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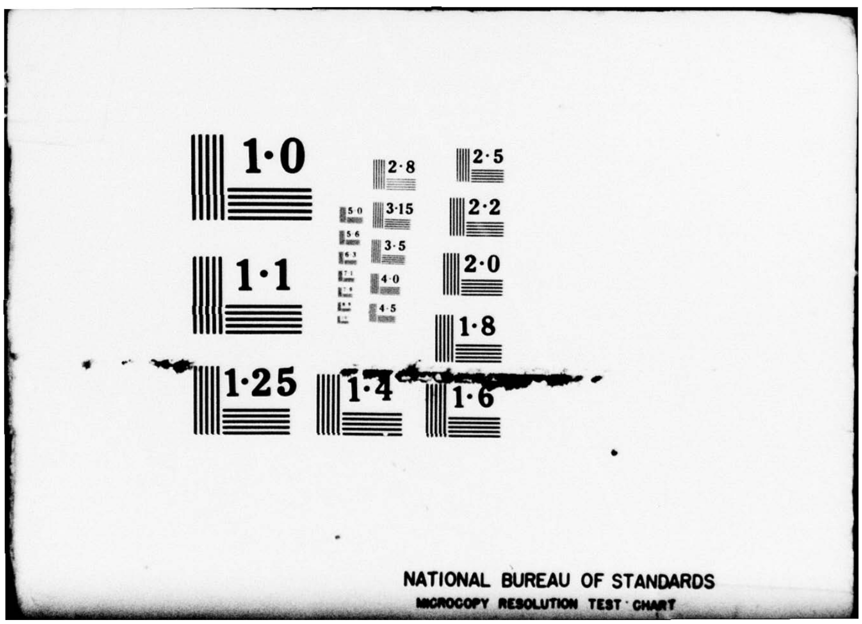
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NWC Technical Memorandum 2930

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HEAT EXCHANGER TECHNOLOGY NEEDS FOR CONSERVATION RESEARCH AND TECHNOLOGY, ERDA

by

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(11) December 1976

(14) NWC-TM-2930

(12) 51 p.

Approved for public release; distribution unlimited.

(15) E(49-28)-1008

This is an informal report of the Naval Weapons Center and is not to be used as authority for action.

(9) Technical memo,

NAVAL WEAPONS CENTER
China Lake, California 93555

FOREWORD

The contents of this report summarize the work supported by the Division of Conservation Research and Technology (CONRT) of the Energy Research and Development Administration (ERDA) under Interagency Agreement E(49-28)1008. The responsible ERDA project officer was J.W. Neal.

This report has been prepared for timely presentation of information. Although care has been taken in the preparation of the technical material presented, conclusions drawn are not necessarily final and may be subject to modification or revision.

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30 September 1976

NWC TM 2930, published by Code 406, 20 copies.
Second printing (November 1976), 8 copies.
Third printing (December 1976), 50 copies.
Fourth printing (March 1977), 50 copies.

CONTENTS

INTRODUCTION

This report summarizes the results of a survey taken by the author, whose purpose was to identify current and future heat exchanger needs within the Division of Conservation Research and Technology (CONRT) of the Energy Research and Development Administration (ERDA). As background information, for those who may be unfamiliar with CONRT, the function and responsibility of CONRT is to provide technology required for successful development and implementation of advanced energy conversion systems and components for ERDA's Office of Conservation. In more specific terms, the objectives of CONRT are to develop technology required to implement identified end-use components and systems and to provide research support for concepts designed to utilize or promote alternative energy sources. CONRT provides assistance in meeting technology needs of the more end-use oriented divisions of Conservation such as Transportation, Buildings and Industry, Electric Utilities and Storage. Given the research and technology responsibility for such a wide spectrum of activities, it is not surprising to find technology needs of other major groups within ERDA, outside Conservation, (e.g. Solar, Geothermal, Ocean Thermal, Fossil, Nuclear) coinciding with those of CONRT.

At present, the emphasis of CONRT's programs is placed on the following:

1. Waste heat energy conversion systems including, (a) organic Rankine cycle bottoming systems that utilize low grade waste heat; (b) high temperature expanders and thermionic topping cycles for high grade waste heat utilization.

2. Advanced gas turbines for industrial power generation.

3. Fuel cells for application to intermediate, cycling and peaking needs of electric utilities.

4. Research and development of components to improve the efficiency and reliability of energy conversion systems.

5. Combustion research and technology to improve vehicle propulsion and utility, and industrial and commercial burner systems.

6. Materials research and technology to improve the efficiency and reliability of energy conversion systems and to reduce the dependence on foreign importation of strategic materials (e.g., chrome).

Many programs supported by the Office of Conservation rely heavily on the performance, reliability and cost of heat exchangers during development and demonstration of efficient energy conversion systems and energy conversion strategies. This is true of programs in other offices of ERDA as well. It should be emphasized that heat exchanger design, construction, and operation involve the interaction of many disciplines and are strongly influenced by a variety of technologies that include flow-induced vibration, high-temperature material behavior, corrosion, erosion, heat transfer, structural analysis, fluid dynamics, low cost manufacturing techniques, and sophisticated nondestructive evaluation techniques.

Current demands on heat exchangers have created a growing number of problems and directed attention to the serious deficiencies that exist in certain heat exchanger technology areas. Many of these problems have delayed development schedules, compromised program objectives, and caused serious concern about future development and implementation of advanced energy conversion systems. CONRT recognized the seriousness of this situation and the apparent lack of attention and planning being given to correct the deficiencies. It was felt that if the deficiencies in heat exchanger technology were not quickly identified and proper corrective measures instigated, it would be difficult meeting many of CONRT's goals and major program milestones. In addition, other programs within the Office of Conservation dealing principally with the demonstration of efficient and reliable end-use systems and components would likely suffer from a variety of heat exchanger related problems. These problems, described later in this report, are expected to occur more frequently because heat exchanger environments are becoming more severe and the quest for higher efficiencies and lower costs have reduced margins of safety, making the unit more vulnerable to design uncertainties.

CONRT requested that a survey be conducted to identify major heat exchanger problems and technology deficiencies that affect current and future programs, plans, and goals of CONRT. A series of interviews, arranged by the author, were held with individuals in universities, non-profit research organizations, private industry, and government laboratories who were actively involved in various aspects of heat exchanger technology. Since many heat exchanger problems and needs are common among ERDA's divisions, pertinent information was also obtained from ERDA projects outside the purview of CONRT. For example, some heat exchanger problems in high-temperature fossil-fuel environments, low-temperature goethermal and ocean thermal applications, and nuclear energy conversion are similar to those of CONRT.

The contents of this report are separated into two main parts. The first contains results of the heat exchanger technology survey, In the second part, an outline of a proposed plan to correct the deficiencies identified by the survey is presented. This plan addresses and supports the following ERDA National Energy and Technology Goals:

1. Increase the efficiency and reliability of the process used in energy conversion and delivery systems.

2. Increase end-use efficiency.

3. Perform basic and supporting research and technical services related to energy.

The private sector is actively supporting research and technology programs in important areas of heat exchanger technology (e.g., corrosion, new alloys, tube vibration, ceramic regenerators). Federal assistance is not required in many of these areas because it is expected that significant results can be achieved in a timely manner. However, much of this work is limited to either a very narrow set of conditions germane to a particular company problem or product or, because of limited funds, is superficial and does not make an important contribution to the technology base. Most of the heat exchanger technology deficiencies identified in the survey and discussed in this report, in the opinion of the author, do required federal support because the private sector cannot (because the necessary costs are too high) or will not (lacks incentive) provide the necessary advances in technology in a timely manner.

The program plan is designed to advance certain areas of heat exchanger technology identified by the survey as being important to CONRT. Part of the justification for support of this plan should be based upon analyses that quantify the benefits derived from improvements in the technology. However, certain elements of this program cannot, at present, be supported by cost-benefit analyses. When dealing with heat exchangers, these analyses are usually unavailable. The myriad of problems encountered by users of heat exchanger equipment often precludes an accurate interpretation of a cost-benefit analysis.

There are two types of heat exchangers of interest to the Office of Conservation that were not considered in this report. These are heat exchangers for automotive applications and heat exchangers used to store chemical and thermal energy. There has been and currently is a significant amount of research and development activity in compact automotive heat exchangers for high performance engines. Within the Office of Conservation, the Division of Transportation supports all automotive heat exchanger work. It was felt that this highly specialized area of heat exchanger technology was not a major concern to CONRT. The Storage Division of Conservation utilizes heat exchangers in thermal and chemical storage systems. These heat exchangers were also thought to be somewhat specialized and, because the needs could not be clearly identified, were not considered.

MAJOR HEAT EXCHANGER PROBLEMS AND DEFICIENCIES AFFECTING CONRT

Prior to the time the public became aware that our nation's economy had become dependent on foreign sources of oil whose cost and supply could not be controlled, and before the subsequent meteoric rise in cost of fossil fuels, heat exchangers were often viewed as a rather pedestrian thermodynamic necessity in energy transfer and conversion systems. Excluding some aerospace and automotive applications, the design of heat exchangers for industrial, commercial and residential use offered relatively little challenge. Standard references (e.g., Kay's and London's Compact Heat Exchangers[1]) and individual collections of data and empirical relationships provided selection and design criteria. Sizable heat transfer margins were often applied to account for the uncertainties in fouling, fluid properties, multi-phase flow effects and local flow characteristics. Correspondingly large structural margins of safety were also incorporated as ignorance factors to hedge against uncertainties in heat exchanger material properties, flow induced vibration, corrosion, erosion and transient thermal stresses. Ample space was usually provided to the heat exchanger core to facilitate cleaning and repair. Because fuel costs were low, there was little incentive to maximize thermal efficiency. Compared to today's applications, many of the heat exchanger environments were less hostile which meant inexpensive alloys could be used in construction. As a result of this conservative design and manufacturing philosophy, it was not surprising to find many industrial and commercial heat exchangers extremely large, relatively inefficient, but functional and affordable.

During this time, which extended into the early 1970s, few were interested in improving heat exchanger design tools, increasing unit efficiency, and significantly lowering costs. Certainly there was no substantial commercial interest in developing efficient heat exchangers for (1) direct application in high temperature (above 3000°F (1649°C)), corrosive, coal-fired energy conversion environments (e.g., coal gasification, coal-fired topping cycles) or (2) converting into useful work the energy contained in our nation's vast, waste heat sources (e.g., engine exhaust, incinerators, steel furnaces, heat treatment ovens, glass melting furnaces). There was, however, a relatively small segment of the heat exchanger community who responded to an identified need and maintained an active interest in reducing heat exchanger size and maximizing efficiency. Portions of the aerospace and transportation industries were busy designing and fabricating customized, compact, highly efficient heat exchangers for space, automotive and defense related applications. For a variety of reasons, many of which still persist today, very little of this advanced technology was used by the industrial and commerical heat exchanger manufacturers.

Today we are searching for alternative fuels and exploiting available energy sources at an unprecedented rate. The forlorn heat exchanger, once relegated to a position of secondary importance, is now considered a critical component in practically all energy systems. Our nation's quest to improve efficiency and speed development of new and improved energy recovery and conversion systems has uncovered a great many deficiencies in heat exchanger design, materials selection, fabrication and reliability. Current deficiencies in heat exchanger technology are causing the frequency of heat exchanger failures to increase which, in turn, are causing unexpected shutdowns in power plants and industrial processes. Many programs suffering from heat exchanger problems cannot look forward to immediate solutions. It is expected that unless a serious commitment is made to advance heat exchanger technology over a broad front, these problems will not only persist but will intensify.

Before specific problems and deficiencies in heat exchanger technology are discussed, there are two poignant examples that serve to illustrate how the exploitation of a plentiful fuel source and the conservation of domestic fuel supplies are being affected by the lack of an adequate technology base. These concern the commercialization of large-scale coal conversion plants (gasification/liquifaction) and the development of efficient waste heat recovery systems that produce electricity. Technology associated with the utilization of coal (direct combustion and converting it into gaseous and liquid fuels) is the responsibility of ERDA's Office of Fossil Energy. However, many problems of components subjected to these hostile environments are germane to heat exchangers that must function efficiently and reliably in topping cycle applications which is of major interest to CONRT.

Coal conversion is being forced to move from research, development, and pilot plant stages into commercialization more rapidly than what is considered normal for industry. Design and reliability problems persist with heat exchangers and other components in coal gasification and liquifaction pilot plants. (It deserves mention that similar problems exist with direct combustion systems and MHD.)[2-9] These problems are difficult to solve because the U.S. has no established, commercial coal conversion industry and there is no meaningful data base or past experience with equipment exposed to these high temperature, corrosive, erosive conditions.

The coal conversion pilot plants are designed to acquire and document engineering data and actual operating experience to provide for eventual scale-up to commercial-sized plants. Unfortunately, it is often difficult at the pilot plant stage to minimize cost while maximizing efficiency and output of the various processes. Materials of construction are frequently used that are recognized as being impractical or uneconomical in larger systems. Widespread use of nickel and chrome alloys in pilot plant equipment is currently required to combat a variety of chemical and mechanical degradation mechanisms that include sulfidation, stress-corrosion cracking, erosion, hydrogen embrittlement, carbonization, high stresses and extensive creep. The available supply and cost of nickel and chrome make it clear that these materials cannot be used extensively in large plants.[5,10]

Material development programs, whether directed at heat exchangers or other components, require laboratory devices and techniques to simulate the particular chemical processes of concern. Many of today's laboratory simulation techniques are poor as evidenced by the fact that material behavior under actual conditions cannot be accurately predicted from data and experience based on laboratory simulations.[5] This deficiency has often reduced the role of laboratory simulation to one of screening material candidates, not developing fundamental understanding and contributing to a sound technology base that can be used to accurately predict material behavior and life-cycle costs.

The critical technology needs of components used in coal conversion/combustion environments are: (1) improved component design and failure criteria, (2) the use of materials that are more abundant and less expensive, and (3) more effective testing techniques that simulate actual field conditions.

An example of the kinds of heat exchanger problems affecting the conservation of fuel relates to efficient waste heat recovery and conversion to electricity. These energy conversion systems (called bottoming cycles) are attractive when operating off the exhaust of gas turbines or diesels because the combined cycle efficiency is significantly higher than the diesel or gas turbine alone. CONRT is currently participating with industry in developing efficient Rankine cycle bottoming systems to generate electricity from 500°F (260°C) to 1000°F (538°C) diesel or gas turbine exhaust gas.[11,12,13] Both steam and organic working fluids are being considered.

To maximize the useful work produced from a given waste heat source, the efficiencies of the waste heat boiler and Rankine cycle must be maximized. The practical limit of boiler thermal efficiency is achieved by extracting as much energy as possible from the flue gas without incurring economic penalties caused by excessive heat exchanger surface area requirements and / or materials problems from low temperature acid corrosion (discussed later in this report). The efficiency of converting this sensible (and latent heat) energy into useful work is maximized by requiring that all heat transfer between (1) exhaust gas-and-heat engine and (2) heat engine-and-environment be accomplished at minimum temperature difference. This is illustrated in Figure 1 where a particular combination of working fluid and heat exchanger has been chosen so that the working fluid temperature will closely follow the exhaust and sink temperatures.[13]

Heat exchangers, especially the waste heat boiler (often called vapor generator), play a critical role in the cost, efficiency, and reliability of these waste heat energy conversion systems. It is particularly important

10

to reduce the cost of the heat exchangers because, in today's market place, Rankine cycle bottoming systems can be relatively expensive. The amount of useful work is limited because of the relatively low source temperatures (as compared to conventional, direct-fired steam boilers where combustion temperatures may be 3000°F (1649°C) and higher). To minimize temperature differences across the heat exchangers and generate as much power as possible, very effective heat transfer surfaces and/or very large heat transfer surface areas are required. One would prefer not to increase heat exchanger effectiveness by adding more surface area since the size and cost of these units are the largest of the system. High-density or compact heat exchanger cores are desired, but concerns related to exhaust side pressure drop, fouling, cost and reliability limit the degree of compactness. Once-through boilers, where a subcooled working fluid enters at one end and superheated vapor exits the other end in a continuous manner, offer certain advantages in this application because of their simplicity and reduced cost.

With waste heat temperatures less than 1000°F (538°C), organic fluid Rankine systems become more efficient than steam cycles.[13] Organic fluids are widely used in refrigeration systems and becoming well known in the process industries but they are, as yet, not widely accepted in large, Rankine cycle bottoming systems. Many of these fluids are admittedly toxic and flammable, the heat transfer and fluid flow characteristics are not well defined, and thermal stability limits under expected operating conditions cannot be adequately quantified. With many organic fluids, therefore, there can exist a relatively high degree of uncertainty related to heat exchanger and system performance, efficiency, cost and reliablilty.

Waste heat steam boilers, on the other hand, have been in existence for many years, providing steam for industrial processes, space heating, generating shaft work and electricity. Even though a steam bottoming system coupled to a gas turbine (or diesel) will increase combined cycle efficiency,[13,14,15] not many of these units are in use. Capital costs are relatively high and today's purchase price of fuel and electricity has not made it economical in many instances. This situation is changing rapidly, however.

At present, there does not appear to be a meaningful commercial interest to design, fabricate,and test compact and highly efficient heat exchangers for organic Rankine cycle waste heat recovery systems. This statement is based upon the experiences of CONRT and companies developing these systems who have found it difficult enticing heat exchanger manufacturers to provide certain equipment (e.g., waste heat boiler) to support their programs. It is not particularly surprising to find this situation because this segment of heat exchanger technology is significantly underdeveloped. There are large uncertainties related to heat transfer, fluid stability, fouling,corrosion, thermal stresses, and flow induced vibration. In addition, facilities to test and certify performance of these units are expensive and sometimes require remote location.

The preceding discussion illustrates the kinds of heat exchanger problems that presently exist in developing alternative energy resources, conserving domestic fuels, and improving the efficiency of energy conversion and recovery systems. Specific deficiencies in heat exchanger technology that relate to these and other problems will now be discussed.

COST

It seems trite to say, but worth remembering, that no matter how advanced heat exchanger technology becomes, unless capital and operating costs can be economically justified by the user, there will be no sale, no savings of energy, and the U.S. will be no less dependent on foreign oil. Estimating the cost of a heat exchanger for a given application depends on the nature of the environment (on the hot and cold side of the heat exchanger), choice of materials and configuration, size, method of fabrication, cost of transportation and installation, maintenance requirements, replacement frequency, production quantities and profit. With this number of variables affecting unit cost, it is clear that only in those applications where many heat exchangers have been sold and there exists a well documented history of heat exchanger performance can heat exchanger cost be considered accurate.

As the previous examples indicated, and as this report will show, there are many applications for heat exchangers in energy recovery and conversion systems where there is no substantial market as yet and no history of performance and reliability. In this situation, heat exchanger designers and manufacturers are often reluctant to consider advanced heat exchanger concepts, choosing instead to apply state-of-the-art technology. This approach has, in many instances, resulted in very large and costly heat exchangers.

The cost of heat exchangers is presently a significant percentage of the total estimated cost of many energy recovery/conversion systems, especially those that involve low temperature processes. For example, waste heat boilers for Rankine cycle bottoming systems (500°F (260°C) - 1000°F (540°C) waste heat temperatures) are predicted to be approximately 20 to 30% of system cost.[13,16] The condenser and evaporator for Ocean Thermal Energy Conversion (OTEC) are estimated to be at least 50% of the total cost because the available temperature differences are so small (less than 10 F degrees across the heat exchanger).[17] With high temperature topping cycles (e.g., closed Brayton cycle), less surface area is usually required by the primary heat exchanger but more expensive materials and fabrication techniques are demanded. Estimates of capital, operating and life-cycle costs for many of these heat exchangers is suspect at best because so little operating experience has been accumulated.

Many energy conversion systems either under study, in various stages of development, or ready for sale are capable of saving significant amounts

12

of energy but are considered economically marginal in today's market place. It can be difficult with the economic situation that exists today for a user to accumulate enough capital to purchase a waste heat bottoming system that produces 1000 kw of electricity at $500/kw. At current energy prices, a user wanting additional electricity, may find it temporarily more economical and possibly involving less technical risk to (1) buy directly from a utility or, (2) purchase a gas turbine-generator for $100/kw or diesel-generator for $200/kw.

There are particular heat exchanger applications in energy conversion systems where cost is not, as yet, a major concern. In such cases, which usually involve extremely severe environments (e.g., coal conversion, coal-fired topping cycles, MHD), acquiring *system performance or process* information is of most interest. Only a limited number of materials may be expected to survive under these conditions and only a few units may be needed; as a result, the heat exchanger is usually very expensive. In these situations, heat exchanger cost will become a concern once system and process parameters have been determined.

CONRT's incentive to reduce heat exchanger costs is to increase the use of more efficient energy recovery and conversion systems. Successfully lowering heat exchanger costs by incorporating more effective heat exchanger surfaces and fluids, using less expensive materials and fabrication methods, and reducing structural margins of safety requires more knowledge about the behavior of materials and working fluids, heat transfer, fouling, vibration and corrosion than we possess today. Reducing the costs of fabrication, inspection and maintenance while increasing reliability offers a significant challenge to heat exchanger designers and manufacturers.

CORROSION

The corrosion of heat exchanger elements depends on the nature, composition and temperature of the heat exchanger elements and the thermochemical characteristics of the environment. A major concern for many years, the scourge of corrosion affects virtually all aspects of heat exchanger design (i.e., heat transfer, fluid dynamics, structural durability, material selection). Corrosion significantly influences cost and operating procedures. There is little doubt that corrosion will continue to create problems as long as heat exchangers are exposed to hostile environments.

There are numerous examples one could cite to illustrate the severity and complexity of corrosion problems. There are just as many, if not more, corrosion studies that address particular corrosion phenomena. The amount of corrosion-related work being supported by government and private industry is prodigious. One merely looks at the numbers of periodicals, reports and professional journals that concern corrosion to verify this. The solutions to corrosion problems in nuclear steam generators, coal conversion, direct-fired boilers, MHD, ocean thermal energy conversion, waste heat recovery and other energy conversion systems have been difficult to achieve without resorting to very expensive approaches. In coal gasification pilot plants, for example, the solution to many corrosion problems has simply been to find a more corrosion resistant alloy, which usually requires a more expensive material. Based upon the large number of variables affecting the corrosion rate of materials in hostile environments it seems inevitable that acceptable solutions to major heat exchanger corrosion problems will take considerable time to appear and require a sizable funding commitment.

In CONRT, current heat exchanger corrosion problems are not, and in the future will not, be much different than found elsewhere within ERDA and the private sector. At elevated temperatures, oxidation, sulfidation, and carbonization of heat exchanger materials are forcing the use of more expensive alloys. The additional cost cannot be tolerated in many of today's energy conversion systems. More use must be made of claddings and coatings for metallic heat exchangers to decrease reliance on strategic and foreign supplied materials such as chrome and nickel. Ceramic heat exchanger materials are often effective in resisting corrosion but inadequate design criteria, high fabrication costs and questionable reliability have proven to be weaknesses (more discussion will follow).

A problem that relates to all heat exchangers exposed to the combustion products of fossil fuels is low temperature sulfuric acid corrosion (sometimes called low end corrosion). This problem has been especially acute with oil-fired steam boilers and, with the price of low sulfur fuels rising rapidly, will begin to affect many more users of heat recovery equipment.[18] The basic causes of this low temperature corrosion phenomena are known. During the fuel-air combustion process, whether it occurs in a steam boiler, a household furnace, gas turbine or internal combustion engine, most of the sulfur in the fuel oxidizes to SO_2. The SO_2 reacts with oxygen to form SO_3 (the details of this process being very complex and subject to conjecture). The SO_3 hydrolyzes with water to form sulfuric acid, H_2SO_4. When the local surface temperature of a metallic heat exchanger falls below the local acid dew point, a film of sulfuric acid forms on the surface causing rapid corrosion. Particles carried with the combustion products adhere to the wetted surface, plug fin passages, and act as collectors for additional acid condensate.[8,19,20]

The concentrations of SO_3 and associated acid dew points have not been determined in many fossil fuel combustion environments. Obtaining this information can be difficult because certain oxides, including iron oxide and vanadium pentoxide, serve as catalysts and aid the formation of SO_3.[8] Predicting H_2SO_4 dew point in heat exchanger environments seems futile because of the large degree of uncertainty associated with the complex thermochemical phenomena (e.g., SO_3 formation).

The current and most preferred method of solving the acid corrosion problem with sulfur fuels is straightforward: keep the metallic surfaces that are exposed to the combustion products well above the estimated acid dew point. Even though a considerable percentage of the total source energy is lost using this technique, it successfully avoids the formation of sulfuric acid condensate. In some situations, however, acid corrosion cannot be and is not being avoided. The available data on acid corrosion rates with heat exchanger materials is very sparse; what little can be found usually applies to oil-fired boilers and large furnaces.[20] These data relate to very specific conditions which severely limits applicability. In addition, this data cannot be used with confidence to estimate replacement frequency because yearly corrosion rates are usually extrapolated from test results of only a few days. The effects of interrupted operation on corrosion rates are nonexistent.

Acid corrosion is so critical to energy recovery and conversion because the lowest permissible temperature of the energy source and heat exchanger is usually dictated by the dew point temperaturee. For example, the lowest recommended heat exchanger temperature in an oil-fired boiler environment, using 3% sulfur oil, is approximately 220°F (105°C) to 250°F (120°C)[16,20] As pointed out earlier, it is desired to extract as much energy from the source as possible to realize a greater thermal efficiency. A recent design study of an organic Rankine cycle energy conversion system showed that every 5.7F° (3.2C°) drop in exhaust temperature would yield 1% greater power output. For this particular application, approximately 20% of the energy contained in the source could not be used because of the concern for acid corrosion.[13] The uncertainty in acid dew point, suggested above by the spread in recommended minimum heat exchanger temperatures, represents a considerable loss in system efficiency.

There are applications where the latent heat of water vapor is a significant fraction of the total energy content of the flue gas and it can be important to condense this fluid to increase energy recovery. It is common practice in some utilities to purposely condense fluid on air preheaters.[20,21] Corrosion is tolerated in these situations with frequent washing being required to minimize material wastage by corrosion. Usually these heat exchangers are relatively inexpensive and replacement costs do not exceed the fuel savings obtained from additional energy recovery. With residential flue gas heat recovery, however, the heat exchanger cost is a major concern. Condensing the water vapor in this application retrieves a rather large percentage of the total energy containedin the flue gas (20 to 25%). When low cost, compact, corrosion resistant heat exchangers become available, flue gas recovery for residential applications will become widespread.

Deficiencies in this area of heat exchanger technology are responsible for heat exchangers corroding and being replaced earlier than expected, and decreasing energy recovery efficiency. To improve this situation, it is necessary to quantify low temperature corrosion phenomena, develop engineering design criteria to maximize thermal efficiency, determine realistic corrosion rates of heat exchanger materials, and develop heat exchangers that can operate efficiently and reliably below dew point temperatures.

FOULING

Fouling is defined as a deposition of material on a surface that impedes heat transfer. Without question, there is less known about heat exchanger fouling than any other heat transfer related subject. Fouling factors used in heat exchanger design are highly empirical[16,22] which is not suggesting that there is a great abundance of fouling data. A common practice among companies who are responsible for designing and constructing heat exchangers is to put the responsibility for selecting fouling factors on the user[23] who often knows less about fouling. The lack of adequate prediction methods and the absence of an organized, comprehensive fouling data base are responsible for practically all heat exchanger problems attributed to fouling. These problems will continue to occur in heat exchangers for energy recovery/conversion systems unless a well coordinated, substantive effort to address fouling phenomena is initiated.

Of the many different kinds of fouling encountered in commercial and industrial applications, those of most concern to CONRT are water fouling (biofouling and scaling), and the deposition of hydrocarbon particulates from the combustion of fossil fuels.

Water Fouling

It is commonly known that biofouling of heat exchangers can be controlled and sometimes eliminated if (1) enough pumping power is available to maintain the velocity of water above certain minimums; (2) bio-toxic materials such as copper alloys, organometallics or fluorochemical paints[17] can be used; (3) quantities of biocides and fungicides can be added to the water. With regard to the latter, chemical cleaning treatments are tolerated only when the concentrations do not exceed environmental limits which are becoming increasingly restrictive.[25]

In actual practice, biofouling cannot be completely eliminated and its effect on heat exchanger performance will depend on the extent of build-up and the available temperature difference. In the OTEC system, for example, only a very small degree of fouling can be tolerated because the available temperature differences across the heat exchangers are so small. This particular problem is made more difficult because (1) ammonia has been temporarily chosen as the working fluid which eliminates the bio-toxic copper alloys as heat exchanger materials; (2) large quantities of chlorine required to control biofouling may not be tolerated because of environmental concerns. With OTEC, as with many systems that must operate in sea water, the inadequate data base on sea water fouling requires costly test programs to verify heat exchanger design predictions prior to unit construction.

The situation with river water fouling is not much better. Each river has its own assortment of aquatic organisms and sediments. Each system requiring river water for cooling must be provided fouling data or estimates of fouling factors to size the heat exchanger. There usually is little or no reliable information that can be used to properly estimate fouling factors. If estimates are not accurate, the unit will exhibit and require frequent cleaning (possibly causing the system to shutdown) or possibly promote fouling by causing the fluid to overheat. Another factor to consider with the conservative approach (anticipating less fouling than allowed in the design) is the possibility that lower design velocities will create a greater fouling problem than what might have occurred at high velocities.[22,26]

Heat rejected from a condensing working fluid in a power plant is ultimately dissipated by either a once-through cooling system (e.g., ocean or river) or a recirculated water system (e.g., cooling towers, ponds). With dwindling supplies of fresh water available to meet commercial and industrial cooling requirements and increasingly tighter controls being placed on thermal discharge to natural sources, more use is being made of recirculating systems where the cooling water is used over and over again.[27,28] Scaling-type fouling in recirculation systems is a growing problem due not only to the chemistry of the natural water supply but to the presence of chemicals introduced to control biofouling and corrosion. Scale prevention in recirculating water systems utilizes control techniques that alter or render inoperative the scale forming mechanism. Blowdown to control concentration, pH control, chemicals to retard corrosion and scale formation, and ion-exchange removal of scale forming constituents are the principle means of scale control today.[27] Due to evaporation and drift losses in cooling towers, the concentration of these chemicals increases with time. Where the natural drift loss is insufficient to limit these concentrations, it is necessary to supplement by means of blowdown. Certain chemicals that have been used for many years to effectively control fouling and corrosion (and are relatively inexpensive) are now being restricted because of health and environmental concerns. New substitute additives have proven to be expensive and have not been as effective.[29]

There is an urgent need to begin a comprehensive, systematic collection of fouling data that pertains to different fouling environments and different heat exchanger configurations. A complementary experimental and analytical effort should be focused on improving prediction techniques; determining how the physio-chemical structure of fouling and fouling rates are affected by (1) new anti-fouling/corrosion inhibiting chemicals, (2) water disposal and cooling strategies, (3) materials of construction, (4) temperature and velocity, and (5) heat exchanger configuration. The impact of legislation affecting the application of anti-fouling/corrosion inhibiting chemicals and disposal of treated water needs to be documented.

In geothermal energy conversion, there is significant concern about water fouling. Unfortunately, there are only a few clean sources of hot geothermal fluid suitable for power generation. Most brine contains varying amounts of dissolved solids (sometimes as much as 300,000 ppm) which can severely foul just about any surface in contact. If it weren't for the severe fouling, the amount of electricity being generated by geothermal resources would be much greater today.[30] At present, there is no practical solution to the geothermal fouling problem. Techniques to mitigate heat exchanger fouling include the use of direct contact exchangers and mixing particulates with the brine to scrub-off the scale (while also enhancing heat transfer). ERDA's Division of Geothermal Energy is providing a significant amount of support to develop practical solutions to this complex problem.

Fouling In Fossil Fuel Combustion Environments

Most fossil fuel combustion products contain some percentage of particulates; natural gas is one of the cleanest with coal and heavy hydrocarbon fuels being very dirty. In oil-fired combustion environments, the fouling of heat exchanger surfaces is particularly acute since the ash contains mixtures of alkaline sulphates with vanadium pentoxide which, besides restricting heat transfer, are corrosive when in contact with many metals. Some of the techniques used to mitigate the heat exchanger fouling problem in fossil fuel applications are, (1) locate the equipment in regions where particulate concentrations are not excessive, (2) fuse and melt the particulates and recover in slag trap, (3) add ingredients to reduce corrosivity and tenacity of the ash, (4) install soot blowers to periodically remove the fouling material, (5) clean heat exchanger surfaces at prescribed intervals.

Fouling in diesel exhausts is a concern with waste heat boilers for Rankine cycle bottoming systems. The large diesels (5000 to 7000 hp) are capable of burning relatively clean No. 2 diesel fuel or heavier residual fuels which emit considerably more particulates. The "smoke" or carbonaceous residue contained in the exhaust products will adhere to heat exchanger surfaces, increase pressure drop and reduce thermal efficiency. Extended surfaces, which are normally required on the gas side of the heat exchanger to increase heat transfer, will severely foul if the extended surface density becomes too large. With fins, sticky particulates can bridge the gaps causing a significant increase in pressure drop. The author has heard reports of ruptured exhaust stacks caused by excessive fouling of waste heat boilers aboard diesel powered ships. Large heat exchanger pressure drops caused by acute fouling not only diminishes heat transfer and increases structural loads but also severely affects diesel performance.

The present methods to alleviate the deleterious affects of fouling in waste heat recovery applications are, (1) reduce extended surface density (reduce fin spacing), (2) install soot blowers between selected rows of heat exchanger elements, (3) periodically wash heat exchanger surfaces, (4) burn-off the fouling matter by preventing cooling fluid from circulating through the exchanger, (5) treat the exhaust stream with a substance that will prevent the particles from sticking. Most of these techniques have the obvious disadvantage of involving additional costs to a system that may already be economically marginal. It is not known if these approaches will be satisfactory with compact heat exchanger cores. Also, with 500°F (260°C) to 800°F (427°C) exhaust, it may be difficult, if not impossible, to achieve a heat exchanger surface temperature that would effectively remove (by burning) the carbonaceous residue.[29] This cleaning technique could not be applied if organic working fluids are present because they would thermally decompose.

There is very little information on the fouling of heat exchanger surfaces in fossil fuel combustion environments. Most of what is available pertains to oil-fired boilers for steam generation.[31] There appears to have been no systematic study, either analytical or experimental, of the fouling in diesel exhaust streams. Air pollution concerns, however, have prompted some work in measuring particle size distributions in light duty diesels.[32,33] Since CONRT's major interest is in large (5000 to 7000 hp) diesels for base load power generation, care must be taken when applying information that pertains to light duty diesels because it may not be appropriate to these larger units that can burn heavier fuels and operate at different conditions.

One of CONRT's most critical heat exchanger deficiencies is an almost total lack of information on the extent and effects of heat exchanger fouling in diesel exhaust streams selected for Rankine cycle, waste heat energy conversion. Efficient bottoming systems are currently being designed and will soon be tested. Most of these units will be demonstrated in waste heat gas streams that promise to be relatively clean (e.g., gas turbines, diesels with distillate fuels). It is clear, however, that these systems will eventually be used in much dirtier environments. Information related to the composition of fouling matter and the effects of fin and tube spacing, fin material and configuration, heat exchanger temperature, air/fuel ratios, type of fuel and flue gas additives is urgently needed at this time. All important waste heat sources (e.g., gas turbines, diesels, remelt furnaces, heat treat ovens, incinerators, etc.) should have a complete set of this information applicable to a variety of heat exchanger core configurations (e.g., plate-fin, honeycomb, finned tube, etc.). Methods to effectively clean component heat exchanger surfaces should be addressed for specific applications.

FLOW INDUCED TUBE VIBRATION

Large margins of safety are usually incorporated into the structural designs of heat exchangers to allow for unknowns related to thermal stresses, material properties and behavior, and flow induced vibration. The vibration environment is one of the most difficult and complex to quantify. The number of flow-induced vibration problems in shell-and-tube heat exchangers has grown dramatically in recent years. These include gross tube failures, fatigue failures, fretting caused by tube collisions, cutting by baffles, leaking tubes and tube-joints, increased shellside pressure drop and intolerably loud noise. Previously, vibration damage may not have been recognized as such and mechanical failure attributed to other causes. The problem has gained prominence with several shutdowns of nuclear power plants due to heat exchanger tube failure caused by flow-induced vibration. It has been estimated that the second greatest cause of nuclear plant outage is the result of excessive vibration.[34] One heat exchanger bundle in a petroleum refinery was destroyed within 24 hours of its initial start-up as the result of a flow-induced vibration problem. Many large chemical plants have lost production due to leaking tubes caused by flow induced vibration.[35]

Heat exchangers with increased shellside flow velocities, close packed tube bundles and less baffles are being used to improve heat transfer, reduce fouling and pressure drop, and lower costs. All of these tend to promote flow-induced tube vibration. Different flow phenomena causing tubes to vibrate include vortex shedding, turbulent buffeting, fluidelastic whirling, and acoustic vibration.

Because of the complexity of these phenomena, studies of tube vibration require a great deal of planning, precision, and equipment. Experimental vibration data have usually been obtained under controlled conditions using single tubes or ideal tube banks exposed to either uniform parallel flow or uniform crossflow. Extrapolation of the results of the idealized tests to predict conditions in an actual exchanger may be seriously questioned due to differences in geometry, in the way the flow is coupled to the motion of the tubes and the nonuniformity of flow direction.[35] Subscale heat exchanger designs which operate without vibration problems are often scaled to fullsize configurations without knowledge of the proper similitude requirements.

Predicting the conditions under which flow-induced vibration will and will not exist, quantifying the vibration behavior, and establishing failure criteria cannot be accomplished with existing technology. Current techniques for predicting flow-induced vibration damage are inadequate. To compensate for this ignorance in heat exchanger design, large factors of safety are usually employed.[36] Since experience and judgement are so important in the assessment of risk when heat exchangers are subjected to potential flow-induced vibration problems, there is a reluctance on the part of heat exchanger manufacturers to guarantee structural performance of their product when the application and design are somewhat unconventional (e.g., advanced energy conversion systems). There are no standards or codes that can be used to guard against vibration damage or failure. TEMA provides general guidelines to minimize the occurrence of vibration damage by recommending maximum unsupported span lengths for different tube materials, sizes and heat exchanger configurations. Design procedures are available,[35,37] but reducing the probability of failure to a reasonable level requires extremely large factors of safety in the design which adds considerable cost to the unit.

It is important to develop a much better understanding of flow-induced vibration phenomena. A comprehensive data base, improved analytical modeling and effective design tools will lead to more optimum configurations resulting in greater reliability and energy savings.

MATERIALS

The majority of heat exchanger problems relate to material deficiencies of one form or another. If a particular material component fails to perform as designed, there are a number of questions to be answered before it is recommended to seek a "better" material. These are: (1) Were the design tools and design criteria adequate? (2) Was the environment satisfactorily characterized? (3) Were the properties of materials well known under the conditions of interest? (4) Was the component fabricated and assembled properly? (5) Was there an appropriate check-out and pre-test inspection performed? If the answers to all these questions are "yes" and the part failed during operation, one would hesitate to select a "better" material since it would not be known what material peoperty to make "better". If the answer to any of these questions is "no", it would seem prudent, but perhaps not expedient, to concentrate on resolving that particular deficiency before one seeks a "better" material. The point of this is simply that "better" materials are not the panacea of heat exchanger materials' problems. Materials fail because of deficiencies associated with the questions above. It is the author's opinion that before ERDA (or any government organization) decides to support a particular material development program (1) the need should be clearly identified and documented, (2) there should be ample evidence supporting the expected benefits from improving a particular property or substituting a "better" material, (3) an explanation should be provided why other available, perhaps lower cost, materials could not do the job as well.

There is an urgent need to improve corrosion and erosion resistance, high temperature mechanical properties, and other important properties of heat exchanger materials for particular applications. As mentioned previously, there can be significant advantages if heat exchangers are allowed to operate at temperatures below the acid dew point. The acid corrosion phenomena is understood with most metallics but in the presence of fouling, as would occur with the combustion of coal and heavy fuels, corrosion becomes more complex. The development of materials that would allow heat exchangers to operate effectively below the respective dew points should be complemented with a study of the corrosion mechanisms in the presence of fouling. The need for a durable, low cost coating on an inexpensive material is apparent. Vitrified enamel coatings have successfully reduced acid corrosion rates but their high cost often outweighs the benefits.[8] Plastic heat exchanger surfaces are beginning to receive more notice and it seems prudent to investigate the feasibility of this class of materials for low temperature heat exchanger applications.

At high temperatures, above 1800°F (982°C), the limits of most super alloys are reached. Since there are a great many (waste) heat sources above this temperature that are suited to topping and bottoming systems and waste heat recovery applications, it is necessary to support the development and demonstration of efficient high temperature heat exchangers that are reliable and economical. Figure 2 illustrates the significant fuel savings obtained by recovering high temperature stack gas and preheating combustion air. There are few, if any, metallic heat exchangers that operate efficiently (with high heat transfer effectiveness) in flue gas environments whose temperatures are above 2300°F (1260°C). Parallel flow metallic heat exchangers are being used as heat recovery units with flue gas temperatures exceeding 2300°F (1260°C); however, these units have a low effectivenes and heat exchanger surfaces are kept at relatively low temperatures.

In a coal-fired, closed Brayton cycle topping system, the primary heat exchanger will have to withstand an intensly corrosive, erosive, high temperature (3000°F (1649°C)) environment. There is no commercially available heat exchanger that can survive and function efficiently for acceptable periods of time under these conditions. It seems possible, however, that a ceramic might resist corrosion and erosion and provide adequate strength at high tempertures. There is a great deal of ceramics research currently being supported by many organizations throughout the world but most of this is directed at high temperature turbines, defense applications, and electronics. Very little ceramics development applies to heat exchanger applications primarily because the availability and cost of fuel have not made efficient high temperature heat recovery economical. At present there does not appear to be an identifiable market for efficient high temperature heat exchangers. In addition, the cost of ceramic research and development is a significant burden for private industry to bear. As a result, private industry has shown little interest in supporting the development of high temperature ceramic heat exchangers.

Current problems with high temperature ceramics relate to difficulties and deficiencies with manufacturing, establishing meaningful mechanical properties, determining realistic failure criteria, and nondestructive evaluation (e.g., identifying and quantifying flaws). In general, experience with ceramic heat exchangers has not been good primarily because the design and manufacturing technology base is substantially underdeveloped. The effects of manufacturing variables on material properties and failure criteria are virtually nonexistent. This information plus extensive testing to document performance and durability under realistic conditions is needed. Accomplishing these tasks takes time and considerable financial support which is why many ceramic component development programs, considering their original objectives and schedule, have not been successful.

Regardless of the technology deficiencies previously identified and the lack of a viable market for high temperature ceramic heat exchangers, there are tremendous quantities of energy that can be recovered if efficient, reliable and economical methods can be developed. Private industry has shown little interest in supporting this work for the reasons previously identified. It is the responsibility of the federal government, because

22

of its proclaimed interest and desire to improve the efficiency of energy conversion systems and conserve fuel supplies, to initiate and support meaningful, long term programs to develop and demonstrate efficient ceramic heat exchangers for high temperature application. In this way, a viable market for these components can be established and private industry will provide supporting technology.

There is a special class of heat exchangers which can efficiently recover energy at relatively high temperatures (up to 1600°F (871°C)); these are the compact, rotary wheels (Ljunstrom regenerators) with ceramic honeycomb-like cores.[37] There are at least two companies manufacturing and selling these units for the industrial market. The major problems of rotary wheel heat exchangers are well known (leaking, seals, thermal stress cracking) but their effectiveness is usually high (above 70%) and the ceramic cores have proven to be resistant to many forms of corrosion at elevated temperatures. It is the author's opinion, that the private sector seems quite capable and eager to develop the necessary technology for ceramic rotary wheel heat exchangers in this temperature range and no federal support is warranted.

In the intermediate temperature regime (800°F (427°C) to 1500°F (816°C)), the major deficiencies with heat exchanger materials are cost, availability, mechanical properties and corrosion resistance. There is a critical need for low cost, heat exchanger materials in this temperature range. The extreme dependence on the use of chrome and nickel to resist corrosion and provide elevated temperature strength must somehow be diminished. With conventional shell-and-tube heat exchangers, for example, the cost per square foot of heat transfer surface area using 304 stainless steel tubes is approximately 50% to 200% higher than carbon steel tubes.[23] Improvements in material processing to achieve desired properties with lower cost alloys should be enthusiastically supported by the federal government. Material development programs should be coordinated with efforts to lower fabrication costs and improve inspection techniques.

HEAT PIPES

Heat pipes are generally recognized as being efficient, compact and simple heat transfer devices. Until recently, their use was confined to rather specialized applications that included thermal control of spacecraft components, space reactors and cooling devices for electronics. There is a growing awareness, however, that the unique features of heat pipes makes them adaptable and competetive in a wide variety of industrial and commercial heat exchanger applications. For example, a few companies are now successfully marketing and selling heat pipe units for recovery of low grade waste heat (gas-to-gas); the energy being used for HVAC (e.g., hospitals, office buildings, schools) and industrial processes (e.g., air dryer, paint and textile drying ovens).[38] Heat pipes are used to cool the support members of the above-ground portion of the trans-Alaska pipeline and protect the permafrost (approximately 100,000 heat pipes, are required).[39] A recent study concluded that present day heat pipes, while not as efficient as some conventional heat exchangers (e.g., Ljungstrom, shell/tube, plate/fin), are competitive in HVAC applications, industrial process dryers and flue gas recovery (to 500°F (260°C)) when compactness, cleanability and ease of installation are important.[40] It has been shown that for high temperature applications (1800°F (982°C)), heat pipes may be overall more desirable than conventional heat exchangers.[41]

In addition to the advantages previously mentioned, heat pipes also offer the capability to transfer, through barriers that prevent or minimize cross contamination, sensible (and latent) heat between fluids that may be corrosive and hazardous. As was pointed out earlier, some organic fluids proposed for use in bottoming systems are considered hazardous and it is important to prevent these fluids from leaking out of the heat exchanger into the flue gas (which may be exhaust gases from turbines or diesels located in municipalities). Incorporating heat pipes into heat exchangers for waste heat recovery applications provides for physical separation of the two fluids which reduces the chances of cross contamination and enhances safety.

At the present time, heat pipe units being sold as gas-to-gas heat exhangers in energy heat recovery applications are presently limited to maximum temperatures of approximately 500°F (260°C).[41] Below 500°F (260°C) there are a wide variety of compatible heat pipe working fluids such as the Freons, water, ammonia and Dowtherm. Above 500°F (260°C), these heat pipe fluids thermally degrade and/or heat pipe performance falls markedly. There are other fluids that potentially can be used to 700°F (371°C) but there has been little work in this area and pertinent information is difficult to obtain (some of it proprietary). From 1000°F (538°C) to almost 3000°F (1649°C), liquid metal (e.g., mercury, sodium, lithium and potassium) heat pipes have been successfully demonstrated for long periods of time using stainless steels, super alloys and refractory alloys as containment materials. In the temperature range 700°F (371°C) to 1000°F (538°C), sulfur heat pipes have been demonstrated but corrosion problems exist.[42] There currently appears to be no widely accepted heat pipe fluid for commercial or industrial applications in the temperature range 500°F (260°C) to 1000°F (538 °C).

There are a great many industrial waste heat sources above 700°F (371°C) (e.g., aluminum remelt furnaces, glass melting furnaces, cement plants, heat treatment furnaces) where heat pipe energy recovery devices could be used providing acceptable heat pipe working fluids were available in the temperature range 500°F (260°C) to 1000°F (538°C). The lack of suitable heat pipe working fluids in this temperature range constitutes a major deficiency in heat exchanger technology. There needs to be a coordinated effort focused on the development of these working fluids and their implementation into heat pipe heat exchangers for energy recovery applications.

The advantages of no moving parts, minimal axial temperature gradients, and provisions for a redundant barrier between fluids make heat pipes attractive as waste heat boilers for organic Rankine cycle engine applications. There has never been an industrial-size heat pipe waste heat boiler designed or tested because the abundance of cheap fuel stifled incentive. The fuel situation is much different today and the need is apparent. It is realistic to assume that a heat pipe waste heat boiler could be designed, fabricated, and demonstrated in a 600°F (316 °C) to 700°F (371°C) environment using state-of-the-art working fluids and materials. Questions related to cost, heat transfer performance and reliability of such a unit can only be answered accurately with a near-full scale demonstration. It is apparent that existing heat pipe companies can not afford to undertake such an ambitious program without assistance.

There are other deficiencies in heat pipe technology which affects their use as heat exchangers for industrial and commercial applications. The theoretical performance of low vapor pressure heat pipe fluids is greater than what has been demonstrated in practice (sometimes being off by a factor of 2).[40] The effects of gravity and its control on heat pipe efficiency needs better definition. More effective methods to improve wicking and the return of condensate will improve heat pipe performance.

The cost of heat pipe heat exchangers naturally assumes a dominant role in the acceptance criteria. At low temperatures (less than 500°F (260°C)), there are ample low cost materials of construction that are compatible with acceptable working fluids. At higher temperatures (above 500°F (260°C)), specific material concerns that influence cost include, (1) working fluid/container compatibility, (2) economical container materials that effectively resist corrosion and erosion in high temperature fossil fuel combustion environments, (3) possible diffusion of low molecular weight gases such as hydrogen through the heat pipe vessel.

The successful demonstration of high temperature heat pipes has required the use of expensive super alloys and refractory metals. In coal-fired topping cycle and high temperature industrial waste heat environments, these materials would probably be too expensive for heat exchanger application and, in some cases, would be unable to combat the rigors of corrosion and erosion. Ceramic heat pipes are attractive because they offer the promise of corrosion and erosion resistance while maintaining strength at high temperatures. Unfortunately, there has never been a ceramic heat pipe fabricated and tested. Questions regarding compatability with working fluid, sealing, joining to walls, wick materials, durability, and performance remain unanswered.

The heat pipe industry is presently very small. The companies are not capable of providing the level of support necessary to correct the major technology deficiencies in a timely manner. Unless this work is accelerated, it will be difficult implementing heat pipe heat exchangers and obtaining widespread user acceptance of heat pipes for many of the applications of interest to CONRT.

HEAT TRANSFER ENHANCEMENT

Improving heat exchanger effectiveness, given a certain set of fluids and a fixed type of heat exchanger (e.g., counter flow, cross flow, etc.), requires an increase in local heat transfer coefficent and/or an increase in heat exchanger surface area. A finned surface is an example of how heat transfer can be increased by surface area extension. There are many different kinds of extended surfaces used by heat exchanger manufacturers.[43] Methods to increase overall heat transfer by enhancing or augmenting local heat transfer coefficent have been known for some time. Many of these heat transfer enhancement techniques have been thoroughly studied in the laboratory and some can be purchased commercially.[44]

All known methods to enhance heat transfer produce a corresponding increase in fluid pressure drop which, in turn, increases fluid pumping power requirements. In many cases, the benefits derived from enhancing heat transfer more than offset pressure drop penalties. In certain applications, however, large pressure drops cannot be tolerated; these include condensers, dry cooling towers and recovering waste heat from internal combustion and gas turbine engines. In these applications, the performance and efficiency of the system is sensitive to pumping losses and/or increases in engine back pressure. There are a number of heat exchanger performance criteria for evaluating the virtues of different enhancement techniques; these must be considered separately for each application.[45]

There are tremendous quantities of low temperature waste heat (less than 500°F (260°C)) generated from stationary power plants and gaseous diffusion processes. Converting this into shaft work requires an extended heat transfer surface and a high degree of heat transfer coefficient enhancement. The important role of heat exchangers in converting low temperature waste heat into useful work is illustrated by this equation which represents the ratio of total heat transfer (source and sink) to maximum output work:[46]

$$\psi = \frac{\text{total heat transfer}}{\text{maximum work}} = \frac{2 - \eta}{\eta}$$

η is the Carnot efficiency. This equation, plotted as Figure 3, shows that the amount of heat transfer required to produce useful work becomes very large with low temperature sources. It is apparent that severe demands will be placed on heat exchanger performance and cost to exploit these low temperature sources. Fouling and corrosion are major concerns.

As mentioned previously, there have been many analytical and experimental studies of methods to enhance heat transfer. There are specially configured tubes, fins, plates and inserts that are commercially available and are being used in heat exchanger applications. In general, however, the use of these enhancement techniques is not widespread because:

1. There is a lack of operating experience with full scale units.

2. The cost of fuel has not yet reached high enough levels to warrant purchasing the higher cost, enhanced surfaces.

3. The methods of enhancement have caused, in some cases, increased rates of corrosion and fouling.

Continued development of enhanced heat transfer techniques should be encouraged with emphasis placed on end-use application and low cost. Field testing full scale units to demonstrate performance and reliability is costly but absolutely necessary to convince potential users of the energy benefits. There is a reluctance in private industry to support the testing and evaluation of enhancement techniques in full scale units. A comprehensive cost-benefit analysis is needed to identify and publicize the potential energy savings using heat transfer enhancement techniques in industrial and commericial heat exchanger applications.

Enhancing heat transfer with a fluidized bed offers promise of low cost and high efficiency in many of CONRT's heat exchanger applications. Very little work has been done in the U.S. with fluidized bed enhancement to improve the efficiency of heat exchangers for high temperature waste heat recovery systems. In Europe, fluidized bed waste heat recovery systems have been successfully demonstrated in a variety of applications that include heat treat furnaces, ceramic kilns and economizers. Studies have shown, however, that the levels of heat transfer enhancement required to realize significant savings in dry cooling towers for power plants cannot be met with today's fluidized bed technology.[47]

One example of a particular need for highly efficient heat exchangers to recover low temperature waste heat relates to one of the largest waste heat sources in the U.S., the cooling water used in ERDA's three gaseous diffusion plants. Following completion of uprating programs currently in progress, the Oak Ridge, Paducah, and Portsmouth Plants collectively will use over 7200 megawatts of electricity. This electrical energy is used in the uranium isotope separation process to drive the large number of compressors required to circulate the processed gas. After compression, a heat exchanger is used to cool the gas with a vaporizing fluorocarbon. The fluorocarbon passes through another heat exchanger where it is condensed by water. The water, heated to approximately 150°F (66°C), is pumped to cooling towers where its temperature drops to approximately 100°F (38°C). The energy content of the circulated warm water is several thousand megawatts. Even though Carnot efficiencies are very low, it appears feasible with very effective heat exchangers to utilize this thermal energy for domestic and commercial purposes including the production of electricity (using an organic fluid Rankine cycle). A study has shown that as much as

10 megawatts of electricity could be generated from this warm water source using ammonia in a Rankine cycle.[48] Other proposed uses of the warm water include aquaculture, lumber and grain drying, space heating of offices, homes and greenhouses.

ORGANIC FLUIDS

A wide variety of organic fluids are being considered in process heating and cooling, as working fluids in Rankine cycle bottoming systems, and in heat pipes. Organic fluids are used in plant heating applications because they can operate at relatively high temperatures without being pressurized; this results in a significant savings in capital cost.[16] In Rankine cycle applications, the properties of certain organic fluids yield higher cycle efficiencies and can reduce thermodynamic irreversibility by lowering the heat exchanger temperature difference (source-to-working fluid). With waste heat source temperatures less than 1000°F (538°C), an organic Rankine cycle provides higher thermal efficiency and more power output even at off-load conditions compared to steam.[13] In addition, organic fluids simplify turbine design and eliminate the need for complex water treatment equipment and controls.

Each organic fluid has its own particular thermal stability characteristics and limits, which, in addition to dependency on temperature and pressure, are affected by contact with different metallic surfaces. Heat transfer characteristics of organic fluids near and above their critical point (many organic fluids are subjected to near critical conditions to improve cycle efficiency) are not well known. Without adequate heat transfer information, there are large uncertainties in fluid stability criteria associated with once-through boilers. The amount of information currently known about thermal stability, heat transfer, and fluid flow characteristics of organic fluids in a dynamic, high-temperature, closed-cycle system is inadequate to confidently predict long term performance and reliability.

The thermal stability limits of organic fluids and their chemical compatability with containment materials are determined empirically.[50] Usually the experiments are performed under static conditions with small sealed containers where temperature, pressure and (occasionally) chemical species are monitored. There is a need for information on the thermal stability of organic fluids under dynamic conditions to determine if static test results can be used to predict behavior under actual conditions of operation. The lack of adequate test procedures forces full scale testing to obtain this information. This approach is obviously expensive, primitive and loaded with potential problems. Before the use and acceptability of organic fluids can be expanded to realize greater component efficiencies, better test methods will be needed to evaluate the high temperature performance of organic fluids under realistic conditions.

Another problem with organic fluids is containment. Some of the organic fluids under study for Rankine cycle applications are considered toxic, flammable or environmentally undesirable (e.g., Fluorinol, Toluene, Freon). At the present time, there is considerable controversy surrounding the tolerable levels of these and similar fluids and it is evident that increasing demands will be placed on heat exchanger designers and manufacturers to prevent leaks and failures that would allow these fluids and their combustion products to escape. An urgent need, therefore, is to establish allowable concentrations of these fluids and their combustion products in case of a heat exchanger leak or total failure. Sensitive leak detectors should be incorporated into the controls of process or energy conversion equipment to minimize the loss of hazardous fluid.

The fluid properties one desires for a particular application cannot always be obtained from available lists of organic fluids. For example, the Biphase energy conversion system requires a fluid with low specific heat, high heat of vaporization and low vapor pressure at 600°F (316°C); a significant performance and cost penalty was incurred using the "best available" fluid with a standard fin-tube heat exchanger.[49] With low grade waste heat, direct contact heat exchangers are particularly attractive but it is difficult finding fluids with specific combinations of chemical, physical and thermodynamic properties. There are no known organic working fluids that can be used in heat pipes above 500°F (260°C) for extended durations. These examples illustrate the need for (1) better documentation and cataloging of available organic fluid properties (2) developing new fluids for specific applications where the energy saving potential is clearly identified.

With an organic Rankine cycle system, a once-through vapor generator (where liquid enters one end and super heated vapor exits the other in a continuous manner) can reduce cost and working fluid inventory compared to a conventional boiler (equipped with drums, vapor separator, recirculation pump). Major problems with monotube and multi-path once-through boilers are related to, (1) a lack of information on heat transfer and fluid flow characteristics of organic fluids near the critical point; (2) fluid instability within the tube causing the boiler to "chug" and creating local hot spots which can damage the boiler and degrade the working fluid; (3) dynamic instability of the coupled system (boiler, pump, turbine, experimental data).[51] With many organic fluids there is a dearth of experimental data related to these problems. This lack of information has forced heat exchanger designers to use more conventional types of boilers and/or operate the system at conditions far below critical to minimize the risks. This choice increases cost and lowers system efficiency.

RECUPERATORS/REGENERATORS FOR GAS TURBINES

Higher fuel costs and restricted fuel supplies have increased the interest in improving the thermal efficiency of gas turbines. There has been and continues to be a considerable amount of work in developing heat exchangers for gas turbine regeneration. The economics of adding regeneration to the gas turbine cycle depends on many factors. At lower pressure ratios (less than 10), there is a meaningful improvement in cycle efficiency with regeneration but the added capital cost ($20/kw_e to $40/kw_e)[52] has, in the past, retarded enthusiasm to purchase these units. It has been reported that operational problems with some large, utility-size gas turbine recuperators have reduced overall plant availability.[13,53] Regenerators (or recuperators) cannot easily be retrofitted to existing gas turbine systems; to optimize system performance the regenerator should be considered in the initial design of the gas turbine. The relatively high cost of efficient heat exchangers, operating at high temperature and pressure ratios, and the advantages of incorporating a bottoming system leads the author to question whether the major gas turbine manufacturers will continue to find regenerated gas-turbines attractive and marketable. To regenerate or not to regenerate is a controversial and complex question that has no simple answer; it will not be addressed in this report.

Regardless of its future, heat exchangers for gas turbine regeneration have basically the same problems as other heat exchangers subjected to cyclic, high temperature (approximately 1000°F (538°C)), corrosive environments. Fouling problems have been comparatively mild, so far, because most gas turbine fuels are clean-burning. Compact heat exchangers have been successful in these applications because high effectiveness can be maintained. As more use is made of dirtier fuels, however, it is expected that fouling and corrosion problems will increase.

The greatest challenge to designers of regenerated gas turbines is lowering heat exchanger costs without sacrificing durability and reliability. Above 1000°F (538°C), mild steel severely oxidizes and mechanical strengths fall rapidly. The reliance on expensive metallic alloys to resist corrosion and maintain strength at high temperature is common to many heat exchangers as previously discussed. Ceramic regenerators and recuperators have been considered but major design and manufacturing deficiencies have severely affected long-term performance and reliability.

A significant amount of research and development work is being directed at improving the efficiency of industrial and vehicular gas turbines. Because of this and questions regarding the future use of regenerated gas turbines for industrial applications, the author feels that additional federal support is not required to speed the development of improved heat exchangers for regenerated gas turbines. The particular plan to improve those areas of heat exchanger technology of concern to CONRT, as outlined in this report, addresses heat exchanger problems that have application to regenerated gas turbines. It is expected, therefore, that results from implementing this heat exchanger technology plan will provide solutions to many of the gas turbine regenerator probblems.

SUMMARY OF HEAT EXCHANGER PROBLEMS AND DEFICIENCIES

The preceding discussion focused upon major heat exchanger technology deficiencies currently facing CONRT. These deficiencies have created problems which are expected to adversely affect the pace of developing alternative energy sources, exploiting waste heat sources and improving the efficiency of components and energy conversion systems. The major areas of concern are summarized below:

(1) Based upon current prices of energy, the buyers' reluctance to spend his limited capital, and the rising costs of heat exchangers, many efficient energy recovery and conversion systems are presently uneconomical or marginal.

(2) Industrial, commercial and domestic users of heat exchanger equipment are not interested in novel, more efficient units unless performance and reliability can be demonstrated in full scale equipment under realistic conditions.

(3) The economical recovery and conversion of low grade waste heat cannot be achieved without developing more effective heat exchangers.

(4) Inadequate design tools and a woeful data base are responsible for gross uncertainties in predicting the behavior, performance and reliability of heat exchangers in environments where corrosion, fouling and flow-induced tube vibration are present. These uncertainties have led to higher unit costs, lower efficiencies and a higher frequency of failure.

(5) The efficient recovery of energy in high temperature, corrosive, erosive environments (greater than 2000°F (1093°C)) cannot be obtained without resorting to ceramic heat exchanger elements. Current technology surrounding the design, fabrication and evaluation of ceramic heat exchangers for these applications is significantly underdeveloped.

(6) Certain characteristics of heat pipes makes them attractive as heat exchanger elements in heat recovery and energy conversion applications. There has never been an industrial-size, heat pipe waste heat boiler designed, fabricated or demonstrated in a high temperature waste heat environment. Without this experience, there remains large uncertainties in predicted heat transfer, efficiency, durability and cost.

Correcting basic heat exchanger deficiencies in a timely manner requires significant advances in selected areas of heat exchanger technology. A plan to provide the needed technology is presented in the following section of this report.

PROPOSED HEAT EXCHANGER TECHNOLOGY PLAN

A comprehensive plan to advance heat exchanger technology is required to solve current problems and correct basic deficiencies that would otherwise adversly affect CONRT's plans for improving component and system efficiencies and conserving fuel supplies. A series of programs to accomplish these objectives is proposed. The programs that comprise this heat exchanger technology plan are divided into the following categories: Heat Exchanger Environment, Materials and Fabrication, Heat Pipes, Heat Transfer Enhancement, and Advanced Heat Exchanger Technology. Specific elements of each category will now be identified and discussed.

HEAT EXCHANGER ENVIRONMENT

This category is responsible for developing those areas of heat exchanger technology that relate to flow induced vibration, fouling and corrosion.

Tube Vibration

To increase efficiency, optimize configuation, reduce material requirements and lower cost of industrial and commercial heat exchangers, useful and accurate engineering models of the excitation mechanisms responsible for flow induced vibration in tube bundles need to be developed. Work performed in this element includes the identification and characterization of fluid excitation mechanisms in tube bundles representative of heat exchanger tube banks. Analytical studies complemented by an extensive experimental program will be directed at fluid/structure coupling in tube bundles as a function of tube geometry, tube spacing, mass density ratio and flow velocity. Experiments will progress from single tube rows to full scale tube bundles. Results will include improved design criteria to minimize the occurrence of vibration problems.

There appears to be a variety of tube vibration work supported by industry which is directed more at solving specific needs than contributing to a solid technology base. Much of this work is proprietary and because the problem is so serious in nuclear power plants, the applicability of results tends to favor nuclear equipment and conditions as opposed to non-nuclear applications (viz. industrial heat exchangers). A comprehensive survey should be taken to (1) gather all pertinent flow-induced tube vibration data related to industrial heat exchangers, (2) establish state-of-the-art design practices, and (3) identify levels of uncertainty. A series of workshops should be scheduled periodically, involving representatives from government and industry who are actively working in this area, to discuss progress and help formulate meaningful government supported research programs. Because of its global significance, it is expected that this entire effort will involve the participation of other nations.

A program of this scope must be government funded for at least five years. CONRT has taken the first step by working together with Heat Transfer Research Incorporated to (1) obtain a large bank of experimental data related to flow-induced vibration of industrial heat exchangers (2) convene a workshop composed of the most knowledgeable individuals from industry and government to identify state-of-the-art practices, critically review current work, and formulate meaningful government supported research programs.

Fouling

It will take a relatively long term commitment (perhaps five years) to develop an adequate fouling technology base because fouling can occur under so many different environmental conditions. A comprehensive survey and study should begin to collect fouling data and quantify the effects of fouling on heat exchanger and system efficiency, cost and reliability. Available techniques to predict the rate and extent of fouling in various types of water and waste heat environments should be cataloged and comparisons made with available data to quantify levels of uncertainty.

A large scale study to investigate the effects of heat exchanger configuration and temperature, fluid velocity and chemical composition, surface materials and fluid additives on the nature and rates of fouling should be initiated. This information along with the results from elements in other categories will be used to improve fouling prediction techniques and to obtain better estimates of operational and life-cycle costs.

Fouling in diesel exhaust streams is an immediate concern to CONRT because it can significantly affect the performance and cost of bottoming systems currently under development. Experimental data that can be used in selecting optimum extended surface configurations should be obtained as soon as possible.

In situations where anti-fouling methods are ineffective, new approaches to reduce fouling should be developed. The effect of legislation restricting the application of certain anti-fouling and corrosion inhibiting chemicals to water coolants should be delineated. As new water treatment techniques are developed, rates of fouling in both open-loop and recirculation systems should be documented, performance penalties determined, operation and life-cycle cost estimates improved.

There is a significant amount of support being given to sea water bio-fouling and brine fouling by ERDA's Divisions of Solar Energy and Geothermal Energy, respectively. Within the Office of Fossil Energy there are programs concerned with certain aspects of fouling in coal and oil-fired systems. All segments of ERDA having an active interest in heat exchanger fouling should work closely together in developing an adequate technology base.

Corrosion

In situations where it is desired to extract as much energy from the source flow as possible, low temperature liquid corrosion becomes a problem. There are two major deficiencies related to the liquid corrosion issue: (1) concentrations and dew point temperatures of gaseous species in the source flow are usually not known, (2) economical heat exchanger materials that effectively resist liquid corrosion are not presently available. What is most urgently needed is a comprehensive survey and study of major waste heat sources of interest to CONRT to quantify their characteristics and chemical composition. In the case of diesel engines for stationary power generation, SO_3 and SO_2 concentrations and dew points in the exhaust flow should be determined as a function of diesel operation variables (fuel type, air/fuel ratios, off-load conditions). In these and other environments, the amount and rates of liquid corrosion should be documented for different heat exchanger materials and configurations. Based upon this information, heat exchanger materials selection and design criteria can be improved. All available information related to acid corrosion phenomena should be collected, documented, and assessed. Fundamental studies of acid corrosion with fouling should be initiated. Corrosion resistant materials should be evaluated to determine the lengths of time heat exchangers can effectively operate below dew point temperatures before replacement is required.

Low temperature corrosion has been identified as a problem for a long time. It is expected to get worse as lower cost and more abundant high sulfur fuels are used. Government support is required because the private sector lacks the commitment and resources to properly address and seek solutions to this problem. The absence of an adequate acid corrosion data base relevant to the needs and interests of CONRT supports the contention that government must provide this support.

At elevated temperatures, the mechanisms responsible for corrosion of heat exchanger materials in fossil fuel exhaust and waste heat environments should be identified and quantified as a function of operating conditions. Since the government and industry are supporting a significant amount of work in this area, meaningful research programs should be formulated after a thorough review has been made of results from past and present programs. Constructive research programs designed to improve the understanding of corrosion mechanisms provide information which (1) helps decide what are most fruitful approaches to follow in developing improved materials, and (2) improves the accuracy of estimating life-cycle heat exchanger costs.

Materials that offer improved corrosion resistance should be evaluated in laboratory and subscale tests that accurately simulate environmental conditions. The test results should be used to improve the methods of predicting corrosion rates of heat exchanger materials in hostile environments. With coal-fired topping systems and high temperature waste heat sources, the corrosion of ceramic materials must be considered. An adequate corrosion data base relative to the specific conditions of interest to CONRT must be established for candidate ceramic materials. The coupled effects of fouling and corrosion deserve special attention. Following subscale tests, full-scale demonstrations should be conducted to document corrosion resistance and verify design criteria.

MATERIALS AND FABRICATION

To efficiently recover energy from sources whose temperatures exceed 2000°F (1093°C), the surface materials of heat exchangers will have to be some type of refractory, metallic or ceramic. At present, private industry has shown little interest and lacks incentive to develop these efficient high temperature heat exchangers because of the high cost required and the lack of a viable market. Perhaps the largest commitment to ceramic heat exchangers has been made by the Electric Power Research Institute. They are supporting two major programs to develop ceramic heat exchangers for solar power and coal-fired Brayton cycle applications. ERDA has a genuine interest in recovering energy from high temperature sources but relatively little is being done to develop the required technology.

To the author's knowledge, the only active program supported by ERDA to advance high temperature heat exchanger technology is a small, ceramic heat exchanger materials effort conducted by the Garrett AiResearch Corporation for CONRT. This work is aimed at evaluating advanced silicon carbide tubular elements in a coal-fired Brayton cycle environment. The evaluation criteria is based upon heluim leak rates, burst strengths, corrosion resistance. Work such as this should be greatly expanded and accelerated to establish a firm technology base upon which adequate designs, performance and cost estimates of high temperature heat exchangers can be made.

Specific areas of study and investigation related to the development of ceramic heat exchangers should include, (1) identifying manufacturing processes that produce acceptable material, (2) the statistical determination of a great many physical, mechanical, and chemical properties needed in design and reliability analyses, (3) quantifying the corrosion resistance under simulated conditions, (4) investgating ways to fabricate complex ceramic shapes (e.g., U-bends, manifolds) and joining ceramic elements to headers and to themselves. It is important to assemble this information in a useable form so that meaningful engineering design and failure criteria can be developed and applied. Subscale and segments of fullscale heat exchangers should be fabricated and evaluated under realistic conditions to verify design criteria.

To combat the deleterious effects of chemical corrosion (e.g., oxidation, carbonization, sulfidation) in waste heat and fossil fuel combustion environments less than 2000°F (1093°C), coatings and claddings for metallic heat exchanger materials should be developed and evaluated. Methods to strengthen low cost alloys to improve high temperature properties (e.g., creep strength) should be investigated with the most promising materials being fully characterized and ultimately fabricated into representative heat exchanger configurations for testing and evaluation.

Improved low cost alloys and coatings to resist low temperature acid corrosion in waste heat environments should be incorporated into heat exchanger designs and tested to document long term behavior and performance.

To lower cost and increase reliability of heat exchanger assemblies, improved brazing and welding techniques (e.g., laser welding) should be identified, characterized, and evaluated. Low cost methods to fabricate extended and enhanced heat transfer surfaces should be devised.

Techniques to nondestructively evaluate (NDE) defect sizes in welds, tubing and related heat exchanger components should be catalogued and critically reviewed. Early detection of corrosion and accurate corrosion depth measurements are important aspects of heat exchanger failure prevention and inspection. Instruments and techniques that can be used to rapidly detect corrosion pitting and stress corrosion cracking are currently being developed for other purposes. A study should be made of the technology associated with new NDE methods and instruments to identify heat exchanger applications. Instruments and techniques should be developed that can be used in the field to detect small leaks and identify defects that might lead to heat exchanger failure. These instruments and techniques should be tested and evaluated with subscale and full-scale heat exchanger components to determine accuracy and practicality. Other instruments developed by the aerospace industry that have potential use as diagnostic or inspection tools for heat exchangers (e.g. thermal imaging instrumentation) should be exploited.

To effectively accomplish these tasks, a close working relationship must be established between all actively interested parties in the private sector, professional organizations and in the federal government. There are many material development activities being pursued throughout the world and it is extremely difficult to identify the work that has application to heat exchangers. Periodic exchanges of information among active parties specifically interested in heat exchanger technology is strongly recommended.

HEAT PIPES

Heat pipes are attractive heat recovery devices in high temperature, hostile environments because they, (1) have no moving parts which improves reliability, (2) can be incorporated into heat exchanger configurations to yield lower thermal stresses (e.g., can have free ends for thermal expansion), (3) can be easily cleaned in some instances, and (4) offer a redundant wall to separate working fluid from heat source. Refractory alloys containing tungsten, niobium and molybdenum have been successfully used as heat pipe containers for special purposes but these materials are not expected to successfully withstand the rigors of many high temperature, highly corrosive environments for sustained periods of time. Ceramic heat pipe concepts should be developed for high temperature applications. Single units should be fabricated and initially tested in simulated waste heat and coal-fired combustion environments. These results should then be used to design, construct, and test full-scale heat exchanger units under conditions representative of high temperature waste heat and topping cycle applications.

To minimize the chances of a hazardous working fluid coming in direct contact with the heat source in a bottoming system, promising heat pipe waste heat boiler concepts should be identified and preliminary designs prepared. The best heat pipe design should be evaluated initially in subscale. Following this, the design of a full-scale unit should be prepared for a particular bottoming cycle application. A demonstration of performance and reliability in full scale should be conducted in a realistic environment.

In conjunction with the development of ceramic heat pipes and heat pipe waste heat boilers, improved heat pipe working fluids for 500°F (260°C) to 1000°F (538°C) applications should be developed. These materials should be evaluated at realistic conditions to quantify heat transfer characteristics and document long term thermal stability and compatibility with heat pipe materials (wick and container). These results would be used to design recuperators and waste heat boilers for energy recovery or energy transport in environments whose temperatures exceed 700°F (371°C).

As was pointed out in the survey of heat pipe deficiencies, the theoretical efficiency of heat pipes often exceeds actual performance. A concentrated level of effort needs to be directed at improving the understanding of heat pipe phenomena. Specifically, fluid-vapor interaction phenomena and the effects of gravity need further study and quantification because they so strongly influence heat pipe performance.

The successful application of gas-to-gas heat pipe heat exchangers in recovering and transfering energy from sources less than approximately 500°F (260°F) has been accomplished by private industry without the overt support of the federal government. There is one particular deficiency in this application, however, that may require federal assistance if it is desired to maximize the effective use of heat pipes in saving energy and conserving fuel supplies. This is, the apparent lack of a concentrated effort to lower fabrication costs. It is recommended that a study be made of current costs and techniques to fabricate heat pipe components for this particular heat exchanger application (it is understood that much of this information may be proprietary). If cost-benefit analyses indicate substantially more energy can be saved by increasing the utilization of heat pipe heat exchangers, and lower cost fabrication techniques can be identified as a means to increase use, a program to identify lower cost fabrication techniques should be initiated.

HEAT TRANSFER ENHANCEMENT

It has been shown that heat transfer rates to extended surface tubes can be substantially increased by emersing the tubes in a fluidized bed. A great deal of work is presently being done in fluidized bed combustion but it appears that very little of this technology is being integrated into efficient heat exchanger designs for industrial, commercial and residential applications. With fluidized beds, not only would heat transfer be increased, which lowerscost, but there exists the real possibility that fouling could be significantly reduced by, (1) the filtering action of the bed and, (2) scrubbing of the heat exchanger surfaces by the bed particles.

Fluidized bed heat exchanger technology should be developed for application to industrial and commercial waste heat recovery, dry cooling towers and topping cycles. A thorough review of fluidized bed heat exchanger work should be conducted to identify the existing technology base and provide insight into potentially beneficial research areas. In Europe, for example, there are examples where small fluidized bed heat exchangers are being used to recover waste heat.[54] The Division of Nuclear Research and Applications of ERDA has sponsored a significant amount of cooling tower research, some of which involved fluidized beds for dry cooling towers. For large nuclear power plants it was found that the level of heat transfer enhancement provided to dry cooling towers by fluidized beds was insufficiant to realize an improvement in system efficiency and cost. These results do not necessarily apply to topping cycle and waste heat utilization systems, however, where system performance is much more sensitive to the efficiency of the primary heat exchanger.

To optimize fluidized bed heat exchanger performance, laboratory and subscale tests should be conducted to evaluate the effects of bed parameters, tube and extended surface shape, and flow characteristics (temperature, velocity, etc.) on heat transfer coefficients and pressure drop. Analytical design tools should be improved for preliminary design and costing studies. The performance of these subscale units should be evaluated in high temperature exhaust flows using heavy hydrocarbon fuels. With these results, potential fluidized bed heat exchanger applications can be chosen and full-scale designs prepared. Full-scale fluidized bed heat exchangers should be demonstrated to verify design criteria and identify possible operational problems.

There are numerous techniques to enhance heat transfer that have been reported and are continuouslybeing devised and proposed. Many have undergone laboratory testing to quantify heat transfer gains and pressure drop penalties. A very small fraction have been tested in full-scale units. Presently there is no test program that takes the best candidate enhancement devices or techniques and demonstrates their performance, cost and reliability in full-scale, realistic environments. There is an urgent need to establish a program to accomplish these tasks. This test and demonstration program would be costly and federal assistance is definitely required.

Particular heat exchanger concepts with heat transfer enhancement that show promise of reasonable cost and modest pressure drop should be evaluated first in the laboratory to verify expectations. Improvements should be made in heat transfer and fluid dynamic analytical models to upgrade design tools. Subscale and ultimately full-scale demonstration tests should be conducted to confirm design criteria and identify any problems with fouling and corrosion.

Enhanced heat transfer is especially important with condensers that must operate efficiently in applications where available temperature differences are very small (e.g., geothermal, ocean thermal, low grade waste heat). Consideration should be given to improving condenser efficiency for these applications using enhanced heat transfer surfaces in novel condenser designs. These designs should be evaluated first in subscale to improved design criteria and identify potential problem areas. Following this, full scale units should be demonstrated to verify performance, document operational difficulties and determine life-cycle costs.

ADVANCED TECHNOLOGY

Once-Through Boilers Using Organic Fluids

The vapor generator or waste heat boiler is the key component in organic Rankine cycle systems. The size, cost and working fluid inventory associated with once-through boilers are significantly less than conventional boilers (with drums, vapor separator and recirculating pump). Major problems with both monotube and parallel path once-through boilers are related to, (1) a lack of information on heat transfer and fluid flow characteristics with organic fluids near the critical point; (2) two-phase fluid instability within tubes; (3) dynamic stability of the system (including boiler, pump, turbine, condenser). There is a critical lack of experimental data with organic fluids related to the above. A study should be made of the requirements and benefits derived from using once-through vapor generators in various bottom cycle power systems. A comprehensive data base should be developed that contains pertinent heat transfer and fluid dynamic characteristics for a variety of organic fluids over a range of conditions from liquid to supercritical. Parallel path and monotube units should be tested as part of an effort to improve or develop analytical models for predicting fluid stability characteristics of organic fluids in once-through boiler systems. Once-through boilers should be designed to meet the requirements of specific systems and tested to verify performance and document reliability.

Organic Fluid Development and Characteristics

Organic fluids have been identified as having many desirable thermodynamic properties for efficient Rankine cycle system application. Problems with organic fluids for heat exchanger applications primarily concern thermal stability and compatibility with containment materials, toxicity and flammability, and a lack of information on heat transfer and fluid dynamic characteristics at elevated temperatures and pressures.

All pertinent information related to commercially available organic fluids of possible interest to CONRT should be collected, critically evaluated and catalogued. Properties of organic fluids that improve performance of energy transfer, recovery and conversion systems should be identified. If cost-benefit analyses indicate that significant energy savings can be realized from using certain types of organic fluids that are presently unavailable, an effort to develop such materials should be initiated. The acquisition of basic heat transfer characteristics and fluid dynamic properties of organic fluids from subcooled liquid to supercritical is urgently needed to establish confidence in the design of once-through boilers and heat pipes. Thermal stability limits and compatibility of organic fluids with candidate heat exchanger materials should be established from experiments conducted under static and dynamic fluid conditions.

The popularity of organic fluids in energy transfer, recovery and conversion systems is increasing. Within ERDA, in addition to CONRT, those responsible for developing solar, geothermal and ocean thermal energy conversion systems have an active interest in organic fluids and are supporting work in some of the areas mentioned above. The necessary tasks to address deficiencies with organic fluids that have application to heat exchangers should be planned in concert with others who may benefit from the results.

Direct Contact Heat Exchangers

Direct contact heat transfer is perhaps the most efficient way to exchange energy between two fluids. Since the two fluids are in direct contact and physically mix together, there is no wall or intermediate barrier to impede energy transfer. The traditional forms of fouling and corrosion are virtually eliminated. A major difficulty with direct contact heat exchanger systems is separating the two fluids after they have mixed. At present, direct contact heat exchanger technology is substantially underdeveloped, most of the support and stimulus being provided by the government. A study should be made to identify potential energy savings in energy recovery and conversion that could result from the development of this technology. Currently, there is work being supported by the Office of Solar Energy in direct contact heat transfer for geothermal applications. This work should be expanded to include direct contact heat transfer/heat exchanger studies and experiments related to waste heat recovery and specific energy conversion systems (e.g., Biphase turbine bottoming cycle)[49] at temperatures above 300°F (149°C). Methods to separate coolant and heat source fluids should be devised. Fluids that have desirable characteristics for direct contact heat exchanger application should be identified and laboratory tests conducted to determine heat transfer, separation, and absorption characteristics. Analytical models should be developed and used to size direct contact heat exchangers for applications of interest to CONRT. Subscale units should be tested to establish performance characteristics. If feasible, larger scale units should be designed, constructed, and demonstrated to verfy design criteria and identify long term operational problems.

Residential Flue Gas Heat Exchangers

Recovering energy from residential furnace flue gases requires heat exchangers that are compact, low cost, reliable and efficient. Compact, efficient and reliable heat exchangers have been developed by the aerospace industry for spacecraft and high performance aircraft applications. Units similar to these can be used to recover flue gas energy provided the cost can be reduced. Economical flue gas heat exchangers to preheat air or water should be developed and tested to document performance and reliability. Since cost will be a major factor, support should be provided to identify and develop ways to reduce the costs of material (especially if acid corrosion is expected), fabrication and maintenance.

Cooling Tower Technology

EPA's effluent guidelines for steam-electric power plants mandate that closed cycle cooling systems must be considered to dissipate the non-recoverable heat rejected from condensers. Cooling towers are currently used in approximately 10% of the 3000 steam-electric generating units in the U.S.[28] The efficiency and cost demands being placed upon new cooling towers require advances in this area of heat exchanger technology. Dry cooling towers are closed systems that do not require make-up water, have a greater flexibility of location, and will not produce condensate plumes or fog. There are only a few dry cooling towers in existence, however, because the high cost of conventional finned surfaces make the unit twice as expensive as wet towers. Studies should be conducted to identify efficient, low cost, wet and dry cooling tower concepts that relate to applications of interest to CONRT. Subscale test should be performed to determine heat transfer efficiency and evaluate performance. The most promising concepts should be incorporated into designs for specific energy conversion system applications (e.g., Rankine cycle bottoming systems) and tested under field conditions to verify design criteria and establish reliability.

As mentioned previously, a significant amount of work related to cooling tower technology is being supported by ERDA's Division of Nuclear Research and Application. The studies outlined above should only be undertaken by CONRT after it has been determined that CONRT's cooling tower needs are not being addressed in existing programs.

Boiler and Condenser Technology

More efficient and reliable direct-fired boiler and condenser concepts should be sought. The reliability of heat exchangers in large fossil fuel power plants has not been particularly impressive as shown in Table I, even though this industry is quite mature. There is a need to reexamine the performance of boilers and condensers and determine the benefits from increasing efficiency and reliability. A study should be made to identify (1) major boiler and condenser problems in industry, (2) the current level of research and development to improve the technology, and (3) the government's role in supporting this work. Applications of this advanced technology to specific interests of CONRT should be identified. Cost-benefit analyses should be performed to quantify potential energy savings. Promising concepts should be evaluated in the laboratory using subscale models to quantify expected efficiencies. Ultimately, full scale units should be designed, fabricated, and tested under realistic conditions to evaluate efficiency, the capability to operate on different fuels and constituents in the flue gas (in the case of direct-fired boilers), long-term performance, and reliability.

NWC TM 2930

SUMMARY OF THE PROPOSED HEAT EXCHANGER TECHNOLOGY PLAN

The proposed plan addresses those heat exchanger deficiencies and problems identified in the survey as being most important to the programs, plans and goals of CONRT. Elements of this plan, intentionally lacking detail, highlight principal areas of concern. Results from recommended research and technology programs will provide critically needed information to speed the development of more efficient, economical and reliable energy conversion systems and components. An outline of the major elements of this plan is shown in Table II.

TABLE I. EQUIVALENT HOURS OF FORCED OUTAGE PER EQUIVALENT HOUR OF FULL SERVICE PER MEGAWATT OF CAPACITY ATTRIBUTED TO HEAT EXCHANGER COMPONENTS FOR FOSSIL FUEL-FIRED STEAM POWER PLANTS[55]

COMPONENT	UNIT SIZE, MW 60-89	90-129	130-199	200-389	390-599	600+
	10^{-7}					
BOILER ASSOCIATED						
WATER WALLS GENERATING TUBES SUPERHEATER REHEATER ECONOMIZER AIR PREHEATER FEED WATER HEATER	1337	1566	1194	968	781	749
FOULING	2	54	48	22	28	45
CONDENSER	71	120	89	94	77	99
OTHER (NOT RELATED TO HX)	1790	2080	1339	1356	1704	2627
TOTAL	3200	3820	2670	2440	2590	3520

TABLE II.
ELEMENTS OF THE PROPOSED PLAN TO ADVANCE HEAT EXCHANGER TECHNOLOGY TO MEET THE NEEDS OF CONRT

HEAT EXCHANGER ENVIRONMENT

- Flow-Induced Tube Vibration (industrial heat exchangers)
- Fouling (Water, fossil fuel combustion products, waste heat)
- Corrosion
  - Low temperature (acid corrosion)
  - Intermediate temperature (oxidation, sulfidation, carbonization of metallics)
  - High temperature (corrosion of ceramics in topping cycle and waste heat environments)

MATERIALS AND FABRICATION

- High Temperature (ceramics)
- Intermediate Temperature (lower cost metallics, coated metallics)
- Low Temperature (low cost metallics, plastics)
- Low Cost Fabrication
- NDE Techniques

HEAT PIPES

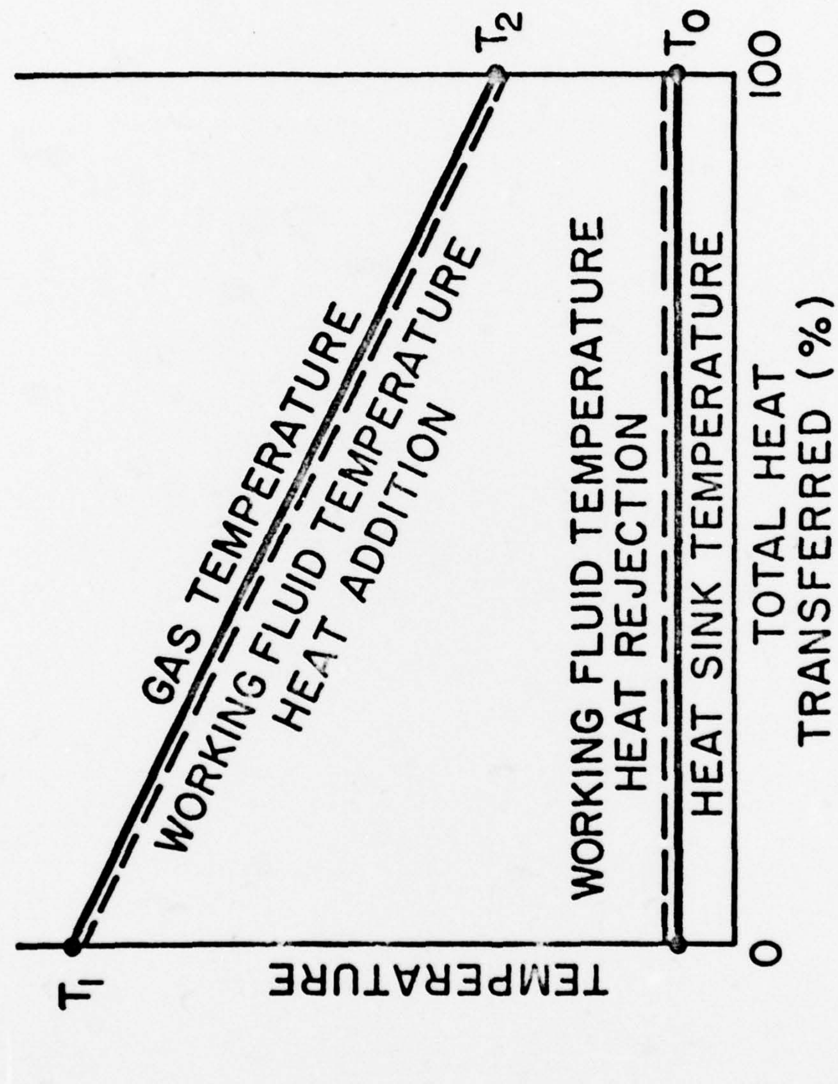
- Ceramic Heat Pipes
- Heat Pipe Waste Heat Boilers for Bottoming Cycles
- Heat Pipe Fundamentals (gravity, fluid-vapor, compatibility)
- Low Cost Fabrication Techniques
- Working Fluids for 500°F (260°C) to 1000°F (538°C) Service

HEAT TRANSFER ENHANCEMENT

- Fluidized Bed
- Evaluation of Enhancement Techniques
- Full-Scale Testing
- Improved Analytical Design Methods

ADVANCED HEAT EXCHANGER TECHNOLOGY

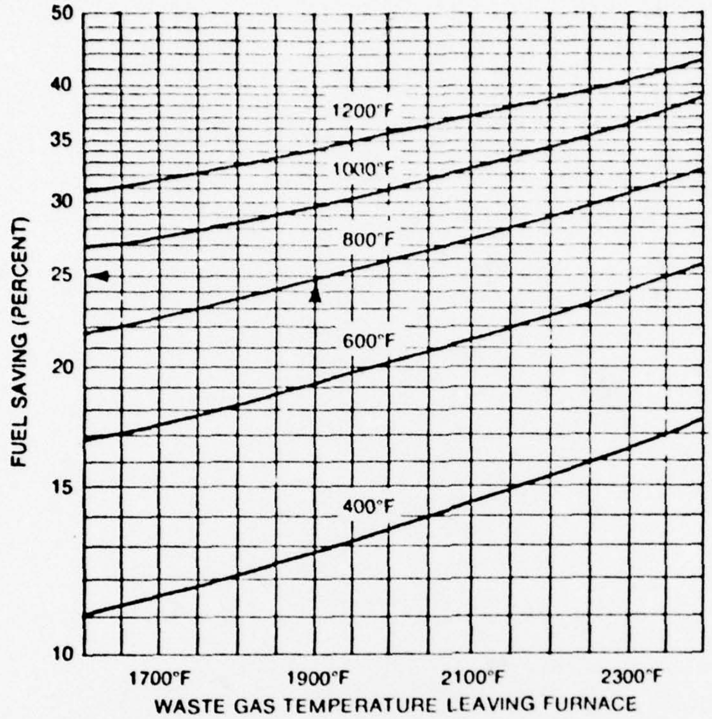
- Once-Through Boilers (organic fluids)
- Organic Fluids (heat transfer, properties, development)
- Direct Contact Heat Exchangers
- Residential Flue Gas Heat Exchangers
- Cooling Towers
- Boilers and Condensers



$$\left[\overline{W}_{REV}\right]_{T_1 \to T_2} = C_{P,\,gas}\left\{(T_1 - T_2) - T_0 \ln \frac{T_1}{T_2}\right\}$$

FIG. 1. The Ideal Relationship Between Working Fluid Temperature and Source and Sink Temperatures to Maximize Power Output[13]

FIG 2. **FUEL SAVED BY PREHEATING COMBUSTION AIR**[56]



OPERATING PARAMETERS

FUEL
NATURAL GAS

GROSS HEAT VALUE
1000 BTU/FT³

EXCESS AIR
10 PERCENT

AMBIENT TEMPERATURE
70F

CASE HISTORY OF FUEL SAVINGS

Fuel	Natural gas at 1000 BTU/CF
Cold air input	22MMBTU/HR
Excess air	10 percent
Waste gas temp. leaving furnace	2200F
Air preheat	700F
Fuel savings	27.3 percent
Hot air input	16MMBTU/HR
Fuel savings	6MMBTU/HR
Fuel savings converted to gas cost at $1.00/MCF	$6.00/HR $12,000/YR (one shift) $24,000/YR (two shifts)
Recuperator cost	$18,000
Amortization	One-two years
Service life	Five-ten years or more

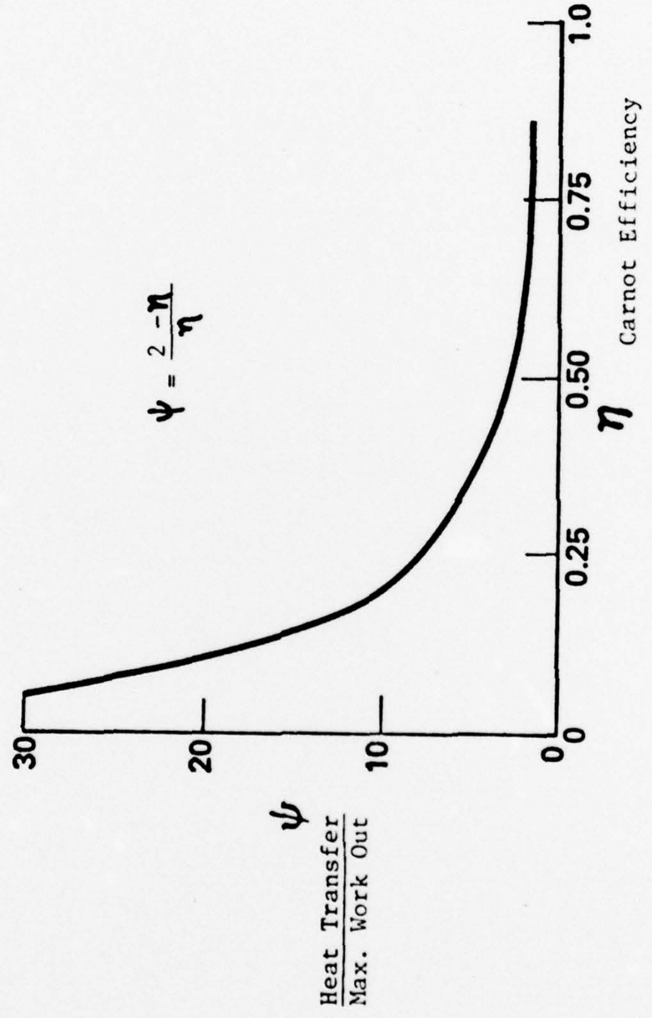


FIG. 3. Heat Transfer Requirements With Low Grade Waste Heat Energy Conversion

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52