ORNL/TM-2000/304

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EXECUTIVE SUMMARY

Because of the changing structure of the electric power industry, new opportunities exist for small-scale power generation technologies in distributed-generation applications. Microturbines (gas turbines that operate in the range of 25 to 500 kW and at a compression ratio of 3 to 6) are prominent among these new technologies. Therefore, the U.S. Department of Energy's Office of Power Technologies (DOE-OPT) is developing a long-range plan to develop ultra-efficient advanced microturbines for distributed power applications.

The goal of DOE Advanced Microturbine Program is to raise microturbine efficiency from its current level of 30% to more than 40% by the year 2007, while attaining low emissions and cost of operation. To reach higher thermal efficiencies, an increase in turbine rotor inlet temperatures may be required. Consequently, research and development (R&D) is needed to produce and evaluate the materials that will be able to withstand the higher operating temperatures. Because the recuperator (heat exchanger) will be the largest and possibly the most expensive component in an ultra-high-efficiency microturbine, a review was commissioned to assess recuperator technology with emphasis on materials requirements and fabrication.

This review was compiled from a study of the current state of microturbine recuperator technology, a review of the literature published since the early 1970s, and interviews with specialists in the field. It covers three topics: microturbine and heat-exchanger designs, metallic recuperators, and ceramic recuperators.

The temperature of the exhaust gas determines the materials requirements for microturbine recuperators. Consequently, R&D is needed to produce and evaluate high-temperature materials for both metallic and ceramic recuperators. Based on this assessment, we concluded that the most effective strategy for recuperator development would be to place immediate emphasis on the cost-effective manufacture of higher-temperature metallic recuperators and to consider the development of ceramic recuperators as a long-term objective.

Also, a further exchange of ideas within the discipline would be useful. As part of its assessment of microturbine technology, DOE convened a workshop where goals for 2005 and beyond were compiled for the new generation of microturbines (see *Summary of the Microturbine Technology Summit*, Orlando, FL, 1998, DOE/ORO 2081). A second, comprehensive workshop entitled "Recuperator Materials for Advanced Microturbines" was held for those involved in microturbine recuperator R&D. Workshop participants discussed technology needs and development priorities for the production of cost-effective recuperators for high-efficiency microturbines.

INTRODUCTION

As a result of the evolving structure of the electric power industry, new opportunities are being created to apply small-scale power generation technologies, such as microturbines, fuel cells, reciprocating engines, and renewable technologies, in distributed generation applications. The U.S. Department of Energy's Office of Power Technologies (DOE-OPT) is developing a long-range plan to develop ultra-efficient microturbines for distributed power applications. The idea is to model this development after the very successful Advanced Turbine Systems (ATS) program, which operated through an integrated, multifaceted, research and development partnership between government and industry. To this end, DOE sponsored a Microturbine Technology Summit, which took place on December 7 and 8, 1998. It was attended by more than 60 people, including representatives from turbine manufacturers, component suppliers, electric and gas utilities, federal and state agencies, and consulting firms.

At the meeting, the current status and future prospects were discussed for microturbines (25-500 kW) as power generation technologies. The potential research, development, and demonstration (RD&D) barriers and opportunities for microturbines[1] were also examined. The attendees concluded that microturbines with higher overall efficiencies (>30%) were needed and that this goal would necessitate operation at temperatures beyond the limits of traditional metals. The attendees discussed that ceramic materials were needed for hot-section parts, such as turbine wheels, combustors, ducts, and possibly for recuperators (heat exchangers). In particular, they wanted a metallic, or eventually ceramic, recuperator that would be both reliable and available at more reasonable costs. Recuperators are currently the largest, and one of the most expensive, components in microturbines (account for 25 to 30% of the cost).

Based on the this workshop and subsequent industry input, the DOE-OPT Advanced Microturbine Program goals to be met by 2007 are:

- **High Efficiency** - fuel-to-electricity conversion efficiency of at least 40%
- **Environmental Superiority –** NO_x emissions lower than 7 parts per million for natural gas machines in practical operating ranges
- **Durable –** Designed for 11,00 hours of operation between major overhauls and a service life of at least 45,000 hours
- **Economical –** Systems costs lower than $500 per kilowatt, costs of electricity that are competitive with alternatives (including grid-connected power) for market applications, and the option of using multiple fuels including natural gas, diesel, ethanol, landfill gas, and other biomass-derived liquids and gases

The purpose of this study is to evaluate and assess recuperator technology for advanced microturbines. The first section reviews the different options for gas turbine cycles and discusses the relevance of each cycle to microturbines. The section concludes that a heat exchanger (recuperator) is necessary to achieve a reasonable and competitive level of efficiency. The second section provides further information on the types of heat exchangers and their efficiency. The next section gives an update on current metal recuperators and the potential to increase temperature capability through alloy development. The final section discusses the status and potential of ceramic materials.

TURBINE CYCLE OPTIONS

A variety of cycles are possible for gas turbine engines. Each cycle is capable of a range of efficiencies depending on the degree of pressurization (the pressure ratio) of the inlet air and the temperature to which the air is heated before it goes through the turbine rotor (the turbine rotor inlet temperature, i.e., the TRIT). For a given pressure ratio and TRIT, the cycles are ranked as follows in increasing order of efficiency.

- the basic cycle;
- the recuperated cycle;
- the recuperated and reheat cycle;
- the recuperated and intercooled cycle;
- the intercooled, reheat, and recuperated cycles.[2,3,4]

Each of these cycles will now be reviewed starting with the basic (simple) cycle and the recuperated cycle.

The Basic Cycle

Figure 1 illustrates the simple open Brayton cycle of gas turbine engines. Air enters the engine and is compressed by the rotating compressor. The compressed air is mixed with fuel and the mixture, ignited inside a combustion chamber. The hot combustion gases expand and rapidly pass through the turbine, converting the chemical energy of the fuel to mechanical energy doing work on a load. Increasing the pressure ratio and the TRIT increases the thermal efficiency.

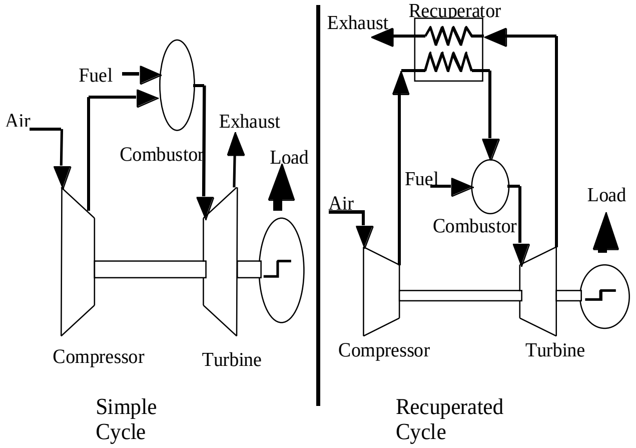

Figure 1 (left). Schematic showing a simple gas turbine cycle

Microturbines utilizing the simple cycle are rather uncommon because the efficiency of those engines ranges from only 16 to 20%. These turbines are occasionally found in applications with a separate heat exchanger that captures much of the waste heat for use in a separate system. Unfortunately, many people believe that microturbines with efficiencies less than 30% will not be competitive in an open market that includes reciprocating engines. These engines that consume natural gas or diesel fuel already demonstrate 42 to 45% efficiency and government programs are being initiated to develop more efficient engines.

The Recuperated Cycle

A recuperated cycle gas turbine is illustrated in Figure 2 below. The only difference from the simple cycle is that a heat exchanger (recuperator) has been added that transfers heat from the exhaust gas to the inlet air. The more the inlet air can be pre-heated, the less fuel is required to heat the air-fuel mixture to the desired TRIT.

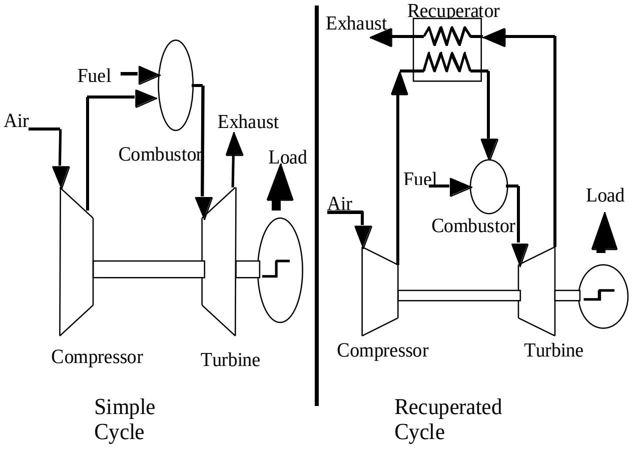

Figure 2 (right). Schematic showing recuperated gas turbine cycle

A recuperated cycle has potential for much higher efficiency than a simple cycle. All of the baseline microturbines on the market today are based on a recuperated cycle and presently operate at efficiencies ranging from 25 to 29%. After improved materials have been developed to increase the TRIT to approximately 1300°C, efficiencies of about 40% should be able to be achieved. On an efficiency basis alone, recuperated microturbines will not be able to compete with reciprocating engines that already demonstrate efficiencies of 42 to 45%. However, recuperated microturbines do have several very important advantages over reciprocating engines. Today's microturbines demonstrate very low emissions without any type of aftertreatment devices. Reciprocating engines typically have problems meeting NO_x and particulate emission standards without costly aftertreatment technology. Furthermore, emission regulations continue to be tightened making siting of reciprocating engines more and more difficult. A second advantage of the microturbines is their high temperature operation. The temperatures of the exhaust gases even after the recuperator is high enough to utilize an additional heat exchanger and capture much of the waste heat. Figure 3 illustrates a typical turbine system utilizing combined heat and power. With combined heat and power, recuperated microturbines can achieve an overall efficiency of about 75% and are more than competitive with reciprocating engines.

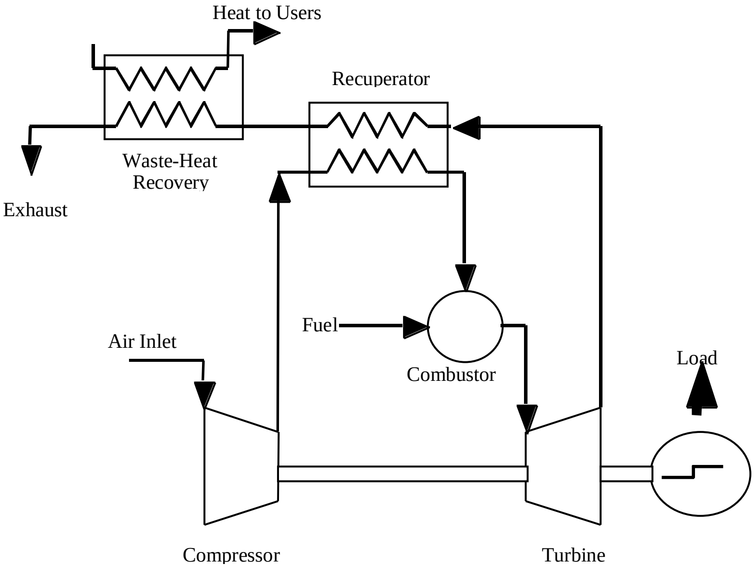

Figure 3. Combined heat and power application

The Recuperated and Intercooled Cycle

The Recuperated and Reheat Cycle and the Recuperated and Intercooled Cycle are actually very similar. The more efficient Recuperator and Intercooled Cycle (Figure 4) will be described first because it is more economically viable and is already being employed in many operating gas turbines. It is more efficient to have two smaller compressors with the intercooler located between the compressors than to have a single large compressor. Air enters the engine and is compressed in the first rotating compressor. The volume of that gas is significantly reduced when the gases are cooled to the ambient temperature by the intercooler. The first compressor continues to act on the gases within the intercooler so the pressure of the gas entering the second compressor is identical to the pressure of the gas exiting the first compressor. Because cooler and denser gas can be more easily compressed, the overall efficiency increases. The work is normally divided equally between the two compressors (compression ratio of stage 1 = stage 2). The temperature of the gas exiting the second compressor will be much lower than that obtained when using a single larger compressor without the intercooler. Consequently, less work is used in gas compression for the same turbine work.

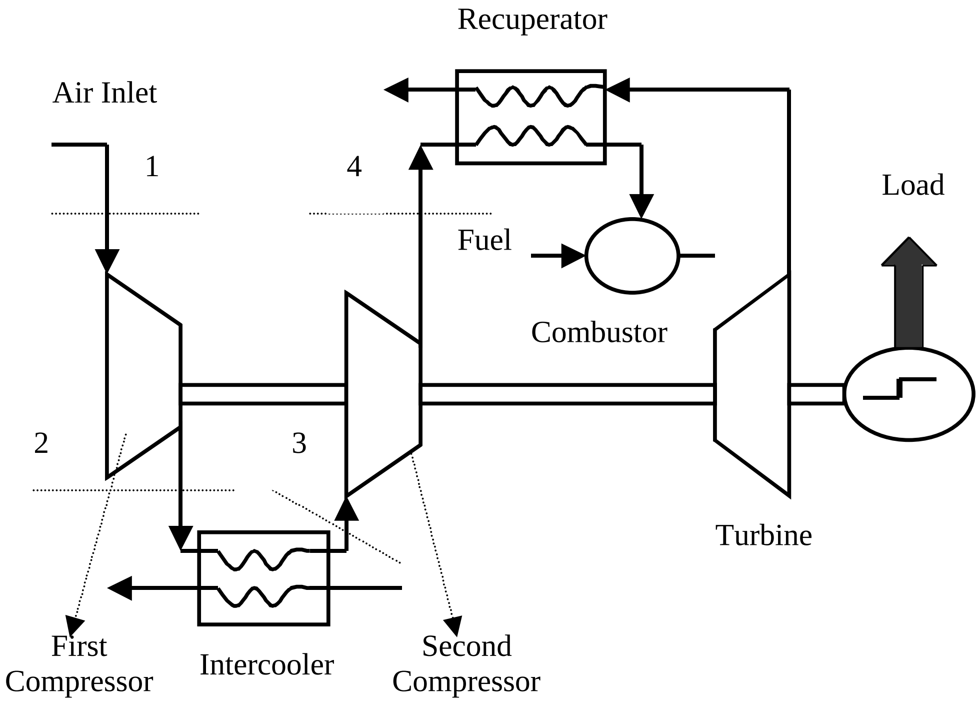

Figure 4. Intercooled recuperated power plant cycle

The recuperated plus intercooled cycle has real advantages in marine propulsion, where the sea provides a heat sink for the intercooler. On land, where air or a chiller is the heat sink, the cycle loses some of the advantages but is still frequently used.

Recuperated and Reheat Cycle

In an ideal system, similar to intercooling that was just discussed, more work would be obtained from the turbine, if the gases did not cool down during expansion. To approximate this, at least two smaller turbines are used with a reheater between the turbines to expand the gas from the maximum to the minimum cycle pressure. In this case, the hot air is expanded to an intermediate pressure as its temperature falls. The reheat raises the temperature to the original level followed by expansion in the second turbine to the minimum cycle pressure. The relation between the intermediate pressure and the maximum and minimum cycle pressures is identical to that for the intercooler. Because more turbine work has been generated for the same inlet conditions and TRIT, the efficiency of the cycle is improved. The efficiency is, however, not as high as the recuperated and intercooled cycle.

Intercooler, Reheat, and Recuperator Cycle

This cycle combines all the features of the various cycles. Thus, in addition to the basic cycle, it has two small compressors and an intercooler, two small turbines plus a reheater, and a recuperator. This makes it thermodynamically the most efficient gas turbine cycle. In practical terms because of the additional costs of including the various processes, it is highly unlikely that microturbines will be operated using this cycle.

Recuperator Designs and Factors Affecting Their Efficiency

Two types of heat exchangers are typically encountered when discussing small gas turbine engines: regenerators and recuperators. A regenerator uses some type of thermal storage material and operates in a cyclic mode.[5] The thermal storage material is heated by the exhaust gases and rotates so that the stored heat can be transferred to the inlet air. Regenerators were often the type of heat exchangers used in automotive gas turbines because they were compact and light weight. Unfortunately, because they must rotate, they are subject to thermal shock damage as well as sealing problems that create leaks between the inlet and exhaust gases. Because size and weight are much less of a problem for microturbines, recuperators are used almost exclusively. This assessment will consider recuperators but not regenerators.

A recuperator, also known as a fixed-boundary heat exchanger, is a continuous heat-exchange device that captures waste heat and continuously recycles the heat back into the process. A measure of the efficiency of the recuperator is the effectiveness factor, ε_r, the ratio of the actual heat transferred to the maximum amount of heat available.

$$\varepsilon_r = Q_t/Q_{max} = (T_{air,out} - T_{air,in})/(T_{gas,in} - T_{air,in}) \qquad (1)$$

The thermal efficiency of a simple recuperated gas turbine is dependent on several factors. Thermal efficiency increases with increasing recuperator effectiveness (Figure 5). This makes sense because the more heat that can be reclaimed from the turbine exhaust and recycled into the inlet air, the less fuel will be required to heat the fuel plus air mixture to the combustion temperature. The thermal efficiency also increases with increasing pressure ratio up to a value between 4 and 5 (Figure 5). Consequently, the compression ratio of simple recuperated microturbines will be less than 6. As the pressure ratio increases, the recuperator effectiveness becomes less and less important. Therefore, recuperators are not cost-effective and never found on turbine systems operating at high-pressure ratios. Finally, thermal efficiency also increases with increasing TRIT. Note in Figure 5 that the thermal efficiencies for a TRIT of 2850°F are always greater than the efficiencies at a TRIT of 2150°F.

Recuperators, especially metallic recuperators are classified by their method of construction into three basic types: shell-and-tube, plate-fin, and primary surface recuperators (PSR). Shell-and-tube recuperators consist of a series of tubes within an outer shell. One fluid flows through the tubes while a second fluid flows between the outer shell and the tubes, exchanging heat from one fluid to the other. They have been used for decades in the process industry and in large gas turbines. Consequently, knowledge is extensive about their design, construction, and operation. Because shell-and-tube recuperators are typically very large and bulky, they are not normally used on microturbines.

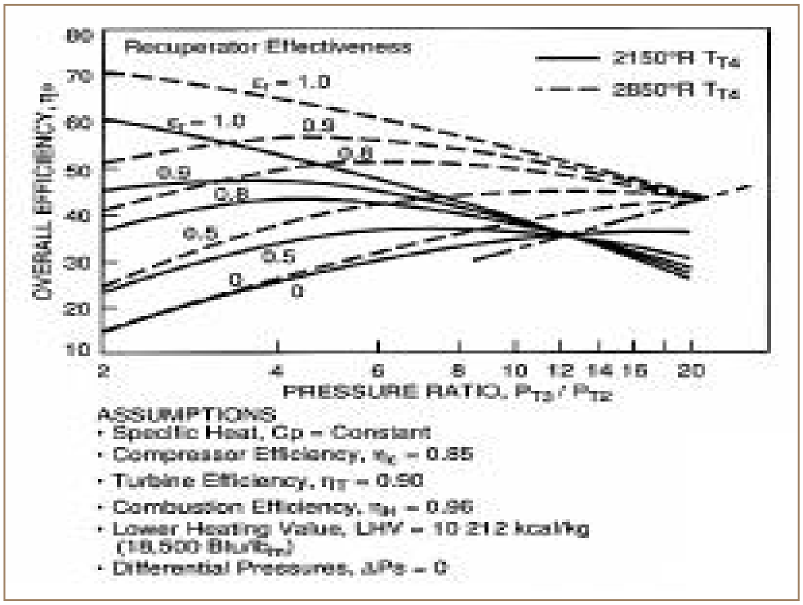

Figure 5. Recuperated gas turbine efficiency vs compression ratio. Source: M. E. Ward, “Primary Surface Recuperator Durability and Applications,” Turbomachinery Technology Seminar, TTS006/395, Solar Turbines, Inc., San Diego, CA (1995).

Plate-fin recuperators, like the shell-and-tube type, have also seen comprehensive use in gas turbine systems. As shown in Figure 6, a plate-fin recuperator consists of fins welded or brazed onto opposite sides of a separating plate. Heat-exchanging gases flow through the fins. Plate-fin recuperators can be fabricated in two configurations, loose or compact, the compact version being more efficient.

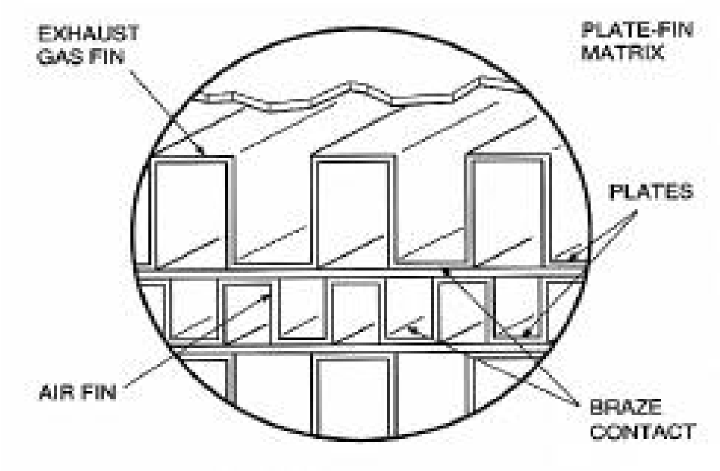

Figure 6. Brazed plate-fin recuperator. Source: M. E. Ward, “Primary Surface Recuperator Durability and Applications,” Turbomachinery Technology Seminar, TTS006/395, Solar Turbines, Inc., San Diego, CA (1995)

Primary surface recuperators (PSRs) consist of folded thin metal foils joined only at their ends (see Figure 7). Ward made a comparison of these three types.[6] For example, it was shown that a given load that requires only a unit volume of PSR is the same as 2.8 volumes of a compact plate-fin, 7.6 volumes of traditional plate-fin, and 11.8 volumes of shell-and-tube. The PSR is more efficient because it has a larger surface-area-to-volume ratio than the others. Consequently, all other things being equal, it is most prevalent in commercial microturbines, which need to be compact for many of their projected uses.

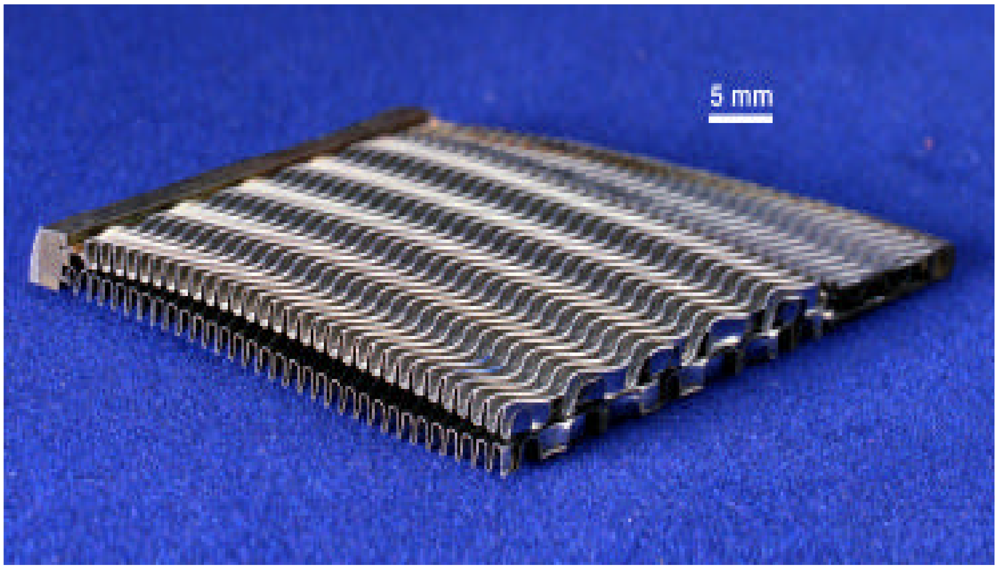

Figure 7. Foil corrugated pattern for primary surface recuperator. Source: P. J. Maziasz et al, "Stainless Steel Foil with Improved Creep-Resistance for Use in Primary Surface Recuperators for Gas Turbine Engines," in Gas Turbine Materials Technology, eds P. J, Maziasz, I. G. Wright, W. J. Brindley, J. Stringer and C. O'Brien, ASM-International, Materials Park, OH (1999) pp. 70-78.

Recuperators may also be classified into three categories according to the direction of flow of heat-exchanging fluids: coflow, crossflow, and counterflow. Thermodynamically, counterflow is the most efficient; coflow is the least efficient. Usually, only a counterflow arrangement gives an ε_r that approaches the 85 to 90% required for thermal efficiencies approaching 40%.

METALLIC RECUPERATORS

There is extensive and varied experience with metallic recuperators as heat exchangers for larger gas turbines, and in the chemical/pertochemical process and power generation industries. Recuperators significantly improve the efficiency of microturbines and muffle noise, but they also need to deliver the highest performance (maximum heat transfer surface density, be compact in size and have low weight, and be low cost). This report will focus on two particular kinds of compact recuperators most appropriate to advanced microturbine applications, the primary surface recuperator (PSR) and the plate and fin recuperator. This assessment examines the different manufacturing requirements for each type of recuperator, as well as their common need for better, more reliable and affordable heat- and corrosion-resistant alloys.

The PSR, whether in the annular or stacked air-cell configuration, has simpler initial manufacturing steps, mainly folding foil for the main body, and then fabricating and welding the outer joints to seal and separate incoming air from exhaust gas (see Figure 7). The folded foils are free to move and absorb strain and accommodate the large thermal gradients associated with rapid startup or shut down. The plate and fin design is much more constrained (see Figure 6) due to continuous brazed joints between plates forming a more rigid structure for the air and exhaust gas air fins. The brazing makes manufacture more labor intensive and creates fatigue concerns due to thermal strains and stresses during transient operation. Both kinds of recuperator technologies must be reliable, durable and cost effective for advanced microturbine applications. Failures are due to restricted air paths (creep or tensile strain), or fatigue and/or oxidation/corrosion driven cracking that leaks air into the exhaust and reduces power and efficiency. Advanced materials for both generally have to be able to perform well at up to 750°C or above.

<u>PSR Fabrication</u>. The description of PSR fabrication presented in this assessment is based on a more detailed description given elsewhere.[6] The PSR is typically fabricated from thin (3–5 mils) metal foils, such as Type 347 stainless steel, which are folded into a corrugated pattern (see Figure 7). These corrugated foils are welded in pairs to form air cells, the building block of the PSR (see Figure 8). Each air cell is pressure-checked and then welded into the recuperator core assembly; there are no internal welds or joints within the air cells. The design ensures minimal leakage between the compressed air and the exhaust gas, thereby avoiding power loss and added fuel consumption. The PSR is resistant to cyclic thermal fatigue because its flexibility accommodates thermal and mechanical strains as individual foils move relative to each other. In addition, each cell within the recuperator moves freely, also accommodating thermal strains and serving as an inherent damper of displacements from vibration sources. Because of the flexibility of the foils, these PSRs can be manufactured in various shapes, from simple rectangular forms to cylinders wrapped around the microturbine core.

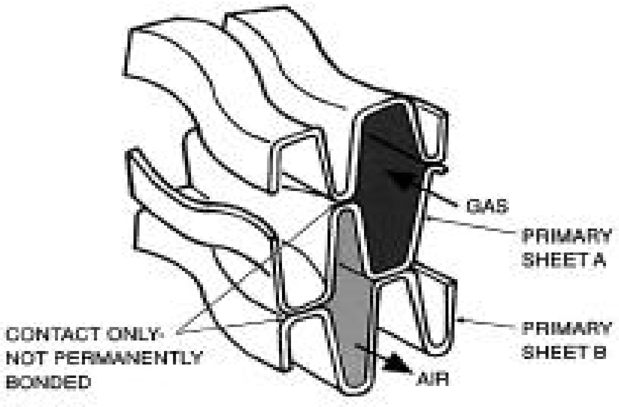

Figure 8. Basic design and operation of a primary surface recuperator. Source: M. E. Ward, "Primary Surface Recuperator Durability and Applications," Turbomachinery Technology Seminar, TTS006/395, Solar Turbines, Inc., San Diego, CA (1995).

The ability to fabricate PSRs depends on whether an appropriate metal can be rolled into thin foils and then folded into a corrugated pattern. This manufacturing consideration is significant because the recuperator gas inlet temperature rises as the engine thermal efficiency increases, necessitating the use of stronger (and possibly less ductile) metallic alloys. The most important feature of the PSR is the air cell through which the heat-exchanging fluids flow. Figure 9 compares a PSR air cell under normal operating conditions and with no creep (left) with cells experiencing excessive creep, in which the hot gas channels are closing up. The closed air cell causes inefficient operation of the PSR, resulting in reduced power production and increased fuel consumption.

The development of a novel gas turbine recuperator made from two continuous sheets of metal wound into a spiral form was reported recently.[7] This spiral recuperator is very compact and can be applied to engines from 25-kW microturbines to large (20-MW) industrial and marine turbines. Its developers claim that it will be less expensive than the current PSRs when in full production. This assessment will further concentrate on the PSR as a preferred recuperation method for metallic microturbine recuperators because it is in production already.

Materials Requirements. The microturbines currently in production use metallic recuperators to raise their efficiencies to approximately 30%. Figures 10 and 11 show the complex relationship between the thermal efficiency, TRIT, recuperator hot-gas inlet temperature, compression ratio, recuperator effectiveness (ε_r), and materials requirements for microturbines. These figures are based on assumptions that are stated on them: single-shaft engine with radial flow, low power range of 25 to 75 kW, and low compression ratio (less than 6).

Figure 10 relates microturbine efficiency to the specific fuel consumption, TRIT, and recuperator effectiveness as technology advances. Region 1 is where the current metallic state-

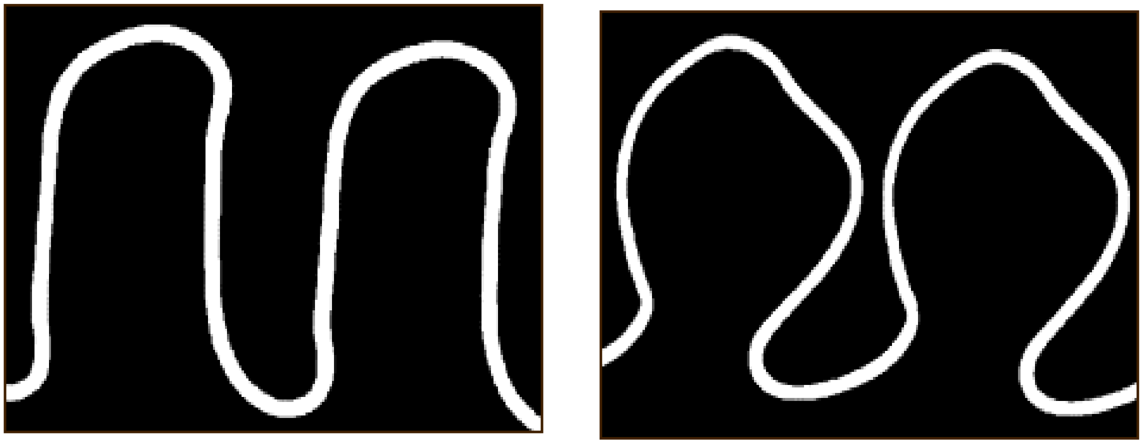

Figure 9. Excessive creep (right) can close up the flow channels in a PSR air cell. Source: P. J. Maziasz et al, “Stainless Steel Foil with Improved Creep-Resistance for Use in Primary Surface Recuperators for Gas Turbine Engines,” in Gas Turbine Materials Technology, eds P. J, Maziasz, I. G. Wright, W. J. Brindley, J. Stringer and C. O’Brien, ASM-International, Materials Park, OH (1999) pp. 70-78.

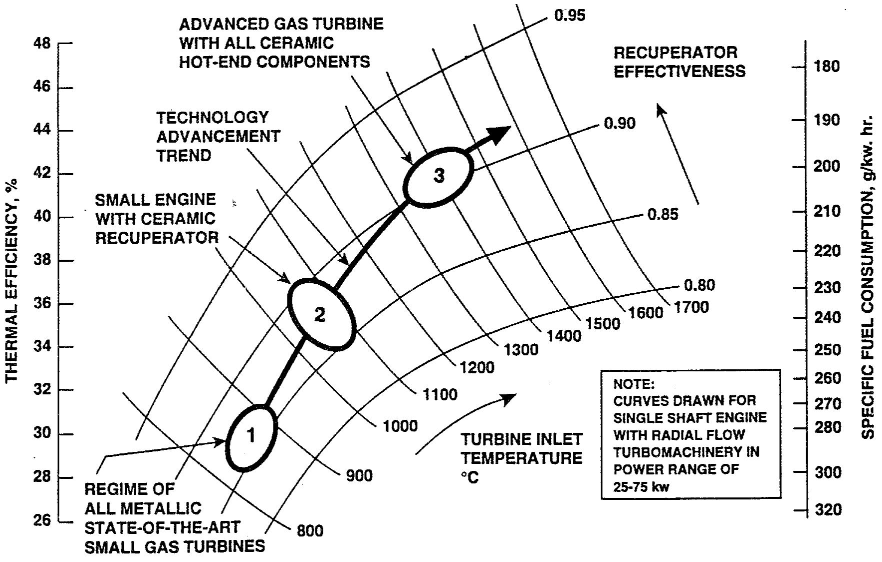

Figure 10. Performance array for very small recuperated gas turbine. Source: C. F. McDonald, Heat Recovery Exchanger Technology for Very Small Gas Turbines,” International Journal of Turbo and Jet Engines, 13, 239-261, London (1996).

efficiencies are in the mid-30s (34-38%), it is projected that ceramic or superalloy recuperators will be required and that their effectiveness will improve from 85% to between 85 and 90%; the TRIT will be over 1000˚C. In Region 3, the efficiency is above 40%, which is the goal of the Advanced Microturbine Program. This is the regime of advanced microturbines with all ceramic hot-end components. The TRIT will be above 1300˚C, the recuperator effectiveness will be 90% and above of-the-art turbines are, with a maximum efficiency of ~30%. To get to Region 2, where the, the specific fuel consumption will fall from over 300 g/kWh to approximately 220 g/kWh.

Figure 11 presents similar information but it also includes the projected recuperator hot-gas inlet temperatures (dashed lines).[8] It shows the limits of the various materials of construction for recuperators and clearly indicates that, without cycle innovation, 40% efficiency in Region 3 cannot be attained without ceramic materials because the recuperator hot-gas inlet temperature is above 900°C. Figure 11 essentially defines the recuperator materials requirements based on the hot-gas inlet temperatures: 400 series ferritic alloys up to 600°C; 300 series austenitic alloys up to 700°C (considered the limit for stainless steel); 800 to 850°C, the limit for advanced austenitic alloys and nickel-based superalloys; and 900°C, the limit for cobalt-based superalloys. Both figures show that when the inlet temperature is above 900°C, ceramics or oxide dispersion strengthened (ODS) alloys will most likely be needed. These temperature limits are based on the materials properties that determine recuperator failure, such as corrosion, oxidation, creep, and strength.

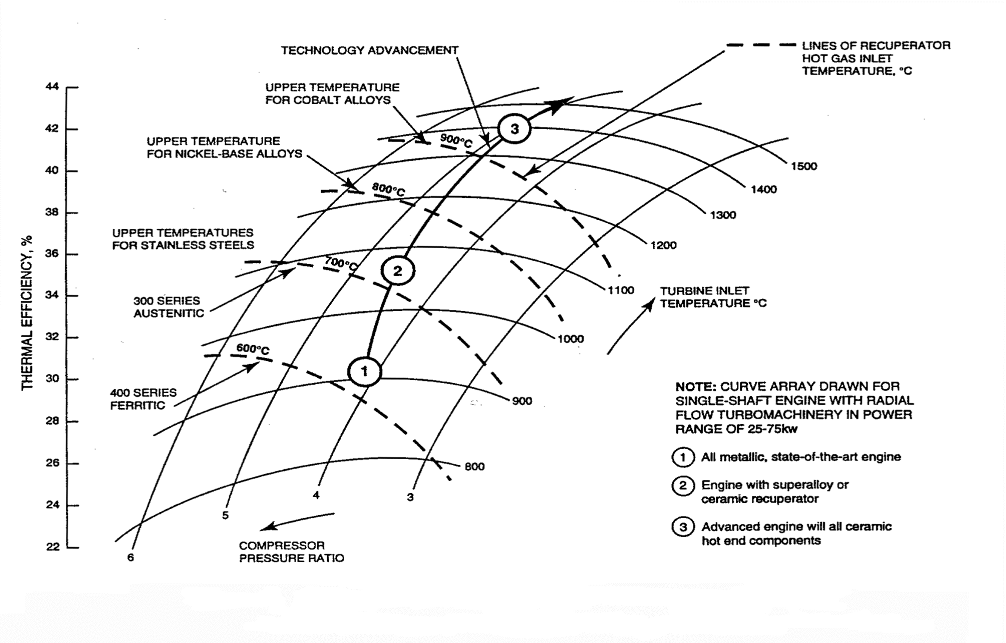

Figure 11. The impact of major parameters on the performance of small gas turbines (without intercoolers or reheat). Source: C. F. McDonald, Heat Recovery Exchanger Technology for Very Small Gas Turbines," International Journal of Turbo and Jet Engines, 13, 239-261, London (1996).

The recuperators now available, such as the PSR, are fabricated from type 347 stainless steel. Table 1 shows the chemistry of additional alloys that may be considered for higher-performance recuperators. The current recuperators can be used where the gas inlet temperature is less than 650°C. The corrosion resistance of type 347 stainless steel is due to 18% chromium (Cr) content, which forms a protective chromium oxide film on the surface of the alloy. Ideally, the formation of a dense adherent external oxide layer inhibits transport of oxygen to the material below the film, thus protecting the alloy from excessive oxidation damage. However at higher temperatures, this protective layer grows at a faster rate, which can lead to oxide spallation and Cr depletion. This oxidation damage leads to a decrease in effective cross section and a consequent failure of the PSR due to creep (Figure 9).

Table 1 - Compositions of Potential Advanced Austenitic Stainless Alloys for Microturbine Recuperator Applications (wt.%)

Alloy/Vendor	**Fe**	**Cr**	**Ni**	**Co**	**Mo**	**Nb**	**W**	**C**	**Si**	**Ti**	**Al**
347 steel/ Allegheny-Ludlum	68.7	18.3	11.2	0.2	0.3	0.64	-	0.03	0.6	0.001	0.003
Mod. 20-25Nb Allegheny-Ludlum (developmental)	53	20	25	-	1.5	0.3	-	n.a.	n.a.	n.a	n.a.
Mod. 803 INCO (developmental)	40	25	35	-	n.a.	n.a.	-	0.05	n.a.	n.a.	n.a.
Thermie alloy (INCO)	2	24	48	20	0.5	2	-	0.1	0.5	2	0.8
Alloy120 (Haynes)	33	25	32.3	3.0*	2.5*	0.7	2.5*	0.05	0.6 (+ 0.2 N)	0.1	0.1
Alloy 214 (Haynes)	3	16	76.5	-	-	-	-	-	- (+ minor Y)	-	4.5
Alloy 230 (Haynes)	3.0*	22	52.7	5.0*	2	-	14	0.1	0.4 (+ trace La)	-	0.3
Alloy 625 (INCO)	3.2	22.2	61.2	-	9.1	3.6	-	0.02	0.2	0.23	0.16

* Maximum amount

As the gas inlet temperature increases, new austenitic alloys and superalloys are needed. Before an alloy can be used for the fabrication of PSR, several questions must be answered. First, the alloy must be capable of being rolled into thin (< 5 mil) foils that have adequate uniform elongation so that they can be formed into the required corrugated pattern. The foil-forming process must lend itself to continuous operation in order to minimize cost. Second, the fine-grained alloy foil must possess the necessary creep strength at the maximum operating temperature. The creep strength is only one measure of lifetime of the alloy, the other is its resistance to oxidation and other corrosive species in the exhaust gas. Third, the final product must be the most cost-effective combination of both. The answer to the first two questions will come from developmental research with a range of existing advanced alloys and the development of new alloys.

Research at the Oak Ridge National Laboratory (ORNL) has shown that 347 stainless steel can be modified to operate at up to 730°C with creep resistance superior to the standard commercial material (see Figure 12).[9] The initial laboratory-scale processing modifications have been creep-tested for up to 10,000 hours and show significantly improved creep resistance. These modified processes need to be translated into a full-scale, continuous foil process for use in the PSR fabrication.

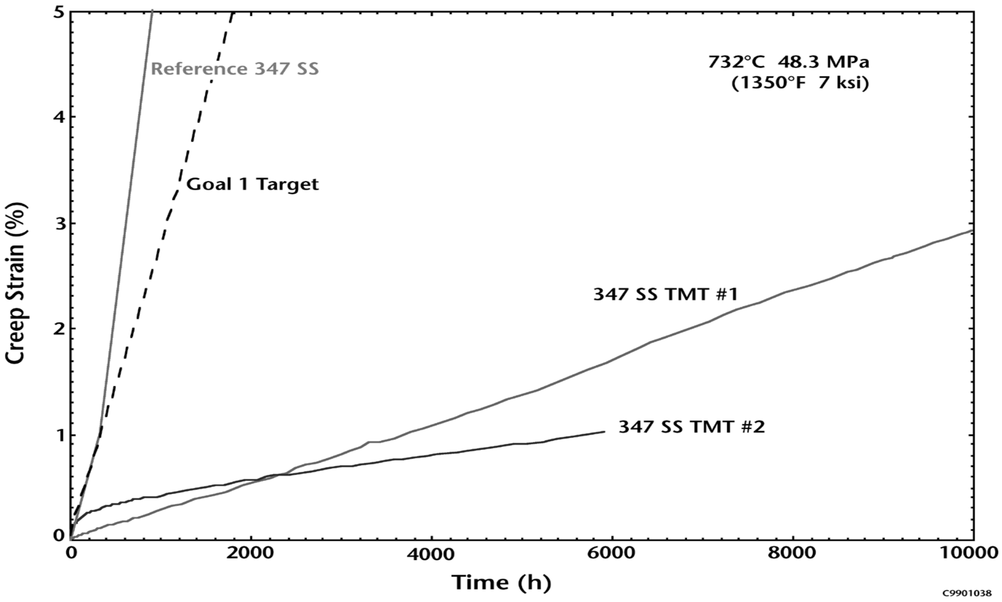

Figure 12. Laboratory-modified processing at ORNL shows dramatically improved creep-resistance for standard 347 stainless steel foil. Source: Maziasz et al., “Stainless Steel Foil with Improved Creep-Resistance for Use in Primary Surface Recuperators for Gas Turbine Engines,” in Gas Turbine Materials Technology, eds P. J, Maziasz, I. G. Wright, W. J. Brindley, J. Stringer and C. O’Brien, ASM-International, Materials Park, OH (1999) pp. 70-78.

A second requirement is that the new material must have the requisite oxidation/corrosion resistance at the new temperature. In a preliminary investigation, B. Pint[10] compared the oxidation of alloys protected by the formation of a chromium oxide (Cr_2O_3) film (such as SS 347, SS 310, 20/25/Nb, 253MA, and Haynes 230) with alloys protected by the formation of an alumina (Al_2O_3) [such as Haynes 214, and ODS FeCrAl alloys (PM2000, Inco MA956 HT)].

Figure 13 shows the total mass gained by representative foils of the two types of alloys heated at 900ºC in laboratory air for greater than 10,000 hours. Coupons of the material were held in annealed alumina crucibles. The Cr_2O_3-forming foils show excessive weight gained in <4,000 hours whereas the thinner (2 mil) Al_2O_3-forming foils show minimal weight gained after 12,000 hours. This is due to the limited reservoir of Cr in those stainless steel foils and the fast Cr consumption (oxidation) at 900˚C compared with the rate of formation of Al_2O_3 on the alloys that contain aluminum.

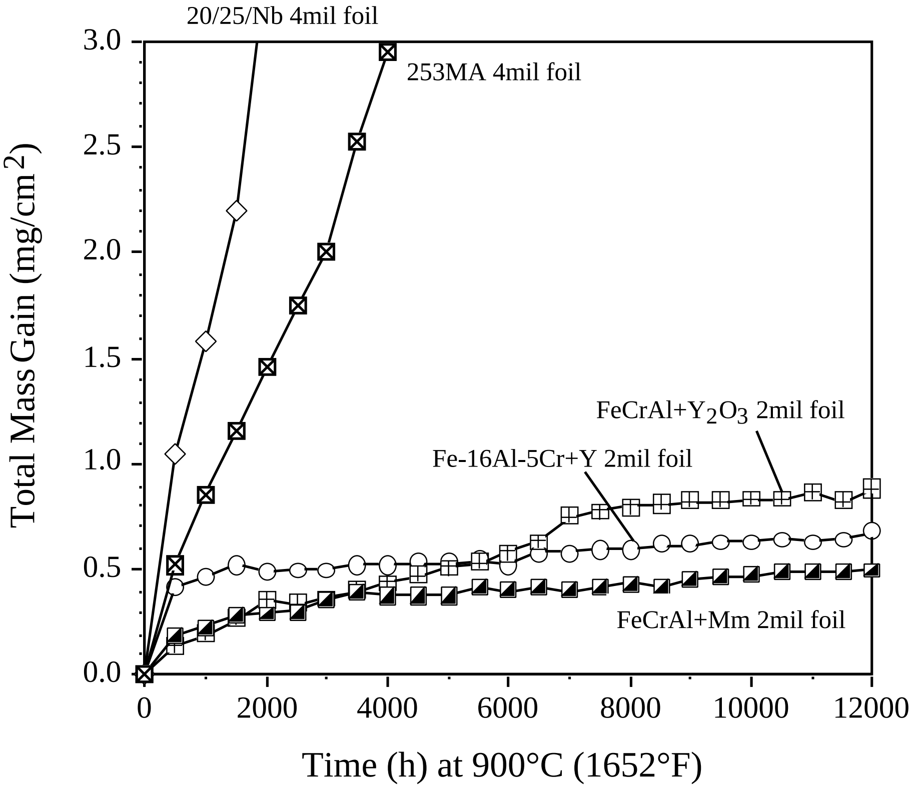

Figure 13. Total mass gain during 500-hour cycles at 900˚C in laboratory air for chromia- and alumina-forming specimens.

This study, as well as others, indicates that alloys that are protected by Cr_2O_3 formation can be used to ~800ºC; beyond that, only alloys protected by Al_2O_3 formation will survive. New recuperator alloys need to be evaluated for oxidation/corrosion in the typical exhaust gas at the inlet temperature to the recuperator because the exhaust gas contents may be more corrosive than laboratory air.[11]

Higher Compression Ratio**.** The assessment has been based on the assumption of considering a simple cycle microturbine with a compression ratio of less than 6. For a given TRIT, the compression ratio is inversely proportional to the temperature of the exhaust gas from the turbine. Thus, by increasing the compression ratio, the exhaust temperature is lowered. Researchers in Japan[12] reported that, in the development of their 300-kW gas turbine (CGT302), they had to increase the compression ratio to 8, which resulted in lower exhaust-gas temperature, so that they could use heat-resistant metals instead of ceramics.

A higher compression ratio also leads to higher efficiencies until an optimum compression ratio is reached.[2,3,4] This is why large (megawatt-scale) gas turbine engines with or without recuperation have higher efficiencies than microturbines. In the discussion of the various turbine cycles, it was shown that using two low-powered compressors, each with a compression ratio of 3 and an intercooler, gives an overall compression ratio of 9. The temperature of the exhaust gas from such a cycle should be sufficiently low to allow the use of metallic recuperators fabricated from current or improved alloys. It was reported at the Microturbine Technology Summit[1] (p. C61) that intercooled and recuperated gas turbine cycles give efficiencies of 42 to 45%. Thus, the use of the intercooled and recuperated gas turbine cycle is an option that microturbine manufacturers may adopt to meet higher efficiencies.

In his review of recuperated gas turbine engines, McDonald[13] implies that technology may advance to a stage where 40% efficiency may be attained by using high-temperature metallic recuperators. He suggests that, because low-cost recuperators will be needed to meet the large demand anticipated in the near term for microturbines, the prerequisite technology may come from the automobile radiator industry. In his recent paper,[14] he discusses in detail low-cost, high-volume production of a metallic recuperator for microturbines in the 25- to 75-kW range.

McDonald believes that, in the long term, the full performance potential of microturbines can be achieved only with ceramic recuperators. As the TRIT is increased in pursuit of higher efficiencies for microturbines, ceramic recuperators will be inevitable. Therefore, ceramic recuperators should be developed in order to meet this potential need.

Summary. The materials requirements for metallic recuperators for microturbines are determined by the temperature of the exhaust gas from the turbine. The exhaust temperature depends on the thermal efficiency of the engine. For a small (25–75 kW) recuperated gas turbine, the current 30% efficiency has been achieved by using a gas inlet temperature of about 650˚C. The material of construction for the recuperator (such as a PSR) is type 347 stainless steel, which survives at this temperature because it forms a protective Cr_2O_3 film. However, there is promising research to improve the properties of 347 stainless steel or similar inexpensive alloys and extend their useful temperature, possibly to 750˚C. This improvement will raise engine efficiency to about 34%. Advanced austenitic stainless alloys and superalloys most likely can be used at 750 to 850˚C. To raise the efficiency to 38% for microturbines, the inlet gas temperature to recuperator approaches 900˚C, where only alumina-forming alloys that contain aluminum are feasible. The properties of these materials need to be investigated and their fabricability needs to be evaluated because of their increased brittleness.

Efficiencies >40% can be obtained by either using the simple recuperated cycle or the intercooled and recuperated cycle. If the latter cycle is used, the exhaust-gas temperature may remain sufficiently low to use austenitic stainless alloys and superalloys. However, if the simple recuperated cycle is used, the gas inlet temperature into the recuperator will be >900˚C and ceramic or outside dispersion strengthened (ODS) metallic recuperators will be required.

Consequently, there is need now for the research and development necessary to produce and evaluate both the metallic and ceramic materials requirements at and beyond these high crossover temperatures.

CERAMIC RECUPERATORS

This section summarizes the materials requirements for microturbines that require ceramic recuperators. Ceramic recuperators are of interest because they can withstand the higher temperatures required to boost the efficiency of microturbines and because they can operate at very high effectiveness (>90%). However, unlike metallic recuperators, ceramic recuperators are not well established in industry.

Historical Background. The interest in ceramic components for recuperators developed in the early 1970s, when ceramics were being considered for components in engines and turbochargers. The oil crisis had driven up the cost of petroleum-based fuels, and it was thought that the prices would continue to rise. Therefore, the aluminum, steel, and glass industries considered coal as an alternative energy source because it was relatively cheap and abundant. At the same time, they investigated methods for capturing waste heat and returning it to the high-temperature process streams. Researchers found that the waste energy was difficult to recover because the streams (at temperatures up to 1650˚C) fouled surfaces with particulate buildup, and, at the high preheat temperatures (>1100˚C), they were corrosive to metal alloys. Ceramics were investigated because, unlike metal alloys, ceramics have sufficient high-temperature strength and oxidation resistance to preheat air up to 1100˚C. However, because the cost of oil dropped in the 1980s, research into ceramic recuperators gradually ceased.

The early research for the development of ceramics for large, industrial recuperators provides information for the current assessment of ceramic recuperators for microturbines. Some of the results of those early investigations are summarized in *Ceramic Heat Exchanger Concepts and Materials Technology*.[15] The materials used and the flow configurations were given, as indicated in the following examples.

- GTE used cordierite, a magnesium aluminum silicate ($2MgO\cdot 2Al_2O_3\cdot 5SiO_2$), in a finned-plate design, in which the fins and plates were staked and bonded. The result is a crossflow matrix, although the system becomes counterflow when staged.
- Midland-Ross used cordierite in a heat wheel with a segmented-matrix configuration.
- Garrett-Air Research (formerly AlliedSignal, now Honeywell) used reaction-bonded Si_3N_4 (RBSN) and SiC in a tube-in-shell exchanger that is crossflow as a single unit but counterflow when staged.
- Solar Turbines, Inc. used sintered SiC for its tube-in-shell design with axial counterflow configuration. Other materials used were phosphate-bonded SiC, alumina chromia, and magnesia chromia.

The following reports summarize the early high-temperature ceramics research:

- *Ceramic Heat Recuperators for Industrial Heat Recovery*,[16] which states that cordierite was selected for its “ease of fabrication, relatively low thermal expansion, good thermal shock resistance and good corrosion resistance”;
- *Technology Assessment of Ceramic Joining Applicable to Heat Exchangers*,[17] which investigates joining ceramics;

- *Economic Application, Design Analysis, and Material Availability for Ceramic Heat Exchangers*,[18] which states that demonstration of performance and durability of the ceramic heat exchangers must be shown before they can be considered for industrial production furnaces;
- *Ceramic Heat Exchanger Technology Development*,[19] which describes the use of siliconized SiC materials;
- *Ceramic Heat Exchanger Design Methodology*,[20] which lists the available materials and their vendors (sintered α-SiC from Carborundum; reaction-bonded SiC from Carborundum, Coors, Norton, and Refel; sintered SiC and sintered Si_3N_4 from Kyocera; and nitride-bonded SiC, reaction-bonded Si_3N_4, and hot-pressed Si_3N_4 from Norton); and
- *Design Methodology Needs for Fiber-Reinforced Ceramic Heat Exchangers*,[21] which distinguishes between design of the ceramic material and design with the ceramic material.

It should be noted that most of the companies that investigated these large-size ceramic recuperators are no longer in the field and several of the companies that manufactured the ceramic materials have also left the business. In both cases, even though new companies replaced the old ones, there are fewer companies in this area now than there were in the 1970s and 80s. Because there are fewer companies and because many of the investigators have retired, the availability of experienced researchers who could work on ceramic recuperators for microturbines will be affected.

Colin F. McDonald has been an active participant in reporting on these events over the years, and several of his publications have been beneficial in this assessment. His 1979 paper, "The Role of the Ceramic Heat Exchanger in Energy and Resource Conservation,"[22] contains both a synopsis of the up-to-date heat-exchanger research and his projection of the role of ceramic heat exchangers for industrial high-temperature waste-heat recovery. His recent papers[8,13,22] discuss ceramic heat exchangers in very small gas turbines (25–75 kW).

In 1995, the Ceramic Technology Project published a report, *Needs Assessment for Manufacturing Ceramic Gas Turbine Components*.[23] Although the report covers all ceramic gas turbine components, its findings are also relevant to ceramic recuperators for microturbines.

<u>Examples of Ceramic Recuperators for Small Turbines</u>. AlliedSignal developed a compact plate-fin ceramic recuperator module for a cruise missile application.[24] It is based on the creation of fins in an extruded plate of silicon. Several plate-and-fin surfaces are laid over one another, and the whole assembly is nitrided to form RBSN and thus is held together as a unit. The cylindrical ends (see Figure 14) are designed to create the counterflow necessary to attain effectiveness (ε_r >80%). Although they have not used the process to make recuperators recently, the AlliedSignal staff is using a similar procedure in their current fuel-cell research activities.

A <u>plate-fin</u> ceramic recuperator for a 60-kW turbogenerator has been fabricated as part of the European Advanced Gas Turbine for Automobiles (AGATA) program to develop a gas turbine hybrid vehicle.[25] A recent paper summarized the activities of AGATA; activities

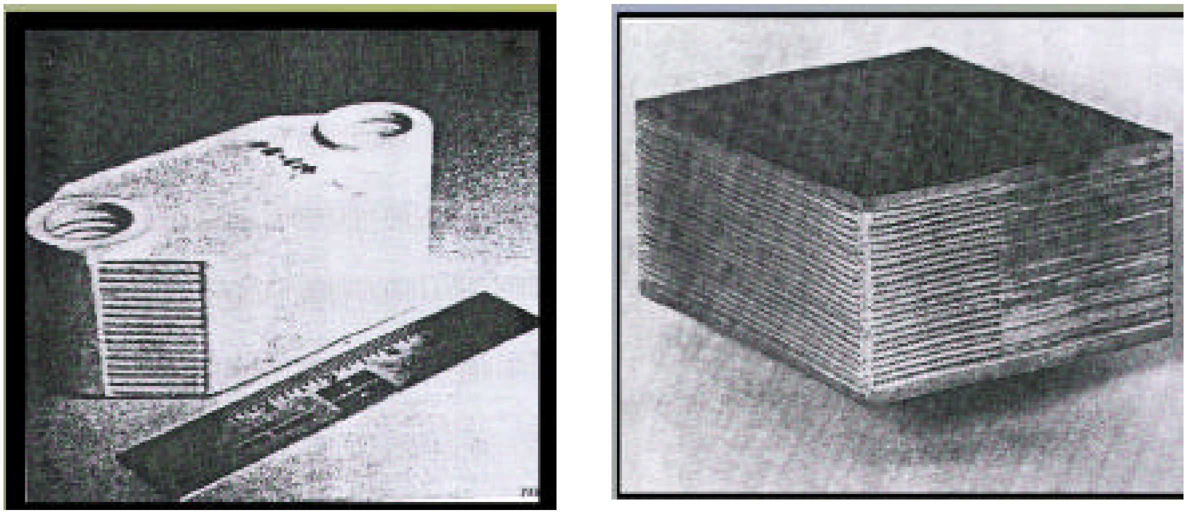

Figure 14. Plate-fin recuperators. Left: AlliedSignal design. Right: AGATA design. Source: C.F. McDonald, “Heat Recovery Exchanger Technology for Very Small Gas Turbines,” International Journal of Turbo and Jet Engines, **13**, 239-261, London (1966).

included fabrication of a ceramic recuperator, a ceramic catalytic combustor, and a radial turbine wheel. The recuperator (see Figure 14) was to operate at up to 1300 K (1027^{o}C) under moderate pressures (4 bars, or ~4 atmospheres). More details of the construction are provided in the paper. The authors claim that the plate-fin design is flexible and that the fin height and geometry can be varied. Cordierite and SiC were investigated extensively. Cordierite was chosen because its safety coefficient, expressed as the ratio of the mechanical strength to the induced stress, was higher. Although the mechanical strength of SiC is much higher, the induced thermal stress for cordierite is very low because its Young’s modulus and coefficient of thermal expansion are lower.

In the 1980s, Coors[26] developed a compact prime-surface ceramic recuperator for a gas turbine to be used in automobiles (see Figure 15). Harrison Radiator Division funded Coors to fabricate a fixed-boundary, all-prime-surface recuperator in a counterflow configuration with internal manifolds. Several materials were evaluated, including Si_3N_4 and RBSN for high resistance to cracking (Si_3N_4 has relatively low thermal expansion for its high strength), SiC for its strength and high thermal conductivity, cordierite, and a proprietary mixture of oxides belonging to Coors. Cordierite was chosen because of its high thermal stress resistance. In the Coors process, the cordierite was fused into a monolithic matrix and fired in a single operation. The method is applicable to other ceramics.

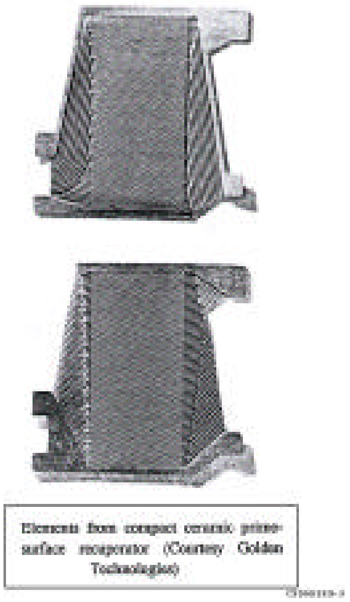

Figure 15. Coors (Golden Technologies) counterflow recuperator design.

In the 1970s, German researchers built a counterflow ceramic recuperator by machining the flow channels from a solid Si_3N_4 ceramic block.[27] Utilizing this modular approach, they planned to fabricate an annular recuperator for a 70-kW vehicular gas turbine.

As part of their gas turbine program, Japanese researchers built a three-pass shell-and-tube ceramic recuperator for the CGT 300 (300-kW) gas turbine.[28] Because the inlet gas temperature was 825^{o}C, the tubes were made of a Si_3N_4 material that was resistant to high temperature. However, to complete the full heat-exchange load, metallic tubes were used at the lower temperatures in the heat exchanger. The ceramic recuperator was designed as an assembly of six modules, one of which was tested. The test results showed that the ceramic tube bundle was structurally stable and gave acceptable performance; the temperature effectiveness was 84.3% and the pressure drop was 2.9%. It was disclosed in a recent report on this program[12] that an all-metal recuperator is currently being used. The use of an all-metal recuperator was made possible by increasing the compression ratio to 8, thereby lowering the exhaust gas temperature.

The GTE industrial ceramic recuperator is a product that has survived the period of intensive development and continue to be used today. Reports by Gonzalez[29] and Gonzalez and Roberto[30] discuss the use of the ceramic recuperators in industry. GTE developed modular crossflow ceramic recuperators (see Figure 16) in three sizes: 10 in. (cube), 12-in. (cube), and 12 × 12 × 18 in., rated at 0.6, 1.0, and 1.5 million Btu/h, respectively, for industrial applications.

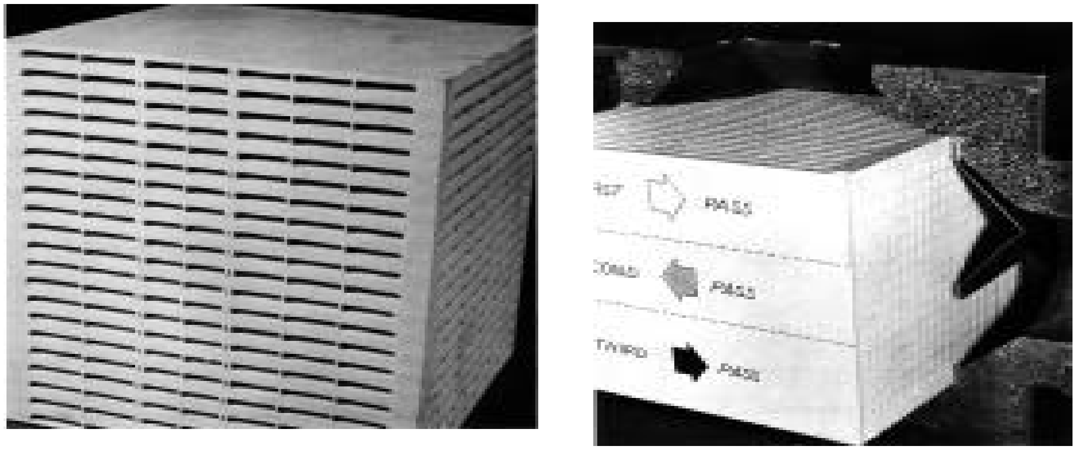

Figure 16. Left: GTE Ceramic Recuperator Matrix. Right: Housed GTE recuperator with cutaway section showing counterflow arrangement. Source: J. M. Gonzalez, "Development of a Zirconia-Mullite based Ceramic for Recuperate Applications," ORNL/Sub/86-22044/2, Dec (1992).

These recuperators used exhaust gas at ~1320˚C to heat incoming air to 705˚C. The best longevity of the recuperator was obtained when the exhaust gas temperature was less than 1100˚C. Although individual units are crossflow, they can be arranged to simulate counterflow, which would increase their effectiveness (see Figure 16). Two points about the GTE recuperators should be noted. The first is that the material of construction is cordierite. The second is that many of these recuperators are still in operation. Communications with Gonzalez, now at Sylvania, indicated that technicians service these recuperators and make some new ones, where necessary. He mentioned the problem of corrosive materials in the exhaust gas and explained that a simple modification of the burners enhanced the success of the recuperators. In addition, he discussed points to note in the design of ceramic recuperators. Based on practical experience, the following observations have theoretical validity:

- conductivity of the material is not important for heat transfer,
- pressure drops must be small,
- leaks should be constant so they can be designed for,
- the design for metallic recuperators cannot be translated to ceramic materials,
- manifolding to attain counter-flow for high effectiveness is difficult, and
- thermal shock and creep resistance are the determinant properties.

Materials Selection. In order to fabricate ceramic recuperators, two critical decisions must be made. The first is the selection of the ceramic material and the second is the selection of the construction method. The review of the activities in ceramic recuperation shows that no one material has been used consistently. This is not unexpected because no one material meets the required specifications, which include the following:

- low thermal expansion,
- high thermal-shock resistance,
- good corrosion and oxidation resistance,
- high thermal strength,

- good creep resistance,
- ease of fabrication, and
- low cost.

During the most active periods of research into ceramic recuperators, the following materials were used: cordierite, Si_3N_4, and SiC (both reaction-bonded and sintered), nitride-bonded SiC, phosphate-bonded SiC, alumina chromia, and magnesia chromia. Some of these materials are no longer considered for high-temperature operations. Of these materials, silicon nitride and cordierite are likely candidates for further development, but both have their drawbacks. In addition, new materials, such as low-thermal-expansion materials[31] or high-thermal-conductivity carbon foam, developed recently at ORNL,[32] should be evaluated.

Silicon Nitride. Silicon nitride has been investigated most extensively (for at least two decades) and has been found suitable for use at high temperatures. Si_3N_4 has excellent creep resistance: its creep lifetimes at stresses and temperatures typical of operating conditions have exceeded 10,000 hours, which is superior to those of nickel-based superalloys. However, it is difficult to fabricate and is very expensive. DOE, through the Ceramic Technology Project, has funded several studies to develop Si_3N_4 with desirable properties for high-temperature structural ceramic applications. Norton produced NT164 Si_3N_4, Kyocera produced SN282, and AlliedSignal Ceramic Component produced AS800. The material properties of AS800 are typical:

- maximum operating temperature: 1400˚C,
- room-temperature flexural strength: 715 MPa,
- Weibull modulus: 20-30,
- fracture toughness: 8 $MPa \cdot m^{1/2}$,
- thermal conductivity: 65 W/mK,
- density: 3.3,
- elastic modulus: 310 GPa, and
- the mean coefficient of thermal expansion (CTE) (20 – 1000˚C): 3.9×10^{-6}/˚C.

Although Si_3N_4 has excellent material properties, it is very expensive; the powder alone costs nearly $40/lb and its processing is complex. A less-expensive form is RBSN, made from cheap Si powder. AlliedSignal used RBSN in its plate-fin recuperator. If the material specifications for the recuperator are less stringent than those for the other hot sections of the microturbine, RBSN may suffice and may be cost-effective. Recently, it has been shown that under high pressure and at the typical TRIT, the corrosion damage of Si_3N_4 is very high in the presence of high-velocity gas streams containing steam.[33,34] There is rapid oxidation of the Si_3N_4, that can lead to cracks in the ceramic material. Although the temperature and pressure in the recuperator for a microturbine will be less than the temperature and pressure in the turbine, the cracking problem is another reason for investigating possible fabrication materials under the anticipated operating environments.

Cordierite. Cordierite was the material used in many of the earlier ceramic recuperators for microturbines (Coors and AGATA). It is the material used in the compact GTE recuperator, which is the only one in industrial application for more than a decade. It is used now as the support for the catalytic combustors in automobiles. Its CTE is low, similar to that of Si_3N_4, and it has excellent oxidation resistance and low density. Its major benefits are its low cost and relative ease of fabrication. However, it may not be applicable at temperatures beyond 900°C (near its glass transition temperature), although the GTE recuperators apparently operate at higher temperatures. This is a strong argument for investigating this material to find its optimum operating temperature. Because of corrosion problems, other oxides (such as mullite), which are being considered as coatings for Si_3N_4, should be included in the search for ceramic materials for cost-effective microturbine recuperators.

New Materials. There is clearly a need to investigate new ceramic materials that (1) fit into the temperature range below the TRIT and (2) can be fabricated inexpensively. Low-thermal-expansion materials have the advantage of low CTE and probably some resistance to oxidation damage, but their strength and creep resistance may be too low at the requisite temperature. High-conductivity carbon foam [specific conductivity up to 258 (copper = 45)] may not be oxidation-resistant at recuperator temperatures, and it is unknown whether recuperators can be fabricated from it.

Fabrication Method. Materials selection and fabricability are closely related. Two methods of construction have been used in the fabrication of the compact recuperators needed in microturbines: the fin-plate and the PSR method. The tube-and-shell method would be unsuitable because the surface area would be excessive for the heat-exchange load in a typical microturbine. Theoretically, the PSR approach may seem a better method because of the poor conductivity of the ceramic fins in the plate-fin approach. However, the plate-fin design may be easier to fabricate and less costly with ceramic materials. In addition, the flow direction of the heat-exchanging fluids, whether counterflow or crossflow, is critical. Unfortunately, crossflow designs may not be able to achieve the high effectiveness (~90%) that will be required for 40% efficient microturbines.

The fabrication method has to be amenable to high-volume production. An extrusion process, which is typically difficult in ceramic processing, may have to be developed. However, a continuous-batch operation would suffice. At this stage, the critical need is to develop a process to fabricate a ceramic recuperator. Scale up to high-volume production will follow later.

Honeywell Composites, Inc. (HCI), formerly Lanxide, has been investigating the fabrication of thin-sheet ceramic recuperators based on paper-making technology.[35] The thin-sheet recuperator is made from alumina (Al_2O_3) particulates in an Al_2O_3 matrix and is designed for counterflow operation. A prototype recuperator has been fabricated and is being tested. Like cordierite, there is concern about permeability of the material in thin sections.

Summary. Research into ceramic recuperators for large manufacturing industries (e.g., steel, aluminum, and glass) and for microturbines began in the 1970s during the oil crisis and was abandoned in the 1980s once the crisis was over. However, as the thermal efficiencies increase to >40%, ceramic recuperators may be needed to achieve the full potentials of microturbines. The observations made then that ceramic recuperators must be shown to be effective in actual operations are still valid today. Two major decisions must be made in order to develop a ceramic recuperator for microturbines: selection of the material of construction and selection of the method of fabrication. Several ceramic materials were used in the prototype manufacture of ceramic recuperators but the selection now is limited to cordierite, SiC, sintered Si_3N_4, RBSN, and new materials such as low thermal-expansion ceramics or foamed carbon. The fabrication technique may be plate-fin or prime-surface with a counterflow configuration. It seems obvious that many years will be required before processes can be developed to fabricate or manufacture reliable, low-cost ceramic recuperators.

CONCLUSIONS

Microturbines in production (or nearly in production) use metal recuperators with gas inlet temperatures of less than 700˚C to raise their efficiency to about 30%. To increase their efficiencies to greater than 40% (which is the DOE Advanced Microturbine Program goal) will require operating at higher gas inlet temperatures, if the compression ratio remains less than 6. Even at higher compression ratios, the inlet temperature will increase as the efficiency increases, necessitating the use of new materials of construction.

The materials requirement for recuperators used in microturbines may be categorized by their maximum operating temperatures: 700, 800, and ~900˚C. These limits are based on the materials properties that determine recuperator failure, such as corrosion, oxidation, creep, and strength. Metallic alloys are applicable in the 700 and 800˚C limits; ceramics are applicable in the 900˚C range.

Most of the heat exchangers in the current microturbines are primary surface recuperators (PSR), compact recuperators fabricated in 347 stainless steel by rolling foil that is a few (>5) mil thick into air cells; the metal recuperators are operated at temperatures below 650˚C. Preliminary research indicates that the use of 347 stainless steel can be extended to 700˚C. However, additional directed research is required to improve the current properties of 347 stainless steel and to evaluate extended demonstrations on recuperators fabricated from it. Beyond 700˚C and up to about 800˚C, advanced austenitic stainless steels or other alloys or superalloys become applicable. Their properties must be measured in the expected operational environment, and recuperators fabricated from them must be evaluated for an extended period.

Temperatures beyond 900˚C exceed the limits of metals, and ceramic materials will be needed. The relevant properties of Si_3N_4 and SiC, (creep, corrosion, and oxidation) have been studied extensively. Prototype ceramic recuperators have been fabricated from both cordierite and RBSN; consequently, their properties and those of other low-cost applicable ceramic materials need to be investigated further. Because no ceramic microturbine recuperators are in production, it will be necessary to fabricate prototype units and evaluate their properties over an extended demonstration period.

A comprehensive workshop for those involved in recuperators for microturbines is recommended to determine how the technology can be accelerated to support the development of ultra-efficient microturbines. The immediate emphasis should be on the cost-effective manufacture of higher-temperature metallic recuperators; the development of ceramic recuperators should be considered a long-term objective.

Acknowledgements

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