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EMERGENCE OF RECUPERATED GAS TURBINES FOR POWER GENERATION

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ABSTRACT

In the emerging deployment of microturbines (25-75Kw), a recuperator is mandatory to achieve thermal efficiencies of 30 percent and higher, this being important if they are to successfully penentrate the market currently dominated by Diesel generator sets.This will be the first application of gas turbines for electrical power generation, where recuperators will be used in significant quantities. The experience gained with these machines will give users' confidence that recuperated engines will meet performance and reliability goals. The latter point is particularly important, since recuperated gas turbines have not been widely deployed for power generation, and early variants were a disappointment. Recuperator technology transfer to larger engines will see the introduction of advanced heat exchanged industrial gas turbines for power generation in the 3-15 Mw range.

After many decades of development, existing recuperators of both primary surface and plate-fin types, have demonstrated acceptable thermal performance and integrity in the cyclic gas turbine environment, but their capital costs are high.

A near-term challenge to recuperator design and manufacturing engineers is to establish lower cost metallic heat exchangers that can be manufactured using high volume production methods. A longer term goal will be the development and utilization of a ceramic recuperator, since this is the key component to realize the full performance potential of very small and medium size gas turbines.

1.INTRODUCTION

With the near plateauing of compressor and turbine efficiencies, and increased turbine inlet temperature paced by materials and cooling technologies, only modest effiiency advances will likely be made with the here-to-fore dominant simple cycle gas turbine, and significant advances in efficiency can only be realized by utilizing more complex thermodynamic cycles, and near-term candicates include intercooling and recuperation.

In the last 50 years, recuperators have found only limited acceptance in gas turbines for electrical power generation. This was essentially a reflection of poor heat exchanger reliability, their bulky size compared with the compact nature of the turbomachinery, and their high cost. Today, recuperator technology has advanced to the point where the first two of these impediments have been overcome, and units in limited quantities have seen reliable service.

The potentially large market for microturbines (25-75Kw), in the distributed power generation field, will see the emergence of recuperated gas turbines in significant quantities starting around the year 2000. This is an application where a recuperator is mandatory to achieve efficiencies of over 30 percent for these very small machines. With new metallic recuperator concepts being developed, that are amenable to high volume production methods, the remaining impediment of high cost should be overcome. Transfer of this technology should lead to the increased acceptance of recuperators for a wide range of applications, including advanced industrial gas turbines rated up to 15Mw, or even higher.

A major theme of this paper is the important role that the recuperator has in achieving high gas turbine plant efficiency.There are many thermodynamic cycles being evaluated, including the coupling of gas turbines with fuel cells, that will benefit from the inclusion of a structurally sound and cost-effective recuperator. This topic is addressed, together with future applications that include power generation, marine propulsion

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hybrid electric vehicles, and eventually aircraft propulsion. Recuperator technology state-of-the-art is briefly discussed, covering currently available heat exchanger types, future developments in metallic units, and the projected eventual use of ceramic recuperators when this technology matures in the first decade of the 21st century.

2. BACKGROUND

Large single-shaft industrial gas turbines for electrical power generation are not adaptable to conventional intercooling, and their high compressor pressure ratios preclude recuperation. Operating in a combined cycle mode, an excellent efficiency of 60 percent is realizable, and the future coupling with fuel cells offers the potential for even higher levels of performance.

Because of lack of heat exchanger technology readiness, there has been only limited use of recuperation for small gas turbines. The emergence of recuperated gas turbines expected after the year 2000 is based on two factors, namely `1) resolution of early recuperator problems, and this will be addressed in a following section, and 2) limited performance gains by conventional means for simple cycle gas turbines.

After over half a century of aerothermal advancements the improvements in the efficiencies of radial and axial flow compressors and turbines are plateauing, although the use of sophisticated CFD methods will continue to yield incremental improvements. The most significant parameter impacting efficiency is turbine inlet temperature, and further increases are dependent on materials and blade cooling technologies. Continuing advancements in the aforementioned areas will, of course, lead to, improved performance, however, gains of say 5 to 10 percentage points in efficiency can only be realized in the near-term by the use of more complex thermodynamic cycles.

Several avenues of development will be pursued towards improving gas turbine efficiency, and some of these will be based on the increasing use of heat exchangers, and this topic has been addressed previously (McDonald, 1989, 1994). It is recognized that exhaust heat recovery exchangers could be considered for a wide range of gas turbine applications (McDonald and Wilson, 1996), and this is illustrated on Fig.1, however it is also recognized that their utilization is very application and user dependent. What this really means is that recuperators will be used initially in large numbers only where they are mandatory to achieve performance goals, with the foremost example of this being the microturbine field, and this will be discussed in a following section.The successful utilization of microturbines for power generation, will lead to the acceptance of recuperators for larger industrial gas turbines.

Todate the only recuperated gas turbine to be produced in large quantities (ie. over 15,000) is the AGT-1500 engine for the U.S. Army M1 main battle tank. This engine utilizes an annular primary surface recuperator (Jen, 1987, Kadambi, 1992). This is an application where the recuperator plays an important role in achieving a flat specific fuel consumption (SFC) curve, since a large percentage of operating time is spent at low power levels. This is an example of a niche for recuperator utilization, and others will be discussed in following sections. While the author feels that intercooling will also play an important role in future engines, the primary focus in this paper is on the utilization of fixed boundary recuperators for power generation gas turbines.

3.RECUPERATOR STATE- OF- THE- ART

This section will be kept brief since the author has addressed this topic in two previous publications (McDonald, 1990, 1995a). Over the last half century recuperators have evolved from large and bulky units with poor reliability to compact and light weight heat exchangers today with proven performance and structural integrity. A convenient way of portraying this evolution is shown on Fig.2.

It is beyond the scope of this paper to discuss in detail what recuperators are available today, but they can be summarized in the following three categories. For industrial applications Solar Turbines has developed a compact and light weight primary surface recuperator that has packaging flexibility, and has been fabricated and deployed in a rectangular geometry (Parsons, 1985), and annular configurations (Ward and Holman, 1992).

Plate-fin recuperators have been fabricated and deployed for many years by Allied Signal for a variety of applications, particularly for industrial gas turbines (Kretzinger, 1985).

Tubular recuperators have also been developed embodying compact enhanced profile tube surface geometries. These units are characterized by their light weight and high pressure capability and are viewed as being well suited for future aircraft propulsion gas turbines (Pellischek, 1992).

The potential user has a choice of the aforementioned recuperator types, the selection much depending on the particular application. Todays' recuperators have demonstrated the performance and structural integrity needed for their deployment over a wide range of applications. However, there is still one area that remains to be addressed, and that is means to reduce heat exchanger cost. Since recuperators have not been fabricated in significant quantities, further work is necessary to establish concepts that are amenable to fabrication using high volume manufacturung methods, like automobile radiators for example. Reduction of recuperator cost for the microturbine class of prime-mover will be particularly important because of the very competitive nature of this power generation market, and this is discussed below.

4. RECUPERATED MICROTURBINES

4.1 Near-Term Deployment

With major changes in the electrical generating industry there is a potentially large market for small generator sets. A small gas turbine can meet the total energy needs (eg. electrical power, heating and cooling) for a variety of complexes including hospitals, supermarkets, schools, factories, office buildings and apartment houses. The advantages of the gas turbine prime-mover over existing Diesel engine generator sets include smaller size and weight, multi-fuel capability, lower emissions, lower noise level, and reduced maintenance. There are about a dozen companies with microturbine generator sets under development towards the goal of penetrating the commercial marketplace, starting around the year 2000.

4.2 Representative Microturbine Features

While different engine concepts are being developed, the configuration shown on Fig.3, and discussed previously (Rodgers,1993), is rather convenient for highlighting the major features. To meet demanding cost goals the engine configuration is kept as simple as possible, and could include the following, 1) single-stage radial compressor, 2) single-stage radial inflow turbine, 3) high speed rotor supported on air bearings, 4) direct-drive high speed air-cooled generator, 5) multifuel combustor (conventional or catalytic type), 6) a simple control system, and 7) a compact high effectiveness recuperator.

To minimize the size of the overall turbogenerator installation the concept shown on Fig.3 embodies a wrap-around annular recuperator that is integrated with the turbomachinery. The advantages of this arrangement include the following, 1) good aerodynamic gas flow paths resulting in low pressure losses, 2) very compact assembly, 3) lower acoustic signature, 4) built in rotor burst shield, 5) eliminates the need for external ducts and thermal expansion devices, and 6) minimizes the amount of external insulation needed. An example of such an engine will be mentioned in a later section.

There is considerable flexibility in packaging of the turbogenerator, and engines with the recuperator installed behind the rotating machiery (O'Brien, 1998) can also meet users' needs.

4.3.State-of-The-Art Performance.

Large gas turbines have the advantage of both economy of performance and scale. The reverse is true for very small gas turbines. Compared with axial flow machines, small engines with their radial flow compressors and turbines have significantly lower aerodynamic efficiencies. This is a result of smaller blade heights, Reynolds number effects, tip clearance effects, manufacturing tolerances , and surface finish, all of which adversely impact efficiency. In addition, the geometries associated with radial turbines make blade cooling very difficult, and thus advances in turbine inlet temperature are solely dependent on materials technology.

For simple cycle microturbines, it is difficult to achieve a thermal efficiency much in excess of 20 percent (Rodgers, 1997). While a recuperator may be a users' option for larger industrial gas turbines, it is mandatory for microturbines to achieve efficiencies of 30 percent and higher (McDonald, 1996).

A convenient and simple way of portraying the effect that two of the major cycle parameters, namely turbine inlet temperature and recuperator effectiveness, have on thermal efficiency of low pressure ratio microturbines, based on radial flow turbomachinery, is shown on Fig.4. Regime Number 1 is representative of first generation, state-of-the-art operating recuperated microturbines, and shows an efficiency of around 30 percent. An excellent example of an operating microturbine embodying proven technology is the 30Kw Capstone compact turbogenerator (Craig,1997), and this unit is shown on Fig.5. This engine has a stainless steel wrap-around annular primary surface recuperator.

Projected evolutionary advancements in microturbine performance are discussed below.

4.4. Microturbine Performance Evolution.

Assuming only modest gains in compressor and turbine efficiencies are made in the next decade, the technology advancement trend line on Fig.4 is based on increasing the turbine inlet temperature and the development of advanced recuperators. It is postulated that a thermal efficiency of 40 percent (Regime 3) is possible with an all metallic engine.To realize an efficiency higher than this value will require the use of ceramics in the combustor, turbine and recuperator.

In November 1997 the President's Committee of Advisors on Science and Technology suggested that R&D be undertaken to achieve a microturbine efficiency goal of 50 percent by the year 2010 (R&D Magazine, 1998).In looking at the data on Fig.4, it can be seen that this represents a challenge, and perhaps an upper value of 45 percent would be more realistic. To realize 50 percent, and even higher, will likely come from the eventual coupling of microturbines with high temperature fuel cells (Moore, 1997).

At this point it is germane to briefly discuss the impact of increasing the value of recuperator effectiveness. An effectiveness of 0.95 for a fixed boundary recuperator in an open cycle gas turbine is essentially unheard of, and such a value is usually associated with a rotary regenerator. If the heat exchanger mass flow rates were kept constant, the impact of increasing the effectiveness from say 0.87 to 0.95 would result in an increase in recuperator size by a factor of about 2.8. However, in moving up along the technology trend line (on Fig. 4) from Regime 1 to 5, this is not the case.

In advancing up the trend line from Regime 1 to 5 the specific power increases significantly as shown on Fig.6. Simply stated, if for advanced variants of the microturbine the power output was kept constant, the airflow through the engine would be reduced, this resulting in a smaller turbogenerator package. While the recuperator effectiveness is increased (to yield higher engine thermal efficiency), the size of the recuperator for the revised thermal duty is also affected by the reduction in air and gas flows, and this is shown on the upper part of Fig.6. Considering Regime 1 as the base case, the relative size of the recuperator actually has a minimum value as the specific power is increased. Such a curve shape was not envisaged at the onset of the analysis, and is, of course, uniquely related to the technology trend line shown on Fig.4. The relative recuperator size curve is clearly influenced by heat exchanger evolutionary changes, and this is illustrated by curves A and B. From the above, one can conclude that a high value of recuperator effectiveness is not out of order when considering microturbine performance evolution.

4.5. Microturbines for Hybrid Electric Vehicles

The development of automotive gas turbines has been underway since the early 1950s, but they have not been able to match the continuously improving fuel economy and cost of spark and compression ignition engines. Today, a direct injection Diesel automotive engine with a modern variable geometry turbocharger (Birch, 1996) is in service with an efficiency of 42.9

percent (SFC of 196 g/kw.hr.). In coming decades it is likely that the performance of advanced automotive Diesel engines will continue to increase (Pischinger,1998), this giving the gas turbine a moving target, as has been the case in the last few decades.

While an all metallic microturbine could likely be developed to give an efficiency of 40 percent (see Figs.4 and 6), the high cost of the superalloys in the hot end components would exclude it from the automotive marketplace. To match the performance of the aforementioned existing Diesel engine a microturbine for a hybrid electric car would have to extensively utilize ceramic components.

The gas turbine has the attributes of multifuel capability, low emissions, and a compact and light weight package, but in the last two years or so it seems to have lost ground as the premium prime-mover for future hybrid vehicles. In the near-term, small Diesel engines are viewed as the most attractive option for small hybrid cars. For the long-term, fuel cells are currently receiving intense focus, particularly efforts to reduce their cost (Brown, 1998, Gottschalk, 1998).

From Figs. 4 and 6 it is clear, that for the microturbine to find acceptance in hybrid electric vehicles, the level of performance for it to be competitive can only be realized by the utilization of ceramic components, including the combustor, turbine, scrolls, and heat exchanger (Rodgers and McDonald, 1997, 1998).

It is recognized that ceramic technology is still in its infancy, but the ever increasing technology base should facilitate the deployment of a ceramic turbogenerator in the first decade of the 21st century. Work in progress towards this goal includes the development of small gas turbines with ceramic rotary regenerators (Bernyi, 1998, Nishiyama 1996), and a fixed boundary ceramic recuperator (Gabrielsson, 1998). Also new ideas are being investigated to establish economically viable automotive gas turbines (Wilson, 1997).

An encouraging aspect of the projected emergence of a family of microturbines for power generation is that it could pave the way for future automotive variants when the necessary ceramics technology matures.

5. ADVANCED INDUSTRIAL GAS TURBINES

In the last few decades, very few industrial gas turbines had been designed from the onset to incorporate a recuperator. The engines that have seen service were basically simple cycle machines, modified later to improve performance by adding a recuperator. The number of such engines was modest compared with simple cycle units, and they were essentially non-optimum from two standpoints, namely, 1) cycle parameters, particularly the compressor pressure ratio, and 2) bulky and heavy package with an "add-on" recuperator.The efficiencies of these machines were generally in the low thirties (Regime 1 on Fig.7).

From the standpoints of fuel conservation and environmental concerns, there is a clear need for more efficient industrial gas turbines, with reduced emissions for service after the year 2000. Towards this goal, development work on advanced industrial gas turbines has been underway by industry for several years. While the actual power range of these new machines will depend on market forces, it does not seem unreasonable to assume that industrial gas turbines in the range of say 3 to 15Mw will benefit from the utilization of recuperation.

The first generation of these small to medium size advanced turbine systems, with axial flow turbomachinery, will operate with a thermal efficiency of over 40 percent. This new class of gas turbine is represented by Regime 2 on Fig.7.

An excellent example of a new class of recuperated advanced gas turbine systems is the Solar Turbines Mercury 50 (Diesel & Gas Turbine Worldwide, 1998, Modern Power Systems, 1998, Farmer,1998), and this is shown on Fig.8. An interesting aspect of this 4.2 Mw gas turbine, with an efficiency of over 40 percent, is that the overall generator set was designed from the onset for recuperation. This unit is based on an optimum selection of parameters, a unique gas flow path to accommodate the proven Solar primary surface recuperator, and minimization in the length of hot gas ducts, to give an attractive and compact overall package.

With technology advancements in coming decades including metallurgical developments, blade cooling, the eventual use of ceramics, and perhaps intercooling, the new class of advanced industrial gas turbines has the potential for considerable performance growth. Unlike the aforementioned and very competitive microturbine market, the economics of these larger industrial gas turbines for power generation and mechanical drives, will permit the utilization of recuperators fabricated from high cost superalloys to eventually yield efficiencies of about 50 percent.

6. OTHER EMERGING APPLICATIONS

6.1.Marine Propulsion

For applications such as marine propulsion, where volume constraints are placed on the engine and it's fuel storage space, high efficiency is paramount. Over the last 40 years recuperated gas turbines have not found acceptance for marine gas turbines, but advancements in heat exchanger technology have removed earlier impediments (McDonald, 1995b).To take advantage of aeroderivative gas turbine technology, intercooling of these high pressure ratio machines is mandatory to utilize a recuperated cycle. Representative parameters for a large intercooled and recuperated (ICR) gas turbine are shown of Fig.9. The major advantage of the ICR engine for marine propulsion is that it exhibits a very flat SFC curve.This is particularly important for naval vessels where a considerable part of the service life is spent at part power conditions.

Work is well underway on the development of an ICR propulsion engine (WR-21), and this has been discussed previously (Bowen,1997, Weiler, 1997). While designed to meet the needs of future naval vessels, it could also find acceptance for merchant vessels, cruise ships, or fast ferries (Ashley, 1998). Whether it will find a niche in the power generation market is debateable, and in fact a simpler aeroderivative variant may be more cost-effective as discussed below.

6.2. ICAD Gas Turbine for Power Generation

While emphasis in this paper is on the utilization of recuperated gas turbines for power generation, it is germane to mention that such a cycle may not be the most cost-effective when considering large aeroderivative gas turbines. For marine propulsion the most attractive feature of the ICR is its high efficiency at part-power, but this attribute is not a major requirement for utility power generation.

With a simple cycle aeroderivative engine in the 50Mw class having demonstrated an efficiency of around 42 percent, interest has been expressed in how such an engine might evolve for utility power generation (Davidson, 1996). Unlike the typical heavy duty single shaft industrial gas turbine, the multi-spool construction of aeroderivatives facilitates the use of a conventional intercooler. A curve array showing the performance of large intercooled aeroderivative (ICAD) engines is given on Fig.10. The advantages of intercooling include, large gain in specific power, a modest gain in efficiency (also facilitates recuperation at higher pressure ratios), and a source of lower temperature compressor discharge air for turbine cooling. These mean that for a given frame size, the power output can be considerably increased. Also the turbine inlet temperature can be increased by a few hundred degrees based on the utilization of the lower temperature cooling air. The portrayal of data on Fig.10 shows that a state-of-the-art 50Mw aeroderivative gas turbine has the potential for an output of about 100Mw when intercooled, with an attendant efficiency increase to 45 percent and even higher. Such an engine would likely be more cost-effective than an ICR variant for power generation. It is not unreasonable to assume that ICAD gas turbines will see service for utility power generation within the next decade.

6.3. Advanced Gas Turbine Cycles.

There are many advanced gas turbine cycles being investigated and researched, but since they are still in early stages of definition, they are really beyond the scope of this paper, which is focused on emerging applications. These include the many humid air turbine (HAT) variants, chemical recuperation, semi-closed cycles, the coupling of gas turbines with fuel cells, closed Brayton cycles for space power, and advanced compressed air storage systems. It is encouraging to the author that most of these future endeavors will embody recuperators in one form or another.

6.4. Aerospace Propulsion.

While not viewed as an emerging application, it seems germane to mention perhaps the ultimate use of recuperators, namely for aircraft propulsion turbines. In a decade or two, when all the simple cycle features (eg. compressor pressure ratio, turbine inlet temperature, bypass ratio, geared fans, multiple spools etc.) have been fully exploited, attention will likely be given to the use of more complex thermodynamic cycles. While initial focus may be on smaller turboshaft and turboprop engines, the ultimate application will be large intercooled and recuperated turbofan engines. It is of interest to note that tentative studies have been performed on this (Pellischek,1990), and a preliminary concept is shown on Fig.11.

7.RECUPERATOR TECHNOLOGY

7.1. Near-Term Development.

It is not the purpose of this paper to discuss in detail the different types of recuperators that are currently available. With proven performance characteristics and demonstrated structural integrity, there are basically two types of recuperators being utilized today, namely, 1) welded primary-surface units, and 2) furnace brazed plate-fin exchangers. Both of these types are characterized by an elemental type of construction that is not really amenable to a continuous and automated manufacturing process. For example, a representative recuperator currently being used in an operating very small gas turbine, embodies over 2000 individual parts that require sophisticated robotic forming, assembling, welding, and sub-element testing before the final matrix is assembled.

A major challenge for the heat exchanger industry is to establish a recuperator with a mininum number of parts that can be continuously formed, with a unit price goal not to exceed 1.5 times the material cost.

Eliminating the time-consuming brazing process would seem to be paramount. A spirally formed annular primary surface counterflow recuperator concept, embodying only five basic parts (plus the inner and outer cylindrical shells), and amenable to automated production for a typical microturbine, is in an early stage of design definition (McDonald,1999).

Reducing the material cost also represents a challenge to designers. Since in a counterflow heat exchanger, the temperature gradient is in the axial direction, efforts should be expended to establish a bimetallic approach, where the high cost alloys are utilized only at the hot end. This approach is perhaps analogous to the fabrication of hack saw blades, where only a thin strip of high quality steel for the teeth section is used. The bulk of the blade being of a lower cost material, with the bonding of the two metallic strips being done by a continuous welding operation.

The above discussion is essentially a preamble to the effect that the near-term development of metallic recuperators, particularly for the many foreseen microturbine applications, really needs to be focused on establishing lower cost units.

7.2. Ceramic Recuperator Development

The various curve arrays in this paper have shown that to fully exploit the performance potential of small engines, an increase in turbine inlet temperature is necessary, with of course, an attendant increase in recuperator hot gas inlet temperature. However, a point is reached where a metallic heat exchanger is no longer viable.

As the technology matures, the use of a ceramic recuperator for microturbine generator sets is viewed as an evolutionary process. If the very small gas turbine is to find acceptance in the hybrid electric vehicle market, a ceramic recuperator is viewed as being mandatory (McDonald, 1997). In support of the European AGATA vehicular gas turbine program, a ceramic recuperator is under development (Ferrato and Thonon, 1997), and a view of this compact plate-fin counterflow ceramic module is shown on Fig.12.

8. SUMMARY

Metallic recuperators are available today that have the performance, structural integrity, reliability, and package envelopes to meet users' needs.

A large market is foreseen for microturbines (de

Biasi, 1998, Scott, 1997), and for this class of machine a metallic recuperator is mandatory to achieve a thermal efficiency of 30 percent and higher. It is this market that will likely see the emergence of recuperated gas turbines in large quantities for electrical power generation for the first time. The demonstration of high reliability from these turbogenerators will give confidence to other potential users of different types of recuperated gas turbines.

After the year 2000, advanced industrial gas turbines in the 3-15 Mw class will be introduced, and in many of these, recuperators will be used to give efficiencies in the low to mid forties. In a larger power class, intercooled and recuperated gas turbines will be introduced for marine propulsion, although it is unlikely that they will be produced in large quantities.

It is thus fair to say, that in the first decade of the 21st century there will be an emergence of recuperated gas turbines for a wide range of applications to meet a variety of users' needs.

The current generation of metallic recuperators, while they meet performance and reliability goals, have a high unit cost, this perhaps being a reflection of their construction type, and the fact that so far they have been produced in only small quantities. Near-term development activities need to be focused on establishing concepts and manufacturing methods to reduce recuperator cost.

It is recognized that ceramic recuperator technology know-how is still in its infancy, but a developing technology base exists, and the realization of a ceramic recuperator that meets the required reliability for gas turbine service in the first decade of the 21st century is really just a matter of resolve. The utilization of ceramic recuperators is the key to realizing the full performance potential of microturbines and small to medium size gas turbines.

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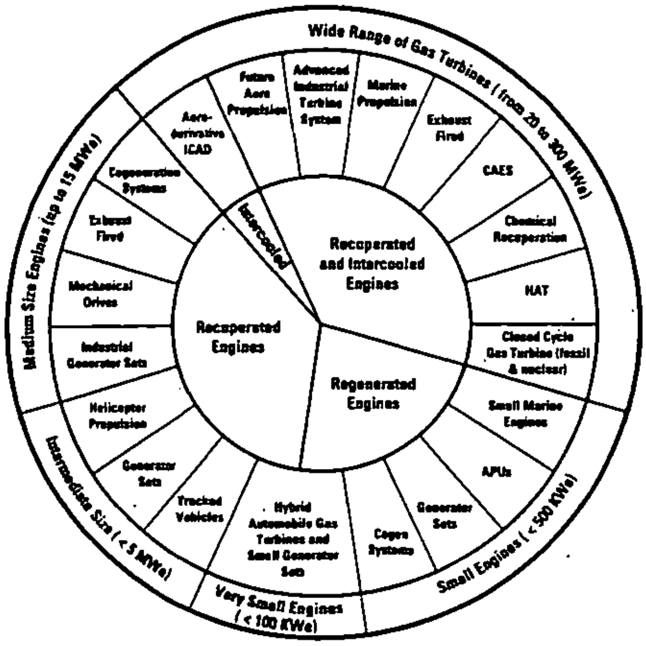

Fig.1 Projected Applications For Recuperated Gas Turbines

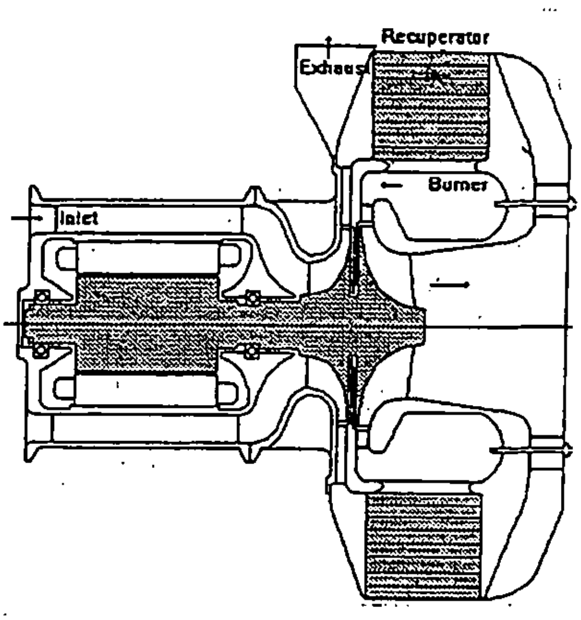

Fig.3 Recuperated Microturbine Concept (Courtesy C.Rodgers, ITC)

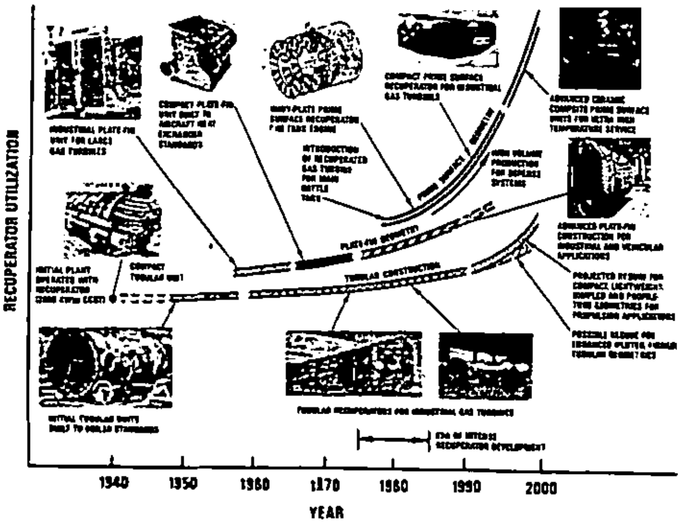

Fig.2 Gas Turbine Recuperator Evolution

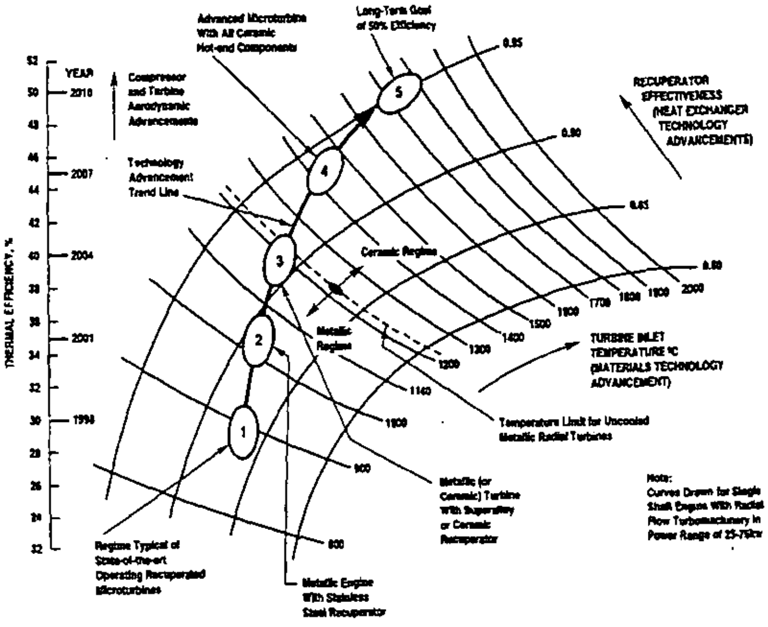

Fig.4 Projected Recuperated Microturbine Performance Potential

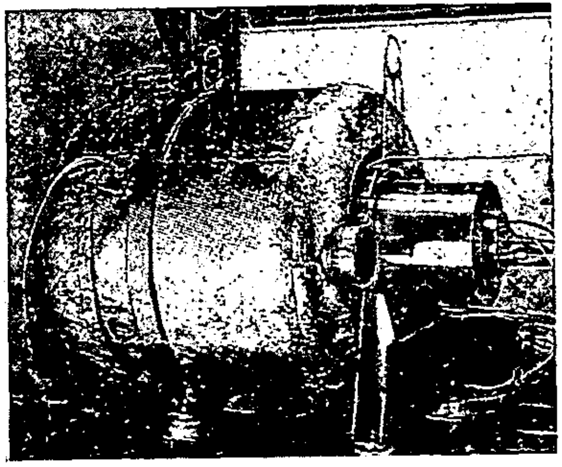

Fig.5 Compact Capstone 30kw Recuperated Turbogenerator (Courtesy Capstone Turbine Corporation)

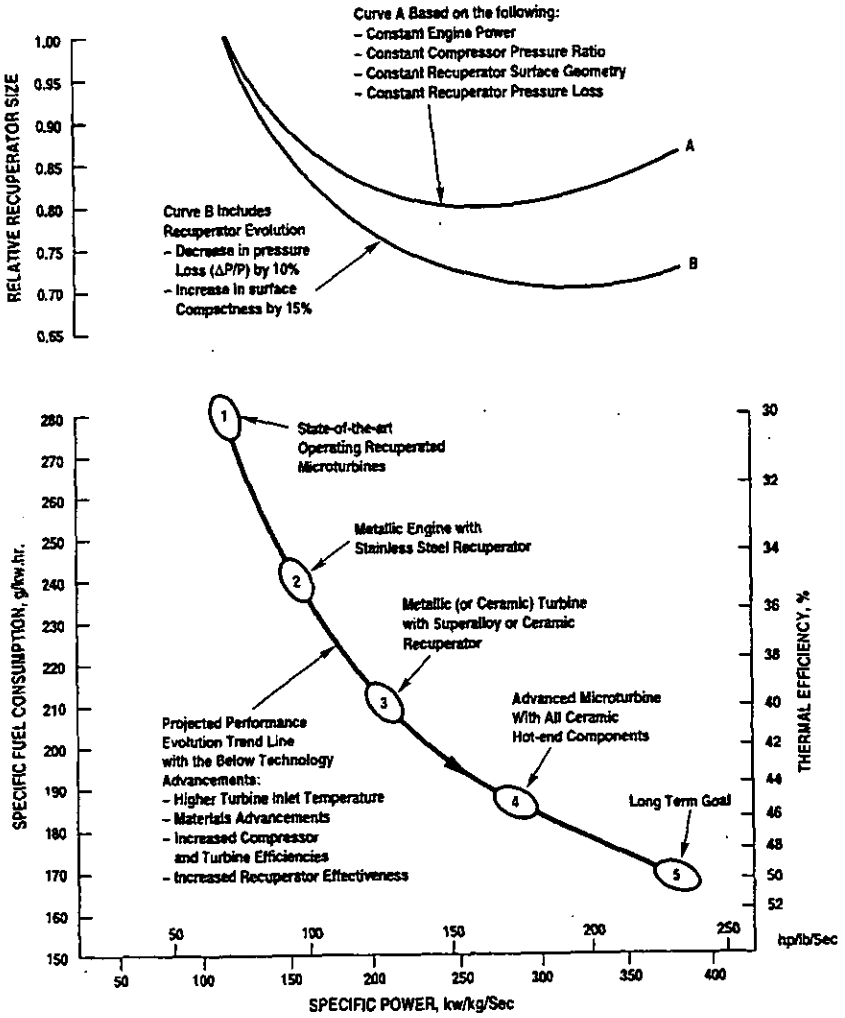

Fig.6 Performance Evolution of Recuperated Microturbines

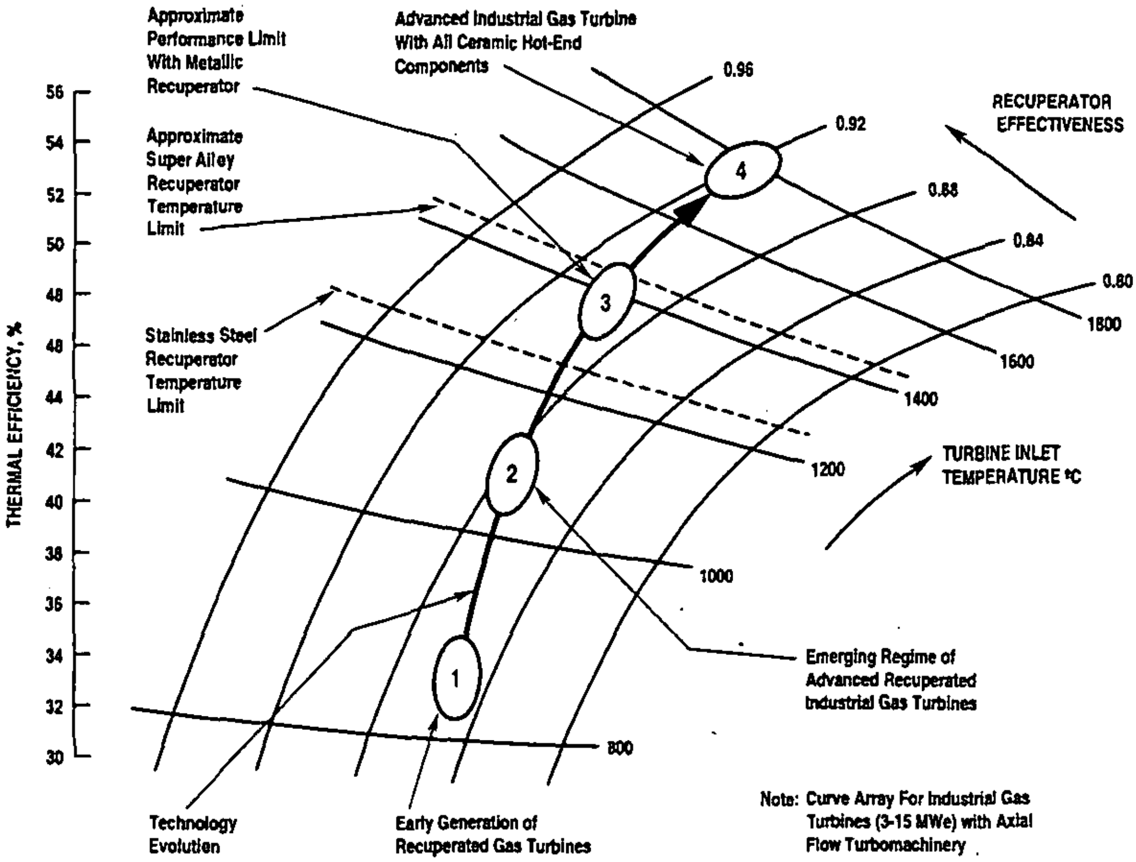

Fig.7 Projected Performance of Advanced Recuperated Industrial Gas Turbines

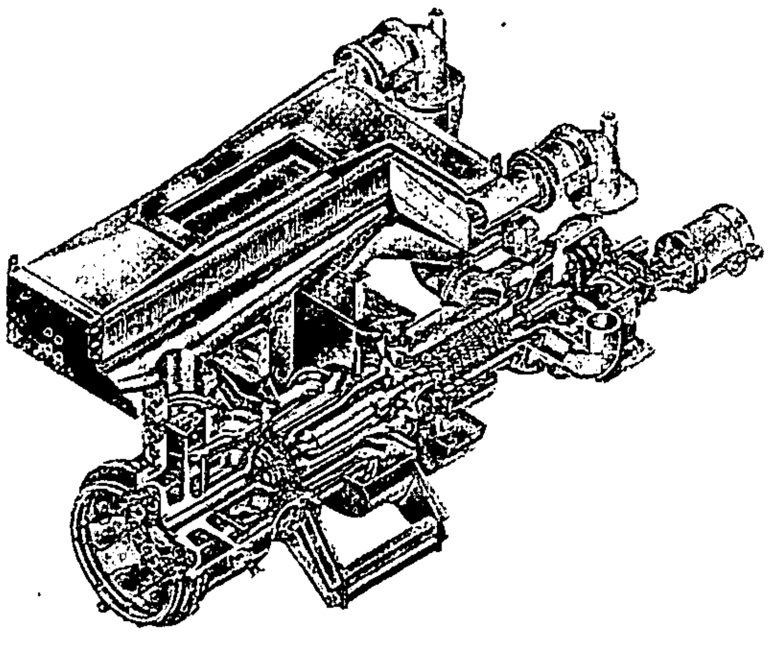

Fig.8 Solar Mercury 50 Recuperated Industrial Gas Turbine (Courtesy Solar Turbines Inc.)

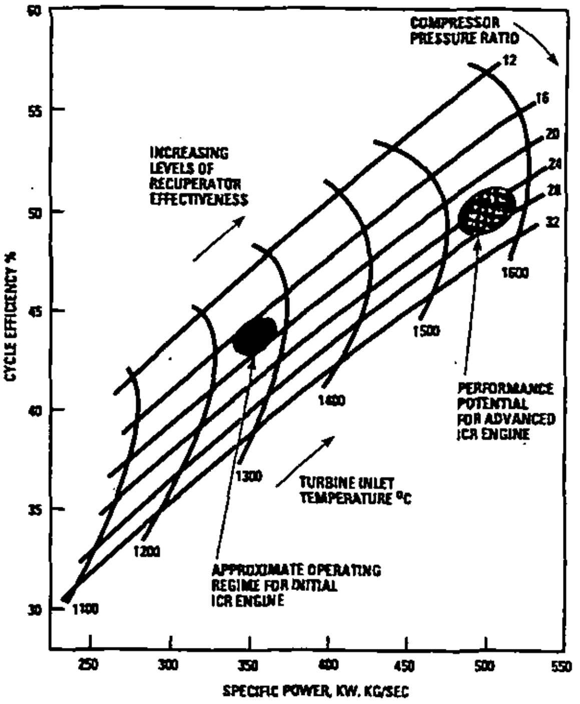

Fig.9 Performance Potential of Large ICR Gas Turbine

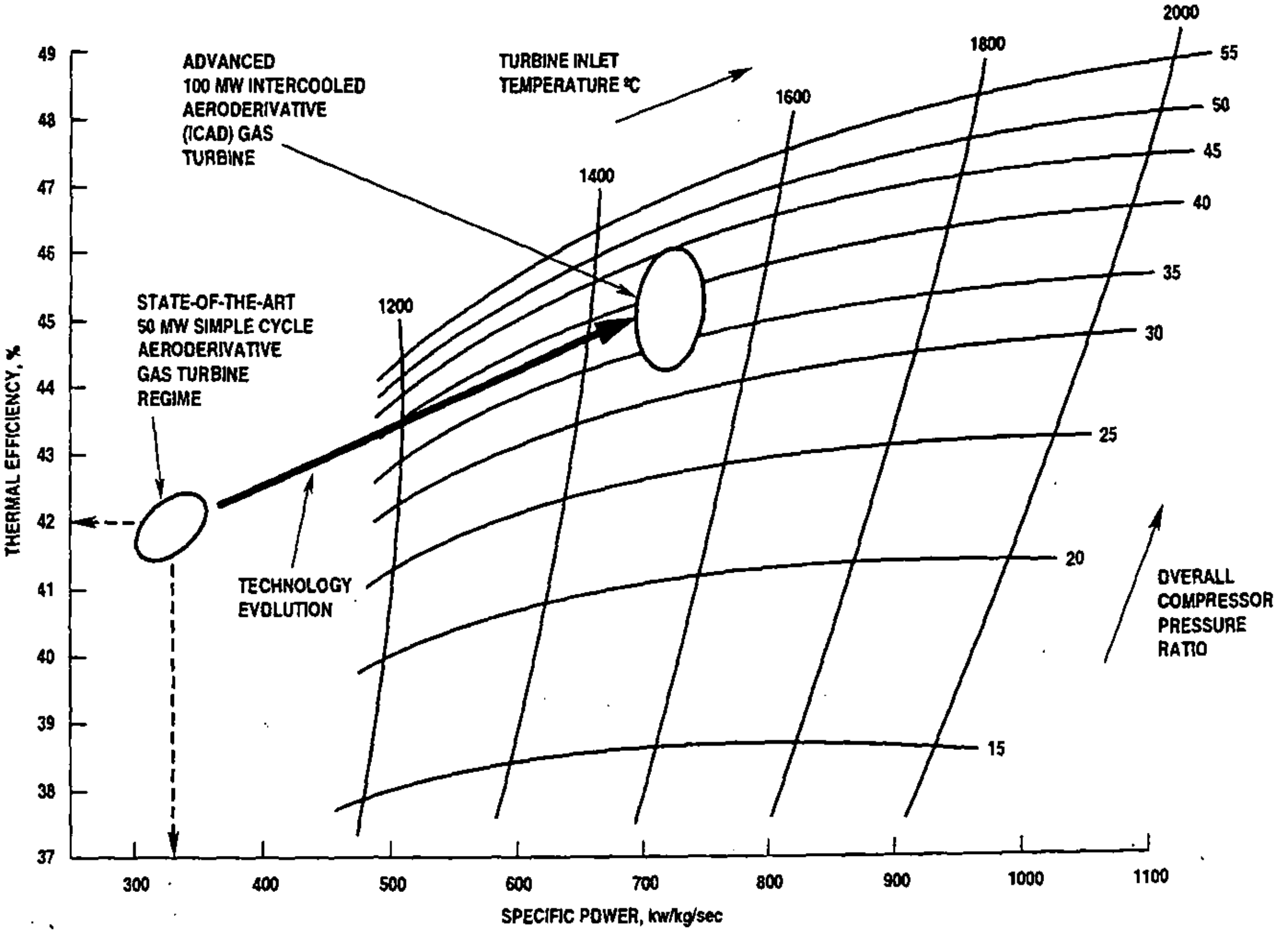

Fig.10 Performance Potential of ICAD Gas Turbine

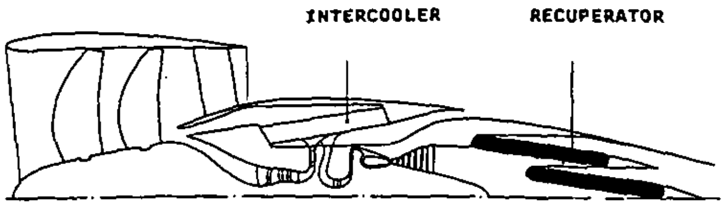

Fig.11 Intercooled and Recuperated
Aircraft Engine Concept
(Courtesy MTU GmbH)

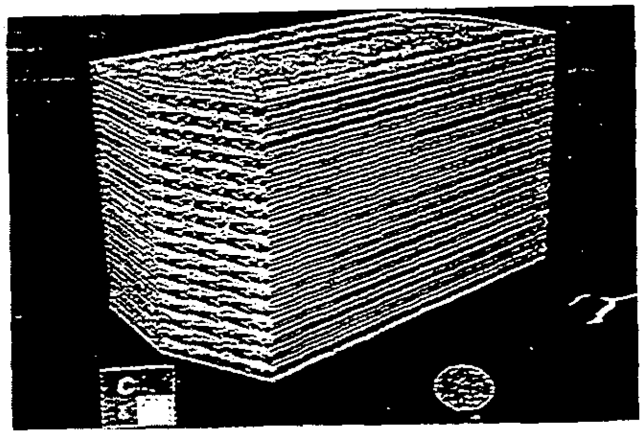

Fig.12 Compact Plate-Fin Ceramic
Recuperator Module
(Courtesy Ceramiques &
Composites S.A.)