Stirling Engines for Gas Fired Micro-Cogen and Cooling

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This article describes the design and performance of free-piston Stirling engine-alternators particularly suited for use as natural gas fired micro-cogen and cooling devices. Stirling based cogen systems offer significant potential advantages over internal combustion engines in efficiency, life, noise and emissions.

The ability of Stirling machines to maintain higher efficiencies at lower power levels than internal combustion engines significantly expands the potential market for micro-cogen. System cost reduction and electric prices higher than the U.S. national average will have a far greater effect on commercial success than any further increase in Stirling engine efficiency. There exist niche markets where Stirling based cogen systems are competitive.

Machines of this design are being considered for production in the near future as gas-fired units for combined heat and power in sufficiently large quantities to assure competitive prices for the final unit.

HISTORY OF STIRLING MACHINES

The crank-driven Stirling engine has a long history of development, first as an air charged, atmospheric pressure pumping engine in the 1800's, and later, after World War II, as a highly refined candidate for automotive applications. In this role it was projected to be efficient, quiet and low in emissions.

However, exceptionally challenging design problems were encountered, including power modulation, containment of high pressure light gas, isolation of lubricants, and cost and complexity of heater head designs able to accept the required high operating temperature and high heat fluxes. As a result of these and other barriers, especially the competition from cheap and ever-improving IC engines, the crank Stirling has never reached commercial production.

The free-piston machine has evolved as a solution to the problems presented by the crank Stirling. Free-piston machines with an attached linear alternator can be hermetically sealed so as to contain the working gas (helium or hydrogen) for extended periods and they require no lubricant other than the working gas. Their power can be varied rapidly and efficiently by displacer amplitude and phase changes relative to the piston. Their high mechanical efficiency allows them to achieve competitive power and thermal efficiency at modest heater head temperatures consistent with relatively inexpensive materials and geometries.

While free-piston machines are at present restricted in power output to several tens of kilowatts by the characteristics of linear alternators, the free-piston/linear alternator is quite well suited for the micro-cogeneration applications discussed here. These designs retain high efficiency and other desirable features over power ranges from a few tens of watts to several kilowatts, the desired power for micro-cogen.

These desirable features of the free-piston machine have drawn attention to it in several potential applications, including heat driven refrigeration, in which a free-piston engine directly drives a free-piston Stirling heat pump (the so-called duplex arrangement), and derivatives such as the free-piston refrigerant or gas compressor, in which the alternator acts as a motor to drive the piston to accomplish its task without cranks or lubricants.

DESCRIPTION OF FREE-PISTON ENGINES

Figure 1 shows a typical layout of a free-piston Stirling engine. The thermodynamic cycle used is an harmonic oscillation approximation to the ideal Stirling cycle of two isotherms connected by two constant volume temperature changes. The piston oscillation causes the compression-expansion and the displacer serves to move the working gas between hot and cold heat exchangers to accomplish the heat flows required for the cycle.

The piston and displacer are tuned as mechanical springmass-damper resonators so as to have the correct phase relation between them to accomplish the desired gas cycle. This method eliminates the crank mechanism and its associated lubrication and side forces. The engine operates at an approximately constant frequency regardless of loading or piston amplitude, which will permit it to be directly attached to the grid without intermediaries.

The piston power is delivered directly to the magnets of a permanent magnet alternator to produce alternating current power at any desired voltage. The components of a typical linear alternator, the stationary inner and outer iron and the moving permanent magnet ring, are shown in Figure 2.

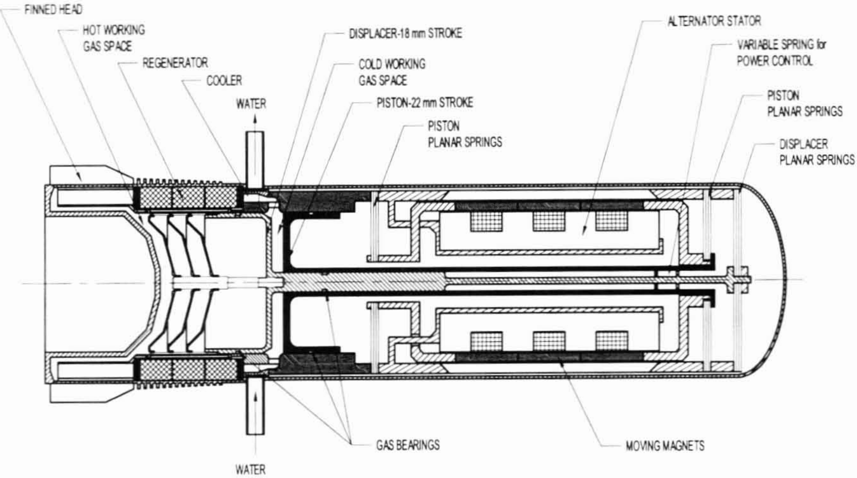

Figure 1. Layout of a free-piston Stirling engine. In this case, the linear alternator has three sets of moving magnets attached to the piston. The displacer and piston resonate with planar springs, and are suspended by non-contact gas bearings. The entire unit is hermetically sealed, with helium as both the working gas to implement the Stirling cycle and to charge the gas bearings.

The life of free-piston Stirling machines has usually been limited by the contact bearings used to support the piston and displacer and the ring seals that separate the different gas volumes within the machines. Recent advances have removed both of these wear limited components [1]. Both piston and displacer float on gas bearings in their cylinders and are resonated by mechanical springs which are arranged to eliminate side loads on the bearings. These planar springs (flat plates with spiral slits) also serve to center and support the large radial loads of the permanent magnets, acting in effect as friction-free oscillating bearings.

The combination of gas bearings to allow wear-free close fits on the pistons and the use of mechanical springs to give both resonant frequency and axial positioning is uniquely advantageous in that it confers high mechanical efficiency and the potential for very long life. In addition, this combination is inexpensive and compact. The sealing function is also met by the close fits of the gas bearings, gas tight sealing is not needed, and the fits and tolerances can be met by standard machining techniques.

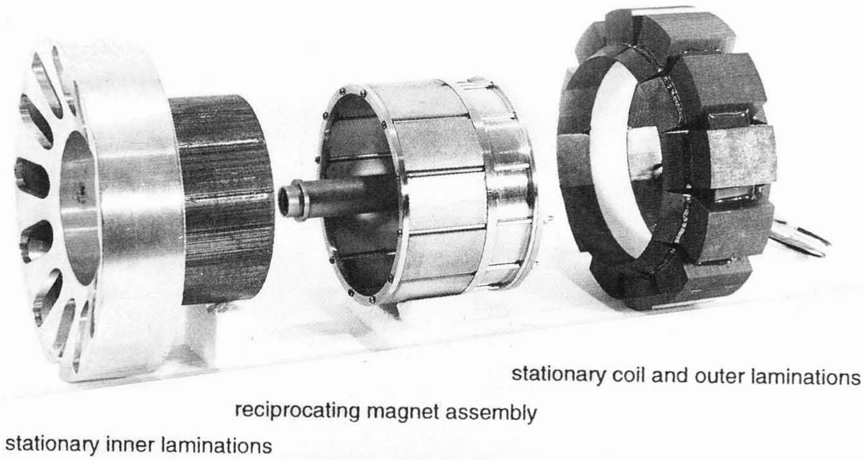

Figure 2. Exploded view of a single window linear motor/alternator. The reciprocating magnet assembly is part of the piston in all types of free-piston machines, including Stirling engines, Stirling coolers, and linear compressors. This particular example is from a linear compressor and is rated at 200 W.

It should be noted that the function of precise positioning of the oscillating bearings and seals is done by the gas bearings, and the separate function of axial springing and rough location is performed by the planar springs. Figure 3 shows a range of planar springs that have been used in free-piston machines. These planar springs are not called upon to provide precise radial centering and, as a result of this limited role, will be inexpensive to manufacture.

In contrast, flexures in other free-piston Stirling designs are required to perform both springing and highly accurate radial centering of the pistons to avoid wear and leakage and would incur greater manufacturing costs. The arrangement of the gas bearings on the piston and displacer and the planar spring supports are shown in hardware in Figure 4.

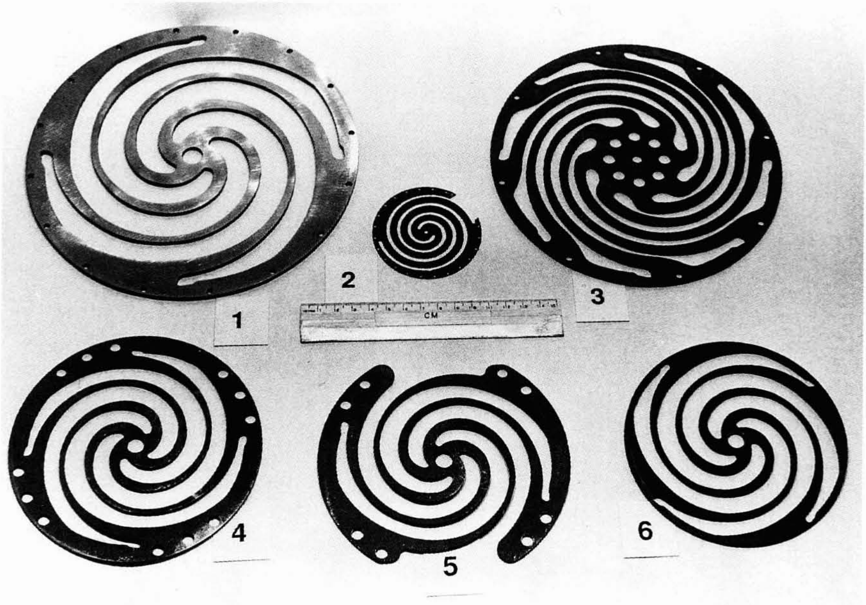

Figure 3. Various examples of planar springs, used in all types of free-piston machines. They are well suited for cost-effective manufacturing by stamping sheet metal.

FEATURES OF THE FREE-PISTON DESIGN

Starting

The engine described above is exceptionally easy to start. Since it is a highly efficient linear oscillator, not a rotator, only a very slight axial impulse is sufficient to start the build-up of oscillations in the presence of a temperature difference between heater and cooler. This starting impulse may be a brief low voltage pulse to the linear alternator.

Power Control

In the past, Stirling engines have earned a reputation for slow, complex and inefficient power variation. This oft-cited criticism has been answered in the free-piston engines with a power control based on a variable stiffness spring between piston and displacer. This spring couples the displacer to the piston to greater or lesser degree

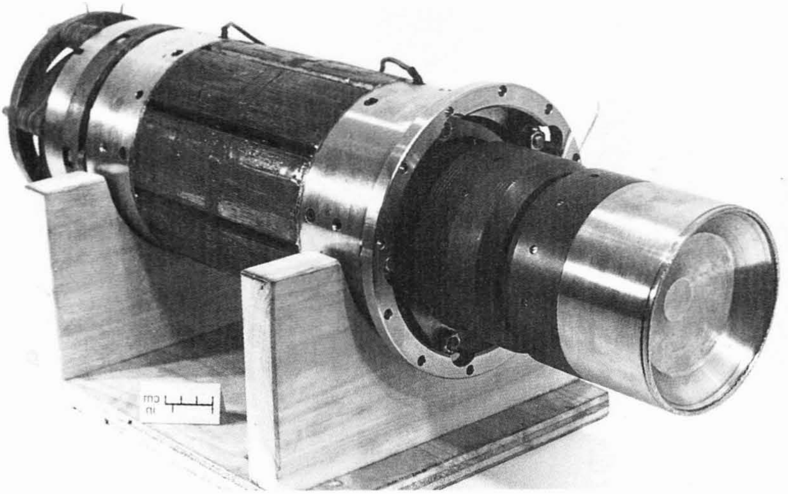

Figure 4. Prototype 2.5 kW free-piston Stirling engine with integral linear alternator. During a series of tests and modifications, this engine/alternator achieved 28% efficiency in some tests. Note the arrangement of gas bearings on the piston (A) and displacer (B), as well as the planer springs (C).

in proportion to its stiffness. When the spring is at maximum stiffness the displacer is essentially locked to the piston and little or no power is generated.

But if the relative spring stiffness is reduced to zero, the engine power can rise to maximum in a very few engine cycles, less than 0.1 seconds in a 60 Hz engine. Such a variable stiffness spring can be implemented in a number of ways [2,3], for example, by a gas spring with a sleeve valve varying the porting out of the spring with its rotation. This spool valve is coupled to desired control parameters such as voltage and/or piston amplitude to allow fully automatic and rapid response to imposed load.

The free-piston engine with this type of power control can operate, for example, as a constant voltage generator with fast response and high efficiency over a wide range of power. Although a non-dissipative relative spring is thermodynamically most efficient, any combination of spring and damper between the piston and displacer can have the same effect on power control.

Heater and Burner

The heater head is a cylindrical heat exchanger with external and internal fins for heat transfer enhancement. The external fins are stainless steel integral with the pressure wall, and the internal fins are folded copper sheet brazed to the inside diameter of the pressure wall. This produces an inexpensive and highly effective heat transfer surface. This configuration also allows good conformity of the heater flow passage with the foil type (annular gap) regenerator so that there is no flow constriction and good flow distribution at their interface. This heat exchanger arrangement removes the large number of critical brazes or welds and the expensive machining required for more typical tube bundle exchangers.

The burner has the duty to keep the heater head temperature at a constant temperature. A typical burner includes an exhaust gas recuperator to assure high efficiency. The close coupling of the burner to the heater head assures short dwell time at high temperature and reduced emissions.

Cooling

The engine is cooled by a conventional water jacket, coolant pump and heat rejector with fan. Increasing water temperature reduces engine power and efficiency, but the system can still operate effectively with coolant temperatures near 100°C. The critical requirement is that the magnets in the alternator must be kept at temperatures below their point of irreversible loss of magnetism. The rejected heat is available for space heating, domestic hot water or other uses. The internal fins of the cooler are fabricated in the same way as those in the heater, as inexpensive folded copper fins, with no critical joints (Figure 5).

OPERATING FEATURES

The sum of the non-contact gas bearings, planar springs, and magnet suspension results in an exceptionally efficient, quiet and durable machine. Mechanical efficiency of over 95% is routinely measured, and electrical energy conversion efficiency is also usually over 92%, limited by the usual cost-efficiency compromises of electrical machinery design.

The most unique and distinctive feature of this machine is the potential very long life and low maintenance. This characteristic is

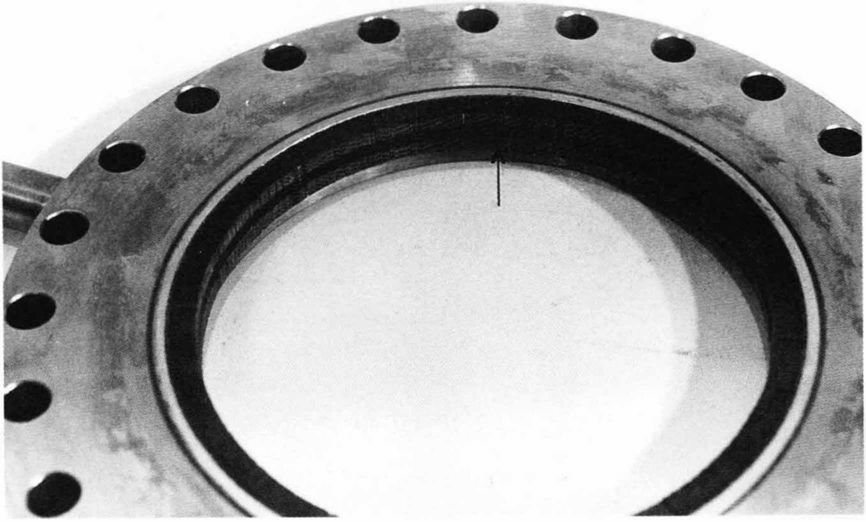

Figure 5. Internal folded copper fins (arrow) of a Stirling engine heat rejector.

derived from its non-contact operation and its hermetic sealing which both obviates and prevents any user maintenance or manipulation. Another attractive feature is very easy starting and operation as long as a source of heating and cooling is supplied.

FREE-PISTON STIRLING COOLING

Free-piston Stirling cooling can be implemented in one of two ways. Firstly, the basic technology, including linear alternator, gas bearings and planar springs, can also be implemented in an electrically driven linear refrigeration compressor [3] using conventional valves. If it is desired to power such a compressor using natural gas rather than electrically, then a free-piston Stirling engine can drive the compressor directly, with, for example, a magnetic coupling, without generating electric power [5] (Figure 6).

Alternatively, electrically driven free-piston Stirling coolers have been developed for domestic refrigeration and freezing temperatures [6] (Figure 7). As with linear compressors the cooler can be driven directly by a free-piston engine. However, in this case the intermediate magnetic coupling is not required since the cooler and engine share the common helium working fluid. Such devices are known as duplex machines.

FREE-PISTON STIRLING COGEN

Advantage of Free-Piston Stirling over Internal Combustion Engines

At power levels of less than 10 kW there have traditionally been no competitors to IC engines as the prime movers in cogen systems. However at these power levels IC engines have numerous limitations and become less feasible below 2 kW. This lack of an ideal power generator at low power levels is probably the main reason for the lack of success of micro-cogen for domestic applications.

Free-piston Stirling engine linear alternator combinations offer numerous advantages over IC engines at the microcogen power levels. They have higher efficiencies than IC engines and this efficiency remains essentially constant at different sizes. This is not true of IC

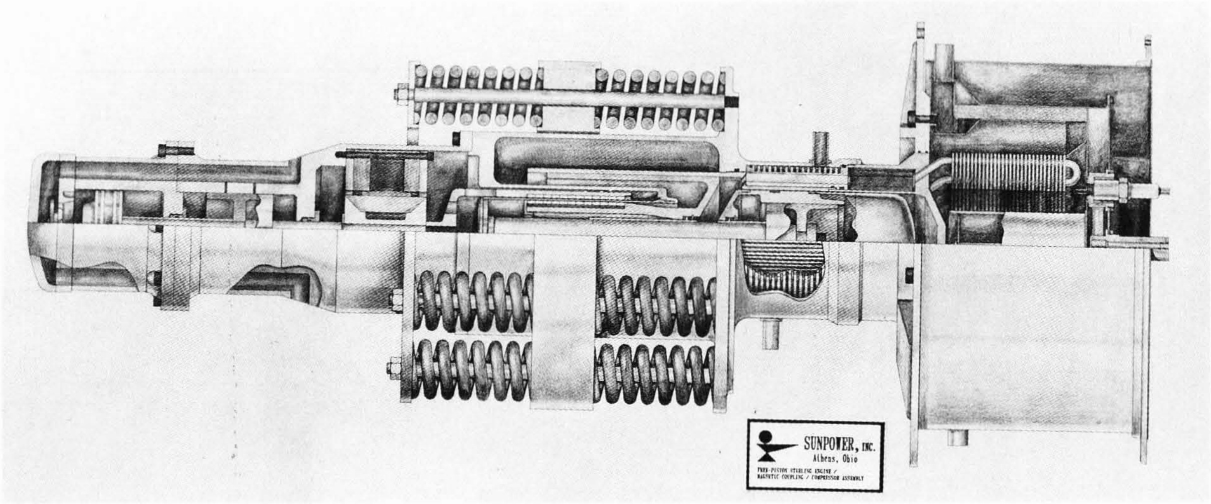

Figure 6. Gas-fired heat pump. In this prototype, the free-piston Stirling engine is magnetically coupled to the gas compressor.

Figure 7. Electrically driven free-piston Stirling cooler. Heat is accepted at one end (note the ball of ice that has formed), and rejected with the aid of a fan from the other. The integral linear motor drives the piston and implements the Stirling cycle. Like a free-piston Stirling engine, the piston and displacer float on gas bearings, are resonated with planar springs, and are hermetically sealed with the linear motor. Helium serves as the working gas and for operation of the gas bearings.

engines. For instance, there is no reason why a 500 W free-piston Stirling engine should not have the same efficiency as a 10 kW engine. Stirling engines also maintain their efficiency at part load, unlike IC engines.

The continuous combustion required by Stirling engines makes them produce fewer emissions and operate more quietly than IC engines. This quieter operation results in a less expensive product package, since soundproofing is not required. IC engines, even those designed for long life, require regular service (typically 2000-4000 hours) and their lives are ultimately limited by the contact operation of the moving parts.

On the other hand, free-piston Stirling engines are hermetically sealed and the moving components are supported on non-contact gas bearings. There are no parts requiring service within the engine and alternator, and lives of greater than 60,000 hours are projected; life will ultimately be limited by heater head creep. The burner does require service but no more than the typical home furnace.

Furthermore the fixed speed operation of free-piston Stirling engines, unlike IC engines, allows for simple grid synchronization. As long as the linear alternator is wound for the correct grid voltage, these machines can be directly coupled to the grid.

Potential Market for Stirling Cogen

A survey of residential single family homes in the United States [7] concluded that of the total of 54 million units only 7 million were appropriate for natural gas fired cogeneration, defined as having floor areas greater than 2000 square feet and situated in the north east and north central areas. Natural gas was not available in 20 million units and 4 million had too low a thermal demand.

However, 23 million units were rejected primarily because they had areas of less than 2000 square feet and there was not a sufficiently small and efficient electric generator available. These 23 million units are a potential market if Stirling based systems producing a few hundred Watts up to 2 kW are available. The total potential market for Stirling systems is therefore 30 million units while that for IC systems is 7 million units.

Other surveys [8] have also based their market potential on the limitations of IC engine systems (electric power levels greater than 5 kW). The use of Stirling systems significantly expands the potential market.

Payback of Stirling Based Systems

Figure 8 shows the variation in payback time of Stirling cogen systems with different engine/alternator efficiencies and different levels of engine reject heat recovery. The analysis uses 1995 average U.S. gas and electric prices, and assumes an 80% efficient burner with 50% of the burner waste heat recovered. Operation is for 4380 hours/year (12 hours/day) and installation and maintenance is assumed to be $1000/kW. The installation cost is based on a cost analysis and projection for a 10 kW engine/alternator being manufactured at a rate of 10,000 units/year. Note that heat is available from two sources, the burner waste heat not used by the engine, and the engine reject heat.

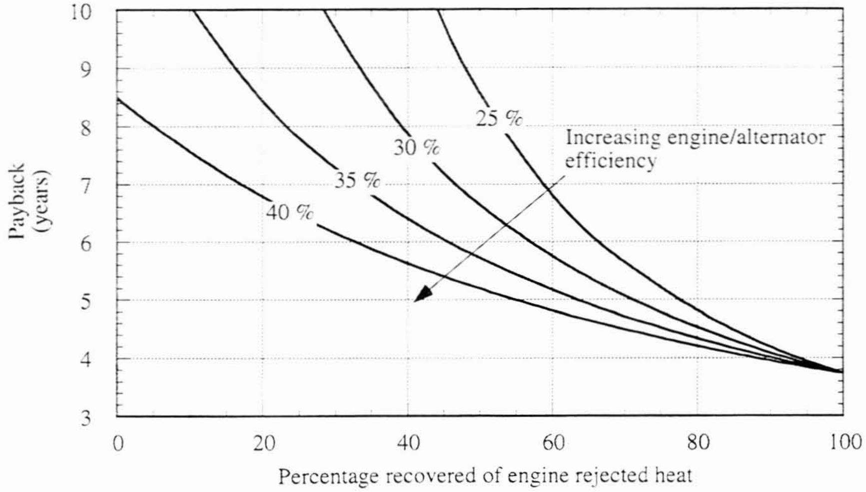

Figure 8. Stirling micro-cogen system payback, based on 1995 energy prices for domestic users: gas, 0.0206 \$/kWh; electric, 0.0841 \$/kWh. Other parameters: burner efficiency, 80%; burner heat recovery, 50%; operation, 4380 h/year (12 h/day); installation and maintenance, \$1000/kW. The four curves represent the effect of increasing engine/alternator efficiency.

As expected, the payback time is reduced at higher engine/alternator efficiencies and when as much as possible of the engine reject heat is used. Assuming an engine/alternator efficiency of between 30 and 35%, achievable with current designs [9], and 70% utilization of the engine reject heat, the pay back time is approximately 5 years. This is probably not low enough to encourage a significant number of end users to purchase the system.

However, the payback time is very sensitive to the electric cost and to system installation and maintenance cost. If the same analysis is applied using variable electric and installation and maintenance cost, the potential of Stirling based cogen system is apparent (Figure 9). In this projection the payback time is shown as a function of electric cost, engine/alternator efficiency, and installation and maintenance cost. The payback time is reduced directly with the installation and maintenance cost.

The \$1000/kW base line figure was based on 10,000 units/year, but this would be reduced at higher volumes. The figure makes clear

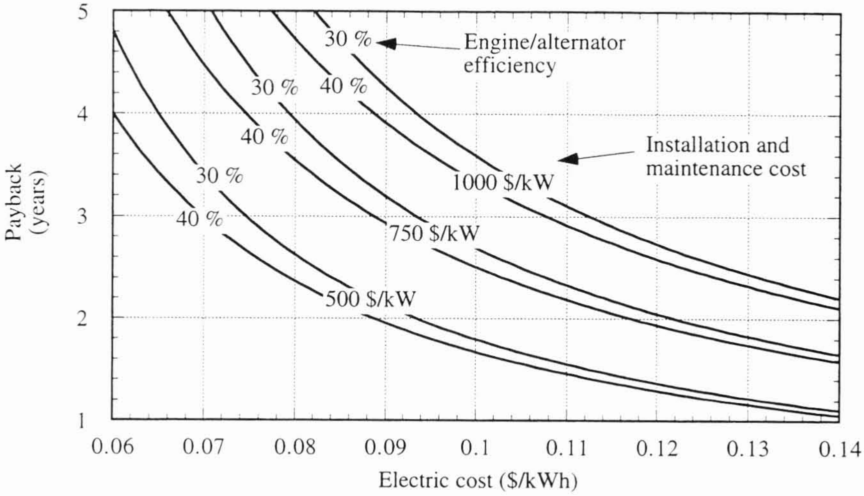

Figure 9. Stirling micro-cogen system payback with varying engine alternator efficiency as well as varying installation and maintenance cost. Parameters: gas, 0.0206 $/kWh (1995 domestic user price); burner efficiency, 80%; burner heat recovery, 75%; operation, 4380 h/year (12 h/day). Payback time is dramatically shortened by reducing installation and maintenance cost, but is relatively unaffected by further increases in efficiency.

that reducing the system cost has more effect on payback time than any likely improvement in system efficiency and that, in areas where the electric cost is greater than the national average, Stirling systems can be attractive to the consumer. At a installation and maintenance cost of $750/kW and electric cost of $0.1/kWh using a 30% efficient engine/alternator, the payback period is less than three years.

There are also immediate attractive opportunities for Stirling cogen systems even if the system cost is not reduced. Figure 10 shows the potential market at various price levels for 5 kW cogen systems in the United States [10]. On the same graph are price data extrapolated from a study of a 10 kW engine being manufactured in volumes of 10,000 units/year. These data are extrapolated by assuming that the cost drops by 10% when the manufacturing volume doubles. It is clear that from volumes between 1000 and 15,000 units/year that such systems can be profitably sold.

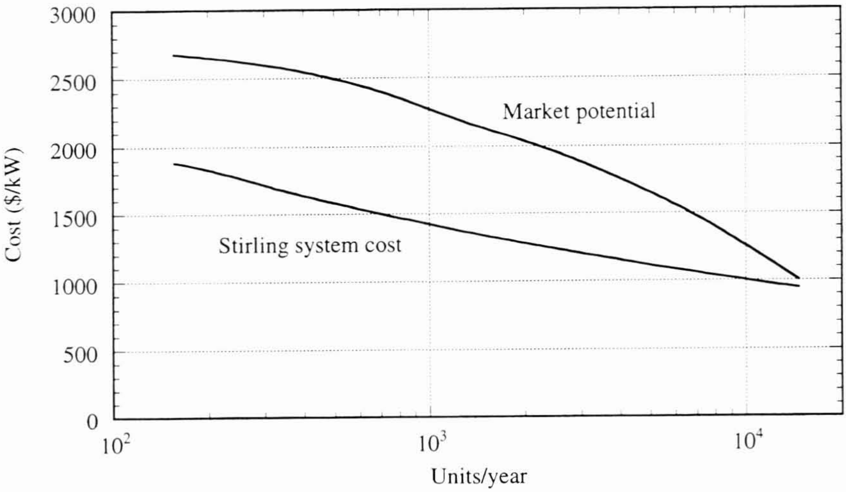

Figure 10. Stirling micro-cogen system market potential for 5 kW systems [10] vs. Stirling system price per kilowatt projected for a 10 kW system. Market potential increases significantly with reduced price, and coincides with estimated real costs at about 10,000 units per year. For certain niche markets with higher than average electricity costs, market potential may be higher than shown at lower volumes (see text).

CONCLUSIONS

Stirling machines offer both heating and cooling capability using natural gas as a fuel. Stirling based cogen systems will be longer lived, quieter, more efficient than IC engine based systems. The high efficiency at low power of free-piston Stirling engines significantly expands the potential market for cogen, especially in domestic applications. The changes most needed for Stirling to succeed in cogen systems are cost reduction and markets where the electric cost is greater than the national average.

Further increases in the already high engine/alternator efficiency, would, in contrast, have little effect on market potential. There are existing niches for Stirling cogen systems that could be exploited with current technology and manufacturing costs. Future pricing of fuels to include more of the costs now considered external will enhance the economic advantage of Stirling cogen.

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