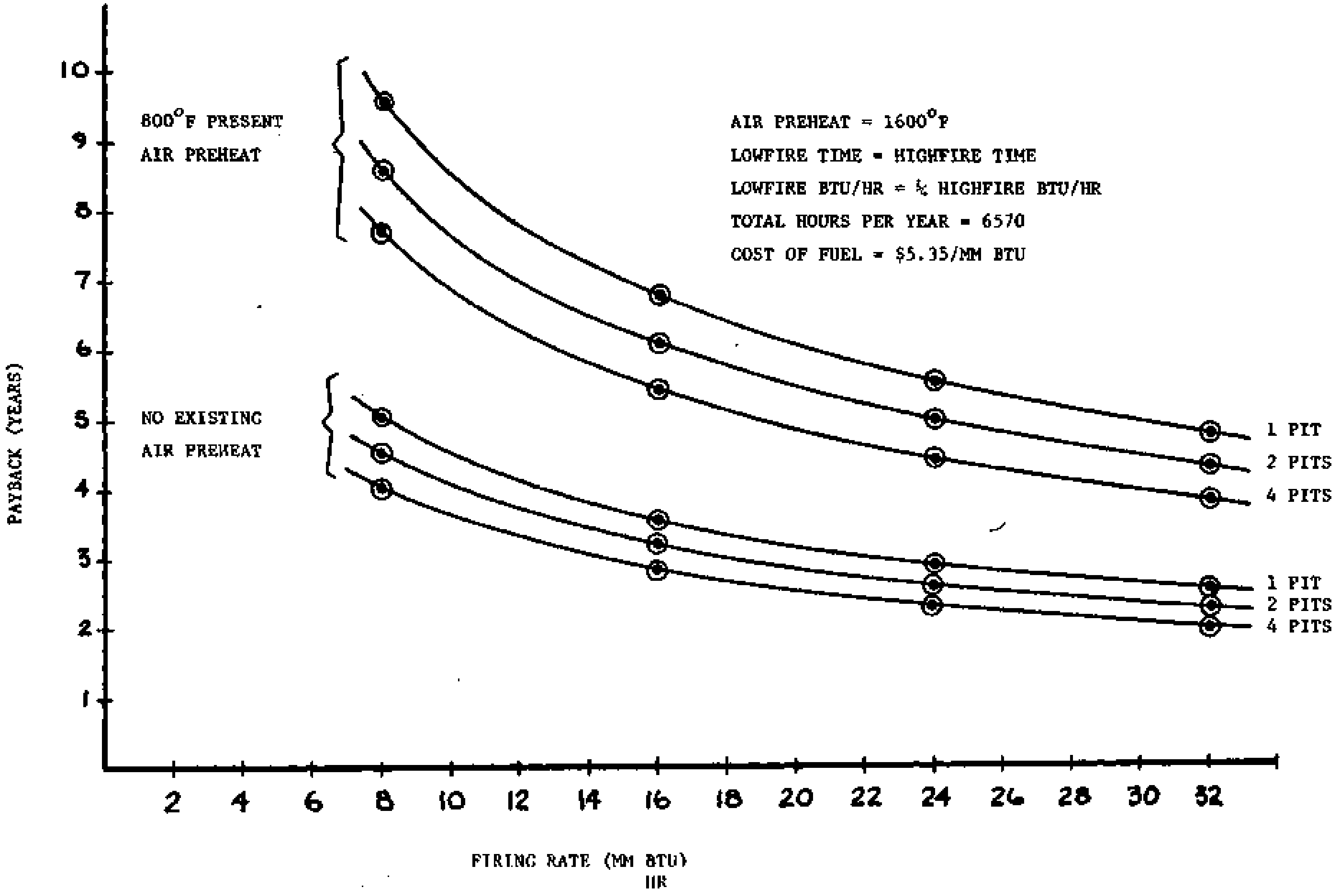
	High Fire	Low Fire
Flue Gas Temperature	2000°F	2200°F
Mixed Air Preheat Temperature	1480°F	1700°F
Existing Preheat Temperature	None	None
Time Fraction	1/3	2/3
Annual Fuel Usage		150,000 MM BTU
Present Fuel Cost ($/MM Btu)		2.79 (Oil)
Projected Fuel Cost ($/MM Btu)		$3.75
High Fire Rate (MM Btu/hr)		30
Low Fire Rate (MM Btu/hr)		10
Total Operating Hours per year		
Pit Btu Rating (MM Btu/hr)		30
Number of Pits		2

Results

Overall Percent Fuel Savings	43%
Fuel Cost Savings per Year per 2 pits	$ 282,000.00
Capital Cost - DOE Subsidized Cost Shared	2,300,000.00
Cost to Steel Co. @ 75 % - DOE Cost Shared	575,000.00
Capital Cost - Future Systems	1,000,000.00
Years Payback - DOE Cost Shared	2.0
Years Payback - Future Systems	3.5

Note: Based on fuel savings only. Increased savings or reduced capital cost from increased productivity not included.

GRAPH OF PAYBACK PERIOD VS. FIRING RATE



AIR PREHEAT = 1600°F
LOWFIRE TIME = HIGHFIRE TIME
LOWFIRE BTU/HR = ½ HIGHFIRE BTU/HR
TOTAL HOURS PER YEAR = 6570
COST OF FUEL = $5.35/MM BTU

FIGURE 24

APPENDIX A

CERAMIC RECUPERATOR THERMAL DESIGN

OBJECTIVE:

The object of this heat transfer analysis was to design a minimum volume, high temperature ceramic recuperator for steel soaking pit applications. Principal design requirements include:

1. A maximum air side pressure drop of 6 inches W.C.
2. A maximum flue side pressure drop of .2 inches W.C.
3. Flue gas passages must not plug with carryover particulate matter from the soaking pit.

SUMMARY:

The purpose of this study was to establish an optimized ceramic recuperator configuration from the various plausible designs. The performance requirements for the ceramic recuperator for a selected installation, which is representative of feasible steel soaking pit applications, is presented in Figure 9 (in the body of this report).

Most of the recuperator optimization was performed at the high fire point because it presents the most severe thermal and pressure drop requirements. The low firing rate performance requirements of the ceramic recuperator were not as difficult to achieve because of the lower air and flue flow rates. During low firing conditions, there is less flue gas flow than at the high fire condition, and therefore lower pressure drop and higher air preheat temperature.

A computer program was developed to expedite the performance calculations of approximately 45 different recuperator configurations. The program can accommodate variations in the recuperator's passage geometries and configurations, flow rates and temperature levels. The geometry which best satisfies the selected design point utilizes 2" x 10" flue gas passages and 1" x 3/8" air passages in a four-air-pass configuration. (See computer run No. 45).

DISCUSSION OF RESULTS:

A tabulation of the thermal and pressure drop results of six selected computer investigations of candidate recuperator designs is presented in Table A of this appendix. The most favorable of the design configurations were the three-flue-pass and the selected four-air-pass configurations (computer runs 34 and 45, respectively). The three-flue-pass version was abandoned primarily because occasional cleaning of fouled flue gas passages would necessitate removal of the relatively complicated manifolds.

Configurations in some computer runs exhibited excellent thermal performance but had excessive pressure drop. The configurations in runs 34 and 44 had satisfactory thermal and pressure drop performance. However, the volume was too large.

For the high fire condition, the predicted secondary air temperature is approximately 1760° F, which is quite close to the 1800°F objective required Air side pressure drop is predicted to be about 5.5 inches W.C. and flue side about .006 inches W.C. This meets the design point requirements of 6 inches W.C. maximum and .1 inches W.C., respectively.

CONCLUSIONS:

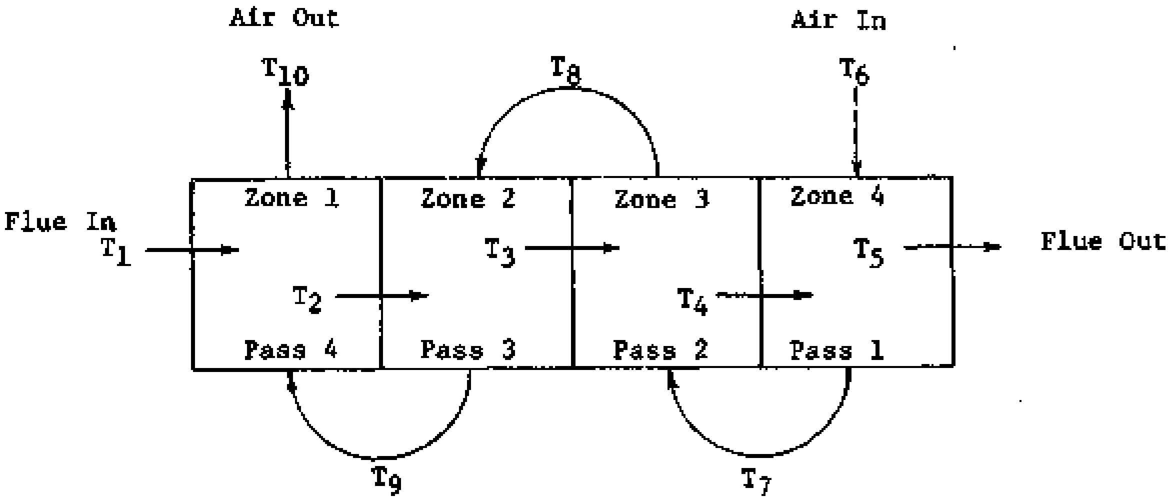
1. A very acceptable design configuration and geometry has been found for a selected steel soaking pit application.

2. If the recuperator is to be used in a clean flue gas environment, as from natural gas, then small flue gas passages may be used. This results in a smaller, more efficient recuperator. Flue gas side pressure drop with somewhat smaller passages (say, 1" x 8") would not be a problem. If, however, the recuperator is subjected to a dirty flue gas environment, as from coke oven gas, then larger passages would be more appropriate than small ones.

3. Multipassing is an effective means of increasing thermal performance by virture of increased gas velocity and by approaching counterflow performance. The number of passes should be as high as pressure drop limitations and structural capability permits.

4. Increased thermal performance is most responsive to an increase in gas velocity, but there is also a corresponding increase in pressure drop. If it can be shown that the ceramic recuperator is capable of tolerating larger pressure differences between its air and flue gas sides than is presently assumed, then large air side pressure drops would be permissible; and a significant increase in the thermal performance is possible.

GUIDE TO TABULATED RESULTS



Recuperator Zones 1, 2, 3 and 4 are the same as air passes 4, 3, 2 and 1.

Temperatures T_1 through T_5 correspond to the flue gas inlet and outlet temperatures of each zone.

Temperature T_6 through T_{10} correspond to the air inlet and outlet temperatures of each zone.

Re - Reynolds Number
h_c - convection coefficient
h_r - radiation coefficient
U - overall heat transfer coefficient

TABLE A — TYPICAL CERAMIC RECUPERATOR THERMAL COMPUTER CALCULATIONS

RUN	34	38	39	42	44	45
Air Side Hole Size	1.00"x.25"	1.00"x.75"	.75"x.20"	1.00"x.50"	1.00"x.375"	1.00"x.375"
Holes, Zone 1	2200	315	315	1775	930	870
Holes, Zone 2	2200	420	-	1775	930	870
Holes, Zone 3	2200	525	-	1775	930	580
Holes, Zone 4	-	630	-	1775	930	580
Flue Side Hole Size	10"x3"	3.00"x10.00"	.75"x.30"	1.00"x3.00"	2.00"x10.00"	2.00"x10.00"
Holes, Zone 1	63	160	300	1215	240	224
Holes, Zone 2	63	160	-	1215	240	224
Holes, Zone 3	63	160	-	1215	240	224
Holes, Zone 4	-	160	-	1215	240	224
Total Area (Ft.^{2})	2888	2200	37.5	5568	3666	3422
Total Volume (Ft.^{3})	440.1	385.5	1.042	437.4	427.4	405.5
Area/Volume	6.56	5.71	36.0	12.73	8.58	8.44
Side Making Passes	Flue	Air	-	Air	Air	Air
Air Side Re, Zone 1	794	3952	1110	805	1667	1786
Air Side Re, Zone 2	949	3182	-	863	1746	1877
Air Side Re, Zone 3	1446	3092	-	1074	3128	3368
Air Side Re, Zone 4	-	3707	-	1554	4674	5014
Flue Side Re, Zone 1	3902	1518	519	807	1358	1456
Flue Side Re, Zone 2	4019	1560	-	846	1417	1518
Flue Side Re, Zone 3	4057	1585	-	878	1473	1577
Flue Side Re, Zone 4	-	1596	-	919	1550	1657
Air Pres. Drop ("w.c.)	.887	2.859	.075	.787	5.027	5.452
Flue Pres. Drop ("w.c.)	.043	.002	.111	.036	.006	.006

TABLE A (Continued) Page 2 of 2

RUN	34	38	39	42	44	45
Air Side h_c, Zone 1	6.15	8.67	4.67	2.85	4.21	4.21
Air Side h_c, Zone 2	5.04	6.52	-	2.53	3.81	3.82
Air Side h_c, Zone 3	3.50	5.23	-	2.07	8.81	9.28
Air Side h_c, Zone 4	-	4.15	-	1.49	8.11	8.55
Flue Side h_c, Zone 1	2.07	3.31	6.75	2.63	1.99	2.06
Flue Side h_c, Zone 2	1.99	2.60	-	2.57	1.97	2.04
Flue Side h_c, Zone 3	1.77	2.09	-	2.42	2.37	2.49
Flue Side h_c, Zone 4	-	1.67	-	2.20	2.18	2.28
Flue Side h_r, Zone 1	3.71	3.77	Small	1.70	3.11	3.10
Flue Side h_r, Zone 2	3.03	3.44	-	1.57	2.84	2.84
Flue Side h_r, Zone 3	2.13	2.89	-	1.34	2.24	2.24
Flue Side h_r, Zone 4	-	2.09	-	1.06	1.47	1.47
U, Zone 1	2.80	3.70	2.71	1.66	2.21	2.22
U, Zone 2	2.37	3.00	-	1.52	2.04	2.06
U, Zone 3	1.75	2.46	-	1.30	2.89	2.99
U, Zone 4	-	1.92	-	.99	2.42	2.51
Temperature 1	2000	2000	2000	2000	2000	2000
Temperature 2	1813	1899	1531	1874	1888	1888
Temperature 3	1553	1755	-	1697	1730	1732
Temperature 4	1260	1556	-	1473	1501	1505
Temperature 5	-	1299	-	1230	1210	1220
Temperature 6	-	75	-	75	79	80
Temperature 7	70	654	-	618	725	714
Temperature 8	725	1085	-	1102	1215	1199
Temperature 9	1281	1390	74	1473	1546	1525
Temperature 10	1672	1602	725	1734	1777	1758

APPENDIX B

Proposal
For
ULTRA HIGH TEMPERATURE RECUPERATION SYSTEM

Prepared For

A SOUTHERN STEEL COMPANY

Prepared By
Contract Research and Development
Technical Center-Capital Goods
MIDLAND-ROSS CORPORATION
Toledo, Ohio

October 6, 1978

SOUTHERN STEEL CORPORATION

RECUPERATOR SYSTEM FOR ULTRA-HIGH TEMPERATURE FLUE GASES

1.0 SERVICES AND EQUIPMENT TO BE PROVIDED BY MIDLAND-ROSS

The equipment and services to be provided by Midland-Ross are summarized below in Section 1.1. Descriptions of the equipment, demolition and installation, and engineering follow in Sections 1.2 through 1.4.

1.1 LIST OF SERVICES AND EQUIPMENT TO BE PROVIDED BY MIDLAND-ROSS

1.1.1 Materials

a. Soaking Pit Burner
b. Air and Fuel Piping and Valves
c. Fabricated and Plain Steel
d. Refractories and Insulation
e. Advanced Ceramic Recuperator
f. Metallic Recuperator
g. Combustion Air Blower, Motor, Starter
h. Flue Gas Exhaust Ejector, Motor, Starter
i. Exhaust Ductwork
j. Instrumentation and Control Equipment
k. Safety Aids

1.1.2 Field Labor and Demolition

a. Craft Labor to Install New Equipment
b. Field Wiring Material and Craft Labor
c. Erection Tools and Equipment
d. Superintendent of Erection

1.1.3 Engineering

a. Demolition Drawings
b. Design Drawings
c. Detail Drawings
d. Installation Drawings
e. Calculations
f. Operating Instructions

1.2 DESCRIPTION OF EQUIPMENT

General Arrangement

The general arrangement of the soaking pit area (pits No. 7 and No. 8) and the new equipment to be supplied by Midland-Ross is as shown in attached Midland-Ross drawings No. D 5051D and No. D 5052D. The ceramic recuperator for each pit will be located inside the building between column rows C and C_1, at elevation 132'-1 1/2". The flue width will be widened outward from the battery centerline to accommodate the ceramic recuperator width. The existing pit damper will be left intact. The metallic recuperator for each pit will be located immediately outside the existing building above the existing flues. Flue ducting and a common jet exhauster for the two pits will also be located outside, just past the existing battery flue manifold. A lean-to enclosure approximately 20' x 22' will be required to house the jet exhauster blower, the two primary (high pressure) air blowers, and the two metallic recuperator dilution air fans, including all of their motors.

Ceramic Recuperator

The ceramic recuperator concept is shown in Figure 3. This advanced, high temperature, high efficiency recuperator will be manifolded to have four air passes. The flue gas passages (2" x 10" cross section) will be one "straight shot" through the recuperator. This large cross section and straight shot will permit use of an air lance should it be necessary to clean out these flue gas passages. Each recuperator will be assembled in place using 16 prefabricated prefired ceramic modules manufactured by a ceramic supplier. The recuperator air manifolding, insulation and structure will also be assembled on the site.

Metallic Recuperator

The metallic recuperator is in development at the present time by Des Champs Laboratories, Inc. It will be a highly efficient, compact recuperator. The metal for the heat resistant portions of the unit will be type 309 stainless steel. Separation of the flue gases from the primary combustion air will be by means of the patented "Z" duct construction. The metallic recuperator will be suitable for a nominal combustion air pressure of 5.0 psig.

(1) Temperature Controller

This instrument receives input from a pit thermocouple. This controller ultimately determines the total input of heat to the pit via combustion air and air/fuel ratio control systems, described below.

(2) End Differential Heating Controller

This instrument receives thermocouple inputs from thermocouples at both ends of the pit. The controller controls the burner characteristics so the larger portion of the hot combustion products are directed to the "colder" end of the pit.

(3) Hi-Limit Temperature Controller

This controller provides a conventional two-position relay output to shut down the combustion system in the event of excessive pit temperature. The input is from a pit thermocouple used only for this purpose.

Combustion Air System

The combustion air control system provides metallic recuperator flow control, metallic/ceramic flow ratio control and blower surge control. The signal generated by the pit temperature controller is converted to a pneumatic signal which operates the pneumatic control valve on the cold air side of the metallic recuperator. The metallic air flow is thus adjusted according to the pit temperature level, the ceramic air flow is slaved to the metallic air flow by a controller which accepts input from an orifice in the metallic recuperator cold air input line and operates a valve in the ceramic recuperator cold air input line.

An anti-surge device will be added to the existing combustion air blower which will supply air to the ceramic recuperators. Anti-surge devices of the motor current sensing and venting type are also planned for the new metallic high pressure air blowers.

Air/Fuel Ratio and Oxygen Control Systems

The ceramic and metallic air flow signals (described above) are further processed to provide control of natural gas or light fuel oil inputs. The individual air flows to the metallic and ceramic recuperators are summed and the resulting sum is the input to a fuel flow controller. The fuel flow is thus slaved to the total air flow.

Burner

A new burner is presently being designed for use with ultra-high temperature preheated combustion air. It will be capable of firing on natural gas or No. 2 fuel oil, consistent with current fuel requirements for your soaking pits 7 and 8. One such burner will be installed in each pit. The centerline of the burner will be at the same elevation as the burner presently employed. The maximum firing rate for each burner will be 20,000,000 BTU's per hour while firing with a preheat air temperature of 1500 to 1700° F.

The new burner incorporates an integral jet pump to aspirate the low pressure secondary air flow into the high pressure primary air. The velocity of the primary air flow is used to create a momentum force in the combustion gases leaving the burner. This system will be capable of providing temperature control from the front to the back of the soaking pit by adjusting the momentum on high fire.

Combustion Control System

Midland-Ross will supply a new instrumentation and control system for each soaking pit. The system is shown schematically on Drawing No. D 4047D. The control system will control the following:

a. Soaking pit temperature
b. Combustion air flow - both primary air (to metallic recuperator) and secondary air (to ceramic recuperator)
c. Total air/fuel ratio
d. Dilution air cooling system
e. Safety aids
f. Process recording systems for temperature recording, flow recording and O_2 recording

These control systems are briefly described as follows:

Thermal Input Control System

The soaking pit temperature is controlled by three different controllers working in conjunction with each other. These are:

Should the ceramic recuperator begin, at some time, to leak air into the flue gas stream, an auxiliary control system has been provided to maintain the proper air/fuel ratio. Uncompensated leakage would cause the combustion system to operate rich since the ceramic air is metered on the inlet side of the recuperator. The flue gas oxygen content would thus drop. A flue gas oxygen analyzer and current proportioning output controller would call for additional air supply to the ceramic recuperator inlet to compensate for the air leakage. This air would bypass the ceramic recuperator air metering orifice in order to avoid upsetting the fuel-following-air feature.

Metallic Recuperator Auxiliary Cooling Systems

Overtemperature protection for the metallic recuperator will be provided. This will be a low pressure blower to deliver dilution air into the flue gas flow upstream of the metallic recuperator when needed. The blower will be controlled by a controller with input from a thermocouple in the flue gases just upstream from the recuperator.

Fuel and Air Trains

Suitable safety aids are to be applied on fuel, atomizing air, and combustion air sources. These will provide system shutdown in the event of power interruption, excessive or inadequate pressures or excessive pit temperatures. Interlocks will be provided to establish the proper sequences for light-off, normal operation and shutdown of the system.

Flame Supervision

Ultra-violet supervision is to be applied to the main burner flame and interfaced to the fuel and air trains. A 1400° F contact will be provided, such that the supervision system acts as an indicator only when pit temperatures exceed this value.

Process Recording Equipment

Three strip chart recorders will be provided for the recording of process variables in each pit.

(1) Temperature Recording
(2) Flow Recording
(3) Flue Gas Oxygen Concentration Recording

The controller applied to the oxygen analyzer will contain a strip chart recorder for this purpose.

Pit Pressure Control

The existing instrumentation, recorder, operator and water cooled damper will continue to provide pit pressure control in existing form.

Air Blowers

New blowers will be required by each pit for the primary combustion air and for the metallic recuperator dilution air. The high pressure primary air to be preheated in the metallic recuperator will be supplied by a 5 psig, 1700 SCFM blower (one for each pit). The dilution air will be supplied by a 1500 SCFM blower at 3" w.c. (one for each pit).

Low pressure air to be preheated in both ceramic recuperators will be supplied by the existing North American combustion air blower. A flow rate of 3000 SCFM at 8" w.c. will be required for each of the ceramic recuperators.

Jet Exhauster

The one exhauster will exhaust both of the pits in this battery. The exhaust from the two pits will be brought together into this one exhauster after the metallic recuperators, as shown in layout drawing D 5051D. The jet exhauster is rated at 3" w.c. and 38000 ACFM at 1200° F. It is powered by a 60 HP centrifugal air blower.

1.3 DEMOLITION AND INSTALLATION OF EXISTING AND NEW EQUIPMENT

Midland-Ross has estimated the cost for the demolition of existing equipment required to install the new recuperators, blowers, burner and instrumentation. Midland-Ross will remove the existing flues and piping as required to accommodate the new equipment. It is anticipated that the existing stack will be left in place and blocked off from pits No. 7 and No. 8. It will continue to be used for pits No. 5 and No. 6. It will be necessary to shut down all four pits to this stack for approximately two weeks to build this block-off wall.

The new equipment, including piping and wiring, will be installed by Midland-Ross or its subcontractors. The equipment has been laid out to minimize any modification or demolition required to the soaking pit buildings and foundations. The pit burner wall will be modified to form the new burner port.

Midland-Ross will restart the new equipment and anticipates being on the site for the time required for the initial data collection and evaluation. Midland-Ross will be returning to the site periodically after the original startup to evaluate the performance of the recuperation over a normal operating period on the soaking pits.

1.4 ENGINEERING

Midland-Ross will provide complete engineering for the entire project. They will supply to the Steel Company a complete set of arrangement and assembly drawings required for the construction and maintenance of the new equipment. Certain detail and assembly drawings will be maintained by Midland-Ross because of their proprietary nature. A complete set of operating instructions and maintenance manuals will be provided with the equipment when installation is complete.

2.0 SERVICES AND FACILITIES TO BE PROVIDED BY THE STEEL COMPANY

The facilities and services that will be necessary for The Steel Company to provide are listed below:

2.1 LIST OF SERVICES AND FACILITIES TO BE PROVIDED BY THE STEEL COMPANY

2.1.1 Test Site

a. Access to site - soaking pits #7 and #8

b. Use of site for tests

c. Place for location of test monitoring gear

d. Office space for technicians

2.1.2 Utilities

a. Construction adaptation to tie into basic utilities as required

b. Use of fuel, power, water and control air during test period

2.1.3 Data Acquisition

Production data and process data from 2 pits with recuperation and 2 pits without recuperation.

a. Data recording

b. Data reporting

2.1.4 Technical Aid

Instrument calibration and installation

2.1.5 Site Modifications

50% of cost of alterations to permanent buildings - real property.

2.2 DESCRIPTION OF PRINCIPAL SERVICE OR FACILITY ITEMS

Further clarification of service or facility items listed above is as follows:

2.2.1 Test Site

The two pits which were indicated as being the most favorable pits for retrofit to high temperature recuperation are pits #7 and #8. The two non-recuperated pits that would be monitored for process and production data for comparison with pits #7 and #8 are pits #5 and #6.

2.2.2 Data Acquisition

Process data and production data will be required as related to measuring fuel usage, fuel savings, production rate, productivity and recuperator leakage. Thus, required data will include ingot data, tons of steel, temperatures, flow rates, O_2 in flue gas and time.

APPENDIX C

PHASE I
Ultra-High Temperature Recuperator Program
Metallic Recuperator Design

(Work Completed During Phase I)

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INTRODUCTION

This program was initiated in March 1978. It was performed as a subcontract to Midalnd Ross Corporation under Government Contract No. EC-77-C-07-1672. The purpose of the program was to design a metallic recuperator to operate in series with an ultra-high temperature tile recuperator to give a high efficiency system for supplying preheated combustion air to burners on a steel mill soaking pit.

Several sets of operating parameters were given during the course of the program. The first set of conditions was investigated in Task I, Thermodynamic Analysis. The second set of conditions together with the thermodynamic computer program and output data appear as Appendix I. The developed computer program permits a metallic plate-type recuperator design satisfying any flow and thermodynamic design constraints.

The work statement delineating the program is given below:

Task I - Thermodynamic Design

a. Define thermodynamic design parameters.

b. Design thermodynamic configuration.

c. Derive flow and thermal characteristics of design as function of temperature, pressure drop, flow rates and flow ratios based on an air analysis.

Task II - Mechanical Design

a. Design the heat transfer matrix to satisfy Task I

b. Design structural housing to satisfy pressure temperature and other environmental constraints.

Task III - Materials Selection

a. Select matrix material to best withstand exhaust products at temperatures of operation with consideration given to economics and ease of fabrication.

b. Select refractory sealant.

c. Select thermal insulation.

d. Select casing material.

Task IV - Materials and Component Testing

a. Test heat transfer plate section under pressure differential and temperature.

b. Fabricate and test in the laboratory other recuperator components as required to enable DLI to establish final design parameters.

Task V - Control System

Design a thermal control system to prevent the metallic recuperator from overheating.

Task VI - Optimize Unit Size

Task VII - Prepare Drawings, Specification and Cost Estimate.

Task VIII - Prepare report that includes results of laboratory tests, justification for materials selected, anticipated performance under demonstration unit operation and definition of post-operation materials tests.

The following was completed prior to work stoppage:

Task I - Thermodynamic Design Complete

a. Defined thermodynamic design parameters.

b. Designed thermodynamic configuration.

c. Derived flow and thermal characteristics of design as function of temperature, pressure drop, flow rates and flow ratios.

Task II - Mechanical Design Complete

a. Designed the heat transfer matrix to satisfy Task I.

b. Designed structural housing to satisfy pressure, temperature and other environmental constraints.

Task III - Materials of Construction were Selected

a. Selected core matrix materials to best withstand exhaust products at temperature of operation with consideration given to economics and ease of fabrication.

b. Selected refractory sealant.

c. Selected thermal insulation.

d. Selected casing material.

Task IV - Determined Techniques and Materials for Testing

a. Met with Midland-Ross personnel to determine method and material samples required for thermal shock and materials integrity tests.

b. Selected and initiated tests at DLI to determine effects of pressure, temperature and potential corrosion on structural integrity of core matrix.

Task VI - Optimized Unit Size for Latest Intended Application

Task VII - Prepared Overall Design Drawings, Specifications and Cost Estimates for Specific Job.

The work remaining to be performed under the Phase I Statement of Work is as follows:

Task IV - Materials and Compenent Testing

Fabricate samples for test at Midland-Ross.

Task V - Control System

Design a thermal control system to prevent the metallic recuperator from overheating.

Task VIII - Prepare Final Report that includes Results of Laboratory Tests and Definition of Post Operation Materials Tests.

METALLIC RECUPERATOR

TASK I

Thermodynamic Analysis

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HIGH TEMPERATURE METALLIC RECUPERATOR

1. Thermodynamic Design

1.1 Introduction

A high temperature plate-type metallic recuperator is to be designed in modular form to satisfy the following conditions:

Flue gas temperature, °F	1400
Heat transfer effectiveness, %	70
Firing rate, BTU/hr	25,000,000
Air flow rate, SCFM	1710
Flue gas flow rate, SCFM	4500
Flue gas static pressure, inches w.c.	+0.5 to -0.5
Air side static pressure, psig	5
Flue gas pressure drop, inches w.c.	1.0
Air side pressure drop, inches w.c.	15.0

In addition, consideration will be given to flue gas temperatures to 1900°F and air side delivery temperatures from 900°F to 1400°F.

The basic plate heat exchanger concept to be used in this program has been used extensively in the past on low to medium temperature applications (-50 to 1000°F) and at relatively low pressures (to 50 inches of w.c.). Thermodynamic parameters established at these less extreme conditions will be extensively used to arrive at the thermodynamic and flow parameters for the present program.

Before proceeding into the thermodynamic design, a brief description of the physical concept of the proposed recuperator will be given.

Figure 1.1 illustrates a sectional view of the proposed recuperator with the hot exhaust gas on one side of a formed and folded metallic

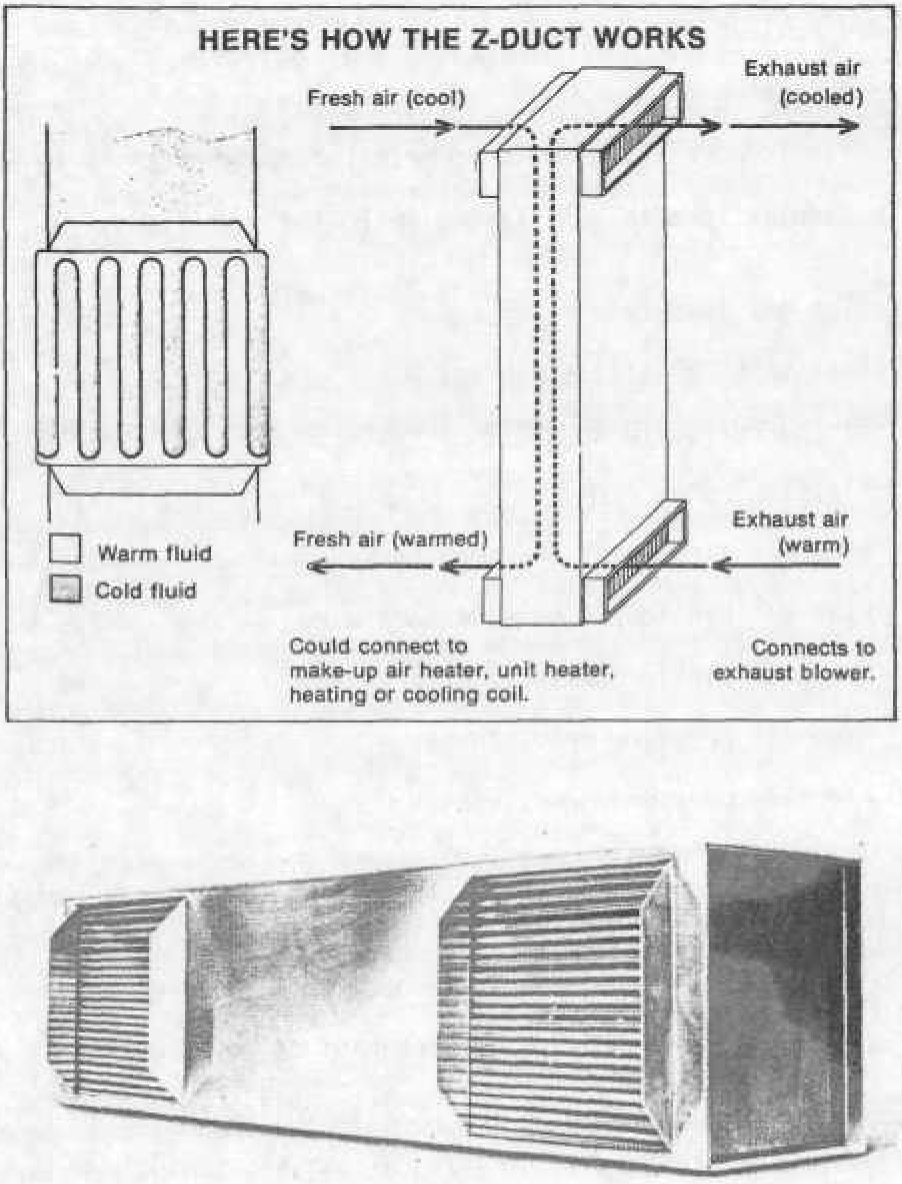

HERE'S HOW THE Z-DUCT WORKS
Fresh air (cool)
Exhaust air (cooled)
Warm fluid
Cold fluid
Fresh air (warmed)
Exhaust air (warm)
Could connect to make-up air heater, unit heater, heating or cooling coil.
Connects to exhaust blower.

Figure 1.1

plate and the fresh combustion air on the other side. The plate that separates the gas streams in this unit is continuous. That is, instead of using many individual plates and welding them together at the seams to give the desired flow passages, as is done in conventional plate recuperators, the Z-Duct(R) concept uses a large continuous coil of material. The material is drawn from the coil, run through a press where strengthening ribs and spacing dimples are formed into the material, and then fed to a mechanism where the plates are folded one upon another. The extreme ends of the formed coil are welded to the recuperator casing. The lengthwise edges of the folded material are subsequently embedded into a structurally reinforced refractory cement to prevent leakage between gas streams as shown in Figure 1.2.

To complete the basic recuperator module, a cover plate must be added to direct the gas flow down into the interstices of the core matrix.

1. 2.0 Gas Flow Pattern within Z-Duct

When designing a high efficiency recuperator, the first constraint that must be considered is that the gas flows should be in opposite direction to each other as they pass through the unit. A counter-flow device having infinite length would be capable of transferring the total available energy. Whereas, if the flow were to be parallel it would be capable of transferring a maximum of 50 percent of the available energy, as shown in Figure 1.3.

Z DUCT™ ENERGY RECOVERY UNIT

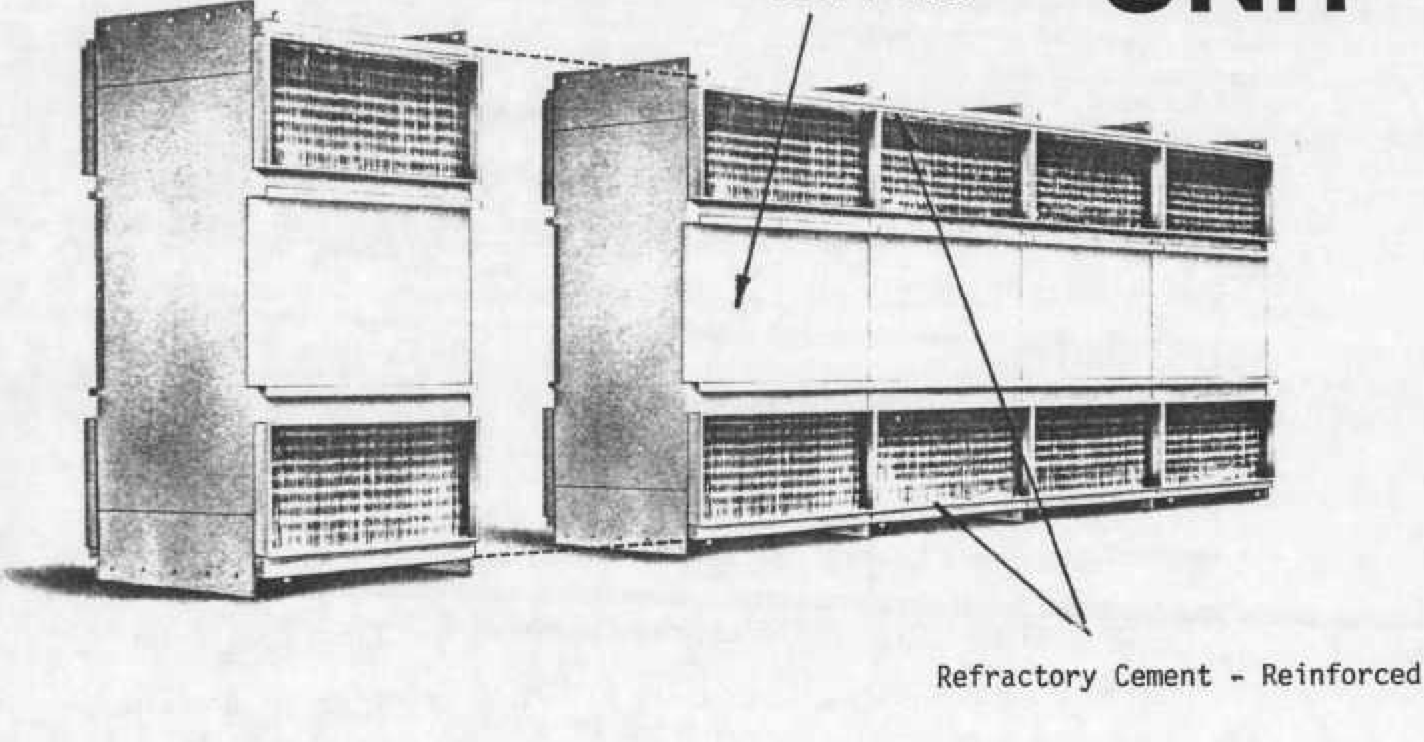


Figure 1.2

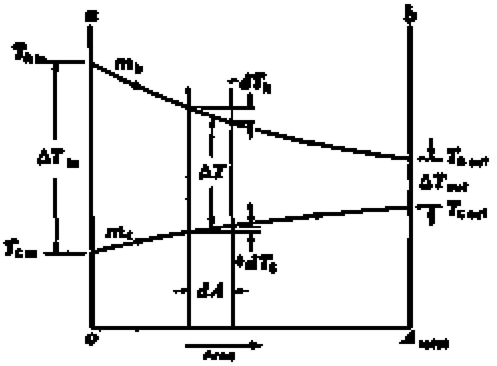


FIG. 1.3a Temperature distribution in single-pass parallel-flow heat exchanger.

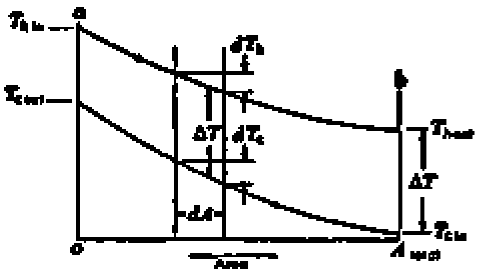


FIG. 1.3b Temperature distribution in single-pass counterflow heat exchanger.

Figure 1.4illustrates the approximate flow pattern and stream lines within the Z-Duct channels. As the ratio of H/W increases, the flow approaches that of a counterflow recuperator. Typical ratios for Z-Duct units are 2.15 to 4.5. The ratio proposed for the present recuperator is

$$\frac{H}{W} = \frac{34.6}{16} = 2.156$$

Each of the flow streams, for either of the gas flows, has an equal pressure drop through the heat exchanger which is expressed by

$$\frac{\Delta P}{P_1} = \frac{G^2}{2gc}\ \frac{v_1}{P_1}\left[\underbrace{K_c + 1 - \sigma^2}_{A} + \underbrace{2\left(\frac{v_2}{v_1} - 1\right)}_{B} + \underbrace{f\,\frac{A}{A_c}\ \frac{v_m}{v_1}}_{C} - \underbrace{\left(1 - \sigma^2 - K_e\right)}_{D}\frac{v_2}{v_1}\right]$$

where: A is the entrance effect

B is flow acceleration

C is core friction

D is exit effect

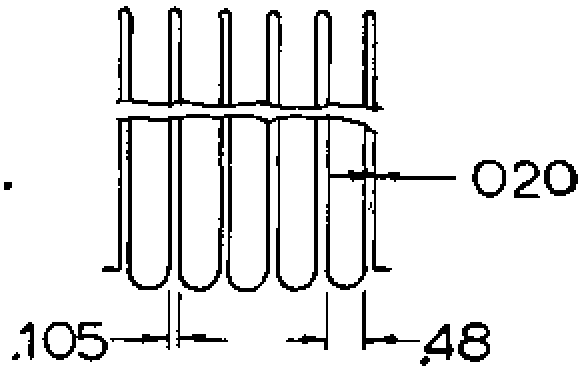


Figure 1.6 Plate spacing.

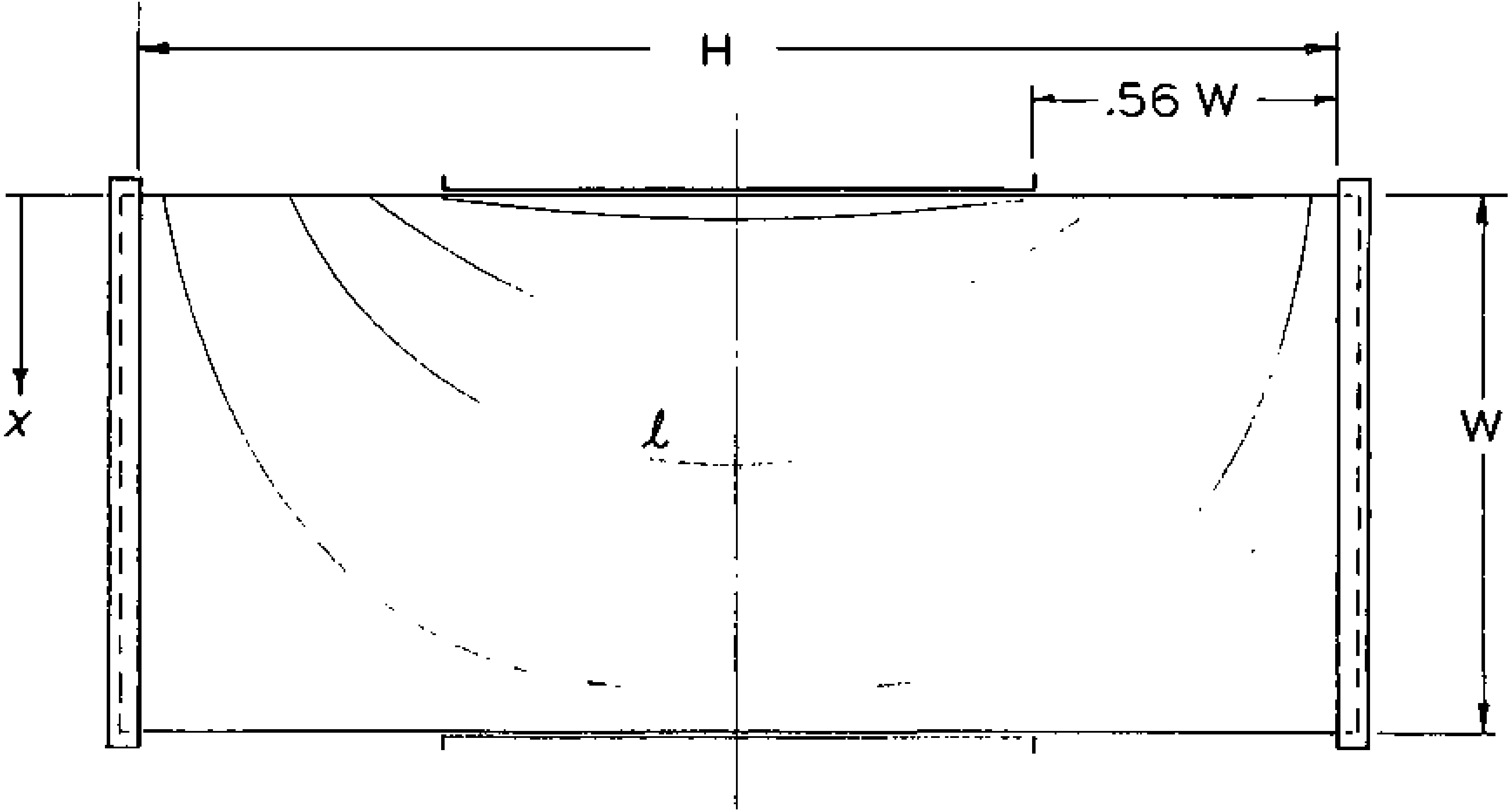


Figure 1.4 Flow path within recuperator

For a first order approximation of the velocity distribution it will be assumed at this point that the exit and entrance losses are the same for all flow streams and that the flow is at constant temperature. The above relationship then reduces to

$$\frac{\Delta P}{P_1} = \frac{G^2 \, v_1}{2gc \, P_1} \; f \, \frac{A}{Ac} \quad \frac{v_m}{v_1}$$

which can be further reduced to

$$V = \left(\frac{C}{\ell}\right)^{1/2}$$

where ℓ is the approximate flow stream length and can be expressed as

$$\ell = 3.12X + (H - 1.12W)$$

and C is a constant for a given set of thermodynamic and design conditions.

For a unit depth of heat exchanger

$$d\overset{o}{\text{Vol}} = \tfrac{1}{2}V dx = \text{ft}^3/\text{sec}$$

$$\overset{o}{\text{Vol}} = \frac{C^{1/2}}{2} \int_0^W \frac{dx}{\left[3.12x + H - 1.12W\right]^{1/2}}$$

Solving

$$\overset{o}{\text{Vol}} = \frac{0.641}{2} \; C^{1/2} \left[\sqrt{2W + H} - \sqrt{H - 1.12\,W}\right]$$

$$C^{1/2} = \frac{2 \, \overset{o}{\text{Vol}}}{0.641 \left[\sqrt{2W + H} - \sqrt{H - 1.12W}\right]}$$

Therefore, the velocity of any flow stream can be approximated for a given configuration and flow through the Z-Duct

$$V_x = \frac{2 \, \overset{o}{\text{Vol}} \, \sqrt{3.12x + H - 1.12W}}{0.641 \left[\sqrt{2W + H} - \sqrt{H - 1.12W}\right]}$$

The shortest and most direct flow stream is the one at which $x = 0$. To design the recuperator to satisfy the pressure drop constraints this path will be analyzed. The pressure drop along other flow paths will be essentially the same.

1.3.0 Recuperator Heat Transfer and Flow Friction Design

1.3.1 Effectiveness

The primary constraint imposed on the metallic recuperator in this program is that it must have an "exchanger heat transfer effectiveness" of 70 percent. Effectiveness, E, is defined as

$$E = \mathcal{E} = \frac{q}{q\ \max} = \frac{c_h\ (t_{h,in} - t_{h,out})}{c_{\min}\ (t_{h,in} - t_{c,in})} = \frac{c_c\ (t_{c,out} - t_{c,in})}{c_{\min}\ (t_{h,in} - t_{c,in}}$$

It is to be noted that, given the operating conditions t_h,in, t_e, in, c_h, and c_c, the magnitude of E completely defines the heat transfer performance. If $c_h = c_{min}$, then $E = (t_{h,in} - t_{h,out})/(t_{h,in} - t_{c,in})$, which is a "temperature effectiveness" for cooling the hot fluid. But if $c_c = c_{min}$, then $E = t_{c,out} - t_{c,in})/(t_{h,in} - t_{c,in})$ which is the "temperature effectiveness" for heating the cold fluid. However, the general definition of effectiveness, as given above, is not a "temperature effectiveness," but rather a "heat transfer effectiveness".

1. 3.2 Number of Recuperator Heat Transfer Units

The number of heat transfer units N_{tu} is a nondimensional expression of the "heat transfer size" of the recuperator. It is defined by

$$N_{tu} = \frac{A\ U_{avg}}{c_{min}}$$

Figure 1.5 gives the relationship between E and N_{tu} for a counterflow recuperator.

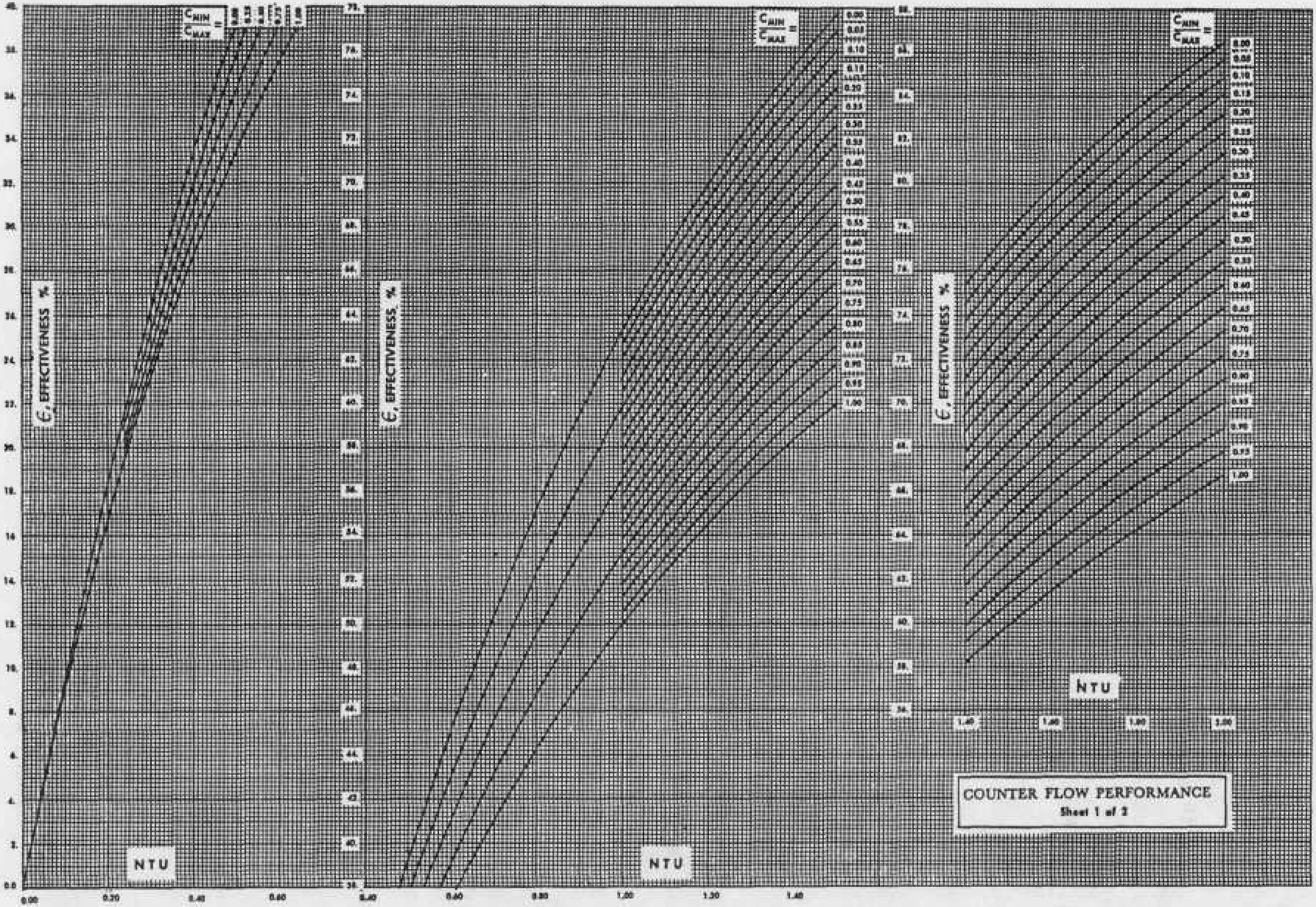

$\frac{C_{MIN}}{C_{MAX}}$ =
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
∈, EFFECTIVENESS %
NTU
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
COUNTER FLOW PERFORMANCE
Sheet 1 of 3

Figure 1.5

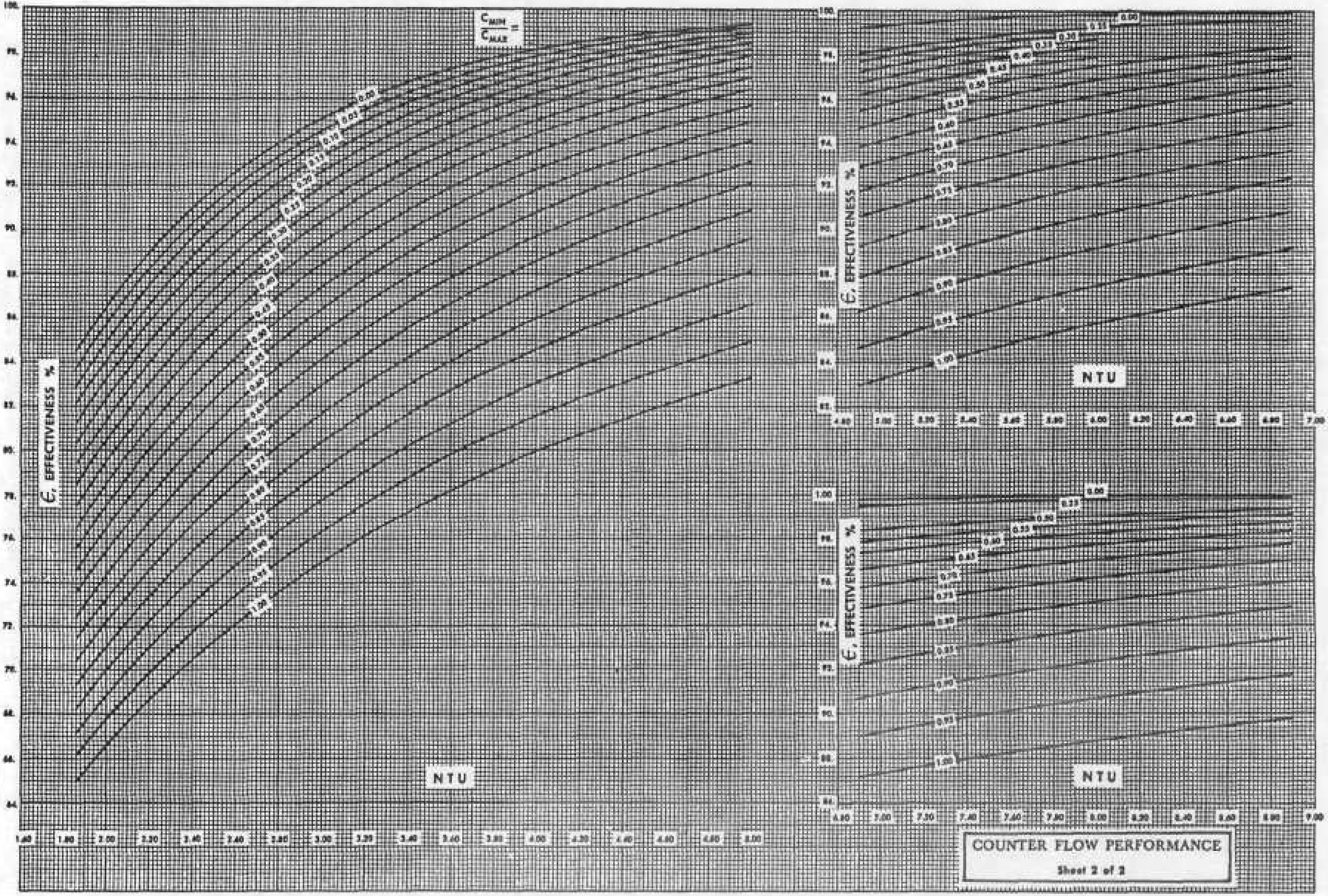


Figure 1.5 Continued

From paragraph 1.1 the values of c_{min} and c_{max} for this program are:

$$c_{min} = 1710 \frac{ft^3}{min} \times 0.075 \frac{lb}{ft^3} \times 60 \frac{min}{hr} \times 0.25 \frac{btu}{lbF} = 1924 \frac{btu}{hr^oF}$$

$$c_{max} = 4500 \times 0.075 \times 60 \times 0.26 = 5265 \frac{btu}{hr^oF}$$

The gas temperatures are:

$$t_{h,in} = 1400 \text{ F}$$

$$t_{c,in} = 70 \text{ F}$$

Therefore,

$$E = 0.70 = \frac{5265 \,(1400 - t_{h,out})}{1924 \,(1400 - 70)}$$

and

$$t_{h,out} = 1060^oF$$

From air energy balance

$$t_{c,out} = 1000^oF$$

The value for N_{tu} from Figure 1.5, for a value of E = 0.7 and $c_{min}/c_{max} = 0.37$, is 1.44. Therefore

$$1.44 = \frac{N_f \; A \; U_{avg}}{1924}$$

or

$$U \; A_{avg} = \frac{2771}{N_f} = \frac{2771}{0.85} = 3260$$

Where N_f is a factor that takes into consideration potential fouling as well as non-effective heat transfer area within the recuperator. It is assumed for this design that N_f has a value of 0.85.

This value of $A \; U_{avg}$ must be attained in order to achieve the desired minimum recuperator effectiveness. The area, A, for a plate recuperator is the total value of the effective plate transferring heat which, for this design, is assumed to be the entire area of the folded and formed Z-Duct matrix. U_{avg} is defined by

$$\frac{1}{U_{avg}} = \frac{1}{h_{h,avg}} + \frac{a}{K_{avg}} + \frac{1}{h_{c,avg}}$$

and is the overall average heat transfer conductance. The term "a" is the plate thickness and K is the thermal conductivity of the plate.

The convective film coefficiencts h_c and h_h are complex functions of the surface geometry, fluid properties, and flow conditions. For the Z-Duct core matrix the convective film coefficient has been determined by experiments to follow the relation

$$h = 0.03448 \frac{K}{D_h} (Re)^{0.8} \quad (Pr)^{0.333}$$

where K is the thermal conductivity of the fluid.

Since this recuperator design is based on an air analysis the following is a tabulation of the approximate average fluid conditions existing within the proposed recuperator.

$$t_{c,in} = 70^{0}\ F \ ; \ t_{c,out} = 1000^{0}F \ ; \ t_{c,avg} = \frac{70 + 1000}{2} = 535^{0}F$$

$$t_{h,in} = 1400^{0}F \ ; \ t_{h,out} = 1060^{0}F \ ; \ t_{h,avg} = \frac{1400 + 1060}{2} = 1230$$

$$c_{p,c} = 0.25 \frac{btu}{lb^{0}F} \ ; \ c_{p,h} = 0.26 \frac{btu}{lb^{0}F}$$

$$K_c = 0.025 \frac{btu}{hrft^{0}F} \ ; \ K_h = 0.0363 \frac{btu}{hrft^{0}F}$$

$\rho_c = 0.040 \frac{lb}{ft^3}$; $\rho_h = 0.0236 \frac{lb}{ft^3}$

$\mu_c = 1.92 \times 10^{-5} \frac{lb}{secft}$; $\mu_h = 2.67 \times 10^{-5} \frac{lb}{secft}$

$Pr_{,c} = 0.68$; $Pr_{,h} = 0.70$

$Pr_{,c}^{0.333} = 0.88$; $Pr_{,h}^{0.333} = 0.89$

$m_h = 5.625 \frac{lb}{sec}$; $m_c = 2.1375 \frac{lb}{sec}$

$c_{min} = 1924 \frac{btu}{hr^{o}F}$; $c_{max} = 5265 \frac{btu}{hr^{o}F}$

$$\frac{c_{min}}{c_{max}} = 0.37$$

As a result of the pressure drop constraints placed on the recuperator, as well as potential fouling problems on the hot gas side, the gas flow channels, at this point, are assumed to have the configuration as shown in Figure 1.6. The exhaust channel has a plate spacing of 0.5 -inch and the combustion air channel has a spacing of 0.125-inch. This configuration, together with an H value of 34.5 inches and a W value of 16 inches will be investigated to determine if it meets the thermodynamic design criteria.

The procedure will be to determine the size of the recuperator to satisfy the heat transfer requirements and then to determine if the pressure drop on the exhaust side falls within the maximum value of 1.0 inch w.c.

For the flow channels the hydraulic diameter, D_h, is

$$D_{h,h} = 4 \frac{A_c}{A} L = \frac{(4)\ (0.48)\ (16)\ (34.5)}{(12)\ (34.5)\ (16)\ (2)} = 0.08 \text{ ft}$$

$$D_{h,c} = \frac{(4)\ (0.105)\ (16)\ (34.5)}{(12)\ (34.5)\ (16)\ (2)} = 0.0175 \text{ ft}$$

Substituting the above values into the relation for the heat transfer coefficient, h, yields

$$h_h = 0.03448 \frac{(0.0363)}{0.08} \left(\frac{0.08}{2.67\text{x}10^{-5}}\right)^{0.8} (G)^{0.8} (0.7)^{0.333}$$

$$h_h = 8.39\ G_h^{0.8}$$

$$h_c = 10.104\ G_c^{0.8}$$

$$\frac{1}{U_{avg}} = \frac{1}{8.39\ G_h^{0.8}} + \frac{0.020}{(10)\ (12)} + \frac{1}{10.104\ G_c^{0.8}}$$

Assuming various lengths for the recuperator (basing the median length on pressure drop data from the Z-Duct commercial heat exchangers, See Figure 1.7), G and A can be calculated resulting in values for U_{avg} and hence the required U_{avg} A values. Figure 1.8 gives these values as well as pressure drop and effectiveness as a function of Reynolds number. Effectiveness, hot side pressure drop and $U_{avg}A$ are plotted as a function of hot side Reynolds number. Cold side pressure drop is plotted as a function of cold side Reynolds number.

For the conditions given in paragraph 1.1, the length required to give a 1.0-inch pressure drop on the exhaust side is 62 inches. The effectiveness for this length is 78 percent and the cold side pressure drop is 6.2-inches water column. An overall recuperator core matrix of 16 X 34.5 X 62 inches satisfies the requirements of this specific program. Therefore, referring to paragraph 1.3.1.

$$E = \frac{c_c\ (t_{c,out} - t_{c,in})}{c_{min}\ (t_{h,in} - t_{c,in})}$$

$$t_{c,out} = 1037 + 70 = 1107^oF$$

This temperature for t_c,out is higher than used to determine the average properties but it is close enough not to repeat the procedure.

Note - See Appendix I for additional information on Thermodynamic Analysis.

Figure 1.7 Friction factors for flow through Z-Duct plate heat exchanger from experimental data (The Wing Company, 1976).

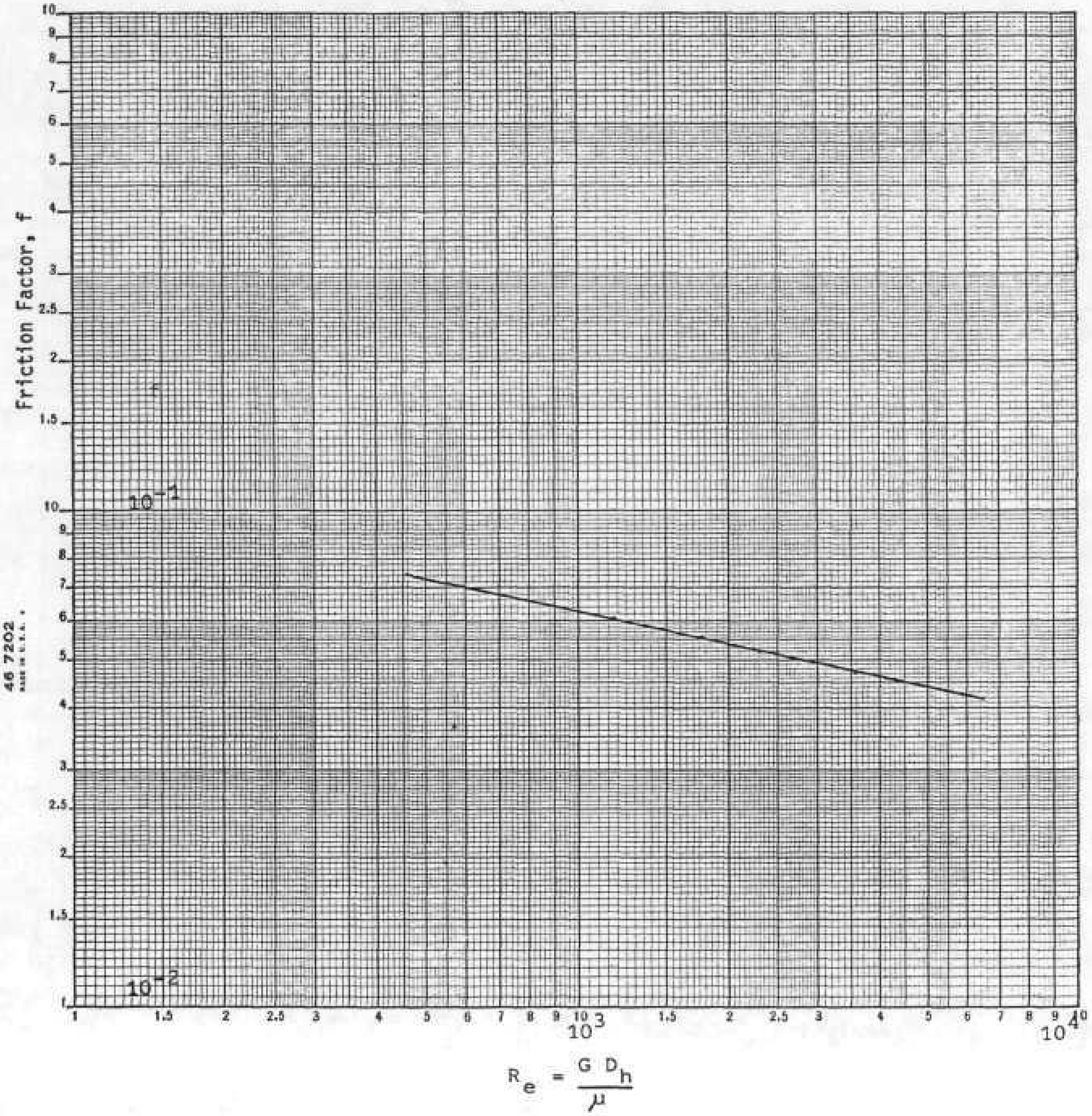
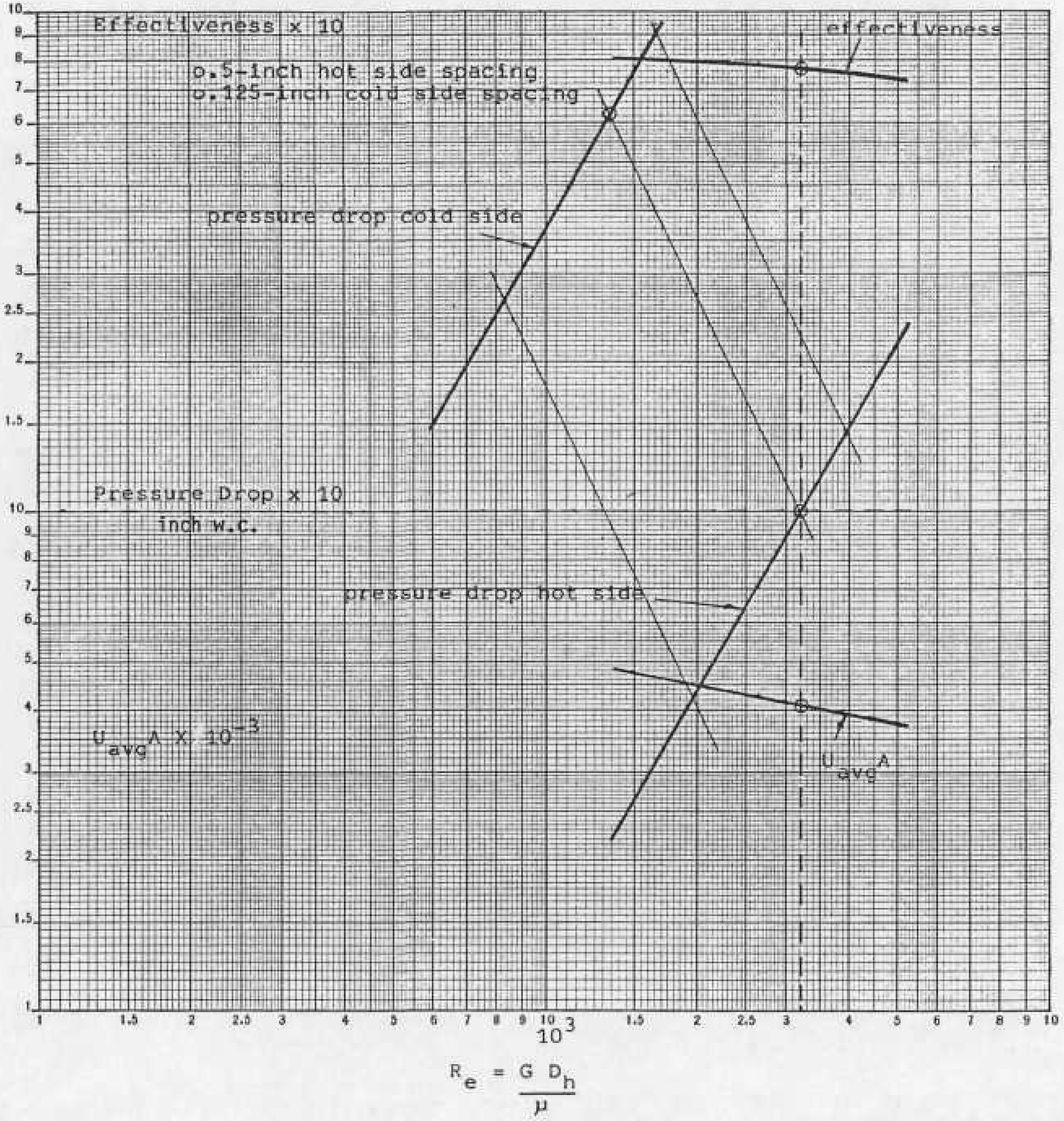


Figure 1.8 Recuperator Thermodynamic Characteristics based on C_{min}/C_{max} = 0.37, C_{min} = 1924 Btu/hrF.



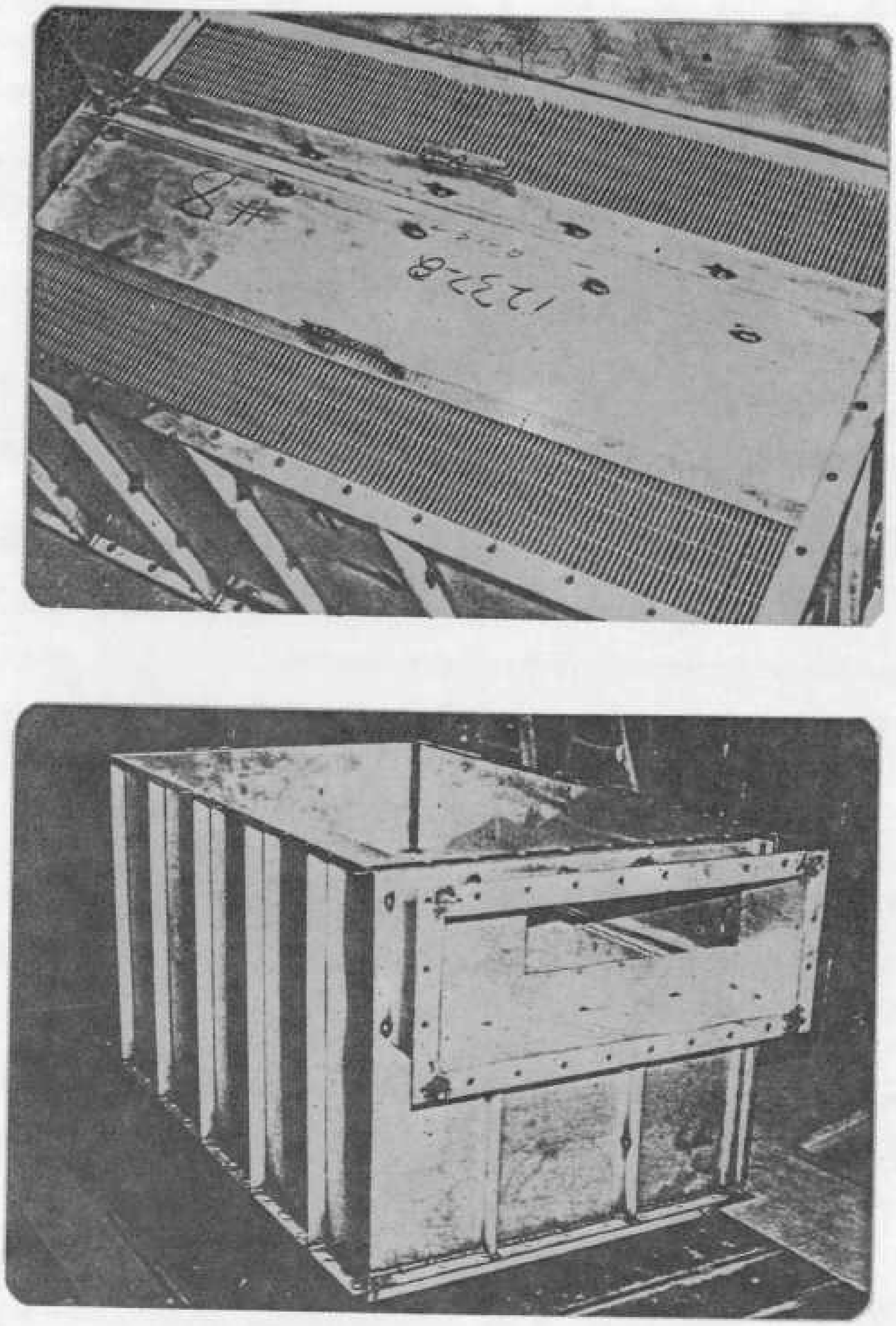
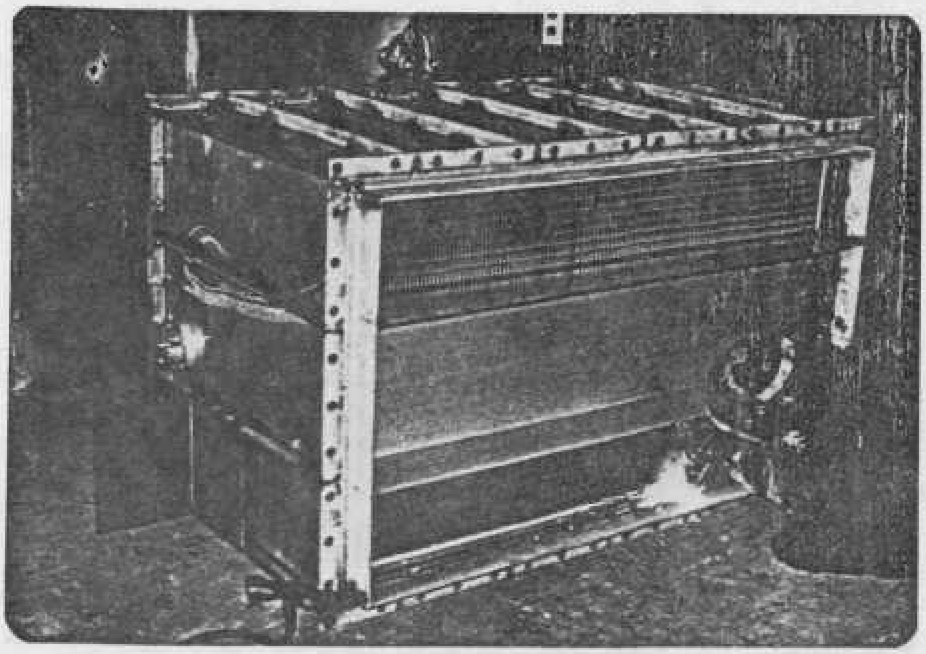


Figure 1.9 High temperature (1200 F) and high pressure (75-inches of water column) Z-Duct recuperator for an iron foundary application. Unit has 4.5 plates per inch, 0.010-inch thick 309 stainless steel core matrix.



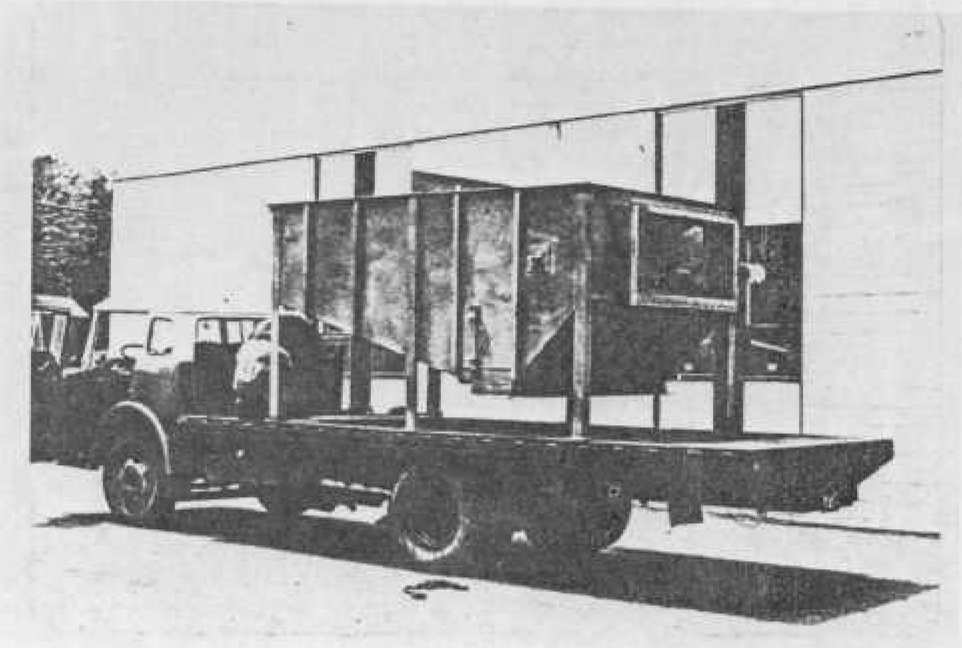


Figure 1.9 (cont'd) Bottom view of high temperature recuperator(top) and ash retrieval system(bottom).

Nomenclature

Most of the nomenclature is defined as it is introduced or else is obvious from the context of its use. However, it is summarized here for convenience.

Any consistent dimensioning system may be used. All the heat transfer and flow-friction parameters are presented in nondimensional form so that a shift to a preferred system of dimensions presents no complications. However, the dimensions of actual test surfaces, and also the illustrative examples, are given in the English system.

English Letter Symbols

A	Exchanger total heat transfer area on one side
A_c	Exchanger minimum free-flow area
A_f	Exchanger total fin area on one side
A_{fr}	Exchanger total frontal area
A_k	Cross-sectional area for longitudinal conduction
a	Plate thickness
a	Short side of a rectangular flow passage
b	Plate spacing
b	Long side of a rectangular flow passage
C	Flow-stream capacity rate (Wc_p)
C_c	Flow-stream capacity rate of cold-side fluid
C_h	Flow-stream capacity rate of hot-side fluid
C_L	Coupling-liquid capacity rate
$C_{\min}$	Minimum of C_c or C_h
$C_{\max}$	Maximum of C_c or C_h
C_r	Rotor capacity rate of a rotating periodic flow exchanger (rotor mass times specific heat times rph)
C_r^*	Rotor capacity-rate ratio ($C_r/C_{\min}$), dimensionless
$\overline{C}_r^*$	($C_r^*\theta_r/\theta_{d,\min}$), dimensionless
$\overline{C}$	Fluid heat capacity within exchanger ($C\theta_d$)
$\overline{C}_{\min}$	$C\theta_d$ for minimum-capacity-rate fluid
$\overline{C}_W$	Wall total heat capacity (exchanger core mass times specific heat of core material)
$\overline{C}_W^*$	$\overline{C}_W/\overline{C}_{\min}$, dimensionless
c	Specific heat
c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume
D	Inside diameter of a circular tube
D_h	Hydraulic diameter of any internal passage ($D_h = 4r_h = 4A_cL/A$)
d	Outside diameter of a tube in a tube bundle, crossed-rod matrix, or a pin in pin-fin surface
E	Friction power expended per unit of surface heat transfer area
F_G	Correction factor to log-mean rate equation, dimensionless
f	Mean friction factor, defined on the basis of mean surface shear stress

Nomenclature

f	Fuel-air ratio
f_x	Local friction factor, defined on the basis of local surface shear stress
$\bar{f}_{app}$	Apparent mean friction factor
G	Exchanger flow-stream mass velocity (W/A_c)
g_c	Proportionality factor in Newton's second law
H/C	Hydrogen-carbon ratio for hydrocarbon fuels
h	Unit conductance for thermal-convection heat transfer
K_c	Contraction loss coefficient for flow at heat-exchanger entrance dimensionless
K_d	Momentum flux correction factor, , dimensionless
K_e	Expansion loss coefficient for flow at heat exchanger exit , dimensionless
k	Unit thermal conductivity
L	Total heat-exchanger flow length; also flow length of uninterrupted fin
l	Fin length from root to center
M	Molecular weight
m	A fin effectiveness parameter $\sqrt{2h/k\delta}$, $\sqrt{4h/kd}$
m_o	Slope of operating line (C_c/C_h), dimensionless
n	Number of passes in a multipass heat exchanger
P	Pressure
p	Porosity of a matrix surface, dimensionless
q	Heat transfer rate
q''	Heat flux, heat transfer rate per unit of surface area
R	Universal gas constant
R	Heat transfer resistance
R_c	Resistance on the cold-fluid side of a heat exchanger
R_h	Resistance on the hot-fluid side of a heat exchanger
R^*	Heat transfer resistance ratio, (R on C_{min} side)/(R on C_{max} side)
r	A radial coordinate
r_h	Hydraulic radius ($A_c L/A$)
r_i	Inner radius of an annuli or inner radius of a circular fin
r_o	Outer radius of an annuli or outer radius of a circular fin
r^*	r_i/r_o
T	Absolute temperature
t	Temperature to any arbitrary scale
t_c	Cold-fluid-side temperature
t_h	Hot-fluid-side temperature
U	Unit overall thermal conductance
V	Velocity
V	Volume
v	Specific volume
W	Mass flow rate
X	Parameter in the log-mean rate equation approach to heat-exchanger design
X_c	Specific-heat correction factor for humidity and products of combustion
X_d	Density correction factor for humidity and products of combustion
x	Axial flow coordinate
x^*	Axial flow coordinate (x/L), dimensionless

2. Mechanical Design

2.1 Introduction

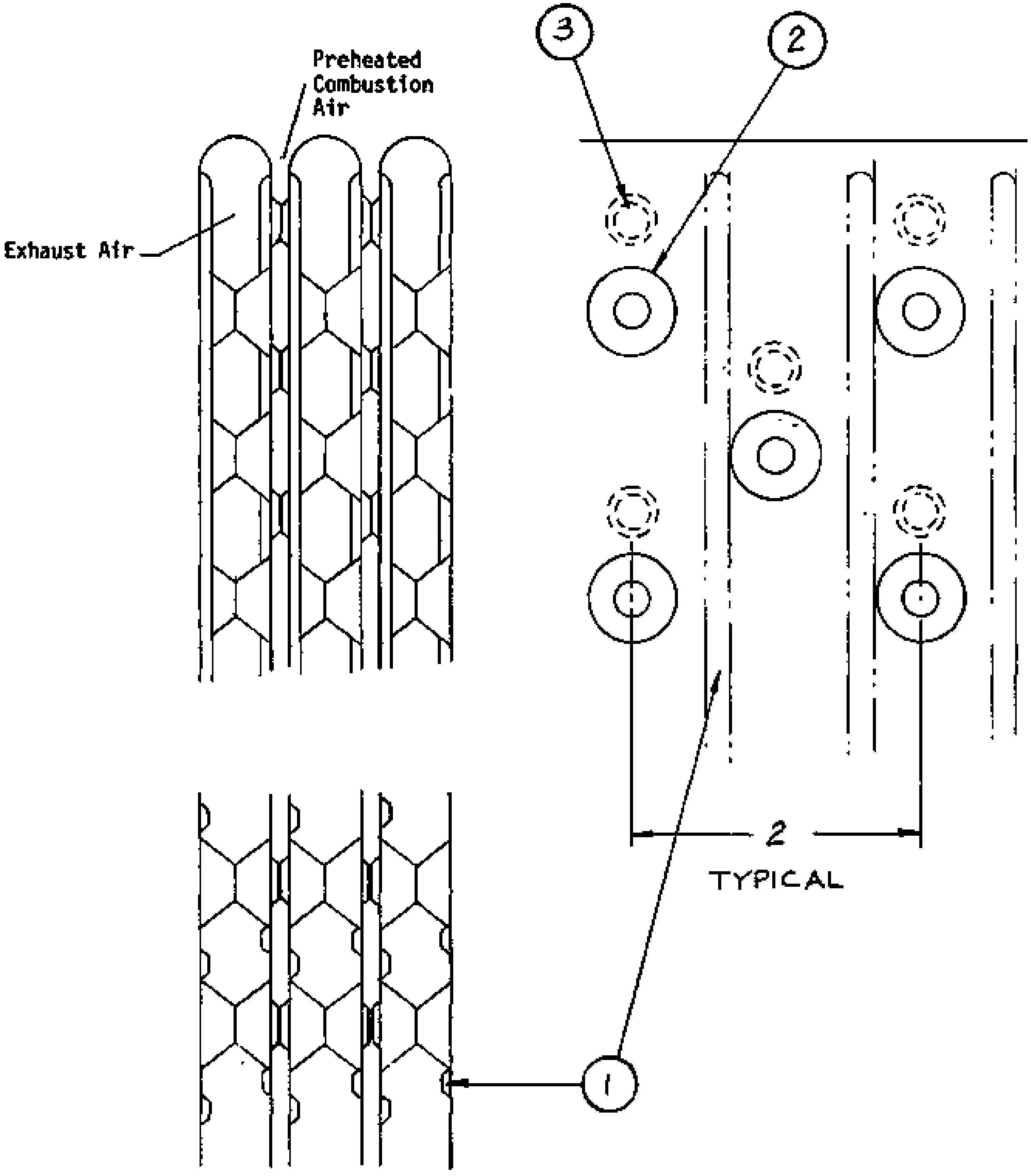
Paragraph 1.1 of Task I outlines the required thermodynamic design parameters for the metallic recuperator (NOTE: A more recent set of specifications were presented to DLI on August 25, 1978, a copy of which is included as a part of this report together with the thermodynamic design data resulting from these specifications). The recuperator must be designed to satisfy these thermodynamic constraints, but even more importantly, it must be capable of withstanding the mechanical demands placed upon it by the environment of a steel mill soaking pit. The combination of high effectiveness (greater than 80 percent), high pressure differential between gas streams (5 psi), high temperature (up to 1500^{0}F), and the requirement for less than 0.25-inches w.c. pressure drop on the flue-gas side of the recuperator demands a unique design if the unit is to be cost effective. A tube-type recuperator would be extremely large in size if it were to achieve the 80% effectiveness. A standard plate-type unit would require a considerable number of welded joints to satisfy the effectiveness requirement as well as require relatively thick plates to stand up to the pressure differential.

The Z-Duct design concept, set forth in Task I, meets these objectives. Starting with a modified version of the basic Z-Duct core concept and "packaging" it to meet the mechanical requirements of this program is the objective of Task II.

Figure 2.1 shows the core matrix (the heat transfer surface) that must be packaged in a manner that allows it to withstand the forces,

BY .... DATE .... SUBJECT Metallic Recuperator Core Design SHEET NO .... OF ....
CHKD. BY NHD DATE 9-78 JOB NO. ....

Figure 2.1



thermal expansion and wear. The core is a formed and folded continuous coil of material.

Material is fed from the coil to a press that forms the dimples and reinforcing ribs into a 16-inch X 36-inch wide section of the material. The press is retracted and another 16-inch section is fed under the press. The reinforcing ribs do not go the entire 16-inch length, consequently this results in a weak line across the 36-inch width which allows folding to be performed at a well defined location. As the material folds upon itself, the dimples automatically space the gap for the two gas streams; in this case 0.48-inches for the flue gas side and 0.105 for the combustion air side. Flag 2 in Figure 2.1 shows the exhaust passageway spacing dimple which has a height of 0.24-inch. Flag 1 is the combustion air spacing dimple and it has a height of 0.053-inch. Flag 1 shows the reinforcing ribs.

Figure 2.2 shows the proposed packaging for the core matrix. It shows a flue gas passage width of 0.480-inch and a combustion air width of 0.105-inch. Core material thickness is 0.020-inch. A high temperature refractory cement (KS-4 manufactured by A.P. Green Company), capable of operating at temperatures up to 2600^{O}F., is used to seal the ends of the core. The folded ends of the core are embedded approximately 3/4 of an inch into the refractory. Weld studs and expanded metal mesh are a proven technique for maintaining the seal integrity between the core and the refractory as well as between the metallic end-cap and the refractory.

The sealed core matrix then has a welded thermal expansion joint connecting its lower periphery to the outer structural casing. This allows the core to expand in all horizontal directions. Support is provided from the downward force of the combustion air pressure by

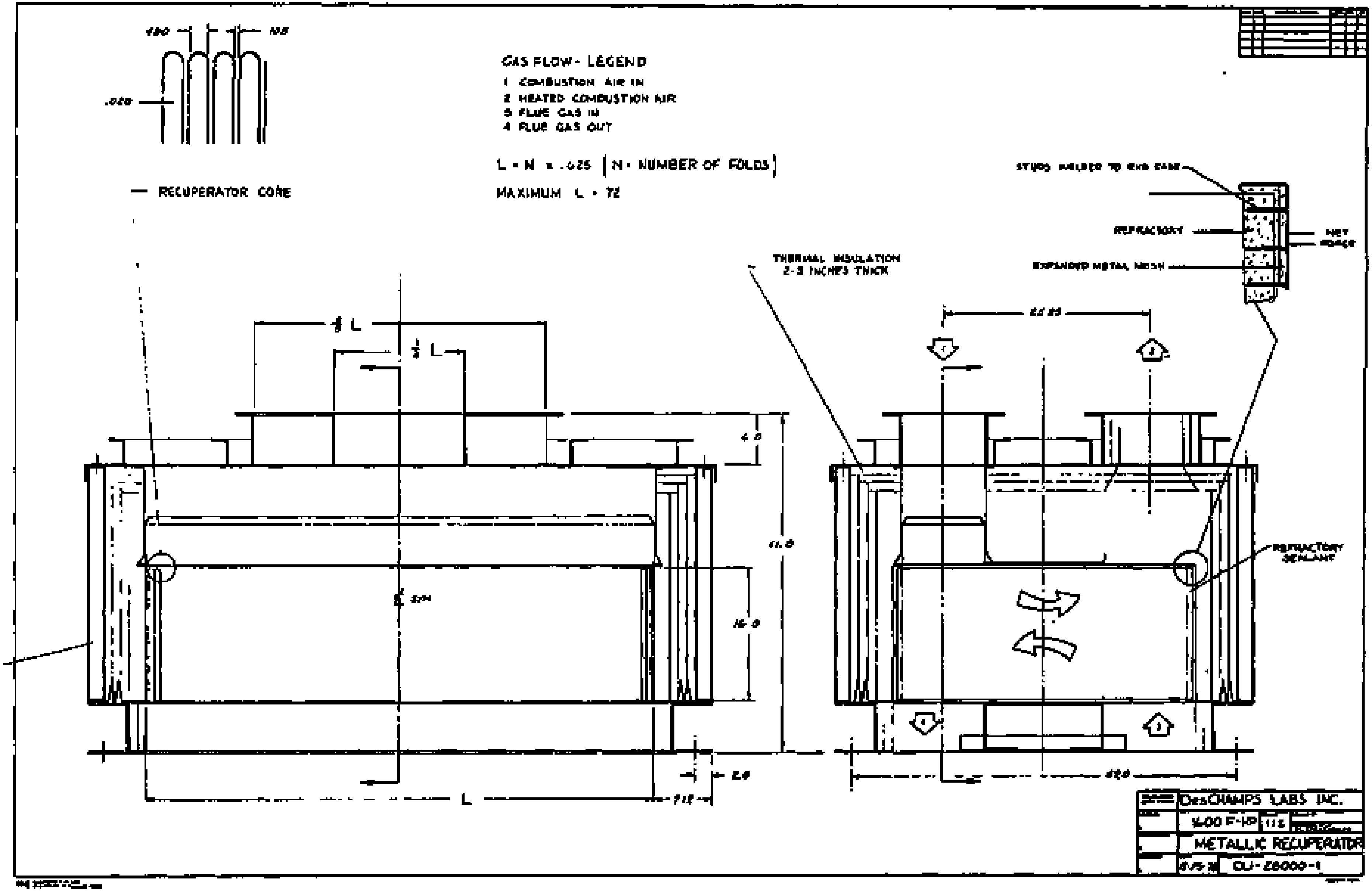

.180
.105
.020
RECUPERATOR CORE
GAS FLOW - LEGEND
1 COMBUSTION AIR IN
2 HEATED COMBUSTION AIR
3 FLUE GAS IN
4 FLUE GAS OUT
L = N x .625 (N = NUMBER OF FOLDS)
MAXIMUM L = 72
STUDS WELDED TO END CASE
REFRACTORY
NET FORCE
EXPANDED METAL MESH
THERMAL INSULATION
2-3 INCHES THICK
22.25
L
L
4.0
41.0
16.0
℄ SYM
REFRACTORY SEALANT
2.0
7.5
L
42.0
1
2
3
4
DesCHAMPS LABS INC.
600 F-HP
METALLIC RECUPERATOR
DJ-20000-1

Figure 2.2

the heavy guage structural member under the core. This member is welded at one end to the lower exterior channel base. The other end is allowed to slide on an angle support.

The cool combustion air enters at point (1) through another expansion joint (vertical). This joint also directs the entering air into the core and prevents bypass around the matrix. By using the expansion joints as shown, the case can be internally insulated, thereby allowing the case to operate at near ambient temperature and better withstand the large forces from the internal pressure.

It should be noted, with the design as shown, that both end caps are under positive pressure. This has the effect of having a net force pushing the end caps against the matrix. This force assists the design in maintaining seal integrity.

2.2 Structural Consideration

An important factor to consider with a plate recuperator is the forces on the core matrix plates resulting from the 5 psi pressure differential between gas streams. Z-Duct, because of its patented formed plate, can be designed to accommodate this pressure by having the correct combination of material thickness, dimple spacing, meterial strength and structural rib design. Figure 2.1 shows the dimple and rib pattern proposed for this program. Figure 2.3 is an enlarged view of the structural rib that is used for increasing the corss sectional moment of inertia of the plate. The ribs run transverse to the bulk gas flow and are placed on 1-inch centers.

At a flue gas temperature of 1200 to 1500^{O}F and a resulting maximum metal temperature of 1100 to 1400^{O}F, the most probable mode of

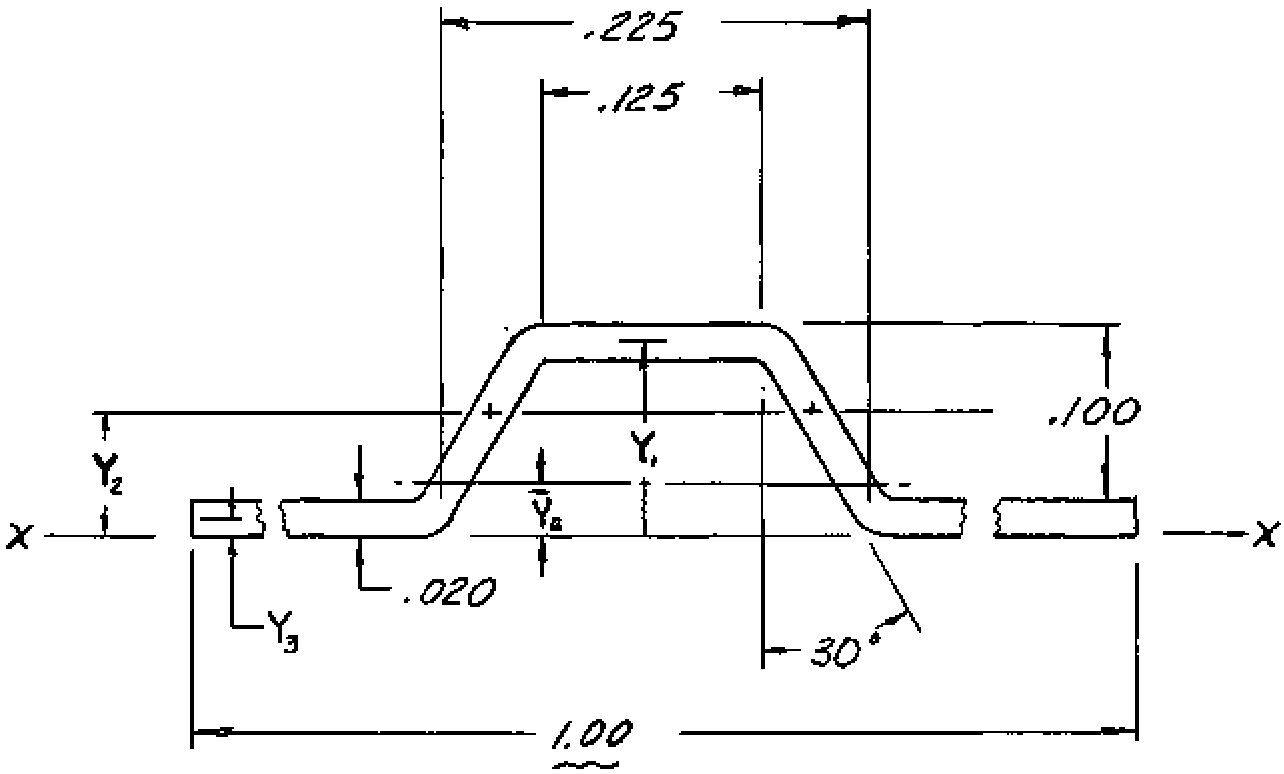


Figure 2.3 Structural Rib Design

structural failure (other than possible corrosion) will be long term creep of the core matrix plates. The ribs main purpose is to increase the moment of inertia of the plates and therby reduce this problem.

With the rib section of Figure 2.3 a calculation will be made to determine if the stress exceeds the value that would cause excessive creep over a period of 7 years with a maximum of 1300^{o}F average metal temperature.

$$\bar{y}_g = \frac{\sum_{i=1}^{n=3} y_i a_i}{A}$$

$$\bar{y}_g = \frac{(0.11)(0.125)(0.02)+(0.07)(0.1)(0.02)(2)+(0.01)(0.02)(.775)}{(0.125)(0.02)+(0.1)(0.02)(2)+(0.02)(0.775)}$$

$$\bar{y}_g = 0.0259 \text{ inches}$$

$$I_{xg} = \sum_{i=1}^{n=3} \left(\frac{1}{12} b_i h_i^3 + (y_i)^2 A_i\right)$$

Where: $y_i = |\bar{y} - y_i|$

$$I_{xg} = 4.47 \times 10^{-5} \text{ in.}^4$$

$$M_{max} = \frac{-1}{12} P\ell\ell = \frac{-1}{12} (5\text{psi}) (2") (2")$$

$$= -1.66 \text{ in. -lbs.}$$

$$c = 0.120 - 0.0259 = 0.094 \text{ inches}$$

$$S_{max} = \frac{Mc}{I_{xg}} = \frac{(1.66)(0.094)}{4.47 \times 10^{-5}} = 3494 \text{ psi}$$

Therefore the maximum stress to be expected within the rib is 3494 psi. From Figure 2.4 it can be seen that for type 309 stainless steel, at 1300°F, a creep rate of 1% per 10,000 hours will result at 4000 psi. The maximum stress within the core matrix will therefore result in an allowable amount of creep.

The dimples are also under stress. There are 288 dimples covering 576 square inches and with 5 psi acting over the entire surface each dimple supports 10 pounds of force. The maximum stress in the dimple is

$$S = \frac{F}{A} = \frac{10}{(\mathrm{SIN}\ 52^{\circ})(\pi)(0.25)(0.020)}$$

$$S = 807 \text{ psi}$$

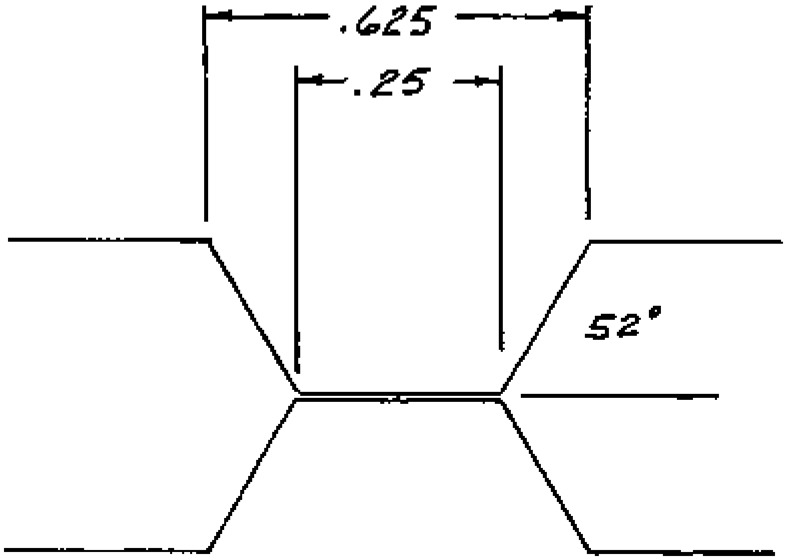
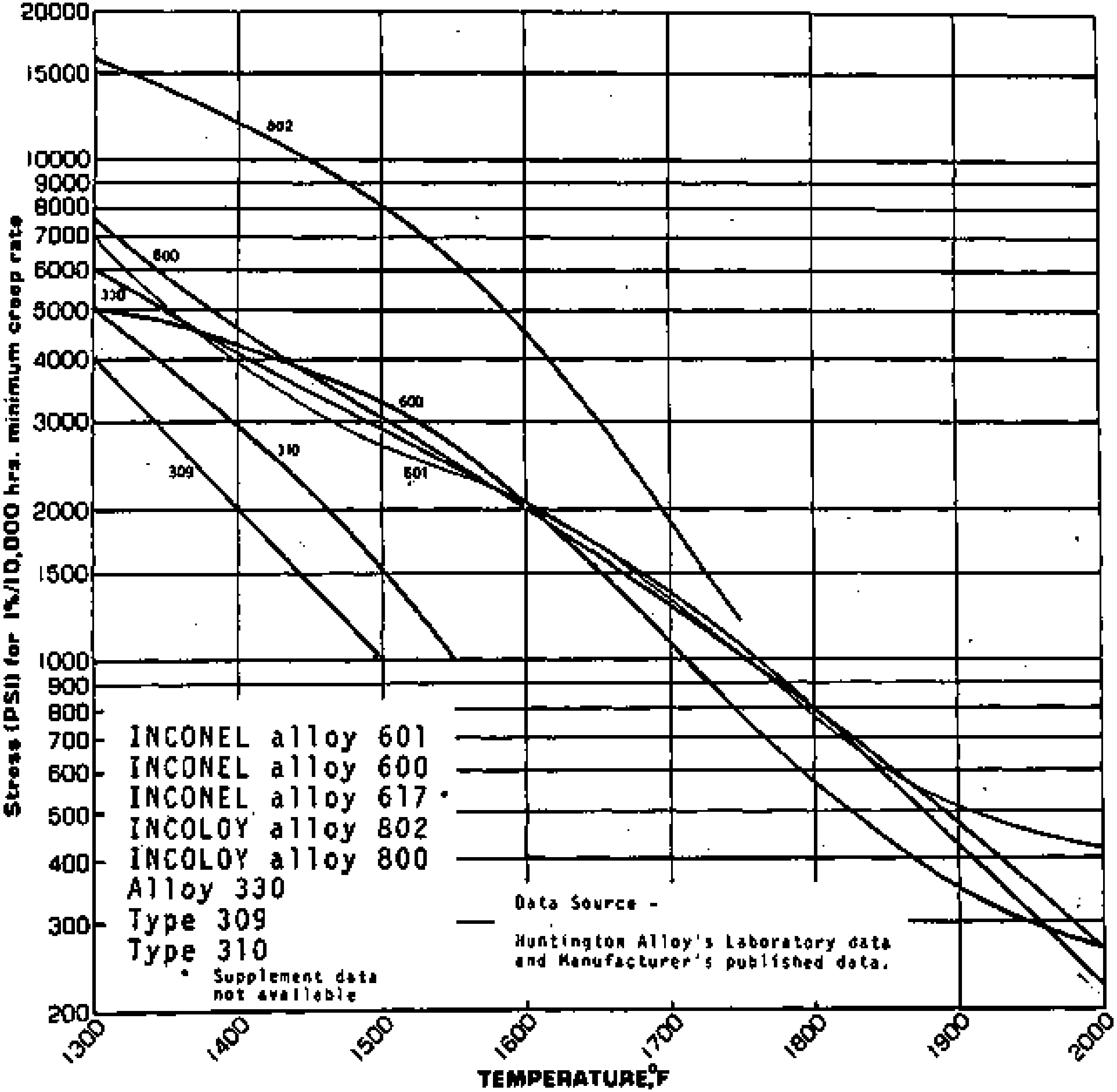


figure 2.4 **CREEP STRENGTH**
(1% Min. Creep Rate/10,000 Hrs.)



3. Materials Selection

3.1 Metals

Proper selection of the optimum grade of stainless steel for a particular set of environmental conditions presents a challenging problem in the design of metallic recuperators. Consideration must simultaneously be given to the high-temperature strength and structural stability, the corrosion resistance to the flue gases, and the economics of return on investment.

A recent report by Oak Ridge National Laboratory(1) indicates that type 430 or 446 stainless steel would be selected for applications in the temperature range 1200-1300°F metal temperature while austenitic steels (300 series) would be used in applications up to 1800°F. For temperatures above 1400°F high-nickel content alloys such as Incolloys (Huntington Alloys Co., Division of International Nickels Co.) and alloys containing 14% Cr and 4% Mo have been found to have the best creep resistance. High vanadium contents in flue gases would generally dictate use of stainless steel containing at least 18% Cr, also with the lowest possible nickel content because of the relatively high incremental cost associated with high-nickel-content stainless steels. Applications in flue gas atmospheres having high sulphur contents generally favor use of the ferritic steels of the 400 series, which have zero or very low contents of nickel, because of the tendency for corrosion of austenitic type steels via nickel-sulfur reactions

(1) V.J. Tennery and G.C. Wei, "Recuperator Materials Technology Assessment", ORNL/TM-6227, 1978.

at high temperatures. In flue gases from natural gas, however, the corrosion rate for both 309 and 446 type stainless steels is 3 mpy at 1500°F(2). Several manufacturers of recuperators(1) have indicated that any recuperator application involving No. 6 fuel oil as a fuel should be limited to metal temperatures below 1150°F. Higher metal temperatures in the presense of the vanadium, sulfur, and other impurities in the combustion gas from No. 6 fuel oil have resulted in rapid corrosion of ferritic stainless steels. Type 446 stainless steel has also been observed to become very brittle when operating in radiation units producing 1300°F air.

For the steel soaking pits being considered in this program natural gas is the primary fuel under consideration. The higher strength at metal operating temperature combined with its corrosion resistance up to 1500°F puts type 309 stainless steel in the foremost position for use in the metallic recuperator program. It is readily available, medium priced, and has a yield strength four times greater than type 446 at the 1400-1500°F maximum metal temperature. Using type 309 alloy it is predicted that the proposed metallic recuperator will function continuously for 6 to 8 years before replacement is necessary. This life could be increased by using superalloys but economics favor replacement instead of the high initial cost.

The replacement time is arrived at by using corrosion rates of 1 to 2 mpy for type 309 stainless steel in the temperature range of 1200 to 1400°F(2). With a 20 mil thick core matrix the integrity of the recuperator should be maintained for the above mentioned period of time.

(2) Sourcebook on Stainless Steels, ASME, 1976.

With 23% chromium content and 12-15% nickel content alloy 309 stainless steel should offer maximum scaling resistance as indicated in Figure 3.1. Figure 3.2 indicates corrosion rates for stainless steels in various gases. 309 alloy is not shown but in a flue gas environment at 1200-1400°F it should be better than type 304 which has a corrosion rate of less than 1 mpy. Table 3.1 gives the corrosion rate for both 446 and 309 for natural gas flue exhaust at 1500°F. The table shows that 446 and 309 have comparable corrosion rates in the expected atmosphere. Figure 3.3 gives relative hot strength characteristics for various grades of steel. As can be seen, the austenitic grades have considerably higher allowable limits than the Martensitic and Ferritic grades at 1200 to 1400°F. Figure 3.4 gives the short-time tensile strengths. Again it illustrates the lack of strength for type 446 above 1000°F as compared to type 309.

3.2 Refractory Sealant

Past experience with DLI recuperators has shown that a refractory castable as manufactured by A.P. Green Refractories and designated as KS-4 will meet the requirements of this program. KS-4 is a dense, strong castable refractory scientifically compounded for use in applications up to 2550°F. It combines high strength with good abrasion resistance and is excellent for thin castings. It has a fire clay aggregate with a density of 118 lbs/ft^3. When cast around an expanded metal mesh matrix it offers good thermal shock and mechanical integrity.

3.3 Thermal Insulation

Cera-blanket thermal insulation will be used throughout for this project. With (3) 1-inch layers of 8 lbs. density insulation the outer skin temperature should be approximately 150°F above ambient at the low fire condition. This will result in a thermal loss of about 150 BTU/hr ft^2 of air-side casing area which translates into less than 3000 BTU/hr per heat exchanger or 4^{0}F temperature loss. The manufacturer's data sheet gives the characteristics of Cere-blanket.

Figure 3.1
Effect of Chromium Content on Scaling Resistance
(At 1800 F or 982 C) (2)

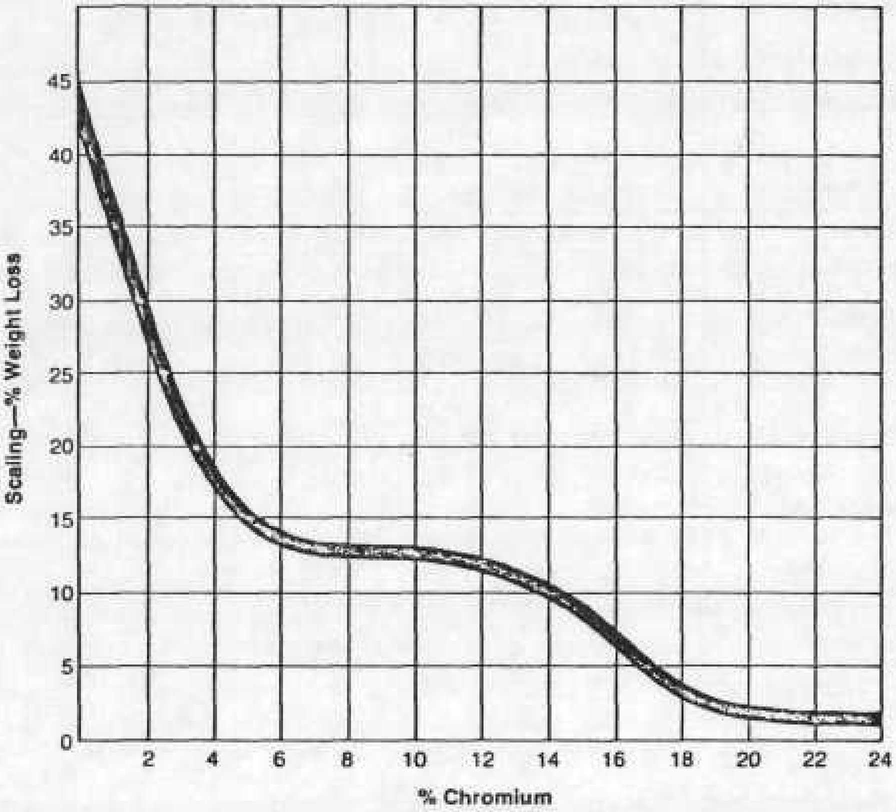
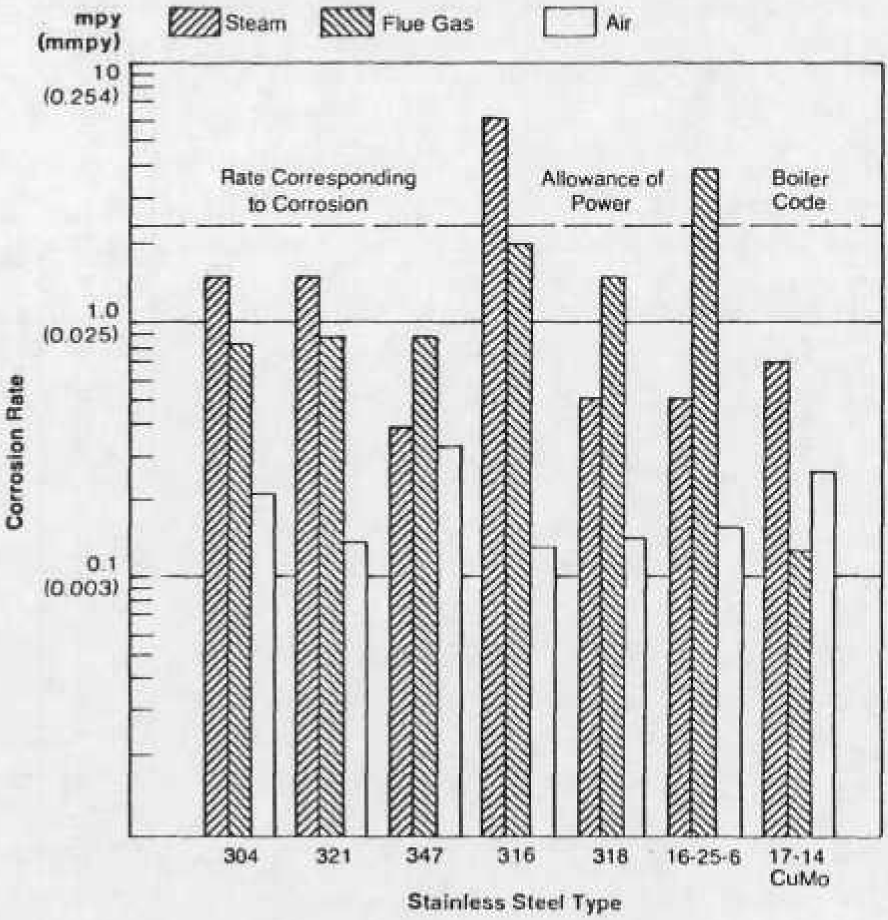


Figure taken from stainless steel industry data.

Figure 3.2

Corrosion Rates in Various Gases (7)



Comparative corrosion rates of stainless steels in steam at 1250 F (677 C), flue gas at 1200 to 1400 F (649 to 760 C), and air at 1400 F (760 C). (Exposure time was 6950 hours for steam and flue gas, 1260 hours for air.)

Figure from: F. Eberle, F. G. Ely, and J. S. Dillon, "Experimental Superheater for Steam at 2000 psi and 1200 F, Progress Report after 12,000 Hours of Operation," Transactions ASME, 76 (1954), pp. 665.

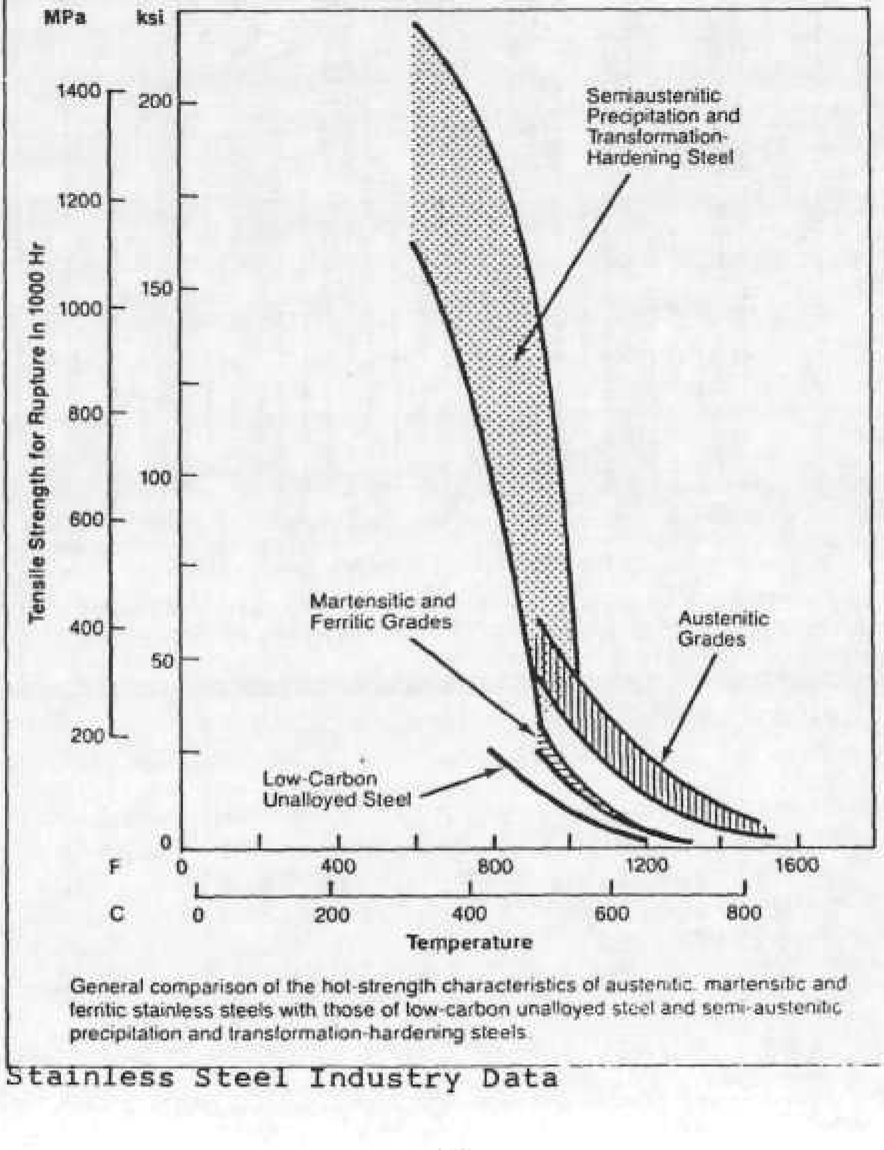
Table 3.1
CORROSION RATES OF STAINLESS STEELS IN FLUE GASES
(EXPOSURE 3 MONTHS) (16)

Material AISI Type	Corrosion Rate					
	Coke Oven Gas (1500 F) (816 C)		Coke Oven Gas (1800 F) (982 C)		Natural Gas (1500 F) (816 C)	
	mpy	mmpy	mpy	mmpy	mpy	mmpy
430	91	2.31	236†	6.00	12	0.30
446(26 Cr)	30	0.76	40	1.02	4	0.10
446(28 Cr)	27	0.69	14	0.36	3	0.08
302B	104	2.64	225†	6.00	–	–
309S	37*	0.94	45	1.14	3	0.08
310S	38*	0.97	25	0.64	3	0.08
314	23*	0.58	94	2.39	3	0.08

* Pitted specimens—average pit depth. † Specimens destroyed

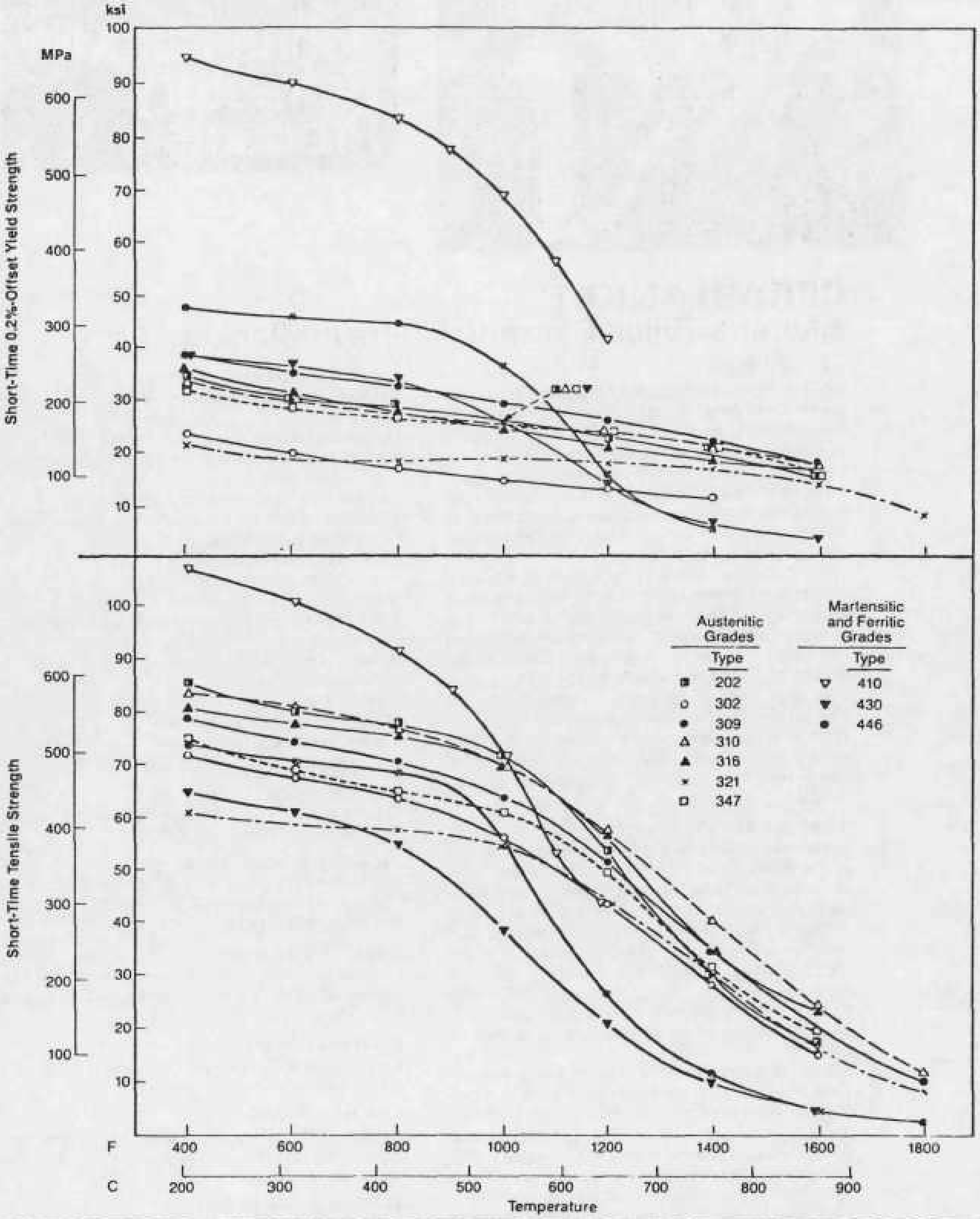
Table from: W. F. White, Materials Protection, 2(1963).

Figure 3.3
Hot-Strength Characteristics (2)



General comparison of the hot-strength characteristics of austenitic, martensitic and ferritic stainless steels with those of low-carbon unalloyed steel and semi-austenitic precipitation and transformation-hardening steels.

Figure3 . 4Short-Time Tensile Strengths (2)



Typical short-time tensile strengths of various standard stainless steels at elevated temperature. All steels were tested in the annealed condition except for the martensitic Type 410, which was heat treated by oil quenching from 1800 F (982 C) and tempering at 1200 F (649 C)

JM

Johns-Manville Refractory Products

CERABLANKET*

Alumina-Silica Ceramic Fibers in Blanket Form

DESCRIPTION:

Cerablanket is a ceramic fiber blanket made without binder from long Cerafiber* ceramic fibers produced from the purest raw materials. It is available in a wide variety of thicknesses and densities.

Cerablanket is particularly suitable for continuous exposure to 2300°F in normal oxidizing combustion conditions; it has the greatest strength after heating of any of the J-M felts or blankets, and also has good strength prior to heating.

Cerablanket has excellent resistance to chemical attack, as it is essentially unaffected by all chemicals except hydrofluoric and phosphoric acids, and strong alkalies. If wet by oil or water, its thermal and physical properties will be fully restored after drying. Its sound absorption ability is far greater than other dense or insulating refractories.

Cerablanket can be supplied on special order with very low water leachable elements on the fiber surface. A J-M Representative can supply additional information for applications requiring this characteristic.

TYPICAL APPLICATIONS:

Furnace and Kiln Linings: Three important features of Cerablanket make it ideal for the hot-face lining of furnaces and kilns. The Cerafiber ceramic fibers used to manufacture Cerablanket are thermally stable to high temperatures. Cerablanket has excellent strength after heating to assure it will stay put on the furnace lining anchors. Its good strength prior to heating means it will resist damage while installing it. Cerablanket can be used in some furnace lining applications to as high as 2400°F.

Further information on furnace lining applications is contained in Johns-Manville's Furnace Lining Hardware Product Information Sheet (IND-3047) for Anchoring Accessories, and our Ceramic Fiber Furnace Lining Guide (IND-3134) for installation recommendations.

Even the most extreme temperature changes will not alter Cerablanket's ability to insulate and stay where it is placed.

Other Applications:

Removable insulating blankets for steam and gas turbines
Insulation wrap on investment casting molds
Reusable insulation blankets for field stress relieving of welds
Flexible high temperature pipe insulation
Sound absorption applications at high temperatures
Glass furnace crown insulation
High temperature gasketing
Low velocity stack linings
Back-up insulation to ceramic fiber boards
Temporary repair of refractory furnace linings and roofs
Pressure vessel fire protection
Furnace door seals
Annealing cover bottom seals
High temperature filter media
Nuclear insulation applications

ADVANTAGES:

Low Shrinkage

Cerablanket has good shrinkage properties at elevated temperatures—to 2300°F

Excellent Thermal Stability

The high purity fibers have good resistance to divitrification. Cerablanket is used to 3000°F in some single use applications

Good Cold Strength

Cerablanket resists damage in applications like furnace linings where it is subjected to a great deal of handling

Excellent Hot Strength

Cerablanket will "stay-put" on fastening devices after exposure to high temperatures

Low Heat Storage

Cerablanket stores approximately 95% less heat than dense firebrick and approximately 75% less heat than insulating firebrick

Thermal Shock Resistance

Even the most extreme temperature changes will not alter Cerablanket's ability to insulate and stay where it is placed

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*Johns-Manville Trademark

Sect. 110 Part 20
Date 3/76 Cancels 7/75

PROPERTIES:

Color	White
Color Code	None
Melting point, °F more than	3200
Normal service temperature, °F (oxidizing atmosphere)	2300
Specific heat, BTU/LB, °F	
@200°	0 20
1000°	0 25
2000°	0 27
Specific gravity	2 65
Permanent linear change,	
24 hours @1800°F soaking temperature	-1 6
2000°F	-2 1
2200°F	-2 8
2400°F	-5 2

The permanent linear change in a 24 hour test is representative of the shrinkage that will be experienced in actual service. Four-hour test data is not representative.

Deformation, %

Lbs/Sq In Load	Deflection under load	Permanent deformation, load removed
1	22 3	5 5
2	33 4	9 3
3	40 0	11 9
4	44 9	13 7
5	48 6	15 1
6	51 7	16 3
7	54 2	17 3
8	56 4	18 2
9	58 3	19 0
10	60 0	19 6

Tensile Strength, Lbs/Sq In

	Density, Lbs/Cu Ft			
	3	4	6	8
½ in thickness	–	5 5	9	12
1 in	4	5	7	8

Air Flow, CFM/In H_2O/Sq. Ft/In

	Density, Lbs/Cu Ft			
	3	4	6	8
@75°F	50 6	32 7	17 6	11 4
1000°F	25 1	16 2	8 8	5 7
2000°F	18 4	11 9	6 4	4 1

Thermal Conductivity BTU/In, HR, Sq Ft, °F

	Density, Lbs/Cu Ft			
	3	4	6	8
@500°F mean temp	0 62	0 54	0 43	0 38
1000°F	1 25	1 11	0 88	0 72
1500°F	2 16	1 99	1 61	1 24
2000°F	3 29	3 11	2 62	1 93

Chemical analysis, %

Alumina	$A1_2O_3$	47 0
Silica	SiO_2	52 8
Ferric Oxide	Fe_2	0 02
Titania	TiO_2	0 01
Magnesia	MgO	0 02
Calcium Oxide	CaO	0 05
Alkalies	Na_2O & K_2O	0 15
Boric Anhydride	B_2O_3	0 01

MILITARY SPECIFICATIONS:

MIL-I-23128A, GRADE 8
extra charge for lot testing required.

STANDARD SIZES:

Thickness, Inches	Density, Lbs/Cu Ft			
	3	4	6	8
¼			X	X
½	X	X	X	X
1	X	X	X	X
1½	X	X	X	

Widths: 24 x 48 inches
Length: 25 feet in rolls

STANDARD SAMPLES: All 6 inches x 6 inches

Sample Number	Contents
1968-1	1 pc ½" x 3 lbs/cu ft 1 pc ½" x 4 lbs/cu ft 1 pc ½" x 6 lbs/cu ft 1 pc ½" x 8 lbs/cu ft
1968-2	1 pc 1" x 4 lbs/cu ft 1 pc 1" x 8 lbs/cu ft

The values given herein are typical values obtained in accordance with accepted test methods and are subject to normal manufacturing variations. They are supplied as a technical service and are subject to change without notice. Check with your Johns-Manville district office to obtain current information.

For information on other J-M Thermal Insulations and Systems, write the Johns-Manville Insulation Center, Drawer 17L, Denver, Colorado 80217 or call (303) 770-1000 Ext Ext 3111

Johns-Manville

Greenwood Plaza • Denver, Colorado 80217

Sales Offices in Principal Cities

Litho in USA

METALLIC RECUPERATOR

TASK IV

MATERIALS AND COMPONENT TESTING

4. Materials and Component Testing

4.1 Introduction

There are two major areas requiring component testing for this phase of the metallic recuperator program; the first is the integrity of the refractory end-seal during thermal shock and cycling and the second is the ability of the flat plate primary surface to withstand the pressure forces at design temperature.

4.1 Seal Integrity

Seal integrity will be investigated by fabricating three sample units having overall plate dimensions identical to those planned for the full size unit. The material will be 309 stainless steel having a thickness of 0.010-inch as opposed to the 0.020-inch thick material proposed for the full size unit. Plate spacing will be equal for both gas streams and be approximately 5 plates per inch (present press and dies do not permit heavier gauge material or variation in plate spacing). There will be 20 plates per unit giving core matrix dimensions of 16 X 36 X 4 inches.

The sealing technique and material will be identical to that proposed for the full size unit (as described in Task III). Fabrication of the units will be by DLI; testing will be performed by Surface Division of Midland Ross, at their Toledo facility.

Since the object of the test is to determine thermal shock, M-R will perform thermal tests that will ensure that the rate of temperature change within the recuperator sample and the temperature variations will somewhat duplicate the expected conditions.

During operation, the gas temperatures entering and leaving the recuperator at low fire are estimated to be: T_1 = 70°F, T_2 = 1200°F, T_3 = 1500°F and T_4 = 1000°F.

The rate of temperature change will be determined by M-R and will be consistant with the proposed system.

After the thermal shock tests are complete, the units will be visually inspected for gross deterioration and then pressure tested to determine leakage rates across the seal. Due to the porosity of the refractory, a small amount of leakage is to be expected even before the thermal shock tests.

The units should be considered satisfactory, from the stand point of cross contamination, if the leakage at 5 psi differential pressure is maintained at below 1% of combustion air flow. The sample units will withstand a maximum of only 3 psi (at operating temperature), therefore an extrapolation procedure must be used to determine estimated leakage at 5 psi. Also, the units should be leak tested at operating temperature with a pressure exerted inward on the end caps as would be the case in actual operation.

4.2 Plate Pressure Tests

Several small samples of plate material will be fabricated having a thickness of 0.010, 0.015 and 0.020-inch and a dimple/corrugation design as described in Task III. Samples will be tested for 300 hours at 1200°F, and 1500°F at a pressure of 5 psi exerted over the surface. The tests will be performed in a small high temperature oven at DLI.

Each sample will measure 4 X 3 inches and have 6 dimples embossed for plate separation. A schematic of the test sample is shown in Figure 4.2. The 4 X 3 sample has a 1-inch thick layer of resiliant high-temperature refractory thermal insulation placed on top of it. When a 4 X 3-inch 60 pound weight is placed on top of the insulation, a pressure of 5 psi is exerted over the surface of the sample.

Before and after each test, measurements will be made to determine the plate spacing and dimple height. Also after the tests, measurements will be made to determine the amount of sag or creep between dimples. By using three different thicknesses, it will be possible to estimate the effects of reduced thickness, resulting from corrosion, on the integrity of the heat exchanger core. That is, in a soaking pit environment, it is predicted that 309 stainless steel will corrode at a rate of approximately 0.001-inch per year. The corrosion is predominantly pitting but the tests on the 0.010 and 0.015-inch thick material will allow a fairly good prediction of the life expectancy of the recuperator.

4.3 Pressure Drop Test

A 24-inch long sample using the proposed flue gas side dimple/corrugation pattern will be used to determine a standard temperature air pressure drop. The measurements will be used to check the pressure drop as predicted in the Task II Thermal Design. If discrepancies exist, then the test data will be used to correct the thermal analysis and recuperator design so that the design goals will be achieved.

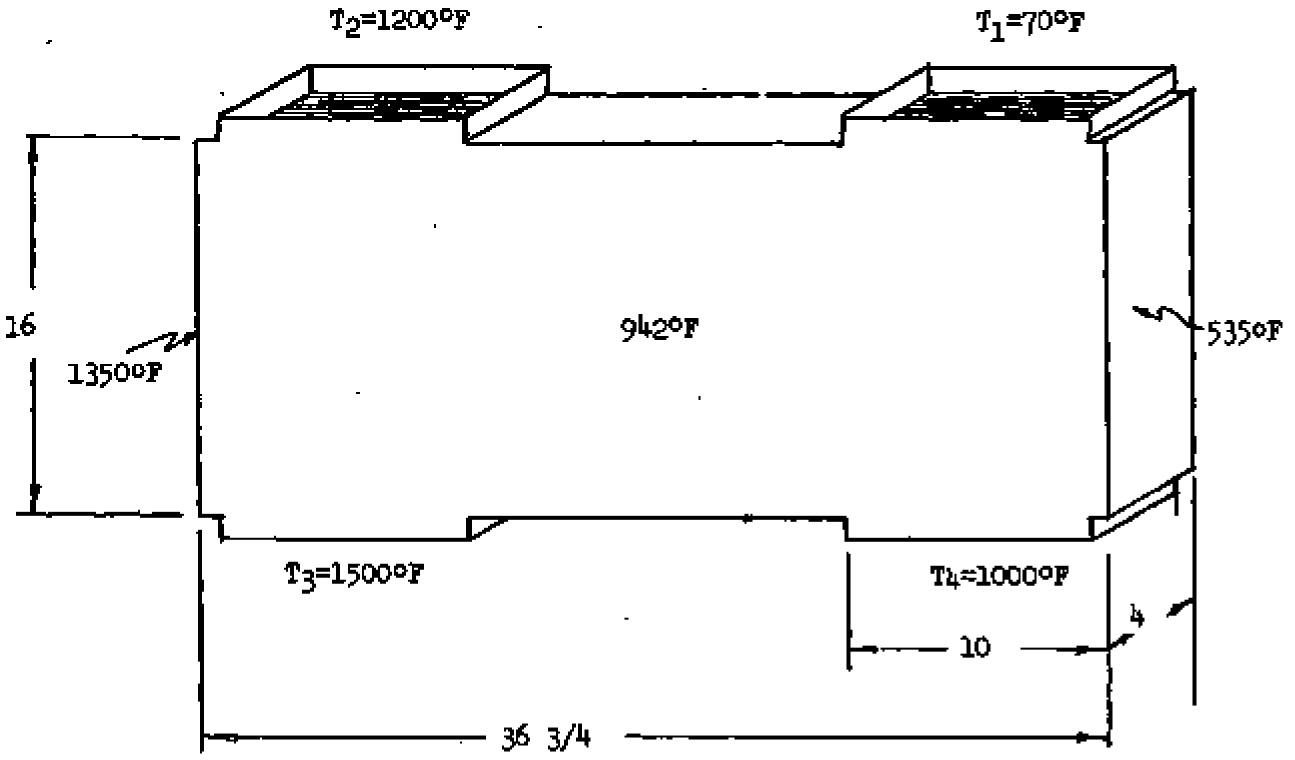

Figure 4.1 Test Sample Configuration For Thermal Shock Tests

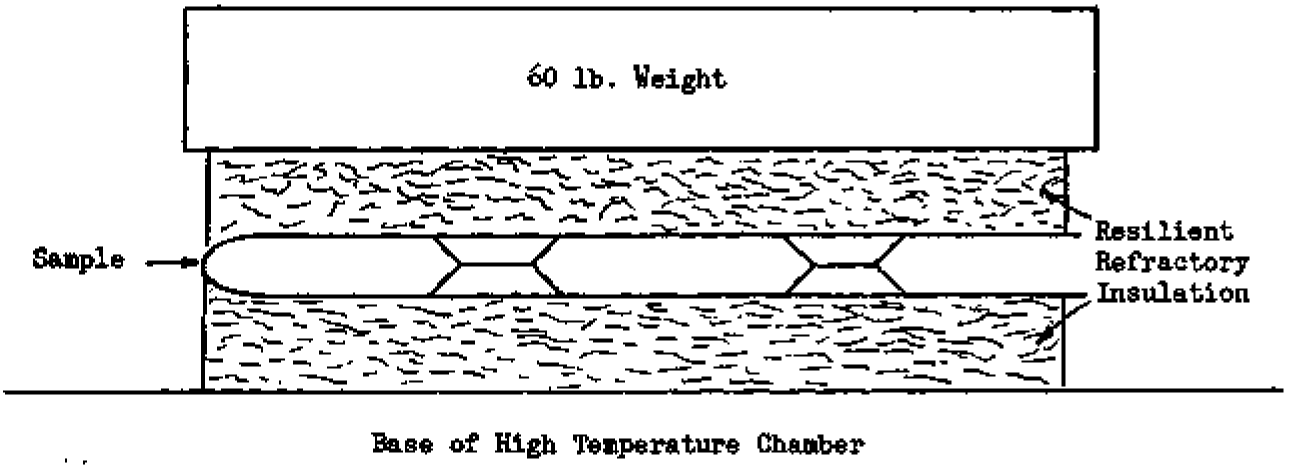

Figure 4.2 Pressure Test Set-Up for Sample Matrix Specimen at Operating Temperature and Pressure

Appendix I

Metallic Recuperator Specifications

Computer Program

August 25, 1978

METALLIC RECUPERATOR SPECIFICATIONS

High Fire Design Point	20 MM Btu/Hr/Pit
Flue Gas Temp. In	1200°F
Air Exit Temp.	1000°F (1145°F if necessary)
Flue Gas Exit Temp.	900°F
Air Temp. In	77°F
Air Flow Rate	1520 scfm
Flue Gas Flow Rate	4175 scfm
Air Pressure	5 psi static
Air Δ P	10 in w.c.
Flue Gas Pressure	Atmospheric ± .1 in. w.c.
Flue Gas Δ P	.25 in w.c.
Low Fire Environment	
Flue Gas Temp. In	1500°F
Air Exit Temp.	1300°F
Air Pressure	5 psi static

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	
002	SF0	16 21 00	
003	*LBL2	21 02	
004	RCL2	36 02	
005	RCL3	36 03	
006	×	-35	
007	RCL7	36 07	
008	×	-35	
009	1	01	
010	4	04	
011	4	04	
012	÷	-24	
013	STO1	35 01	
014	RCL3	36 03	
015	RCL4	36 04	
016	×	-35	
017	RCL7	36 07	
018	×	-35	
019	7	07	
020	2	02	
021	÷	-24	
022	STO3	35 03	
023	1/X	52	
024	RCL2	36 02	
025	×	-35	
026	RCL5	36 05	
027	×	-35	
028	3	03	
029	÷	-24	
030	STO5	35 05	
031	RCL6	36 06	
032	RCL2	36 02	
033	÷	-24	
034	STO4	35 04	
035	RCL5	36 05	
036	×	-35	
037	RCL0	36 00	
038	RCL1	36 01	
039	+	-55	
040	2	02	
041	÷	-24	
042	4	04	
043	6	06	
044	0	00	
045	+	-55	
046	STOA	35 11	
047	.	-62	
048	7	07	
049	Y^X	31	
050	1	01	
051	.	-62	
052	6	06	
053	EEX	-23	
054	7	07	
055	CHS	-22	
056	×	-35	
057	÷	-24	
058	STO7	35 07	
059	.	-62	
060	2	02	
061	1	01	
062	5	05	
063	CHS	-22	
064	Y^X	31	
065	.	-62	
066	2	02	
067	8	08	
068	×	-35	
069	.	-62	
070	0	00	
071	0	00	
072	3	03	
073	×	-35	
074	RCL8	36 08	
075	RCLA	36 11	
076	×	-35	
077	5	05	
078	3	03	
079	6	06	
080	÷	-24	
081	×	-35	
082	RCL7	36 07	
083	×	-35	
084	RCL4	36 04	
085	X²	53	
086	×	-35	
087	RCL2	36 02	
088	÷	-24	
089	PRTX	-14	
090	RCLA	36 11	
091	.	-62	
092	8	08	
093	1	01	
094	Y^X	31	
095	9	09	
096	.	-62	
097	4	04	
098	EEX	-23	
099	5	05	
100	CHS	-22	
101		-35	
102	RCL7	36 07	
103	.	-62	
104	3	03	
105	Y^X	31	
106	×	-35	
107	RCL5	36 05	
108	.	-62	
109	3	03	
110	Y^X	31	
111	×	-35	
112	RCL5	36 05	

REGISTERS

0 T_1	1 T_2	2 d_c	3 W	4 H	5 l_c	6 $\dot{m}_c$	7 N_c	8 v_{mc}	9 Pr_c
S0 T_3	S1 T_4	S2 d_h	S3 W	S4 H	S5 l_h	S6 m_h	S7 N_h	S8 v_{mh}	S9 Pr_h

A	B	C	D Cp_c	E Cp_h	I Fouling Factor

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
113	÷	-24		169	RCL1	36 01	
114	.	-62		170	×	-35	
115	0	00		171	CHS	-22	
116	3	03		172	STO6	35 06	
117	9	09		173	RCL2	36 02	
118	×	-35		174	RCL5	36 05	
119	F0?	16 23 00		175	÷	-24	
120	GTOB	22 12		176	STOA	35 11	
121	GTOC	22 13		177	CHS	-22	
122	*LBLB	21 12		178	1	01	
123	STOB	35 12		179	+	-55	
124	PRTX	-14		180	×	-35	
125	CF0	16 22 00		181	eˣ	33	
126	P⇄S	16-51		182	CHS	-22	
127	GTO2	22 02		183	STO5	35 05	
128	*LBLC	21 13		184	1	01	
129	STOC	35 13		185	+	-55	
130	PRTX	-14		186	RCL5	36 05	
131	RCL6	36 06		187	RCLA	36 11	
132	3	03		188	×	-35	
133	6	06		189	1	01	
134	0	00		190	+	-55	
135	0	00		191	÷	-24	
136	STOD	35 14		192	STO1	35 01	
137	×	-35		193	PRTX	-14	
138	RCLE	36 15		194	P⇄S	16-51	
139	×	-35		195	RCL0	36 00	
140	P⇄S	16-51		196	P⇄S	16-51	
141	STO2	35 02		197	STO3	35 03	
142	STOE	35 15		198	RCL0	36 00	
143	RCL6	36 06		199	-	-45	
144	RCLA	35 11		200	RCL1	36 01	
145	×	-35		201	×	-35	
146	RCLD	36 14		202	RCL2	36 02	
147	×	-35		203	×	-35	
148	STO9	35 09		204	STO4	35 04	
149	STOD	35 14		205	RCLD	36 14	
150	RCL2	36 02		206	÷	-24	
151	X≤Y?	16-35		207	RCL0	36 00	
152	GTO5	22 05		208	+	-55	
153	X⇄Y	-41		209	PRTX	-14	
154	STO3	35 03		210	STO1	35 01	
155	RCLE	36 15		211	RCL4	36 04	
156	STO5	35 05		212	RCLE	36 15	
157	*LBL5	21 05		213	÷	-24	
158	RCLB	36 12		214	CHS	-22	
159	RCLC	36 13		215	RCL3	36 03	
160	×	-35		216	+	-55	
161	RCLD	36 14		217	PRTX	-14	
162	RCLE	36 15		218	RCL1	36 01	
163	+	-55		219	RCL0	36 00	
164	÷	-24		220	-	-45	
165	RCL3	36 03		221	RCLD	36 14	
166	×	-35		222	×	-35	
167	RCL2	36 02		223	PRTX	-14	
168	÷	-24		224	RTN	24	

LABELS					FLAGS	SET STATUS		
A	B	C	D	E	0	FLAGS	TRIG	DISP
a	b	c	d	e	1	ON OFF 0 ☐ ☐ 1 ☐ ☐ 2 ☐ ☐ 3 ☐ ☐	DEG ☐ GRAD ☐ RAD ☐	FIX ☐ SCI ☐ ENG ☐ n ____
0	1	2	3	4	2			
5	6	7	8	9	3			

METALLIC RECUPERATOR - HIGH FIRE

Cold Side Air		Hot Side Flue	
77.0000	0	1200.0000	T_1 and T_3, °F
981.0000	1	567.0000	T_2 and T_4, °F
0.1050	2	0.4800	Plate Spacing, d, Inches
16.0000	3	16.0000	Core Depth, W, Inches
34.5000	4	34.5000	Core Height, H, Inches
34.5000	5	34.5000	Flow Length, l, Inches
1.9900	6	5.2190	Flow Rate, m, Lb/Sec
200.0000	7	200.0000	Number of Flow Passages for each Flow
5.5500	8	13.3400	Specific Volume, Ft^3/Lb, at 70°F
0.6870	9	0.6950	Prandtl No.
0.9921	A	0.9921	N/C
5.0721	B	5.0726	N/C
9.1815	C	9.1815	N/C
0.2500	D	0.2500	Specific Heat Air Side
0.2600	E	0.2600	Specific Heat Flue Side
0.8500	F	0.8500	Fouling Factor

Number of Flow Channels	160.0000	180.0000	200.0000	220.0000	240.0000
Pressure Drop Air Side, In. w.c.	2.4650	1.9976	1.6551	1.3562	1.1953
Heat Transfer Coefficient Air	11.4273	10.4068	9.5675	8.9551	8.2690
Pressure Drop Flue Side, In. w.c.	0.3396	0.2753	0.2280	0.1922	0.1647
Heat Transfer Coefficient Flue	6.2543	5.6915	5.2316	4.8477	4.5218
Effectiveness, %	0.8592	0.8649	0.8695	0.8742	0.8782
T_2, °F	1041.5354	1048.1940	1053.7716	1058.7255	1062.1721
T_4, °F	862.2571	860.6313	856.0753	855.2449	854.7862
Heat Recovered, BTU/Hr	1643968.505	1650741.756	1670279.496	1678751.327	1686354.294

See Figure 2.2 for definitions of symbols.

METALLIC RECUPERATOR - LOW FIRE

Cold Side Air		Hot Side Flue	
77.0000	0	1500.0000	T_1 and T_3, °F
1390.0000	1	1075.0000	T_2 and T_4, °F
0.1050	2	0.4500	Plate Spacing, d, Inches
16.0000	3	16.0000*	Core Depth, W, Inches
34.5000	4	34.5000	Core Height, H, Inches
34.5000	5	34.5000	Flow Length, l, Inches
1.4250	6	3.9140	Flow Rate, m, Lb/Sec
200.0000	7	200.0000	Number of Flow Passages for each Flow
9.3500	8	13.2400	Specific Volume, Ft^3/Lb, at 70°F
0.5270	9	0.6950	Prandtl No.
0.3921	A	0.3921	N/C
9.0720	B	9.0720	N/C
9.1815	C	9.1815	N/C
0.2500	D	0.2500	Specific Heat Air Side
0.2600	E	0.2600	Specific Heat Flue Side
0.2500	F	0.8500	Fouling Factor

Number of Flow Channels	160.0000	180.0000	200.0000	220.0000	240.0000
Pressure Drop Air Side, In. w.c.	1.7513	1.4157	1.1723	0.9923	0.8455
Heat Transfer Coefficient Air	9.4321	9.5939	7.3900	7.2106	6.3152
Pressure Drop Flue Side, In. w.c.	0.2419	0.1960	0.1624	0.1370	0.1177
Heat Transfer Coefficient Flue	5.1604	4.6963	4.3167	3.9956	3.7309
Effectiveness, %	[illegible]	0.8865	0.8918	0.8950	0.8986
T_2, °F	1331.1247	1338.4966	1344.5433	1350.6506	1355.7553
T_4, °F	1060.3622	1058.7520	1056.1255	1054.1272	1052.2387
Heat Recovered, BTU/Hr	1608414.647	1617665.442	1626136.002	1633456.878	1640006.511