Stirling Engine Assessment

Technical Report

Stirling Engine Assessment

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REPORT SUMMARY

Stirling engines are reciprocating engines that are fueled by an external heat source. This report presents a summary of the technical trends, commercialization status, and economic viability of Stirling engine technology for distributed generation (DG) applications.

Background

EPRI strives to provide its utility members with information about emerging DG technologies that may offer new business opportunities and attractive customer solutions. While fuel cells and microturbines have received a majority of the recent focus, Stirling engine technology is beginning to receive more attention as a viable—and potentially competitive—DG option.

Objectives

To document the state of the art in the commercial development of Stirling engine technology for DG applications as of June 2002.

Approach

The information in this report was obtained through research consisting of literature and web-based searches and telephone interviews with nineteen companies worldwide that are involved in the development and/or sales of Stirling engine technology.

Results

Recent interest in distributed generation has sparked new activity in the Stirling industry; however, only a single commercially available distributed generation product based on the Stirling engine has emerged thus far. Numerous companies are striving to bring a wide array of Stirling products to market for a breadth of applications. Most popular are products planned for residential combined-heat and power applications and small-commercial DG, particularly where “free” or “inexpensive” fuels are readily available.

Several Stirling companies presently have prototype products available for testing and demonstration. These systems range in size from 1 to 25 kW_e and vary widely in price from \$2,000 to \$36,000/kW_e. Through economies of scale, most Stirling developers ultimately plan to decrease the selling price of their products to less than \$1,000/kW_e.

EPRI Perspective

While field test experience is not yet sufficient to allow for full commercialization of Stirling engines, it is substantial relative to some of the other emerging DG technologies. The primary challenge is to develop a Stirling engine product that may be mass produced at a competitive cost while maintaining a performance that is superior to the incumbent technologies, particularly internal-combustion engines. Today's Stirling developers may be able to meet the challenge with improvement in several areas of engine design, including speed control, sealing, mechanical linkage, and heat transfer. Prototype testing and demonstration is the only meaningful way to determine if vendors are able to solve these fundamental technical issues.

Keywords

Stirling engines
Stirling cycle
External-combustion engines
Reciprocating engines
Engine generator sets
Distributed generation

ABSTRACT

This report documents the state of the art in the commercial development of Stirling engine technology for distributed generation (DG) applications. Utilities seeking new business opportunities and customer solutions based on emerging DG technologies will benefit from it. While fuel cells and microturbines have been a primary focus for emerging DG technologies, Stirling engine technology is beginning to attract more attention as a viable—and potentially competitive—DG option.

Though only a single DG product based on the Stirling engine is commercially available, numerous companies are working to bring a wide array of Stirling engine products to market. At this point, products are planned for residential combined-heat and power applications and small-commercial DG. Current prototype products range in size from 1 to 25 kW_e and vary widely in price from \$2,000 to \$36,000/kW_e. As the market matures, the selling price should fall to less than \$1,000/kW_e. By improving engine design, developers may be able to mass produce Stirling engine products at a competitive cost while maintaining performance that is superior to existing technologies—particularly internal-combustion engines.

Utilities can refer to this report for an up-to-date summary of the technical trends, commercialization status, and economic viability of Stirling engine technology for DG applications.

EXECUTIVE SUMMARY

The Stirling engine, an example of an external combustion engine, is an emerging prime mover technology for distributed generation (DG) applications. In a Stirling engine, heat is transferred through the hot-end cylinder walls to a confined working fluid and is then converted to mechanical work via the Stirling thermodynamic cycle. To complete the cycle, heat is absorbed from the working fluid through the cold-end cylinder walls by a coolant. This differs from an internal combustion (IC) engine, which relies on the ignition of fuel within the engine cylinder to force the piston down with large amounts of heat rejected in the exhaust gas. *Kinematic* Stirling engines have a crankshaft with a conventional generator, whereas *free-piston* Stirling engines typically generate electric power with a linear alternator.

In general, Stirling engines have relatively high thermodynamic efficiencies. Because they require only heat, Stirling engines also permit high fuel-flexibility and allow for better control of emissions. However, regardless of these benefits, the IC engine has still become the incumbent prime-mover technology for transportation and stationary power generation applications, while the Stirling engine has yet to reach commercialization. This is likely due to size and weight benefits of the IC engine combined with several other design and operational advantages.

Recent interest in distributed generation has sparked a high level of activity in Stirling technology development. Stirling engines are now positioned as a potential competitor to other on-site power generation technologies, particularly the mature IC engine and emerging technologies like microturbines and fuel cells.

This report provides a state-of-the-art assessment of Stirling engine technology for DG applications as of June 2002. The results are based on the status of nineteen companies worldwide with plans to develop and/or sell Stirling engine products. Emphasis is placed on technology trends, commercialization status, and economics.

Technology Trends

Stirling engine technology developments have been directed at a wide range of applications over the last several decades, including vehicle propulsion, gas-fired heat pump drives, aircraft propulsion, auxiliary power, and submarine power generation. The most commonly cited application for Stirling engines under development today is distributed generation for baseload or backup power. This report reveals the following technology- and design-related trends:

- Most Stirling companies are developing products for residential combined heat and power (1-5 kW_e) or commercial on-site power generation (25 kW_e).
- Several developers are focused on niche markets that take advantage of the Stirling engine's inherent fuel-flexibility by utilizing free or inexpensive renewable fuels and heat sources, such as landfill gas, biomass waste, and industrial waste heat.

- More than 60% of the companies investigated favor the kinematic design over the free piston design.
- The majority of Stirling engines under development have operating temperatures of 1,200-1,400 ºF. One developer plans to operate at 2,000 ºF to achieve higher thermodynamic efficiency. Alternatively, several others are designing low- to medium-temperature engines (200-1,000 ºF) in order to reduce material problems.
- Most Stirling engines operate at a high speed (or piston frequency). However, several companies are designing low-speed engines to reduce viscous losses and lengthen the useful life of the engine. Larger Stirling engines are more likely to have lower speeds, and smaller engines will exhibit higher speeds, similar to the trend seen in IC engines and microturbines.
- While hydrogen and helium are the most common working fluids, they have high diffusion and leakage rates. Four Stirling developers have chosen to use nitrogen or air as the working fluid to reduce leakage.
- Free-piston Stirling engines typically employ expensive hermetical seals to contain the working fluid. Kinematic engines generally use conventional seals, but require a periodic "charge" of working fluid due to leakage.

Commercialization Status

Stirling technology development companies have spent years in the lab designing engines and optimizing theoretical performance. Until recently, very few prototype systems had operated in the field. The present status of Stirling engine commercialization may be described as follows:

- More than half of the companies investigated have built and tested at least one prototype of the product that they plan to commercialize.
- BG Group, SOLO Kleinmotoren, and Stirling Technology Company each have dozens of pre-production prototypes undergoing field tests. Sigma Elektroteknisk and STM Power are planning to begin similar field demonstration programs in 2002.
- Two companies have successfully commercialized a product: Kockums has a 75-kW$_e$ system for submarine power generation, and Whisper Tech has a 1 kW$_e$ DC system for battery charging and remote power.
- STM has the highest *demonstrated* system efficiency – 29.6%, and ADI has the highest *target* efficiency – 50%. By contrast, the commercially-available Whisper Tech system has an efficiency of 12%.

Lack of proven operation and durability are perhaps the largest obstacles in the way of Stirling engine commercialization. As companies scale-up designs and perform field demonstrations, performance characteristics of the Stirling engine systems will likely improve.

Economics

Currently, Stirling engines are built individually in small numbers with specialty materials. This translates to high first costs. The logarithmic plot in Figure ES-1 displays the range of prices reported by the companies. Both the current beta demonstration prices and the target prices at higher production levels are widely scattered as a result of the varying engine sizes and designs. Additionally, some of the developers may have chosen to subsidize a portion of the actual cost in order to make their products more economically-attractive. All of the developers are working to reduce cost through a combination of design refinements, material substitution, and/or temperature-reduction. The product price will be further reduced through economies of scale.

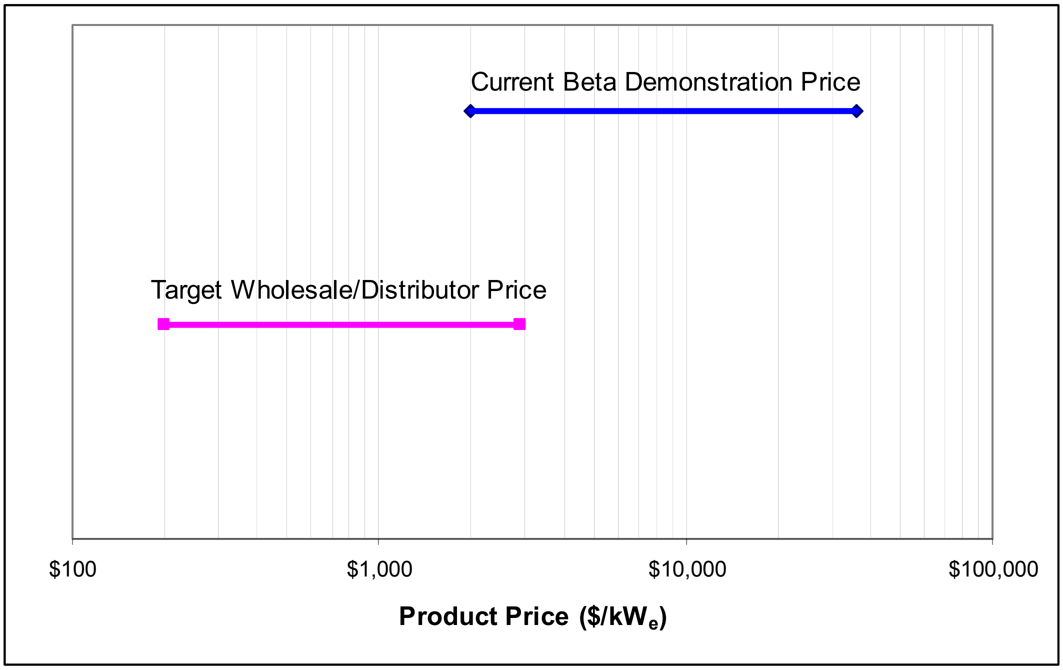

Figure ES–1
Stirling Engine Product Price

Installation cost data are not readily available for Stirling engines due to the present lack of widespread adoption. It is anticipated that installation costs will become available as field demonstrations increase over the next several years. Most developers estimate operation and maintenance costs of 0.5-1¢/kWh over a useful product lifetime of 5,000-10,000 hours. As with competing DG technologies, the high first cost of Stirling engines may ultimately be offset through cogeneration for space or water heating and/or through net metering in grid-connected applications.

Conclusions

Table ES-1 provides a comparison of the Stirling engine to mature and emerging competitive technologies. The IC engine is clearly the most cost-effective and mature technology today for distributed generation applications. However, Stirling engine generator sets may ultimately be built with half the moving parts of an IC engine and may reach similar prices. The Stirling engine also has much greater fuel flexibility and more easily controlled emissions than both IC engines and microturbines. It is likely that the efficiencies of IC engines and mature Stirling engine generators will be comparable, whereas microturbines are likely to remain less efficient.

Fuel cells (FC) are highly-efficient, electrochemical devices that rely on specific chemical reactions for the generation of electricity. While Stirling engines can accept heat from almost any source, fuel cells require hydrogen as a fuel. Although hydrogen can be extracted from numerous hydrocarbon fuels, there is typically a high cost associated with fuel reforming. Fuel cells, like IC engines and microturbines, also require extensive and costly clean-up of the fuel to prevent equipment damage. Fuel cells are in a pre-commercialization stage, which is reflected in the current prices.

Table ES-1
Distributed Generation Technology Comparison

	MATURE	EMERGING					
	IC Engines	**Stirling Engines**	**Micro-turbines**	**Molten Carbonate FC**	**Phosphoric Acid FC**	**Proton Exchange Membrane FC**	**Solid Oxide FC**
Power Output (kW)	5-5,000	1-200	30-200	250-10,000	50-500	1-250	5-5,000
Efficiency (LHV to AC)	25-45%	7-38%	20-30%	45-55%	36-42%	30-40%	45-55%
Operating Temperature (°F)	250	200-2,000	500	1,200	400	200	1,800
Current Cost ($/kW)	440-830	2,000-36,000	700-1,110	4,100	3,000-4,000	5,000-30,000	4,000-15,000

In theory, the key advantages of Stirling engines include fuel flexibility, controllable emissions, and high thermodynamic efficiency. If these qualities can be proven through a significant amount of additional field test experience in the near future, then Stirling engines may make a significant impact in the distributed generation market as an economically competitive and environmentally “green” alternative to mature DG technologies. EPRI has implemented a demonstration program wherein one or more Stirling engine systems will be tested in the laboratory and at field sites.

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INTRODUCTION

The objective of this report is to provide a worldwide assessment of Stirling engine systems covering technical trends, commercialization status, and economic feasibility. The assessment includes free-piston and kinematic Stirling engine designs of commercially available and emerging technologies for distributed resource (DR) applications.

Motivation for the Report

This report supports EPRI's goal of providing utility members with information about emerging DR technologies that may offer new business opportunities and customer solutions. While fuel cells and microturbines have received a majority of the recent focus, Stirling engine technology is beginning to receive more attention as a viable DR option. It is possible that Stirling engines will soon become competitive with other emerging DR technologies.

Stirling engines for DR applications are reciprocating engines powered by an external heat source.[1] Current Stirling development for DR applications falls into two categories:

- Fossil-fuel fired engines
- Solar- or waste-heat powered, for generation of "green" and renewable power

As an external combustion engine, fuel is burned in a continuous manner outside of the Stirling engine's cylinders. This is unlike an internal combustion (IC) engine where the fuel is injected into the cylinders and burned intermittently. The Stirling engine has several *potential* advantages over internal combustion engines:

- Lower emissions that are more easily controlled
- Quieter operation due to the absence of a valve train and intermittent firing
- A wider variety of fuel sources, including combustion of fossil or biomass fuels, concentrated solar heat, and high-grade waste heat from industrial processes, for different configurations of the same basic design
- Higher theoretical efficiencies
- Higher torque across a wide range of engine speeds

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[1] For cooling applications, the Stirling cycle is reversed. Mechanical or electric power is used to move the pistons, which produces refrigeration.

Nonetheless, few Stirling engine products are commercially available today. The challenge has been to develop and mass-produce reliable, low-cost Stirling engines that can compete with the cost and performance achieved by other traditional technologies, internal combustion engines in particular. Many Stirling products are under development and will likely be available for stationary DR applications within a few years. Some prototype systems are available today for as little as $2,000 per kilowatt. As production levels increase, Stirling engines may reach prices as low as $500 per kilowatt, making them comparable to conventional gas-fired internal combustion engines and turbines.

Organization of the Report

The information presented in this report was obtained through secondary research consisting of literature and web-based searches, and telephone interviews with nineteen vendors that are involved in the development and/or sales of Stirling engine technology.

The *Technology Overview* section summarizes the various types and configurations of Stirling engines, describes how Stirling engines work, and explains the basic theory behind Stirling engine operation.

The *Technology Trends* section introduces the Stirling engine vendors and compares the various design approaches that are being taken. Technical obstacles are also addressed in this section.

The current state of Stirling engine technology is covered in *Commercialization Status*. Technology demonstrations, performance characteristics, development timelines, and commercialization obstacles are highlighted in this section.

The *Economics* section discusses the different cost components associated with Stirling engine technology, including capital cost, installation cost, and operation and maintenance (O&M) cost.

The leading Stirling engine developers interviewed for this report are compared in tabular format in the *Summary and Conclusions* section.

A detailed profile of each vendor, including contact information, is contained in Appendix A of this report. Each profile contains company background, a description of the technology, a discussion of the product status, and EPRI's opinion about the company's position.

2

TECHNOLOGY OVERVIEW

The Stirling engine is based on simple concepts. In fact, the Stirling cycle engine was conceived more than 80 years before the Diesel and Otto cycle engines. Since its conception, the Stirling engine has been recognized for its potential to attain high cycle efficiencies; however, it has failed to reach its full potential due to design challenges such as seals, materials, heat transfer, size, and weight. In the past 200 years, individual inventors and corporate research laboratories have produced scores of technical and patent literature on thousands of Stirling engine designs.

The Stirling engine is a reciprocating, externally-heated engine. The heat is transferred to the working gas and is then converted to work via expanding the gas inside the cylinder. Heat is added continuously and at constant temperature to the expanding gas. This constant temperature heat addition implies a very high heat transfer rate through the cylinder, one of the main technical challenges with the Stirling engine. The conventional, reciprocating internal combustion (IC) engine, by comparison, burns an air-fuel mixture inside the cylinder to generate the heat and pressure which is converted to work at the crank shaft. The temperature is generally not constant during the power stroke in the IC engine, but varies as the combustion and piston motion proceeds. Since heat is supplied externally to the Stirling engine, a wide variety of heat sources can be used:

- Heat of combustion of any gaseous, liquid, or solid fuel, including all of the conventional fossil fuels and low-cost solid fuels such as biomass (IC engines, by contrast, have rather restrictive fuel property requirements to ensure reliable combustion)
- Solar irradiation (e.g., concentrated by solar dishes)
- Heat from radioisotopes
- Waste heat from industrial processes (e.g., metal casting, glass manufacturing, etc.)
- Waste heat from heat recovery devices (e.g., from IC engine exhaust)

To complete the thermodynamic cycle, a Stirling engine must be externally cooled to relieve the pressure on the piston and thus allow it to return it its original position. This can be accomplished in a variety of ways:

- Forced or free convection cooling (e.g., air flowing over fins)
- Water, ethylene glycol, or a mixture of both, circulated through a cooling jacket surrounding the cold end of the engine (the coolant is typically kept cool by an air-cooled heat exchanger similar to an automobile radiator)

In addition, the Stirling engine is "reversible;" that is, mechanical power input can be used to provide cooling. This characteristic also differentiates the Stirling engine cycle from the cycle that produces power in IC engines.

External combustion allows for more controlled burning of the fuel, which can result in lower emissions. Continuous external combustion also provides the extra benefit of much less noise and vibration as compared to IC engines.

Solar energy, normally concentrated by some type of parabolic dish, can be transferred to the Stirling engine by means of a heat pipe to warm the working fluid. In fact, many Stirling engines were developed under government contracts to develop power conversion units for solar collectors.

Although Stirling engines have broad flexibility when it comes to fuel or heat source, such flexibility is generally not needed in practice from an individual unit. Usually only a small number of fuel types or heat sources are available. Therefore, a Stirling system will often be designed for only one or two types of heat sources. For example, a Stirling system may utilize solar irradiation as the primary heat source, but a natural gas burner could also be added to provide heat during nights and cloudy periods.

To obtain optimal performance from a Stirling engine that has been designed to operate on more than one heat source, the heat (whether provided by a heat exchanger or combustor) must provide similar thermal output and a similar hot end temperature. In military applications, the freedom to use a variety of different fuels in the same engine offers a clear advantage, but details of the combustor design (nozzle spray pattern, nozzle flow rate, quantity of excess air, ignition method) must vary from fuel to fuel.

Mechanical Configurations of Stirling Engines

Hundreds of Stirling engine designs have been developed over the years that embody the basic thermodynamic concept. These Stirling engine designs can be classified by their mechanical configurations. For example, they can have kinematic or free-piston arrangements:

Kinematic engines have a crankshaft and a mechanical linkage to the power piston. Electricity is generated with a rotating synchronous, permanent magnet, or induction generator. The amplitude of the power-piston motion is constrained by mechanical linkages. The amplitude and phasing of the displacer (a component unique to Stirling engines) may also be constrained by mechanical linkages. Kinematic machines are generally mechanically complex, but relatively simple to analyze.

Free-piston engines typically generate electric power with a linear alternator formed by the oscillatory travel of the power piston in a magnetic field. The displacer and power piston typically move as tuned spring-mass-damper systems in response to pressure differences. Free-piston machines are mechanically simple but dynamically and thermodynamically complex. For power generation applications, electricity is transferred from a linear alternator connected directly to the power piston; for cooling applications, the power piston is driven by an integral linear motor. This is done without dynamic seals that may leak or fail.

Stirling engines can also have alpha, beta, or gamma arrangements:

- Alpha engines (see Figure 2-1) have two or more separate pistons mechanically linked to oscillate with constant phase lag. The working gas passes through a cooler, a regenerator, and a heater as it moves back and forth between the cylinders. Each piston requires its own seals to contain the working gas. All alpha engines are kinematic engines.

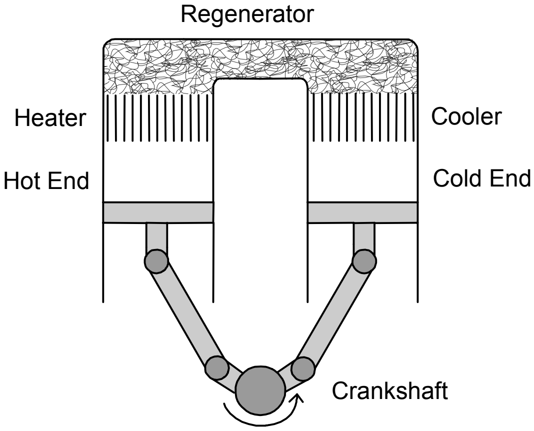

Figure 2-1
Alpha Configuration

- Beta engines (see Figure 2-2) have a displacer-piston arrangement in which the displacer and the power piston are in line with each other. The displacer shuttles the working gas back and forth between the hot and cold ends of the engine. The hot end is the expansion space, and the cold end is the compression space. As the working gas moves back and forth, it passes through a cooler, regenerator, and heater. Beta engines can be either kinematic or free-piston engines.

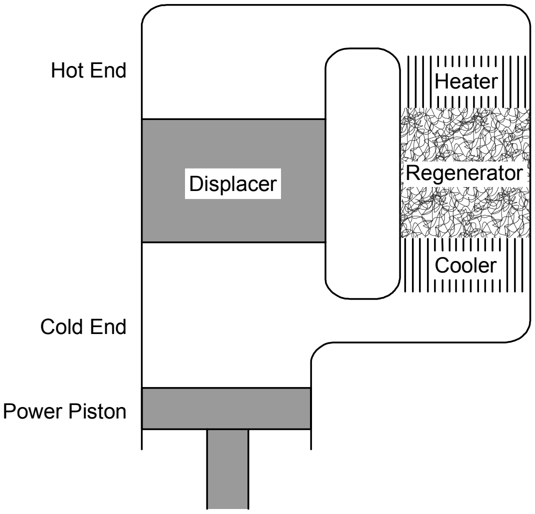

Figure 2-2
Beta Configuration

- Gamma engines (see Figure 2-3) have a displacer-piston arrangement where the displacer and power pistons are in separate cylinders. The displacer shuttles the working gas back and forth between the hot and cold ends of the engine. The cold end space includes the cold side of the displacer as well as the power piston. As the working gas moves back and forth, it passes through a cooler, a regenerator, and a heater. Gamma engines can be either kinematic or free-piston engines.

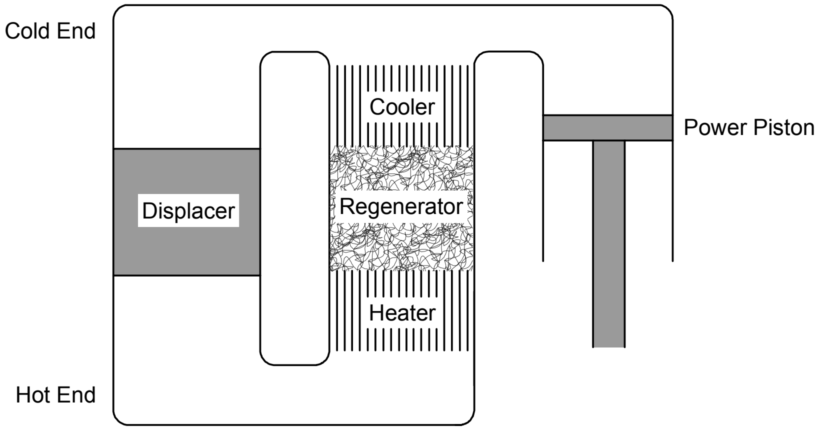

Figure 2-3
Gamma Configuration

Examples of Kinematic Stirling Designs

The power piston in a kinematic Stirling engine is mechanically connected to an output shaft. A very large number of such linkages have been designed over the years, and this remains an area of active development in order to improve power transfer and engine durability. During the history of Stirling engines, the claim is often made that a proposed novel linkage will "solve all the problems." But, as one problem is solved, new ones usually emerge.

Kinematic engine advantages:

- The oscillations of the moving parts are mechanically coordinated to ensure proper reciprocating motion during start-up, normal operation, and load fluctuation.

Kinematic engine disadvantages:

- The cranks and rotating parts generate lateral forces and require lubrication.
- More moving parts imply more frequent maintenance.
- Moving seals are required between the working gas and the crankcase.

Some of the common designs for mechanical transfer in kinematic Stirling engines are described below.

Wobble-plate or Z-crank

The wobble-plate design (see Figure 2-4) consists of a wobble plate in sliding contact with the crankshaft (journal bearings) and with pivoting connections to the piston connecting rods. In addition, the connecting rods have pivot point connections to the pistons to ensure straight travel in the cylinder. The wobble plate does not rotate. Piston thrust is transferred to the crank through the offset angle of the wobble plate during the power stroke. This style of drive mechanism is used on double-acting Stirling engines. Double-acting engines use the power stroke of one cylinder to compress the cold working gas for the adjacent cylinder; the power piston for one cylinder is the displacer piston for an adjacent cylinder.

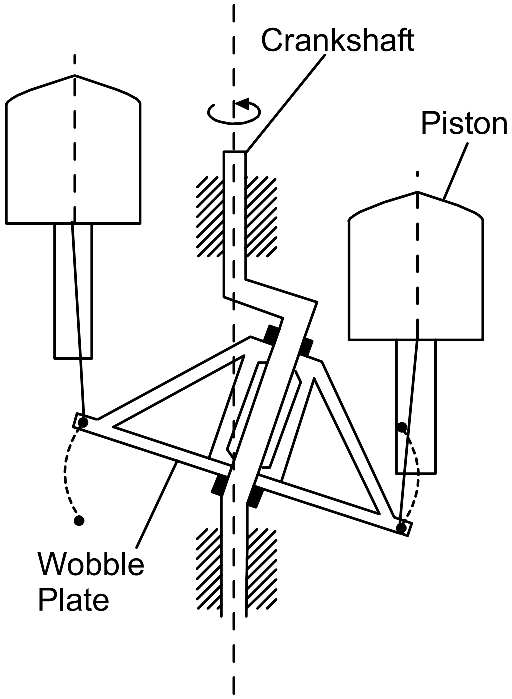

Figure 2-4
Wobble-plate Design

The Z-crank design is similar to the wobble plate. The pistons connect directly to the crankshaft instead of a plate. Pivot points are necessary at the crankshaft and pistons to ensure true axial motion of the piston in the cylinder. This engine design is more compact than a single-piston Stirling engine of comparable power.

The wobble plate design has two weaknesses:

- The pivots at the pistons are under heavy cyclic load and wear quickly. These connections are under continuous compression and bending loads.
- Double-acting Stirling engines have a piston-lubrication problem. Oil vapor may flow into the regenerator of the next piston, fouling the regenerator and external heat transfer surface area and reducing the overall cycle efficiency.

Swashplate Drive

The swashplate drive is superficially similar to the wobble plate in design, but it differs in significant ways. The swashplate is connected to the crankshaft by wedge bearings and rotates with the crankshaft, whereas the wobble plate does not rotate and is attached to the shaft by journal bearings. This difference allows the swashplate to maintain the axial orientation of the pistons without the use of pivot points. The pistons are attached to the swashplate by connecting rods that slide over the surface of the swashplate.

The swashplate concept (see Figure 2-5) provides several advantages:

- Operation is quiet, and lubrication problems are minimized due to better sealing of the cylinder.
- The swashplate can be designed to meet the required stiffness for good power transfer (flexure of the mechanism results in wasted motion of the power piston and thus lower efficiency).
- The swashplate can be balanced and built so that additional sets of pistons can run on the same swashplate. This increases the power output and reduces the power to weight ratio to a level more comparable with IC engines.

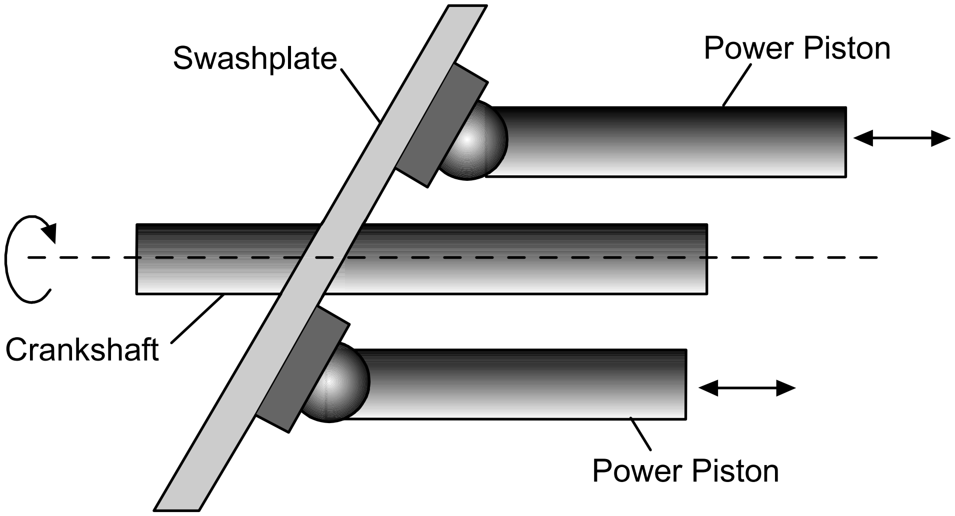

Figure 2-5
Swashplate Drive

Rhombic Drive

The rhombic drive is a different approach to power transmission from piston to crankshaft. The power piston and the displacer piston are connected to yokes. These yokes are linked to twin crankshafts with connecting rods, as illustrated in Figure 2-6. The rhombic drive mechanism forces the power piston and the displacer piston to reciprocate with constant phase lag.

The rhombic drive mechanism provides several distinct benefits:

- The rhombic drive is built for complete balance. This prevents lateral forces from developing in the piston and provides a good cylinder wall seal. The engine also runs virtually vibration-free.

- Rhombic drive engines have the ability to run at higher pressures, which allows for a higher specific power.
- Rhombic drive units can readily be stacked side by side to provide multi-cylinder engines.

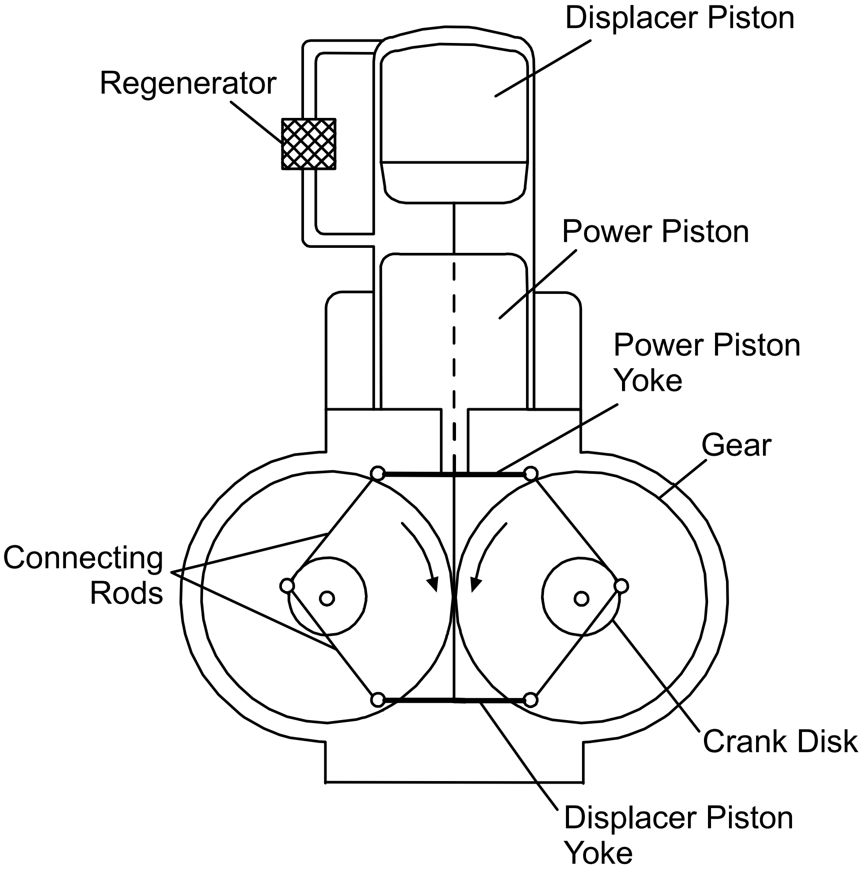

Figure 2-6
Rhombic Drive (Simplified Diagram)

Examples of Free-piston Stirling Engines

The free-piston Stirling engine is typically comprised of two oscillating unconnected pistons (the displacer and the power piston) contained in a common cylinder (see Figure 2-7). The displacer is a very small mass compared to the power piston, and its oscillation is damped by the gas flowing through the regenerator. The heavier power piston oscillates undamped except for the forces from the magnetic field. Oscillation of the displacer is encouraged by physical springs or by the compressibility of the working gas. The spring between the displacer and the power piston provides the forces necessary to initiate harmonic oscillations of the displacer. The temperature difference across the displacer maintains the oscillations, and the system operates at the natural frequency of the mass-spring system.

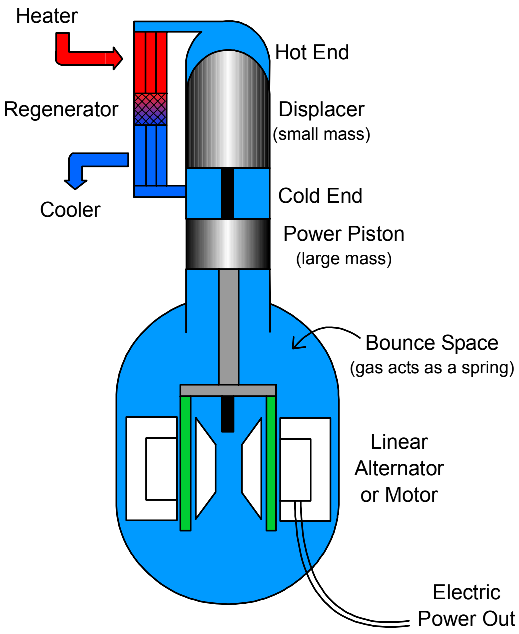

Figure 2-7
Free-piston Stirling Engine

The power from a free-piston Stirling engine is typically generated from a linear alternator (i.e., oscillation of the power piston windings in a magnetic field). However, several recent free-piston designs have been revealed in which a hydraulic drive is incorporated with a crankshaft. The use of hydraulics reduces the lateral forces on the cylinder. This is particularly beneficial in engines that have a high torque due to low piston frequency.

Free-piston engine advantages:

- There are no cranks or rotating parts to generate lateral forces and require lubrication.
- Fewer moving parts allow potentially longer times between maintenance.
- The engine can be built as a hermetically-sealed unit, preventing loss of the working gas and allowing operation in variety of environments.

Free-piston engine disadvantages:

- The oscillations of the moving parts are not set mechanically but are determined by the interactions of the whole system, including the applied load. This requires complex calculations to ensure proper reciprocating motion and the ability to meet load requirements.
- Due to the oscillating nature, load response time lags in comparison to kinematic and IC engines.
- Piston position becomes a critical area of control. If one piston drifts from its required neutral position, the oscillation will become unbalanced and power output is affected.

Principles of Operation

The essential parts of a generic Stirling engine were schematically illustrated in Figure 2-1 to Figure 2-3. The displacers and power pistons reciprocate in sealed cylinders filled with a fixed charge of the working fluid, typically helium, hydrogen, nitrogen, or air. The use of hydrogen or helium leads to higher efficiencies than the use of heavier working gases due to the low viscosities and high thermal conductivities of these gases. On the other hand, the high diffusivity of hydrogen and helium molecules makes sealing a more difficult challenge. The lower-diffusivity nitrogen and air molecules permit the use of more conventional sealing techniques, whereas hermetic seals are often required on engines that employ hydrogen or helium as the working gas. The higher viscosity and lower thermal conductivity of air and nitrogen tend to reduce the ability to achieve high cycle efficiencies.

All external heat is transferred to the working fluid at the cycle maximum temperature and rejected at the cycle minimum temperature. The regenerator absorbs heat from the working fluid as the gas passes through it from the hot end to the cold end. The heat stored in the regenerator is then returned to the working gas on its return from the cold end to the hot end with minimal thermal loss.

As the displacer reciprocates, it shuttles the working gas through the regenerator between the hot and cold regions of the engine. The pressure oscillations created by varying the average working gas temperature in a fixed volume are applied to the power piston, thus reciprocating it. The displacers and power pistons are phased so that more work is put into the power piston in the expansion stroke (when most of the working gas is in the hot space), than the work that the piston returns to the working gas a half cycle later (to compress the mostly cold working fluid). The net surplus of expansion work less compression work is extracted as useful work by the power piston.

Figure 2-8 illustrates the four phases of the Stirling cycle, which are somewhat analogous to the compression, power, exhaust, and intake strokes of the Otto cycle. In this illustration, it is assumed that the two pistons are mechanically linked to hold a fixed phase lag between the hot end and the cold end of the engine. That is, the cold end lags the hot end by 60 degrees in this example. The pressure-volume diagram and the temperature-entropy diagram for this example are shown in Figure 2-9 and Figure 2-10, respectively. The following four phases are illustrated in all three figures:

- During cold compression, the hot piston is nearing the top while the cold piston is moving up rapidly, compressing the cold working gas. The heat of compression is removed by the cold-end metal surfaces, causing the average entropy of the working gas to drop while the temperature hardly changes. The kinetic energy of the pistons and other moving components performs compression work on the working gas.
- During regenerative heating, the hot piston is starting down while the cold piston is nearing the top, causing the working gas to move from the cold end to the hot end of the engine as the pressure continues to rise. The average temperature of the working gas rises rapidly as it passes through the regenerative heater, building pressure. The average entropy of the working gas increases as heat is absorbed from the hot-end metal surfaces and from the regenerator.

- During hot expansion, the hot piston is nearing the bottom while the cold piston is just starting down. Since the hot working gas is expanding while the pressure is high, this phase corresponds to the power stroke in the IC engine. As heat is absorbed from the hot-end metal surfaces, the entropy continues to increase even as the average working gas temperature starts to drop.
- During regenerative cooling, the hot piston is starting up while the cold piston is nearing the bottom, causing the working gas to move from the hot end to the cold end of the engine as the pressure continues to fall. The average temperature of the working gas drops rapidly as it passes back through the regenerator. The average entropy falls as the working gas is cooled by the cold-end metal surfaces and by the regenerator.

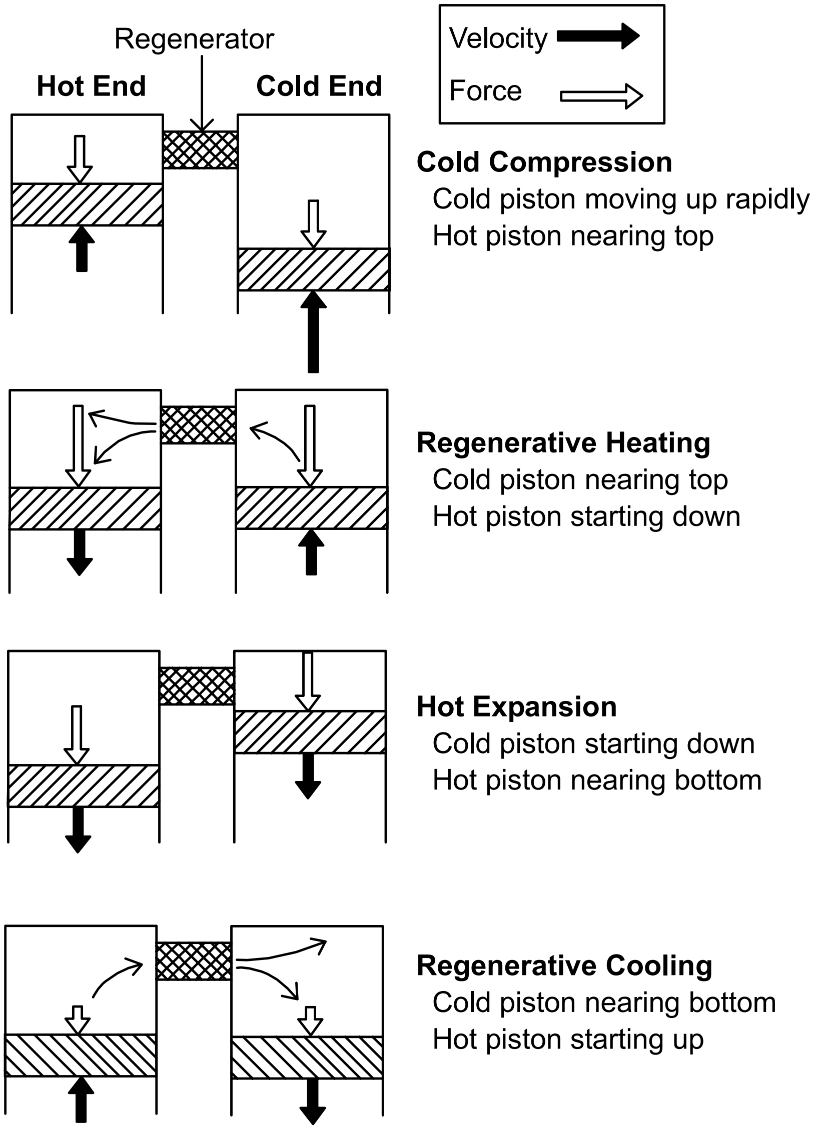

Figure 2-8
Four Phases of the Stirling Cycle

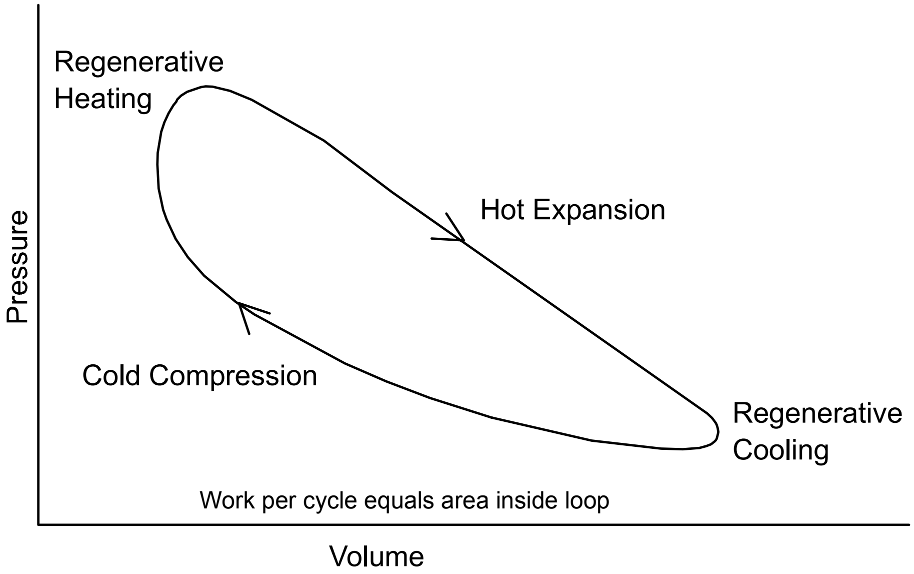

Figure 2-9
Pressure-Volume Diagram for a Stirling Engine

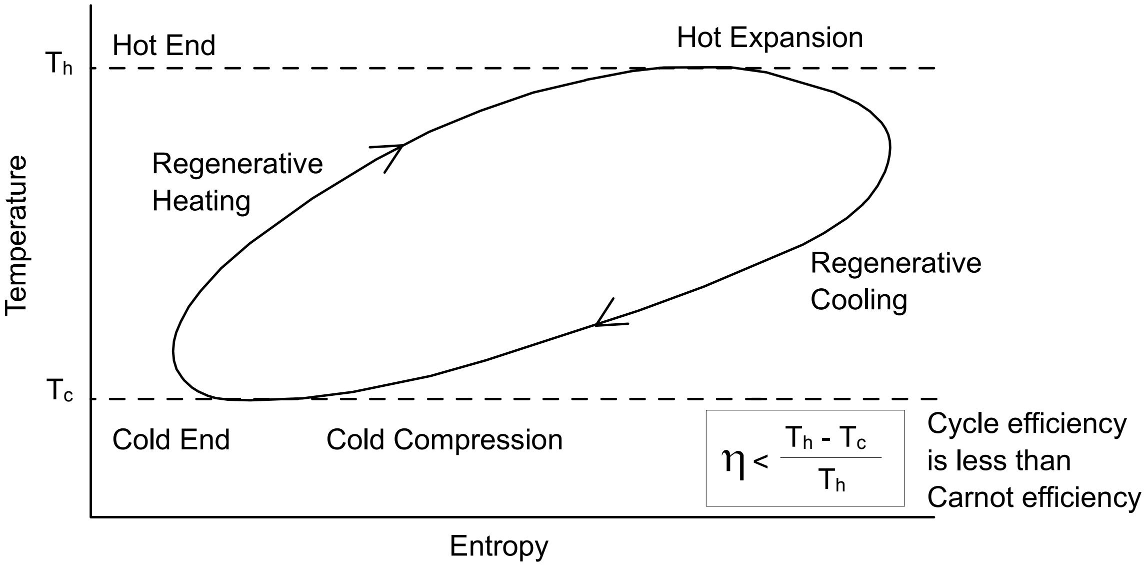

Figure 2-10
Temperature-Entropy Diagram for a Stirling Engine

The area inside the loops in Figure 2-9 and Figure 2-10 represents the net work output. The equation on Figure 2-10 indicates that the Stirling cycle efficiency is less than the Carnot efficiency[2] based on the temperatures of the hot and cold ends. The trend of the Carnot efficiency

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[2] The energy conversion efficiency of a heat engine is the ratio of the useful work output to the energy input as heat. The Carnot efficiency is the energy conversion efficiency of any reversible heat engine for which energy is transferred as heat from an assembly at one temperature (T_h) to a second assembly at a lower temperature (T_c). The

equation is illustrated in Figure 2-11. A Carnot efficiency of about 80% corresponds to a hot-end temperature of approximately 2,500 ºF and a cold-end temperature of 100 ºF. It should be noted that some Stirling manufacturers report efficiency as a percentage of the theoretical Carnot efficiency. For example, if the Carnot efficiency of a given engine is 72%, and the company reports an efficiency of 46% of the Carnot, then the actual engine efficiency is 29%.

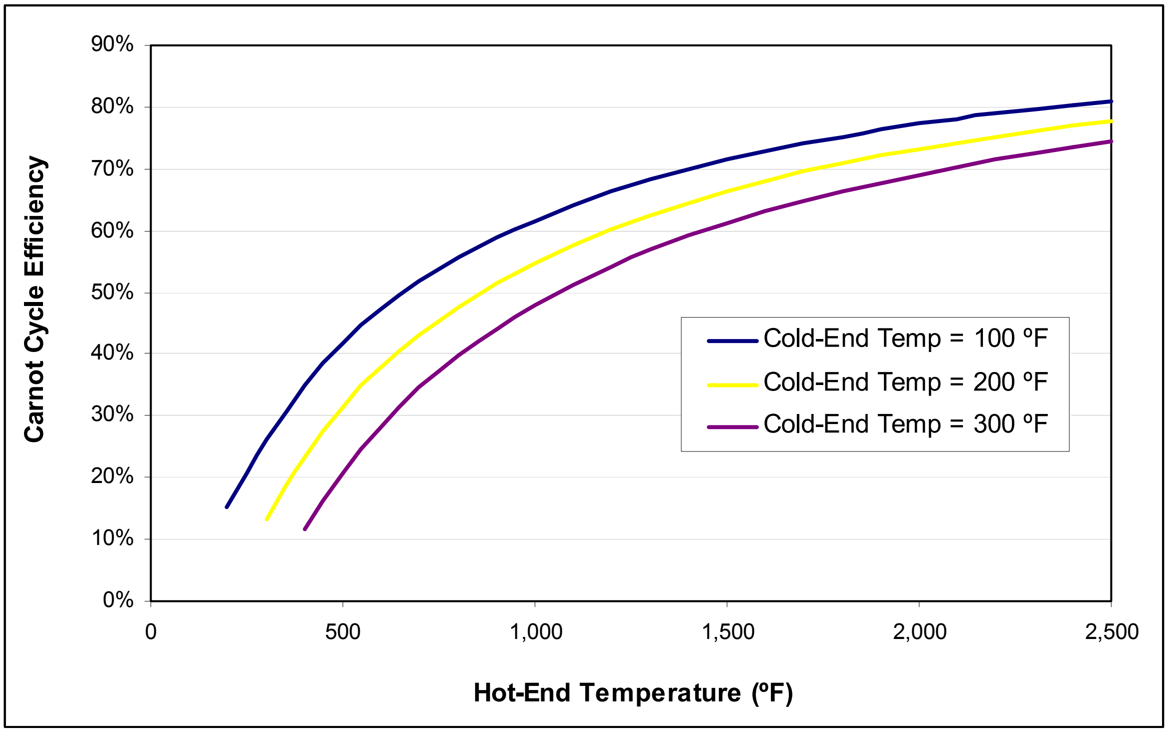

Figure 2-11
Carnot Cycle Efficiency Diagram

In general, increasing the average operating pressure of the working gas increases the power output per unit volume more than it increases the efficiency. As illustrated in Figure 2-12, low-pressure engines must operate at a higher speed to achieve optimum efficiency, while high-pressure engines may operate at a lower speed.

Carnot efficiency is thus the theoretical upper limit for the performance of any heat engine operating between the hot-end temperature and the cold-end temperature, and it has the value $(T_h-T_c)/T_h$, where T_h and T_c are *absolute* temperature values.

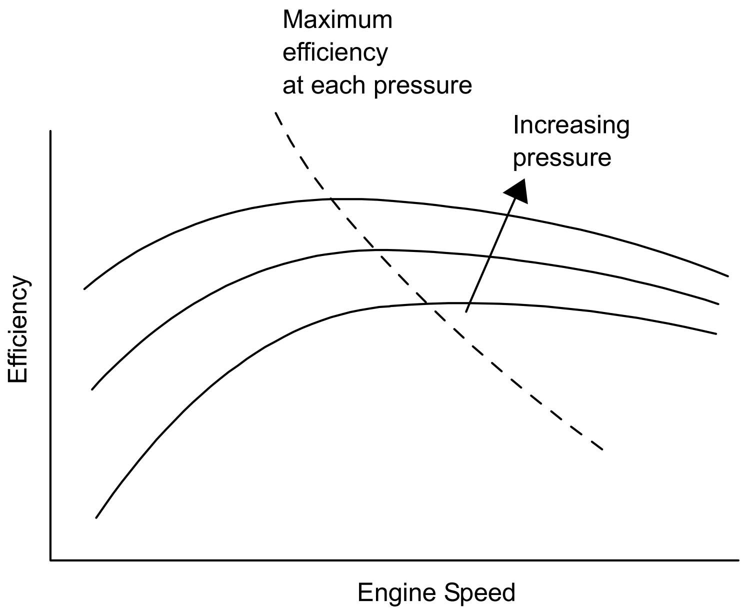

Figure 2-12
Efficiency Versus Operating Pressure and Engine Speed

Turning these cycles and mechanisms into hardware which can compete with IC engines has been challenging. The following areas are undergoing continued development:

- Control of heat transfer in both the working gas and the solid engine components
- Improved speed and part-load control, which is more complex than in IC engines
- Robust, low-friction mechanical component designs for linking the power and displacer pistons and for providing shaft output
- Improved sealing techniques to prevent leakage and contamination of the working gas

3
TECHNOLOGY TRENDS

This section of the report provides additional background on the history of Stirling research and development (R&D) and introduces the leading companies involved in Stirling engines today. The strengths and weaknesses of the companies' varying Stirling design approaches are discussed. In addition, the markets and applications for Stirling engines are identified.

Research and Development History

Invented by Robert Stirling in 1816, the Stirling engine is the oldest of the combustion-driven heat engines. Although it is a simple engine that does not depend on careful timing of fuel injection and ignition like an IC engine, it has had a very cyclic history, ranging from periods of rapid development to virtually total neglect. While some Stirling enthusiasts have existed throughout the volatility of the industry, other developers have come and gone with each new wave of interest.

Stirling technology has been a subject of curiosity and tinkering from its earliest days. The potential for demonstrating high cycle efficiencies, along with the challenge of producing a durable mechanical method for harnessing its energy, have resulted in literally thousands of Stirling engine designs finding their way into the technical and patent literature. For example, a very large number of linkages have been designed over the years to connect the power piston in a kinematic Stirling engine to the output shaft. Although there have been numerous patent claims for novel linkages which "solve all the problems," none seem to solve the problems without introducing new ones.

While the Stirling cycle predates both the Otto and Diesel cycles, the internal combustion (IC) engine has become the preferred choice for power generation in countless applications. There are several factors that might have contributed to this selection many years ago:

- Size and Weight – IC engines are typically smaller and lighter than Stirling engines and have higher power outputs. This has been particularly beneficial in automotive applications.
- Lubrication – Stirling engines generally require lubricants that can withstand higher temperatures than those used in IC engines. It is also important to protect the working fluid of a Stirling engine from contamination by the lubricant. In some cases, this is achieved through hermetical seals, which add to the Stirling engine cost.
- Heat Transfer – Whereas an IC engine burns fuel directly in the cylinder to do work on the power piston, a Stirling engine relies on the transfer of heat through the cylinder to the working fluid. The heat flux achieved through the flames in an IC engine is much higher than that achieved through the cylinder surface.

- Control – The fuel and air flow to an IC engine are adjusted for immediate response to a change in load; whereas, it is more difficult to achieve dynamic operation with prompt response in a Stirling engine. Like size and weight, fast response is an important factor in automotive applications.

Stirling technology developers have worked for many years to reduce the impact of these factors in order to shift the preference from IC engines to Stirling engines. Much of the development of Stirling engines has occurred in Europe. Most notable are the efforts of the Philips Company in the Netherlands just after World War II, and the Swedish efforts, which continue to this day. The results of the extensive Philips program are the basis for many of the designs now being prepared for commercialization around the globe. Philips examined every aspect of the engine, from theory to materials, with various internal designs. When the company abandoned its engine program in 1953[3], much of the technology was licensed to other Stirling developers and, ultimately, to the US automobile companies, which continued to try to make a viable vehicle power plant. The military also funded development of a Stirling field generator to take advantage of its multi-fuel capabilities, but this has not resulted in significant production or in any derivatives for the civilian market.

The US Department of Energy (DOE) has long supported (since the 1980s) a substantial amount of work on large solar heat-powered Stirling engines. The concept is to place a Stirling engine at the focal point of a large mirror array to provide very high temperatures to the hot end of the engine. Derivatives of this work on kinematic and free-piston engines have now evolved into more advanced engines and hybrid systems for power generation applications. Some of these engines are discussed elsewhere in this report.

With US electric deregulation underway, interest in Stirling engines for small stationary distributed generation (DG) applications is growing once again. Stirling engines will have competition from other emerging technologies (e.g., fuel cells and microturbines) in these applications. Stirling engine generators may be particularly well-suited for small, residential applications. European developers and governments are especially interested in the potential for residential combined heat and power (CHP) systems.

Stirling engine companies have a wide variety of market targets, including appliance power, small residential cogeneration units, commercial and light industrial power, auxiliary power units (APUs) for marine craft, and remote power stations. Currently, however, Stirling developers have generally focused on 100 kW_e units or smaller, with many units under 1 kW_e.

Dozens of developers have tried to find a viable market niche for Stirling engines in the past 20-30 years. Their efforts have ranged from "backyard do-it-yourself" operations to sophisticated technology programs funded by the US DOE. Others have focused their work on the past efforts of the Philips Company in order to take advantage of proven and patented design concepts, modifying the designs to correct known problems. Other Stirling engine companies are trying fresh ideas, starting from the ground up with their engine designs. It is unclear which approaches will win; hence, EPRI plans to test prototype engines as they become available.

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[3] In the early 1950s Philips was investing heavily into television technology. The Engine Division was dissolved in December 1953 as a result of the company's need for funding to allocate to this new priority.

Stirling Engine Technology Developers

The research phase of this project identified nineteen companies worldwide that are (or were) involved in the development and/or sales of Stirling technology for power generation applications.[4] Seventeen of the companies are technology developers and/or product developers, as shown in Table 3-1. It can be seen that the majority of today's leading Stirling companies are located in the United States.

Most of the companies included in this report are technology developers that have designed a unique Stirling engine. The exceptions are BG Group, External Power, SOLO Kleinmotoren, and Stirling Energy Systems, all of whom have chosen to offer a Stirling engine system product based on another company's engine. Those companies that have developed the intellectual engine property have chosen to either license the engine technology to a product packager (like the four mentioned above) or to develop a product on their own.

It may also be noted that the Stirling companies are at varying stages of development. Some companies have successfully completed design and demonstration of an engine or system; whereas others are just beginning the design process. The status of each company is represented numerically in Table 3-1, based on the following scale:

1 = Design/lab stage, may have a single unit in testing

2 = Multiple (≤10) early units in testing (alpha)

3 = Many (10-20) pre-production prototypes in the field (beta)

4 = In production

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[4] Stirling Technology, Inc. of the US has stopped its engine development efforts to focus on its energy recovery ventilation product; Sanyo Electric Company of Japan has shifted its focus to Stirling coolers.

Table 3-1
Stirling Engine Technology and Product Developers

Company	Country	Technology Developer	Engine Product	System Product	Product Status
ADI Thermal Power Corp.	US	✓		✓	1
BG Group [1]	UK			✓	3
BSR Solar Technologies	Germany	✓	✓		1
External Power [1]	US			✓	1
Kockums	Sweden	✓	✓		4
Quiet Revolution Motor Company	US	✓	✓		1
Sigma Elektroteknisk	Norway	✓	✓		2
SOLO Kleinmotoren [2]	Germany			✓	3
Stirling Advantage	US	✓		✓	1
Stirling Energy Systems [2]	US			✓	2
Stirling Technology Company	US	✓	✓		2 [3]
STM Power	US	✓		✓	2
Sunpower	US	✓	✓		3
Sustainable Energy Systems	UK	✓	✓		1
Tamin	US	✓	✓		1
Uwe Moch	Germany	✓	✓	✓	1 [4]
Whisper Tech	New Zealand	✓		✓	3 [5]

[1] Utilize the Sunpower Stirling engine technology.

[2] Utilize the Kockums Stirling engine technology.

[3] Status for the RG-450, RG-1000, and RG-3000 engines.

[4] Status for the wood-fired system.

[5] Status for the AC system.

Markets and Applications

In many cases, Stirling engines are suited to the same applications as other existing and emerging power generation technologies, such as IC engines, microturbines, and fuel cells. For example, all of these technologies may be used to provide power for distributed generation in residential, commercial, and/or industrial applications. Microturbines, fuel cells, and Stirling engines have also been considered as the power source for transportation applications; however, none has been able to match the inexpensive and technically proven IC engine.

Stirling engine developments have been directed at a wide range of applications, including vehicle propulsion, gas-fired heat pump drives, aircraft propulsion, auxiliary power, and submarine power generation. However, distributed generation for base-load or back-up power appears to be the most commonly cited application for Stirling technology today. This is evident from the products and applications targeted by the developers, shown in Table 3-2. Many of the intended applications take advantage of Stirling engine's inherent fuel flexibility by utilizing inexpensive (or free) renewable fuels.

Table 3-2
Stirling Engine Product Applications

	Targeted Applications										
Company	Residential CHP	Commercial DG	Solar Heat-Powered DG	Waste Heat-Powered DG	Biomass-Fueled DG	Other "Free-Fueled" DG	Back Up or Remote Power	Naval-Submarine	APU – RVs, Marine, etc.	Power Tools	Direct Drive Compressors
ADI Thermal Power Corp.		✓				✓	✓				
BG Group	✓										
BSR Solar Technologies		✓	✓	✓							
External Power					✓						
Kockums	✓	✓	✓					✓			
Quiet Revolution Motor Company		✓							✓	✓	✓
Sigma Elektroteknisk	✓										
SOLO Kleinmotoren	✓		✓		✓						
Stirling Advantage		✓		✓	✓	✓					
Stirling Energy Systems			✓								
Stirling Technology Company	✓		✓		✓						
STM Power		✓	✓	✓	✓	✓					
Sunpower	✓				✓						
Sustainable Energy Systems	✓	✓	✓		✓	✓	✓				
Tamin	✓						✓		✓		
Uwe Moch	✓				✓						
Whisper Tech	✓						✓		✓		

It is also interesting to note that the markets and applications for Stirling engines vary globally. There has been a great deal of interest in residential combined heat and power in Europe. This is likely due to the fact that a majority of Western European homes presently utilize hydronic heating systems as the primary space heating equipment. BG Group plans to capitalize on this market by offering a residential CHP product as a replacement for conventional hydronic boilers. The benefit of owning a Stirling engine system as a primary heating appliance is that it will supply electricity as a byproduct. European utilities also tend to be relatively liberal with grid interconnection, eliminating costly permitting and delays prior to installation.

Technical Obstacles

The major technological hurdles faced by Stirling engines have been long-term durability and reliability. Some of the common durability challenges have included:

- Seals to separate the high-pressure hydrogen (or helium) space from the lubrication in the mechanical drive train of kinematic engines
- Low-leakage piston rings and bearings for operation in the unlubricated working engine space
- Minimization of material stress and corrosion in the high-temperature and/or high-pressure heater heads
- Blockage of fine-meshed heat matrices used in the regenerator assemblies with particles/fines generated through the rubbing action of piston rings

While these durability challenges have delayed the penetration of Stirling engine technology, manufacturers are now beginning to approach run-times that may be acceptable in some distributed power applications. For example, Kockums has operated its engines continuously and without maintenance for more than 18,000 hours (more than 2 years). Although in order to be economical in stationary power generation applications, a system lifetime of 10-20 years with minimum maintenance is generally required. The cost of replacement parts and labor also play an important role in the acceptance of Stirling engines for DG applications. For example, it may be acceptable for inexpensive parts to have a shorter life; whereas, expensive parts should last much longer.

In terms of performance characteristics, it is unlikely that major breakthroughs will appear to significantly improve the operation of Stirling engines. Several developers have set out to achieve higher efficiencies or better durability, but advances in the technology are apt to be minimal as major advances have already been realized after decades of active development. In many cases, a significant improvement in one operating parameter has adverse effects on another. Successful advances in Stirling engine technology will rely upon the optimization of several design parameters that combine to create an efficient, durable, low-cost engine. The strengths and weaknesses of these design parameters and the trends occurring in each are discussed below.

Strengths and Weaknesses

Despite that fact that the Stirling engine was invented long ago, many basic design issues are still unresolved. Is it better to generate electric power with a crankshaft and a generator or with a linear alternator? Is it better to operate the engine at a high temperature or a low temperature? Is it better to operate the engine at a high speed or a low speed? Is it better to modify older designs or start fresh? Is it better to use working gases with low molecular weight or medium molecular weight? Each Stirling engine developer has chosen its own unique path in Stirling engine design.

Free-piston vs. Kinematic

Compared to kinematic Stirling engines, free-piston engines are mechanically simple: the displacer is free to move and, in most cases, the power piston is linked to a linear alternator. There are usually no crankshafts, bearings, dynamic (sliding) seals, or complicated mechanical linkages. In addition, free-piston engines can potentially achieve better fuel efficiency than fixed-stroke-and-phase kinematic engines.

On the other hand, free-piston engines are dynamically and thermodynamically complex. The displacer and power pistons must be adjusted to move as tuned spring-mass-damper systems in response to pressure differences, or must be controlled in some other fashion to optimize the energy delivery per cycle. Free-piston engines are generally most applicable to DR applications where electric grid power is available to stabilize the operating frequency of the engine.

Like an internal combustion engine, kinematic engines are generally mechanically complex, with a crankshaft and a mechanical linkage to the power piston. The amplitude of the power piston motion is constrained by mechanical linkages, and the amplitude and phase of the displacer may be constrained by mechanical linkages. Kinematic engines are applicable to both grid-parallel and stand-alone DR applications.

More than 60% of the companies that are active in Stirling engine technology development today favor the kinematic engine design (see Table 3-3). Of the five companies that have committed to free-piston Stirling engines, two have incorporated a hydraulic drive and crankshaft into the system. The preference of kinematic engine designs with mechanical linkages and shaft output may also result from the power generation industry’s familiarity of the similar operation of IC engines and combustion turbines.

Table 3-3
Types of Stirling Engines Under Development

Kinematic	Free-Piston
ADI Thermal Power Corp.	BSR Solar Technologies
Kockums	Quiet Revolution Motor Company [1]
Sigma Elektroteknisk	Stirling Advantage [1]
STM Power	Stirling Technology Company
Sustainable Energy Systems	Sunpower
Tamin	
Uwe Moch	
Whisper Tech	

[1] QRMC and Stirling Advantage incorporate a hydraulic drive and crankshaft into the free-piston design.

Operating Temperature

Like other heat engines, Stirling engines with high operating temperature have higher thermodynamic efficiency, but the higher temperatures bring materials problems, thermal stresses, expensive high-temperature metal alloys, and the potential for higher conduction heat losses. Most of the Stirling engines under development have hot-end operating temperatures in the range of 1,200 to 1,400 ºF. By using an operating temperature of 2,000 ºF, one developer plans to achieve at least 50% electrical efficiency. Stirling engines of the future will likely have high operating temperatures, but this will be possible only after the technology problems are resolved.

Two of the leading developers have designed Stirling engines with a low to medium operating temperature (200-1000ºF). These engines have lower thermodynamic efficiency but have many fewer materials and mechanical problems:

- Lower thermal stress and less hot-side material degradation lead to longer life.
- Lower temperatures lead to less conduction heat loss.
- Common materials allowed by low-temperature operation lead to lower costs.
- Lower NO_x emissions from the burner are achievable (to match the low heater head temperature, excess air is added to the burner to reduce the flame temperature, which, in turn, reduces NO_x emissions).

Although low-temperature Stirling engines have low thermodynamic efficiency, their developers claim that this negative effect will be counterbalanced by the selection of more efficient subcomponents within a Stirling engine system.

Operating Pressure

Increasing the average pressure in a Stirling engine will increase the power output and the power density, just as it does in an internal combustion engine and a microturbine. Efficiency also increases with pressure to a limiting value, where pressure is no longer a factor. On the other hand, an increase in pressure also increases the material stress, the required wall thickness, and working fluid containment problems. While all of these factors are critical for consideration throughout the Stirling engine design process, it does not appear that there has been a trend either way towards high-pressure or low-pressure engines. The companies investigated for this project report operating pressures between 150 psi and 2,200 psi.

Engine Speed

High-speed Stirling engines have higher power density (watts of output power per cubic meter of engine volume, weight, or engine displacement) and fewer torque-related problems. Although high-speed Stirling engines are much more common, several developers have opted to design engines with low piston frequency. For example, Stirling Advantage chose a low-speed engine with a hydraulic drive system to enable free-piston operation and to avoid the problems associated with high torque, such as high lateral forces on the piston bearings. Like internal combustion engines, low-speed (or low-piston-frequency) Stirling engines tend to have longer life and higher torque. The following additional characteristics are common in low-speed Stirling engines:

- Lower wear
- Lower viscous drag losses in the working gas
- Lower friction losses on seals
- Somewhat higher efficiency
- Smaller heat exchanger and regenerator components

It appears that larger Stirling engines will likely be lower-speed engines; whereas smaller Stirling engines will exhibit higher speeds. This is similar to the trend seen in IC engines and microturbines.

Dynamic Operation

Stirling engine companies take into account several factors when selecting a dynamic control strategy that will permit the engine to vary output in response to the electric load. The intended application for the Stirling engine product and the design features of the engine (e.g., kinematic, free-piston, types of mechanical linkages) frequently have an impact on this decision process.

The usual response of a Stirling engine to load changes is to speed up or slow down. This is unsatisfactory if the Stirling engine is being used to generate electric power with a constant-speed synchronous or induction generator. There are several options to dynamically control the power output of a Stirling engine while holding the engine speed constant:

- Control the fuel and air flow. Reducing the heat input lowers the hot-end temperature, which, unfortunately, reduces the efficiency. The response time is slow – many seconds.
- Control the cooling rate. Reducing the cooling rate allows the cold-end temperature to rise, which also reduces the efficiency. The response time is slow – many seconds.
- Control the mass flow of the working fluid in concert with controlling the fuel and air flow. The response time can be under a second. This has the advantage of keeping the hot-end temperature high and the efficiency high. However, a complicated means of adjusting the mass flow of the working fluid is required. This action can be used to reduce the average pressure, thereby reducing the pressure ratio and the power output.
- Control the power stroke (with a swashplate for example) in concert with controlling the fuel and air flow. Reducing the stroke reduces the displacement and the pressure ratio and therefore the net power out. The response time can be under a second, the hot-end temperature remains high, and the efficiency remains high. This change leaves the average pressure constant, and reduces the pressure ratio.

Working Fluid Containment

Theoretically, the most efficient Stirling engines will result from the use of low-molecular-weight gases such as hydrogen and helium for the working fluid due to their high thermal conductivity and low viscosity. However, low-molecular-weight gases tend to have higher diffusion and leakage rates. Even with expensive efforts to hermetically seal free-piston engines, some gas loss occurs, which reduces the actual efficiency and incurs maintenance costs to replenish the gas. Automatic replenishment of the working fluid may be achieved by incorporating a replaceable or refillable gas bottle into the engine design. STM has actually included a small electrolyzer to recharge the hydrogen in its system. In other instances, replenishment of the working fluid is part of the routine maintenance on the Stirling engine. In any case, replenishment of working fluid is an added cost.

Using a denser working fluid such as nitrogen or air reduces the engine efficiency (relative to hydrogen or helium gas), but it allows the use of more conventional seals. Conventional seals reduce engine fabrication costs, and make the internal engine components readily accessible for maintenance work, as opposed to hermetically sealed engines that must be designed for little or no maintenance. Even with these benefits, only four of the thirteen Stirling engine developers have chosen to use nitrogen or air as the working fluid.

4

COMMERCIALIZATION STATUS

This section of the report will provide the development status of the Stirling engine companies as of June 2002, while attempting to address some of the performance issues and design characteristics related to Stirling engine commercialization.

Technology and Product Demonstrations

Table 4-1 displays the testing and demonstration activity of the Stirling engine and Stirling system developers. The companies are categorized by their development status. Companies with several products in various stages of development are listed more than once.

Of the seventeen active Stirling engine developers that were investigated for this project, more than half have built and tested at least one prototype of the product that they plan to commercialize. Several of these companies have large numbers of engines or systems that are undergoing demonstration in the field, while others are just beginning the field testing phase. Several other companies have completed only engine designs and have not yet begun to actually work with hardware.

There are only two companies that have successfully commercialized a Stirling product (albeit in small quantities): Kockums and Whisper Tech. Kockums has successfully developed a liquid-oxygen-fueled, 75-kW_e system that has been installed on submarines by the Swedish, Danish, and Japanese navies. The company's engine technology is also utilized in the demonstration products of Stirling Energy Systems and SOLO. Whisper Tech has sold hundreds of its small DC systems for battery charging and remote back-up power applications. The company is now in the process of commercializing a similar system with AC output. Several more companies are in the field demonstration phase and hope to soon join the ranks of Kockums and Whisper Tech.

Table 4-1
Stirling Engine Technology and Product Demonstrations

Company	Testing & Demonstration Activity
Design/lab stage, may have a single unit in testing	
ADI Thermal Power Corp.	25-kW_e prototype system in operation (3^{rd} gen. design) 60 hours total run-time Several field demos planned for 2002-3
BSR Solar Technologies	1-kW_e prototype system in operation 2-3 additional prototypes planned for completion late 2002
External Power	2.5-kW_e prototype system in operation 100-system field demo program planned for 2003
Quiet Revolution Motor Company	75-kW_{shaft} engine design complete Proof-of-concept engine scheduled for completion late 2002
Stirling Advantage	200-kW_e system design complete 25-kW_e prototype engine scheduled for completion late 2002
Sustainable Energy Systems	10-kW_e engine prototype in operation Four additional prototypes scheduled for completion late 2002
Tamin	Subscale engine tested in the 1990s 10-kW_{shaft} prototype engine scheduled for completion fall 2002
Uwe Moch (System Product)	950-We system prototype in operation 1,400 hours of run time
Multiple (<10) early units in testing (alpha)	
Sigma Elektroteknisk	6 CHP systems in operation – 4 in-house, 2 in the field More than 1 year of run time on a CHP system 30-system demo program scheduled for mid-2002
Stirling Energy Systems	2 solar-Stirling systems in operation – 1 in-house, 1 in the field 3 additional system demos scheduled for 2002 Plan to demonstrate 40 systems as part of DOE program 10,000 hours of run time on a single system
Stirling Technology Company (RG-1000 Product)	3 CHP systems in field operation 6 engines in production for demo in spring 2002 100-system demo program in planning
STM Power	10 in-house systems in operation Several systems planned for field demo in summer 2002
Many (10-20) pre-production prototypes in the field (beta)	
BG Group	28 systems in field operation
SOLO Kleinmotoren	150 engines built and tested to date – 150,000+ hours of run time 20,000 hours on single engines with 6,500 hours maintenance-free 16 CHP systems in field operation 15 solar-Stirling and cryocoolers in operation
Stirling Technology Company (RG-350 Product)	20+ engines in operation 67,000 hours of main.-free run time on a single 10-We engine
Sunpower	See BG Group and External Power
Uwe Moch (Engine Kit)	70 engine kits sold with 40+ engines in operation

Company	Testing & Demonstration Activity
Whisper Tech (AC Product)	50 systems in field operation 6,000+ hours of run time on a single system
In production	
Kockums (4-275 Naval Product)	200+ engines built 18,000 hours run time without maintenance 5 systems installed in submarines 12 additional submarine installations planned See SOLO and Stirling Energy Systems for stationary applications
Whisper Tech (DC Product)	450 systems sold in FY2001 2,000+ hours run time demonstrated 500 systems on back order Anticipate sale of 1,500 systems in FY2002

Performance Characteristics

Considering the lengthy development of Stirling engine technology over many decades, new technological advances in the technology are likely to be *evolutionary* as opposed to *revolutionary*. Developers have taken a variety of approaches in order to increase the appeal of Stirling engines to customers. Some of the approaches include:

- Improving efficiency
- Increasing the maintenance interval
- Extending overall product lifetime
- Decreasing emissions
- Decreasing cost through less expensive materials
- Focusing on inexpensive fuels

This section of the report highlights the performance characteristics of today's Stirling engines.

Fuels

Stirling engines have tremendous versatility in potential applications, primarily due to their inherent fuel-flexibility. Because the engine requires only heat for operation, many types of fuels and heat sources may be used to supply the heat. While some Stirling developers are focusing on power generation in locations with easy access to fossil fuels like natural gas or diesel, other developers are targeting locations with less-conventional fuels, "free" or "inexpensive" fuels, and other "free" heat sources. Note that no fuel or heat source is truly free because of the cost of collecting the fuel or heat and then controlling it.

Several companies, along with the US government, have shown support for solar-Stirling hybrid power systems, in which solar concentrators are used to provide the heat to the engine. Solar heat is considered a "free" fuel for the Stirling engine, theoretically decreasing the operating cost of the system. Many more companies have turned their attention to niche applications that provide other “free-” or “inexpensive-fuel” options. Identifying niches appears to be a trend not only for Stirling engine companies, but for all DG developers. Biomass in the form of waste-wood, landfill gas, and digester gas are popular fuel choices. Because Stirling engines burn the fuel externally, extensive pre-cleaning of these “dirty” fuels is not required, and emissions are easier to control. This gives the Stirling engine an advantage over other DG technologies, which require filtration and/or removal of certain compounds, such as sulfur and water.

Electric and Thermal Output

The majority of Stirling engines under development have power outputs of 25 kW_e or less (as shown in Table 4-2). The exceptions are the 75-kW_e product under development by Quiet Revolution Motor Company and the 200-kW_e system under development by Stirling Advantage. There is not one specific reason for the popularity of small engines, but rather several contributing factors. Many of the Stirling companies have developed engines that are derivatives of the kinematic Philips technology, thereby maintaining an output of approximately 25 kW_e. Others have chosen to modify engines that were initially designed for automotive applications, resulting in similar electric outputs. These developers plan to provide higher power levels by siting several engines or systems.

Stirling engines are easily scaled down in size, which has led to several products planned for the residential market. Most of the companies that have started fresh with new engine designs have opted to start small. It is the goal of these developers to design an engine that will permit future upsizing through increasing the size of the engine cylinder or by increasing the number of cylinders, while at the same time overcoming the technical obstacles that have prevented widespread adoption of traditional Stirling engine designs.

Quiet Revolution and Stirling Advantage have taken a different design approach. These companies believe that the largest market opportunity for Stirling engines lies in distributed generation for commercial-scale applications. Although both companies have planned for an initial product with an electric output that is significantly higher than that of their competitors, neither company has demonstrated such a system. It is also important to note that both companies have designed multi-cylinder systems, where each cylinder has comparable output to the single-cylinder products of their competitors.

The usable heat outputs of those products that are being initially targeted for cogeneration or combined heat and power (CHP) applications are also provided in Table 4-2. Both the BG Group and Sigma products are specifically designed for residential applications. In fact, an auxiliary burner is provided with the BG Group product in order to match the thermal output of conventional residential boilers. The SOLO system is suitable for both individual households and multi-family dwellings (e.g., apartment complexes).

Table 4-2
Stirling Engine Products Under Development

Company	Product Output	Usable Heat Output
ADI Thermal Power Corp.	25 kW_e	---
BG Group	1.1 kW_e	15-36 kW_{th}
BSR Solar Technologies	5-10 kW_e	---
External Power	15 kW_e	---
Kockums	25 kW_{shaft}	---
Quiet Revolution Motor Company	75 kW_{shaft}	---
Sigma Elektroteknisk	3 kW_e	9 kW_{th}
SOLO Kleinmotoren	2-10 kW_e	8-24 kW_{th}
Stirling Advantage	200 kW_e	123 kW_{th}
Stirling Energy Systems	25 kW_e	---
Stirling Technology Company	350 W_e 550 W_e 1.25 kW_e 3 kW_e	---
STM Power	25 kW_e	44 kW_{th}
Sunpower	1 kW_e	---
Sustainable Energy Systems	10 kW_e	---
Tamin	10 kW_{shaft}	---
Uwe Moch	900-950 W_e	---
Whisper Tech	950 W_e (AC) 1-1.1 kW_e (DC)	6 kW_{th}

Efficiency

The theoretical limit for the efficiency of a Stirling engine is the Carnot efficiency. Therefore, the efficiency of Stirling engines is highly dependent on the temperature of operation. Some developers have chosen to operate at high heater head temperatures, thereby increasing the efficiency but presenting materials issues. Others have designed low-temperature systems, which have low thermodynamic efficiency. In this case, the negative effect of low temperature is typically compensated for by operating at lower speeds, which significantly reduces viscous losses. System efficiency may also be increased by choosing subcomponents with higher efficiencies (e.g., less friction, less drag, etc.).

The developers included in this project report target efficiencies of up to 50%. However, the highest demonstrated efficiency comes from an STM 25-kW_e PowerUnit system – 29.6% based on the lower heating value of the fuel to AC electricity out. STM believes that it will ultimately be able to reach 34.3%. By contrast, Whisper Tech reported an electrical efficiency of 12% from its commercially available Stirling engine system. The company anticipates that its AC system will have a similar efficiency.

Brake Mean Effective Pressure

Brake mean effective pressure (BMEP) is a parameter that represents the average pressure on a reciprocating piston during its work stroke. It is typically expressed in pounds per square inch (psi) and is used to measure the intensity of effort (i.e., force per unit area) exerted by a piston at a given speed and power output. Although BMEP is generally associated with IC engines, it may also be applied to Stirling engines. (For the purposes of the BMEP calculation, the Stirling engine is treated as a two-stroke engine with one power stroke per crank revolution.) A low BMEP translates to a larger piston displacement, or a higher engine speed, to achieve a given power output. Table 4-3 lists the mechanical power output and BMEP for selected Stirling engines (assuming a generator efficiency of 90%). Comparable data are also included for a common natural gas-fired reciprocating engine, the Waukesha F18GL.

Table 4-3
Stirling Engine BMEP

Company	Rated Shaft Output (bhp)	BMEP (psi)
Uwe Moch	0.7	19
STM	37.3	69
Sigma	4.5	136
SOLO	14.9	400
ADI	37.3	574
Waukesha – Single Cylinder (F18GL IC Engine)	73 (at 1,800 rpm)	176

The numbers listed in Table 4-3 are displayed graphically in Figure 4-1. The Stirling engine BMEPs vary widely without a distinguishable trend. This is due in part to the different stages of development for each engine. For example, the Uwe Moch engine is a small, proven, do-it-yourself kit meant for hobbyists; therefore, a low *measured* BMEP is expected. On the other hand, the ADI engine is in the design phase with a high *target* BMEP. The exception is SOLO, which has dozens of units operating in the field with relatively high BMEPs.

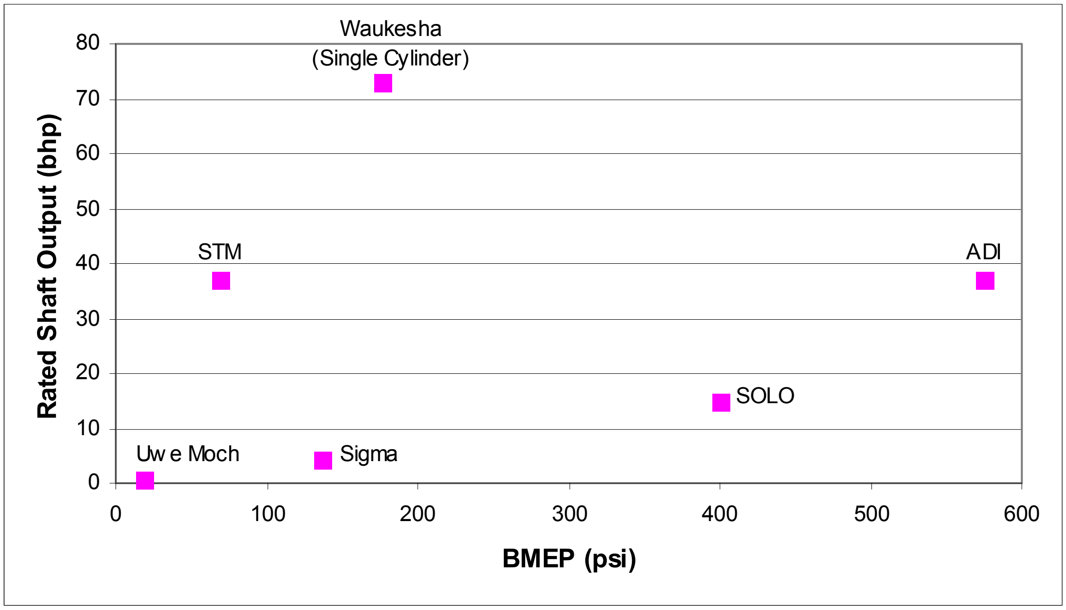

Figure 4-1
Stirling Engine BMEP Versus Mechanical Output

The SOLO product is the only Stirling engine today that has demonstrated a significantly higher BMEP than the Waukesha engine. If SOLO and other Stirling engine developers can consistently demonstrate their target BMEPs, then Stirling engine costs may ultimately be lower than those that are achievable today with IC engines. On the other hand, if the target BMEPs are unattainable, then a larger engine size and weight will be required to achieve a given output. Combined, these factors will have a negative effect on the capital costs of Stirling engines.

Emissions

The emissions from Stirling engines are typically low and easily controlled. There are two primary reasons for this:

- No combustion or chemical reactions need be involved – only heat is required for operation. Therefore, solar heat is an “emission-free” option. Waste heat from other processes may also be used to operate a Stirling engine without adding to the emissions.
- Combustion occurs externally. If a fuel is burned to produce the heat required for operation, it is burned continuously and to completion outside of the engine cylinder. Thus emissions are easier to control than in an IC engine, where fuel is mixed with air and burned intermittently within the cylinder.

Many of the Stirling products under development have targeted NO_X, SO_X, CO, and HC emissions lower than those from conventional IC engines. The exceptions are products that are designed to operate on high-sulfur or “dirty” fuels, like landfill gas, digester gas, and biomass.

Table 4-4 compares the target emissions of the natural-gas-fueled STM PowerUnit prototype (based on the 4-120 Stirling engine) to the emissions from the Waukesha F18GL lean-burn engine (assuming 90% generator efficiency). The volatile organic compound (VOC) and non-methane hydrocarbon (NMHC) emissions of the two technologies are comparable. It is shown that the STM engine has lower emissions than the IC engine only in the NO_x category. STM is ultimately tailoring its engine development to comply with the stringent air quality standards imposed by organizations like the California Air Resources Board and the Texas Natural Resource Conservation Commission.

Table 4-4
IC Engine Versus Stirling Engine Emissions

	STM 4-120		Waukesha F18GL	
Pollutant	**g/bhp-hr**	**lb/MWh**	**g/bhp-hr**	**lb/MWh**
NO_x	0.34	1	2.69	7.94
CO	2.03	6	1.41	4.17
VOC	0.34	1	---	---
NMHC	---	---	0.27	0.79

Noise and Vibration

Stirling engines are much less prone to noise and vibration problems than IC engines since fuel is burned smoothly and continuously outside of the cylinder/s. An 8-cylinder IC engine running at 3,000 rpm has a total of 200 ignitions per second. In one case where mechanical vibration was initially a problem, the Stirling developer redesigned the engine with two cylinders in such a way that the lateral forces of one cancelled the lateral forces of the other, thus greatly reducing vibration. Most of the small Stirling engine products under development for residential applications have audible noise levels of less than 53 decibels at 3 feet. Developers of larger Stirling engine systems anticipate slightly louder products with levels of less than 68 decibels at 3 feet.

Footprint and Weight

Footprint, volume, and weight of Stirling systems all increase with power output. This trend is demonstrated with footprint in Figure 4-2, based on the information available from Stirling engine system developers. Small systems for residential applications typically have a footprint between 2 and 10 square feet and a weight of about 200 to 1,000 lbs. Systems with a 25-kW_e output have a footprint of 15-20 square feet. Large footprints (> 40 square feet) are representative of the products that are planned for larger applications. These larger systems may ultimately be placed on a skid or in a trailer for easy transport, and may weigh up to 10,000 lbs.

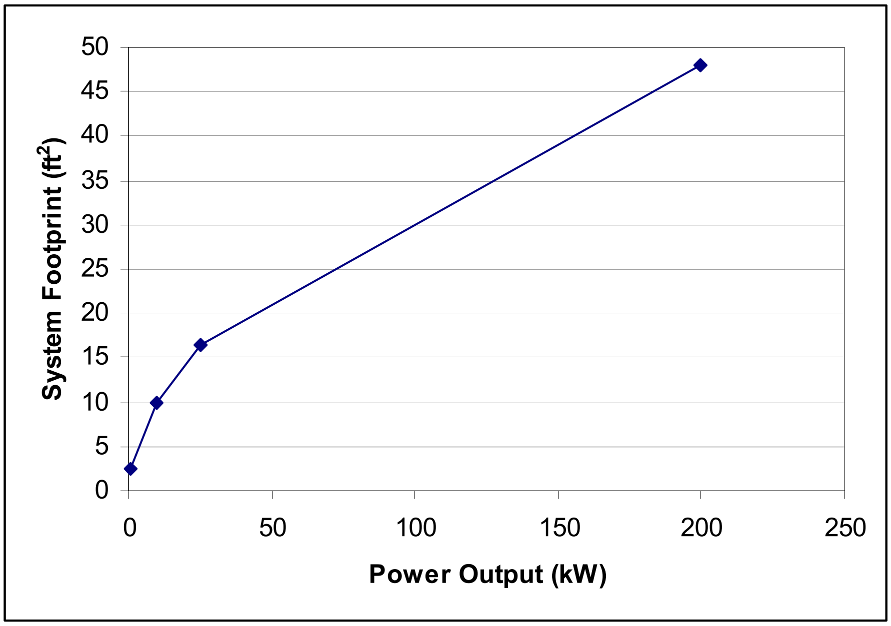

Figure 4-2
Stirling System Footprint Versus Power Output

Product Lifetime and Maintenance

Stirling companies have set engine design criteria for long life with little or no maintenance. This has been particularly important for companies that have developed products for government applications. For example, Kockums was challenged with these requirements when it began the development of engines for use on submarines. Today, Kockums has operated its engines for 18,000 hours without maintenance. Stirling Technology Company also focused on long, maintenance-free engine life when it began development of Stirling engines to provide power for human hearts. The company's 10-W subscale engine has operated maintenance-free for more than 67,000 hours.

These original design criteria have trickled into the development of Stirling engines for stationary power applications. Today's developers anticipate that their Stirling engine products will have long lifetimes, achieving 30,000 to 100,000 hours of operation over 10-20 years. Engine maintenance will typically entail replacement of seals, filters, and lubrication. Some companies envision one to four maintenance inspections per year. Others, particularly those with hermetically sealed units, believe that their engines will operate maintenance-free for many years. Maintenance responsibility may increase for those systems that operate on "dirty" fuels, particularly biomass. In this case, it may be necessary to clean and remove residue from the burner daily.

Development Timelines

Stirling engine companies are competing with each other, and with developers of other conventional and emerging power generation technologies, to get products to market. While some developers are still in the design phase, others are just around the corner from large-scale production. As shown in Table 4-5, there are four companies that presently have demonstration systems available for purchase. Of these four, three are focused on residential markets and the fourth is developing a solar-Stirling system.

Table 4-5
Availability of Stirling Engine Systems for Demonstration

Company	Demo Unit Availability	Final Product Availability
ADI Thermal Power Corp.	Late 2002-Early 2003	---
BG Group	Now	2003
BSR Solar Technologies	2003	---
External Power	2003	---
Quiet Revolution Motor Company	2003-2004	---
Sigma Elektroteknisk	Late 2002	2003-2004
SOLO Kleinmotoren	Now	2003
Stirling Advantage	2004-2005	---
Stirling Energy Systems	Now	2003-2004
Stirling Technology Company	Mid-Late 2002	2003-2004
STM Power	Mid-2002	Late 2003
Sustainable Energy Systems	Late 2002	---
Tamin	Early 2003	---
Uwe Moch	2003	---
Whisper Tech	Now	---

Timelines for product commercialization are highly dependent on the field demonstration phase. If the company does not get the financial support and interest that it anticipates for testing prototypes, it is likely that its target date for product availability will not be met. The companies that are presently demonstrating systems in the field plan to have commercially-available products by 2003-2004.

Commercialization Obstacles

Lack of proven operation and durability is perhaps the largest hurdle in the way of Stirling engine commercialization. Many companies have spent years developing Stirling technology and optimizing theoretical performance. However, there are relatively few companies that have placed numerous systems in the field for testing.

Between 1995 and 2000, Whisper Tech was able to design a Stirling engine system, build and test several prototypes, complete a production design, and offer a DC product for niche applications. The company has since modified the design in order to commercialize a product that generates AC electricity. Although the Whisper Tech system has relatively low efficiency and high cost, the company has proven that it is feasible to design and produce Stirling engine systems in shorter timeframes.

It is likely that the performance characteristics of Stirling engines will improve as companies gain more "real-world" operating experience. However, in order to place demonstration systems in the field, developers must secure funding to design and build prototypes. Lack of investment is another significant commercialization hurdle. Over half of the Stirling engine developers are seeking funding at this time. Without the required investments, these companies may not be able to continue with development plans as scheduled.

5
ECONOMICS

The previous section of this report addressed the technical and performance challenges of Stirling engine development over the last two to three decades. Another primary challenge facing the developers is the Stirling engine's reputation (both real and perceived) for high cost.

The first-cost of Stirling engine technologies has been a continuing challenge to commercialization of the technology due to a number of material-related issues specific to the design architecture. Among these are:

- High-temperature heater head assemblies require large surface areas, and must be made from exotic materials that are particularly difficult to machine, braze and weld.
- The cooler section also requires large surface areas to permit sufficient heat transfer with minimal void volumes.
- The regenerator assembly has a need for very fine mesh heat-transfer matrices that can operate near heater head temperatures, and therefore requires high-temperature materials.
- Shaft-seal assemblies separating the high-pressure hydrogen (or helium) working space from the generator are expensive due to the required seal complexity and tight tolerances. Some designers have placed the generator inside the pressure vessel to avoid this problem.
- Complex mechanical mechanisms.

Developers are currently working to address these issues through a combination of design refinements and material substitution. For example, Sigma has put a considerable amount of effort into the engine hot-end design, which generally accounts for about 50% of the total engine cost. The company has developed a platelet design that was originally developed for rocket engines. Sigma believes that this design will eventually permit operation at much higher temperatures, thereby increasing the thermodynamic efficiency. The company estimates that its new flat-plate plate design will reduce the hot-end cost to 5% of the total engine cost.

Other companies, like BSR Solar and Alternative Designs, have taken an opposite approach to cost reduction by reducing the operating temperature. Lower-temperatures permit the use of less-exotic, and thus less-expensive, materials. However, low-temperature operation also has a negative effect on efficiency, which will increase fuel costs for these Stirling engine systems.

Stirling engines are on the cusp of being able to produce economically competitive electricity. Their ability to provide on-site power (with associated benefits in power reliability and offsetting grid extension costs) could shift the economics in their favor in some locations. It is particularly noteworthy that in Stirling engines nearly all of the heat is rejected to an internal water-cooling system (i.e., very little heat is rejected in exhaust), which facilitates the addition of cogeneration functionality, and may also serve to increase their economic competitiveness.

Near-term Capital Costs

Many of the Stirling engine companies are presently offering or are planning make available prototype systems for field demonstration. Six of the companies included in this project provided pricing for these demonstration systems (see Table 5-1).

Shown graphically in Figure 5-1, the prices vary widely for Stirling demonstration systems. SOLO provided the lowest price at $2,000/kW$_e$ for a system with a 10-kW$_e$ peak output.

Table 5-1
Stirling Engine Beta/Demonstration System Prices

Company	Product	kW$_e$	$/demo	$/kW$_e$
SOLO Kleinmotoren	System	10	20,000	2,000
Stirling Technology Co.	Engine	1.25	45,000	36,000
Stirling Energy Systems	System	25	250,000	10,000
STM Power	System	25	60,000	2,400
Uwe Moch	System	0.95	17,000	17,895
Whisper Tech	AC System	0.95	13,000	13,684

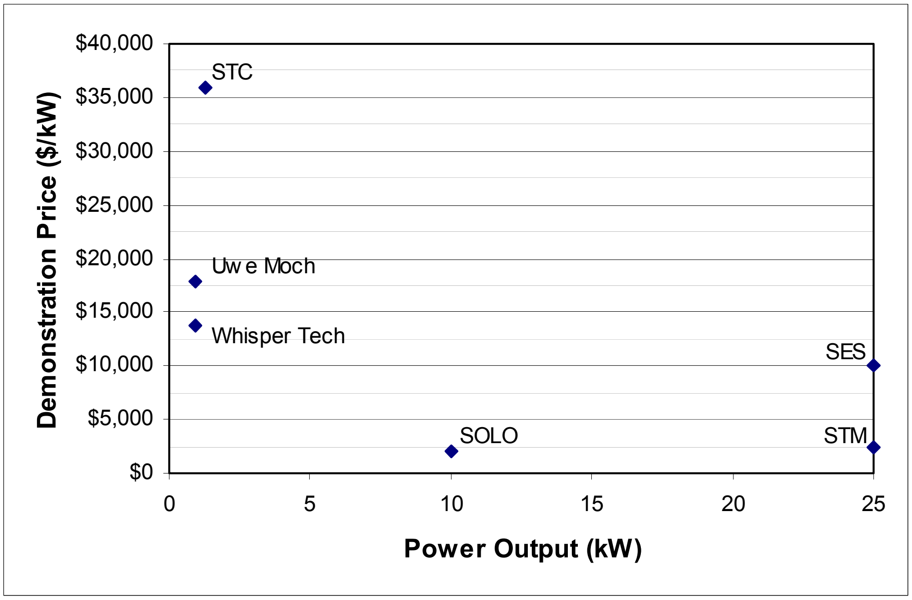

Figure 5-1
Stirling Engine Beta/Demonstration System Prices

Longer-term Capital Costs

A majority of the Stirling developers have set capital cost targets based on a specific production level. These forecasts are presented in the tables and figures that follow.

Two of the developers report these numbers as manufacturing or production costs, as shown in Table 5-2. It is interesting to note that both BSR and Stirling Technology Company provide similar cost targets in $/kW$_e$. However, STC believes that it will require a production volume of 100,000 units per year in order to achieve this cost, whereas BSR bases its estimate on the production of 250 units per year.

Table 5-2
Stirling Engine Manufacturing/Production Costs

Company	Product	kW$_e$	$/kW$_e$	units/yr
BSR Solar Technologies	Engine	7.5	675	250
Stirling Technology Co.	Engine	1.25	800	100,000

Other companies provide cost targets based on the wholesale price or the price that they intend to charge a distributor. Table 5-3 displays the projections of seven Stirling engine developers. In this case, the least expensive estimate is $333/kW$_e$ provided by Sigma at 100,000 units per year. Like Sigma, Whisper Tech is developing a system that is also intended for residential CHP applications. But Whisper Tech's price target is close to nine times that of Sigma's at the same production volume of 100,000. Sigma also recently issued a press release that stated a price of $1,267/kW$_e$ for 10,000 3-kW$_e$ units.

Table 5-3
Stirling Engine Wholesale/Distributor Prices

Company	Product	kW$_e$	$/kW$_e$	units/yr
ADI Thermal Power Corp.	System	25	450	45,000
External Power	Engine	2.7	1,000	10,000
Sigma Elektroteknisk	Engine	3	333	100,000
SOLO Kleinmotoren	System	10	1,500	2,000
Stirling Advantage, Inc.	System	200	450	4,000
Tamin	Engine	10	200	10,000
Whisper Tech	AC System	0.95	2,900	100,000

The production cost and wholesale cost estimates that were obtained from the Stirling engine developers are charted on a logarithmic plot in Figure 5-2. There is no clear trend to establish the true relationship between production volume and capital cost. The lack of pattern is likely due to the varying stages of Stirling engine development, in addition to the wide variety of planned products.

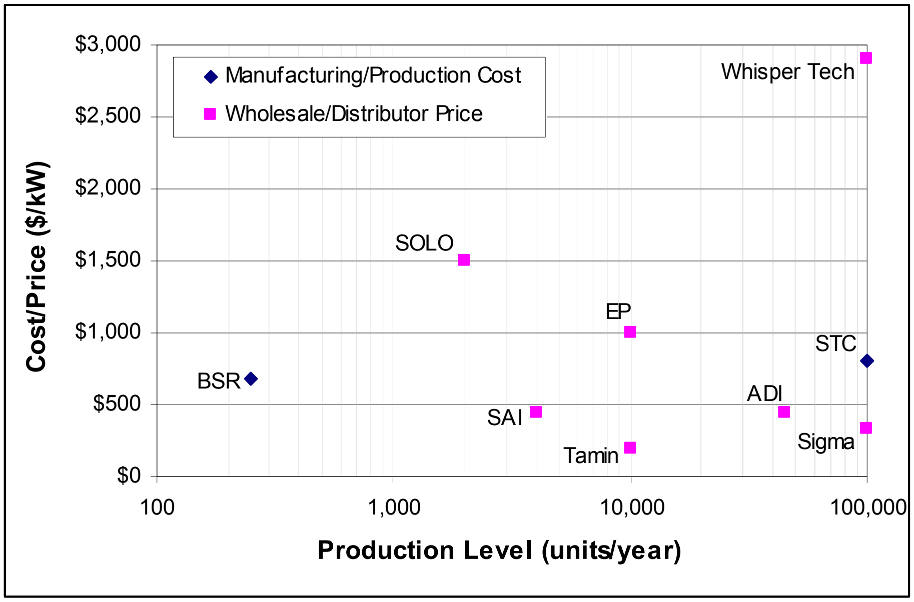

Figure 5-2
Stirling Engine Capital Costs

Once again, it can be seen that Whisper Tech has a target price that is significantly higher than its competitors. However, it is important to note that Whisper Tech is the only Stirling developer that has begun to produce a Stirling engine product and make it commercially available. Perhaps the company has used its experience to lend a dose of reality to the Stirling engine price targets.

As shown in Table 5-4, a handful of Stirling companies have chosen to provide target economic figures in terms of the retail or end-user price. The numbers provided for Kockums and Sunpower are representative of the price for a single, individually-made engine. Both of these companies have licensed their Stirling technology to others for integration into a packaged product. The Uwe Moch product represented in the table is an engine kit that may be ordered for self-assembly. It is estimated that the company sells approximately ten of these kits per year.

The $1,000/kW$_e$ price obtained from STM is the company's target for 2003. The production level is estimated at 50 units per year. Whisper Tech's DC system production level is representative of the number of units sold by the company in FY 2001.

The retail price data listed in Table 5-4 is represented graphically in Figure 5-3.

Table 5-4
Stirling Engine Retail/End User Prices

Company	Product	kW_e	$\$/kW_e$	units/yr
Kockums	Engine	25	4,000	1
STM	System	25	1,000	50
Sunpower	Engine	1	35,000	1
Uwe Moch	Engine Kit	0.5	6,800	10
Whisper Tech	DC System	1.1	11,000	250

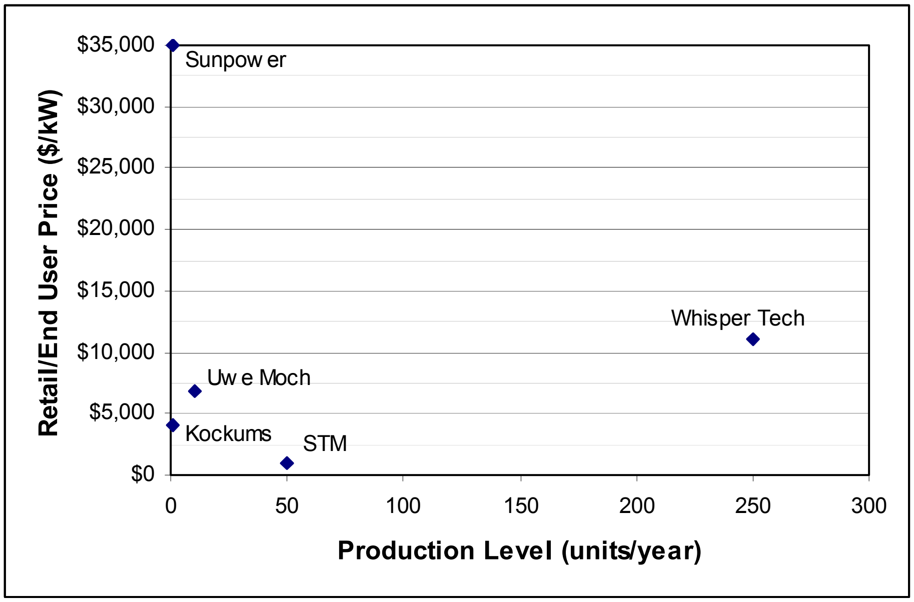

Figure 5-3
Stirling Engine Retail Prices

Installation Costs

Due to the lack of widespread adoption of Stirling engines, installation cost data is not readily available. These costs are likely to be comparable to similarly-sized internal combustion engine generators.

O&M Costs

Developers assert that economic viability will depend upon the core engine structure achieving lifetimes of at least 40,000 hours. However, parts subject to systematic wear (shaft seal assembly and piston rings) will more likely have useful lifetimes of 5,000-10,000 hours in the near term. Current strategies assume that these shorter-lifetime components will have to be replaced on a periodic basis, typically yearly or after 7,500-10,000 hours of operation. Stirling engine developers equate this to an estimated O&M cost of approximately 0.5-1¢/kWh.

6

SUMMARY AND CONCLUSIONS

This report provided a comprehensive review of the status of Stirling engine technology. A total of nineteen developers were profiled to determine technology trends, commercialization status, and economics related to the market entry of Stirling engine products. Seventeen of the nineteen companies are actively pursuing the development of Stirling products for stationary power generation applications. This section summarizes the key aspects of these companies and their products.

Company Comparison

For the past 20-30 years, Stirling engine development has been cyclical in development activity. Recent interest in distributed generation has sparked new activity in the Stirling industry. Numerous companies are striving to bring a wide array of Stirling products to market for a breadth of applications. Most popular are the products planned for residential combined-heat and power applications and small-commercial DG, particularly where “free” or “inexpensive” fuels and heat sources are readily available.

Table 6-1 provides an alphabetical summary of the seventeen Stirling engine developers and the products that they are developing for stationary power generation applications. Companies with several products in various stages of development are listed more than once. The specifications provided are target values that the developers hope to meet with their first products.

Based on the data in Table 6-1 and the information gathered throughout the course of this project, the Stirling companies may be compared based on a variety of factors related to technology, capabilities, market-readiness, and target costs. Target efficiency may be used as a measure of the likely product performance. ADI has a target efficiency of 50%, which significantly higher than other developers. It should also be noted STM has actually demonstrated an efficiency of 30%, so its near-term target of 31% should be achievable.

If target price is used to judge salability, then the ADI, Sigma, SAI, STM, and Tamin products are all attractive at less than \$1,000/kW$_e$. However, one of the most attractive current prices is that of the SOLO beta demonstration system for \$2,000/kW$_e$.

The number of units that have been operated by each company and the longest duration of runtime on a single unit may represent the durability and proven operation of planned products. Whisper Tech has by far the most operational experience, with more than 450 units sold and tested and run times of greater than 10,000 hours. The Kockums engine has also undergone a significant amount of testing, with up to 18,000 hours of maintenance-free run time on more than

200 engines. Also notable is the single subscale 10-W engine by STC that has logged over 67,000 hours.

The availability of field demonstration units may be used to judge market-readiness. In this case BG Group (using Sunpower engine technology), SOLO (using Kockums engine technology), SES (using Kockums engine technology), STC, and Whisper Tech are considered closest to commercialization with demonstration systems available now.

The ability of each company to meet its goals may be measured by several factors: (1) the status of funding, (2) the number of employees that are dedicated to research, development, and demonstration of the technology, (3) strategic relationships that have been established to accelerate commercialization, and (4) production capacity at current facilities. STM, Kockums, SOLO, STC, and Sunpower stand out in this regard.

Table 6-1
Stirling Engine Company and Product Summary

Company	Product	Output (kW_e)	Eff.[15]	# of Units Tested	Longest Run Time (hours)	Demo Avail.	Target Distributor Price ($/kW)	Funding Status	# of Empl.	Facilities (units/yr)	Strategic Partners
ADI	System	25	50 %	1	< 60	2002-3	400-500	Seeking	6	50	Alliant Energy, Northwest NG, IHI
BG	System	1.1	< 22%[1]	28	Unknown	Now	Unknown	Stable	Unknown	Unknown	Rinnai Corp.
BSR	Engine w/ Generator	5-10	35%	1	Unknown	Late 2002	850-1,100[2]	Seeking	11	Unknown	Indian JV, German JV
EP	System	15	7%	1	Unknown	2003	1,500[3]	Unknown	24	10,000	Energidalen
Kockums	Engine	25[6]	38%[7]	200+	18,000+	N/A	N/A	Stable	25[4]	N/A	SES, SOLO
QRMC	Engine	75[6]	41%[7]	0	N/A	2003-4	Unknown	Seeking	6[5]	Unknown	None
Sigma	Engine w/ Burner & Generator	3	27%	6	> 1 year	Mid-2002	333	Seeking	Unknown	< 2,000	Kockums, STM, Statoil, Ricardo, Baxi
SOLO	System	10	24%	16[8]	20,000	Now	1,400-1,600	Stable	8[4]	2,000	Schlaich Bergermann und Partner
SAI	System	200	38%	0	N/A	2004-5	450	Seeking	5	Unknown	None
SES	System	25	33%[12]	2	10,000	Now	N/A[9]	Seeking	18	6	Arizona PS, Gamesa Energia

Company	Product	Output (kW)	Eff. [15]	# of Units Tested	Longest Run Time (hours)	Demo Avail.	Target Distributor Price ($/kW)	Funding Status	# of Empl.	Facilities (units/yr)	Strategic Partners
STC	Engine w/ Burner & Generator	0.35	18% [1]	20+	67,000 [10]	Now	Unknown	Seeking	30+	Hundreds	None
STC	Engine w/ Burner & Generator	0.55	24% [1]	Unknown	Unknown	Unknown	Unknown	Seeking	30+	Hundreds	Undisclosed Licensee
STC	Engine w/ Burner & Generator	1.25	18% [1]	3	Unknown	Now	1,150 [2]	Seeking	30+	Hundreds	ENATEC Microgen
STC	Engine w/ Burner & Generator	3	31% [1]	Unknown	Unknown	2002	Unknown	Seeking	30+	Hundreds	None
STM	System	25	31%	10	4,400	Mid 2002	700 [11]	Stable	53	2,400	DTE Energy Technologies
Sunpower	Engine w/ Alternator	1	28%	30+	Unknown	Now	Unknown	Unknown	50	N/A	BG Group, External Power, Global Cooling
Sustainable	Engine w/ Generator	10	Unknown	1	Unknown	Late 2002	Unknown	Seeking	3	N/A	None
Tamin	Engine	10	35%	1	Unknown	Early 2003	200	Seeking	6	Unknown	None
Uwe Moch	Engine Kit	0.5	Unknown	70+	Unknown	N/A	6,800 [13]	N/A	> 6	Unknown	None
Uwe Moch	System	0.95	21%	1	1,400+	2003	Unknown	Seeking	> 6	Unknown	None

Company	Product	Output (kW)	Eff. [15]	# of Units Tested	Longest Run Time (hours)	Demo Avail.	Target Distributor Price ($/kW)	Funding Status	# of Empl.	Facilities (units/yr)	Strategic Partners
Whisper	DC System	1.1	12%	450	10,000+	Now [14]	Unknown	Stable	60	2,000	Orion, Meridian Energy
Whisper	AC System	0.95	12%	50	6,000+	Now	2,900	Stable	60	2,000	Orion, Meridian Energy

[1] Assuming a maximum burner efficiency of 80%

[2] Assuming a 30% margin after production cost

[3] Assuming gasifier/burner and system integration will add 1/3 to the price

[4] Full-time employees dedicated to the Stirling program

[5] One full-time employee and five part-time employees

[6] Shaft output

[7] Assuming a maximum generator efficiency of 90%

[8] SOLO has also built and tested more than 150 engines

[9] SES ultimately intends to sell power purchase agreements

[10] Hours accumulated on a subscale 10-W engine

[11] Assuming a 30% margin to distributor

[12] Based on solar heat in to AC out

[13] Price for commercially available engine kit

[14] Commercially Available

[15] Based on LHV fuel in to AC out, unless otherwise noted

Stirling Engine Outlook

This investigation of the current technical state of the art and commercial activity in Stirling engine and product development revealed the following:

A great variety of designs and sizes have reached the prototype stage, and a few engines have been commercially produced, albeit in limited numbers. Several companies that are currently undergoing field demonstrations plan to have products available within the next 1-2 years.

In contrast to IC engines, or even microturbines, there is much greater diversity in approach and design in the various Stirling products. Virtually every developer has a different mechanical approach (and accompanying set of claims for the superiority of that particular design). Low-temperature and low-speed designs are becoming much more common.

Several new Stirling developers, particularly in the US, have entered the market within the past five years.

Developers appear to be focusing on niche applications within distributed generation in order to get units operating. These markets may be less critical of system performance and economics.

Most of the developers have designed a product in one of two distinct size/output ranges: residential combined heat and power (1-5 kW_e) and commercial on-site power generation (25 kW_e).

Pricing and performance information is widely scattered among technology types and product sizes without a noticeable trend (e.g., increasing price with increasing power output).

While field test experience is not yet sufficient to allow for full commercialization of Stirling engines, it is substantial relative to some of the other DG technologies. Efforts to develop Stirling engines into commercial products are still too weak to expect these engines to make a significant impact in the near future. If and when these markets mature, Stirling engines could provide an economically competitive and environmentally “green” alternative to current choices. EPRI has implemented a demonstration program wherein one or more Stirling engine systems will be tested in the laboratory and at field test sites.

A
COMPANY PROFILES

Appendix A includes profiles of the following 19 vendors that are involved in the development and/or sales of Stirling engine technology:

- ADI Thermal Power Corp. (USA)
- BG Group plc (UK)
- BSR Solar Technologies GmbH (Germany)
- External Power, LLC (USA)
- Kockums (Sweden)
- Quiet Revolution Motor Company (USA)
- Sanyo Electric Company, Ltd. (Japan)
- Sigma Elektroteknisk A.S. (Norway)
- SOLO Kleinmotoren GmbH (Germany)
- Stirling Advantage, Inc. (USA)
- Stirling Energy Systems, Inc. (USA)
- Stirling Technology Company (USA)
- Stirling Technology, Inc. (USA)
- STM Power, Inc. (USA)
- Sunpower, Inc. (USA)
- Sustainable Energy Systems Limited (UK)
- Tamin (USA)
- Uwe Moch (Germany)
- Whisper Tech Limited (New Zealand)

The profiles are arranged alphabetically. Each profile begins with the company name and contact information. Each company is also categorized by one or more of the following market roles, listed at the top of each profile with the contact information:

- Engine Developer – The company designs and develops Stirling engine technology.
- Engine Manufacturer – The company manufactures or plans to manufacture a Stirling engine.

- Product Packager – The company integrates a Stirling engine into a complete system.
- Product Distributor – The company sells or plans to sell a complete Stirling product to the end user.

The information contained in each of the vendor profiles was obtained through literature and web-based searches, and through phone interviews with each company through June 2002. While the goal was to obtain the same depth of information from each Stirling engine company, not every company was willing to provide complete details. Additionally, the companies are in different stages of development and some have not yet determined product-related specifications. Therefore, the length of the company profiles vary based on the amount of information provided by each specific company. Each profile includes an introductory paragraph and then contains the following sections, detailed below.

Company Background

This section includes information about the history of the company, the facilities, and employee count. The ownership of the company, financial resources, and strategic partnerships are also included.

Technology Overview

This section describes the company's Stirling engine technology and/or integrated system design and how it works. Technical development issues are included where applicable. Intellectual property ownership is also addressed.

Technology Status

This section discusses current and/or future products offered by the company. Product parameters, pricing, availability, applications, demonstrations, channels to market, and commercialization obstacles are provided. This section also contains a specification table for each current or planned product. Table A-1 on the next page provides a complete list and explanation of the specifications that may appear in the individual product tables. Each individual product table contains only those product parameters that are applicable and that were made available by the specific vendor.

EPRI Perspective

This section provides EPRI's opinion about the company's market position, technical and commercialization issues, and timeline.

Table A-1
Sample Product Specification Table

Product	Engine or Integrated System
Product Status	Design/Lab Stage, May Have a Single Unit in Testing Multiple (<10) Early Units in Testing (alpha) Many (10-20) Pre-Production Prototypes in the Field (beta) In Production
Engine Type	Kinematic or Free-Piston
Cylinders / Power Pistons	One, Two, Three, or Four
Working Fluid	Hydrogen, Helium, Nitrogen, or Air
Hot End Temperature	ºF ºC
Cool End Temperature	ºF ºC
Pressure	psi
Engine Shaft Speed	rpm
Generator / Alternator	Induction Generator Synchronous Generator Asynchronous Generator Poly-phase Generator Linear Alternator
Power Output	kW_{shaft}, kW_e DC, or kW_e AC
Phases	3-Phase or Single-Phase
Voltage / Frequency	VAC @ Hz
Usable Heat Output	kW_{th}
Fuel	Natural Gas, Propane, Diesel, Biomass, etc.
Electrical Efficiency	LHV Fuel In to Shaft Power Out LHV Fuel In to DC Electricity Out LHV Fuel In to AC Electricity Out
Overall Efficiency	LHV Fuel In to DC Electricity and Usable Heat Out LHV Fuel In to AC Electricity and Usable Heat Out
Physical Size (w x d x h)	In mm
Weight (dry)	Lbs kg
Noise Level	dbA at ft
Emissions	ppm at 15% O_2
Servicing Interval	hours or years
Product Lifetime	hours or years
Warranty	Years
Production Cost	$/kW_e$ @ number of units per year
Price to Distributor	$/kW_e$ @ number of units per year
Price to End User (Retail)	$/kW_e$ @ number of units per year
O&M Cost	$/kWh

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Role: Engine Developer, Engine Manufacturer, Product Packager

ADI Thermal Power Corp. (previously doing business as Alternative Designs, Inc.) is a developer of high-temperature, kinematic Stirling engine technology. The company has developed a 25-kW$_e$, natural gas-fueled system for demonstration purposes. ADI ultimately plans to commercialize Stirling engine systems with power outputs up to 100 kW$_e$ for distributed generation applications. The company is targeting an electrical efficiency of 50%.

Company Background

ADI Thermal Power Corp. (ADI) was formed in May 2001 to focus entirely on the kinematic Stirling engine development begun by Alternative Designs, Inc. in 1995. The company has concentrated on two key criteria in its Stirling engine design: high-temperature operation (which permits high thermodynamic efficiency) and low-cost production. ADI has designed a patented "dual-shell" Stirling engine that permits an operating temperature as high as 2,000 ºF and an electrical efficiency up to 50%. The company presently has six employees at its 3,500 square-foot facility near Seattle in Woodinville, Washington.

ADI has received approximately $1.7 million in funding over the past three years. Investors include Alliant Energy, EPRI, Ishikawajima-Harima Heavy Industries (IHI), an east coast group of individuals, and several ex-Boeing "angel investors," including ADI founder and President, Wayne Bliesner, and Vice President, Gerald Fargo. The company seeks to raise an additional $4 million in 2002 to add employees, prepare its Stirling engine for market, fabricate and support field demonstration units, and prepare for initial manufacturing.

ADI has established a strategic relationship with Northwest Natural Gas for testing and demonstration of up to 20 Stirling engine prototype systems. EPRI, Alliant Energy, and IHI will also be involved in the demonstration and commercialization of ADI Stirling engine systems.

Technology Overview

ADI has received two patents on its kinematic “dual-shell” Stirling engine design and has an additional nine patents pending in the US, Canada, Western Europe, and Japan. The “dual-shell” engine permits the separation of pressure from temperature. It was created in order to achieve electrical efficiencies of 50% while dramatically reducing production cost to $300-600 per kilowatt. The single-cylinder, “dual-shell” engine utilizes helium as the working fluid and employs a wobble plate design to mechanically connect the power piston and the displacer. ADI believes that the “dual-shell” design has a number of competitive advantages:

- The “dual-shell” engine design permits high-temperature (up to 2000 ºF) and high-pressure (up to 1000 psi) operation, while at the same time reducing stress on the components that are at high temperatures and improving efficiency. Stress reduction permits the use of common, inexpensive materials and increases the lifetime of the engine.
- The engine employs a wobble plate/crank design that permits several cylinders to be connected to a common crank (i.e., modularity).
- The engine has a simplified heater head design that decreases the number of brazes required from 280 to 30, dramatically reducing the size of the heater head. ADI has also developed a proprietary process in which all 30 brazes occur simultaneously in one step, lowering the production cost.
- The “dual-shell” engine utilizes an advanced regenerator that improves heat transfer to and from the working fluid, while minimizing heat and pressure losses. This improves the efficiency of the engine.
- The “dual-shell” design isolates the inner shell from the outer shell of the engine, permitting rapid start-up and response time.

The primary risk in ADI’s “dual-shell” design is material corrosion from high-temperature operation. The company has chosen materials that have been successfully tested under the system operating conditions. One element incorporates a proprietary coating that is presently only available from a government laboratory. However, it is anticipated that the laboratory is willing to license the coating process to industry suppliers.

Technology Status

ADI ultimately plans to offer multi-cylinder, integrated Stirling engine systems with power outputs up to 100 kW. The company’s first product will be a single-cylinder, 25-kW_e Stirling engine system (see Table A-2 for target specifications). The company began operation on its first prototype system in July 2000. ADI recently completed fabrication of a single third-generation prototype for a cost of $50,000. It operates on propane and employs a 3-phase synchronous generator. The prototypes have accumulated more than 60 hours of operation combined, with 90% on the third-generation prototype. ADI plans to replace the 3-phase synchronous generator with a poly-phase generator.

Once operation of the beta system is fully proven and optimized, ADI anticipates that it will be able to secure additional funding for the fabrication of complete systems for demonstration. The company plans for demonstrations to begin in late 2002 or early 2003. ADI estimates a total cost of $100,000 to $200,000 for a year-long system demonstration, including start up and field support. Alliant Energy will likely receive the first demonstration unit. Northwest Natural Gas has also committed to up to 20 systems for testing and demonstration at many sites in the Northwest US (mostly in Oregon), including Fred Meyer stores, Albertson's stores, and commercial processing plants. In addition, ADI has had discussions with Puget Sound Energy regarding possible demonstrations.

Table A-2
ADI Target Specifications – 25-kW$_e$ System

Product	Integrated System
Product Status	Design/Lab Stage, May Have a Single Unit in Testing
Engine Type	Kinematic
Cylinders / Power Pistons	One
Working Fluid	Helium
Hot End Temperature	Up to 2,000 °F Up to 1,100°C
Pressure	Up to 1,000 psi
Engine Shaft Speed	1,200-1,800 rpm
Generator / Alternator	Poly-phase Generator
Power Output	25 kW$_e$ AC
Phases	3-Phase
Voltage/Frequency	480 VAC @ 60 Hz
Fuel	Natural Gas
Electrical Efficiency	50% (LHV Fuel In to AC Electricity Out)
Overall Efficiency	80% (LHV Fuel In to AC Electricity and Usable Heat Out)
Servicing Interval	2 years (smaller bearings, seals, etc.)
Product Lifetime	10-20 years (with continuous operation)
Price to Distributor	$400-500/kW$_e$ @ 40,000-50,000 units/year
O&M Cost	$0.005/kWh

ADI plans to make its first product, the 25-kW$_e$ Stirling engine system, commercially available in 2003 or 2004 at a price of about $650 per kW$_e$. The long-term target price is $400-500 per kW$_e$ at a production level of 40,000-50,000 units per year (near the end of the decade). ADI's current facility has a production capacity of 50 systems per year. The company plans to expand these facilities or purchase new facilities in order to complete final assembly of its Stirling products in house, while outsourcing the manufacturing of most subcomponents. ADI will initially sell its products through utilities for stationary distributed power generation applications.

Ultimately, ADI envisions several products, including a two-cylinder, 50-kW_e Stirling engine system and a four-cylinder, 100-kW_e system. ADI plans to make products available for a variety of fuels, including biomass. The company also has an interest in integrating its Stirling engine systems with high-temperature fuel cells (MCFC or SOFC). In this case, the Stirling engine would operate on the exhaust heat from the fuel cell, increasing the overall system efficiency to 70-80%. The timeframe for a hybrid product has not yet been established.

EPRI Perspective

ADI is pursuing commercialization of the highest-temperature Stirling engine technology under development. While high-temperature operation theoretically signifies a high thermodynamic efficiency (ADI's is much higher than other developers), it also produces a harsh operating environment that may contribute to material corrosion. Although ADI has proven short-term operation of a single engine, it remains to be seen whether the company's engines will be able to withstand high temperatures without degradation over a long period of operation. In addition, the company must secure a significant amount of funding in the near-term in order to meet the commercialization milestones it has set.

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Role: Product Packager

BG Group, headquartered in the U.K., is an integrated natural gas technology company that has operating divisions for exploration, production, transmission, and distribution of natural gas and liquefied natural gas (LNG). The company has developed a product called the MicroGen energy system that is based on core free-piston Stirling engine technology from Sunpower in the U.S. The MicroGen provides 1.1 kW_e and has a range of thermal outputs to suit the space heating and hot water needs of European homes. The MicroGen energy system is intended for boiler replacement in residential and light commercial premises. Rinnai Corporation, a leading boiler manufacturer in Japan, is expected to commence volume production of the MicroGen product in 2003.

Company Background

In December 1999, BG plc (formerly British Gas plc) was restructured and split into two groups. The first group, Lattice Group, is made up of several operating divisions, including Advantica and Transco. Advantica is the technology leader within the group, while Transco is a regulated division that handles natural gas transmission and distribution within the United Kingdom. The second group resulting from the split is BG Group plc. BG Group is involved in the exploration and production of oil and gas, the development and operation of an infrastructure for liquefied natural gas (LNG), the transmission and distribution of gas and electricity, and power generation.

BG Group is a public company, with shares traded on the London Stock Exchange under the ticker symbol BG and on the New York Stock Exchange under ticker symbol BRG. The company is headquartered in Reading, England, with operations in approximately 20 countries worldwide. As of year-end 2000, BG Group had more than 4,000 employees, more than half of whom were located outside of the United Kingdom.

Technology Overview

BG Group has developed a Stirling engine-based product for residential and light commercial cogeneration applications. The product, MicroGen, is based on Sunpower's free-piston Stirling engine technology. As a product integrator and packager, BG Group has made a variety of technological modifications to the engine and surrounding system to develop a low-cost, high-quality product. BG Group owns rights to key intellectual property used in the MicroGen.

The Stirling engine employed in the MicroGen system is hermetically sealed and uses helium as the working fluid. This design ensures limited wear on moving parts and a long product life. The product is combined with features of a typical home boiler system to result in a product that provides both electricity and hot water.

BG intends for the MicroGen system to be competitive with, and to supplant, the traditional residential boilers that are in use today. Therefore, cost is an overriding factor in the product development process. BG's near-term priority is the design of a low-cost manufacturing method for the MicroGen product.

Technology Status

The electric output from the MicroGen system is rated at 1.1 kW, with a heat output matching the range available from conventional boilers (see Table A-3). The MicroGen product is designed to operate in a grid-parallel mode or as a stand-alone system. The MicroGen has a design life equivalent to modern boilers, with maintenance intervals comparable to standard residential condensing boilers. Since the product is based on a free piston Stirling engine technology, it requires no lubrication. It also has fewer moving parts than a kinematic Stirling engine, potentially increasing the lifetime of the engine. NO_X and CO_2 emissions from the MicroGen are expected to be competitive with the best available boilers.

The MicroGen product is in the testing and demonstration phase. Prototypes have been operating in the field since late 2001. In January 2002, BG Group announced the formation of an exclusive product development partnership with Rinnai Corporation of Japan. Together, the companies plan to invest up to $40 million to launch the MicroGen product. BG Group and Rinnai plan to begin large-scale production in 2003. The initial target market for the MicroGen is the U.K., followed by other selected markets.

Table A-3
BG Group Target Specifications – MicroGen System

Product	Integrated System
Product Status	Many (10-20) Pre-Production Prototypes in the Field (beta)
Engine Type	Free-Piston
Cylinders / Power Pistons	One
Working Fluid	Helium
Generator / Alternator	Linear Alternator
Power Output	1.1 kW_e AC
Phases	Single-Phase
Voltage / Frequency	240 VAC @ 50 Hz
Usable Heat Output	15-36 kW_{th}
Fuel	Natural Gas, Propane

EPRI Perspective

With the backing of Stirling technology powerhouse Sunpower and collaboration of its licensee, External Power, LLC, the BG MicroGen product is likely to be a durable, reliable, and highly-efficient combined heat and power system. It remains to be seen whether BG and Rinnai will succeed in the development of a low-cost manufacturing method in time to meet their commercialization goals. However, if the company does succeed, the MicroGen Stirling engine product will have the potential to become the first successful and economically feasible MCHP system on the market. Furthermore, recognition of the BG name may help to boost sales in the UK market and abroad.

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Role: Engine Developer, Engine Manufacturer, Product Packager

BSR Solar Technologies GmbH (BSR) of Germany has developed a low-temperature (100-500+ ºC), free-piston Stirling technology called *SUN**PULSE***™. The company also has core technology in magnesium hydride-based, thermo-chemical heat-storage systems called SOLARSTORAGE™. BSR plans to commercialize solar-fueled Stirling engine systems that can operate 24-hours per day with power outputs up to 100 kW. The company is also developing 5-10 kW_e natural gas-fueled engines based on the *SUN**PULSE*** ™ technology.

Company Background

BSR Solar Technologies GmbH (BSR) was founded in May 2001 by Jürgen Kleinwächter and Claus Colsman-Freyberger. The company emerged from the private research institute KLERA and the Bomin Solar Group. KLERA was formed in 1971 by the late Professor Hans Kleinwächter to invent and develop technologies based on a strong physics, electronics, mechanical engineering, and material sciences know-how. KLERA joined forces with the oil company Bomin in 1980, forming Bomin Solar GmbH and later Bomin Solar Research. BSR's primary business focus includes heat storage systems and Stirling engine systems powered by renewable energy, particularly solar radiation.

BSR is a privately-held company with facilities in Lörrach, Germany. The company's majority shareholder is Jürgen Kleinwächter. BSR operates on private investments and government-sponsored contracts, totaling in excess of DM 30 million or more than $13 million over the last thirty years. BSR has eleven full-time employees and works closely with its development and industrial partners.

BSR has established a joint venture with an undisclosed industrial partner in India. The new company, Bomin Solar Research India Pvt. Ltd., will adapt the current BSR products for employment in the Asian sun-belt countries. The joint venture will also serve as an Asian distribution, sales, and marketing arm for BSR.

BSR is also the development partner for a joint venture of a German industrial company and PowerPulse Holding AG (formerly Bomin Solar Holding AG). The undisclosed German company has a parent company in the U.S. The joint venture has been granted worldwide rights by PowerPulse to commercialize the Stirling engine in natural-gas-fired cogeneration applications.

Technology Overview

BSR began its Stirling development work in the 1980s (at that time the Bomin Group) with a conventional kinematic Stirling engine that operated with a hot-end temperature of about 800 ºC. The company then moved on to design a free-piston engine based on the core technology of Professor William Beale of Sunpower. This engine also operated at a high temperature similar to that of BSR's kinematic engine. Through a joint venture with Sunpower, Bomin developed a 10-kW_e free-piston Stirling generator and a 10-kW_e free-piston Stirling heat pump. Next, Bomin developed a magnetically-coupled free-piston Stirling engine for solar applications that, like its predecessors, operated at a high temperature. The company successfully tested the engine with a specially-designed membrane solar concentrator with fixed focal point.

Following the development of these engine designs, Bomin came to the conclusion that all conventional high-temperature Stirling engines lead to an economic dead end. The company also concluded that high-temperature designs yield only about 50% of the ideal Carnot efficiency.

Concurrently with its Stirling work, Bomin jointly developed a thermo-chemical heat storage technology called SOLARSTORAGE™ with the Max-Planck Institut in Germany. The magnesium-hydride SOLARSTORAGE™ system permits 24-hour operation of solar power stations by storing the solar heat at 400-500 ºC. However, the company's Stirling engine at that time required temperatures of 800 ºC for efficient operation. This confirmed BSR's belief that a lower-temperature Stirling engine is required for cost-effective production and operation of Stirling engine systems.

Therefore, in the early 1990s Bomin began the development of a unique Stirling technology called *SUN**PULSE*** ™. This technology is based on the following characteristics:

- Low- to medium- temperature (i.e., 100-500+ ºC)
- Low piston frequency (i.e., 0.5-3.0 Hz)
- Relatively high electrical efficiencies (~35% - heat in to AC out)
- Free-piston technology (i.e., no crankshafts)
- Air working fluid (i.e., no hermetical seals)

The *SUN**PULSE*** ™ technology (system schematic shown in Figure A-1) is protected by patents in Europe, the United States, Japan, China, and other countries. BSR plans to work with development and industrial partners to commercialize this technology in stationary power generation applications.

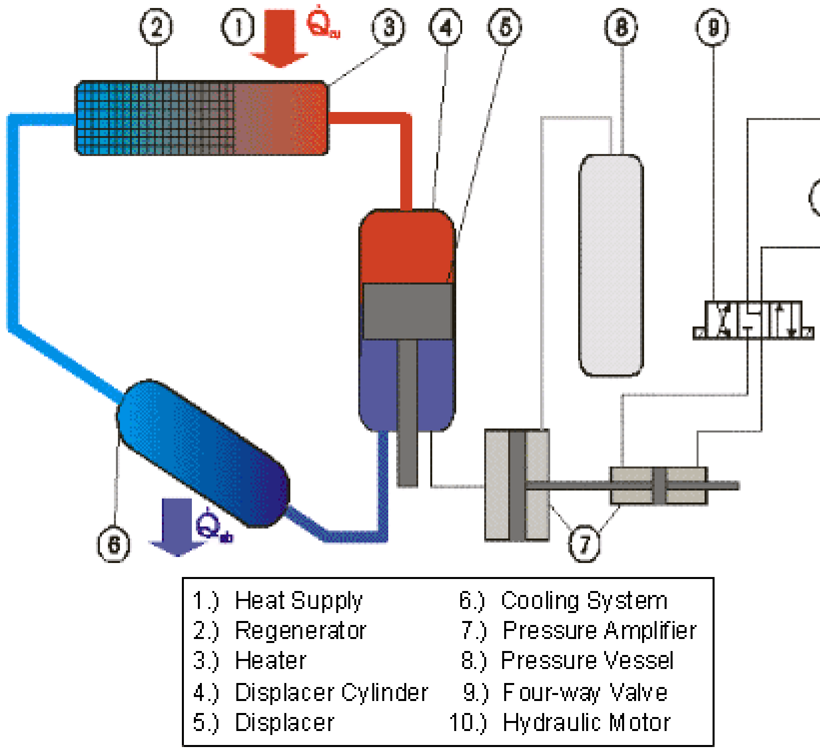

Figure A-1
BSR *SUNPULSE™* System Schematic

Technology Status

The BSR ***SUNPULSE*** ™ engine is designed for operation with low-temperature heat input, such as unconcentrated sun radiation. The engine can also be adapted to operate on conventional fuels. BSR has built a natural-gas-fueled demonstration unit (shown in Figure A-2). This system, which operates at a hot-end temperature of 700 ºC, has an electrical output of approximately 1 kW_e and has undergone extensive testing at BSR facilities in order to prove its functionality. The unit achieves approximately 90% of the ideal Carnot efficiency, as shown in the actual pressure-volume diagram (see Figure A-3.)

BSR plans to build two to three more of these prototypes over the next year for field demonstrations. The joint venture of PowerPulse and an undisclosed German industrial partner has been granted worldwide rights to the ***SUNPULSE*** ™ Stirling engine for cogeneration applications. The cogeneration products will ultimately have power outputs in the 5-10 kW_e range.

Figure A-2
BSR *SUNPULSE* ™ Demonstrator**

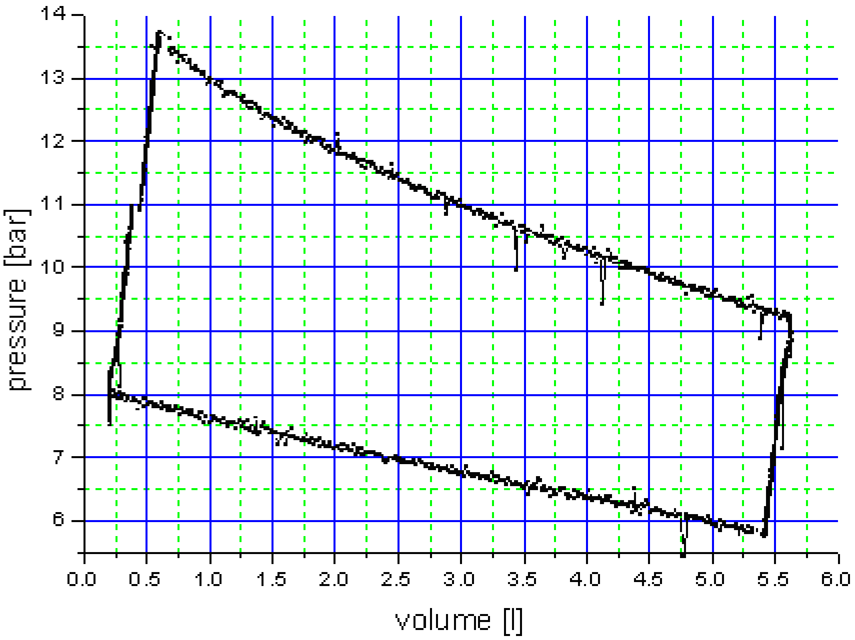

Figure A-3
Measured P-V Diagram of BSR *SUNPULSE*™ Demonstrator**

BSR is also continuing to work on its solar Stirling systems under a contract with the German government. The company is developing a 5-kW$_e$ solar thermal power station that will integrate the BSR Stirling engine with the BSR heat storage technology. These systems are designed for distributed power generation applications, particularly in sun-belt countries. It is anticipated that the demonstration systems may feed electricity to the grid as opposed to supplying electric loads directly. The target electrical efficiency is 35% (solar in to AC out). BSR intends to commercialize the solar Stirling systems through its joint venture in India. The company may also consider establishing additional partnerships to commercialize the *SUN**PULSE*** ™ - SOLARSTORAGE™ system in the United States.

BSR is also considering waste heat as a possible fuel source for its middle-temperature *SUN**PULSE*** ™ engine. The company believes that exhaust from other DER technologies (e.g., fuel cells, microturbines, etc.) may be attractive applications. In fact, BSR discussed this possibility with Capstone Turbine Corporation about two years ago. While it was too early to progress with the idea at that time, BSR has not lost sight of the waste heat or exhaust fuel option.

BSR estimates a long lifetime for the *SUN**PULSE*** ™ engine, due to the relatively low operating temperatures and low operating frequency. Use of air as the working fluid also eliminates the requirement of a hydrogen or helium bottle typically needed for recharging. The *SUN**PULSE*** ™ products are still in the early stages of development; thus, physical and operating specifications have not yet been determined. BSR estimates a market entry (or breakeven) production volume of less than 250 units per year, with a manufacturing cost of $600-750 per kilowatt.

Table A-4
BSR Solar Target Specifications – *SUNPULSE™* Engine

Product	Engine
Product Status	Design/Lab Stage, May Have a Single Unit in Testing
Engine Type	Free-Piston
Cylinders / Power Pistons	One
Working Fluid	Air
Hot End Temperature	200-900 °F 100-500 °C
Power Output	5-10 kW_e AC
Fuel	Solar Radiation, Waste Heat, Natural Gas
Electrical Efficiency	35% (LHV Fuel In to AC Electricity Out)
Production Cost	$600-750/$kW_e$ @ 250 units per year

EPRI Perspective

BSR's low-temperature philosophy and Stirling engine design is unique compared to other technology developers. While the company is still in the early stages of development and has not yet tested large numbers of systems, early results from the first natural-gas-fueled *SUN**PULSE*** ™ demonstrator are very promising. The BSR technology bears watching.

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Role:	Engine Manufacturer, Product Packager

External Power, LLC was created in 1996 to commercialize free-piston Stirling engine systems as the exclusive licensee of Sunpower's engine technology. Since then EP has modified the core Sunpower Stirling engine to create a unique "twin-opposed" engine that generates 2.7 kW_e. The company has partnered with Wood-Mizer Products, Inc. to integrate this engine with a two-stage burner for undensified biomass fuels (e.g., wood chips, wood chunks, saw dust) as a light-industrial-scale cogeneration system. WM plans to distribute Stirling engine products through its established network of distributors for portable saw mills.

Company Background

External Power, LLC, (EP) was created by Wood-Mizer Products, Inc. (WM) in 1996 to focus on the commercialization of Stirling engine systems based on the core Sunpower Stirling engine technology. Sunpower exclusively licensed its free-piston Stirling engine technology to Wood-Mizer in 1994. This license was then assigned to External Power upon formation of the company. Wood-Mizer is a manufacturer of portable saw mills with an established distribution network in more than 100 countries worldwide. External Power plans to utilize this channel for distribution of Stirling engine products heated by the combustion of gas and undensified biomass fuels. External Power has also granted a technology sublicense to BG Group of the UK. This sublicense extends worldwide an accompanying license granted to BG by Sunpower for the sale of domestic combined heat and power appliances in Western Europe.

External Power has about two dozen employees that are split between two facilities. The company has an office in Indianapolis, Indiana near the Wood-Mizer headquarters. EP also has a production facility in close proximity to Sunpower in Athens, Ohio. Wood-Mizer and External Power are both privately-held companies. Don Laskowski, founder and CEO of both companies, has been a primary source of funding at External Power. The company has also secured funding for the past several years through a multi-phase Department of Energy contract.

Technology Overview

External Power holds an exclusive license to commercialize Sunpower's free-piston engine technology using three primary energy sources (fossil fuel, biomass fuel, and solar energy) to produce three kinds of useful output power (electric, hydraulic, and pneumatic). The Sunpower free-piston engine has a single cylinder, utilizes helium as the working fluid, and is hermetically sealed. EP has modified the Sunpower engine design in order to achieve an electrical output of 2.5 kW. EP's "twin-opposed" engine design incorporates two cylinders (i.e., two power pistons and two displacers) with a single heater head. This new engine design eliminates the vibration (1-2 mm in amplitude) that was present in the single-cylinder Sunpower engine.

The External Power Stirling engine system incorporates a gasifier-burner unit that can accept a wide variety of biomass fuels with varying levels of moisture content (e.g., wood chips, sawdust, chuck wood, wood pellets, etc.). This versatility, combined with modularity, makes the product attractive for a wide variety of applications.

Technology Status

External Power's initial focus is on the development of manufacturing processes for Stirling engines. The company plans to confirm these processes in a pilot production plant capable of manufacturing up to 10,000 units per year. EP has identified undensified biomass as an appealing niche market to serve through its partner, Wood-Mizer, which sells portable saw mills throughout the world. These small saw mills generate a significant amount of waste sawdust that may be expensive to remove. An attractive alternative is to use the waste sawdust as a fuel to supply heat and power for the saw mill operation. EP plans to connect six "twin-opposed" to yield a system that can provide about 15 kW_e for each saw mill.

Since portable saw mills are located in territories with a large supply of biomass fuels, EP expects WM distributors to reach several other light-industrial, commercial, and institutional customers as well. For example, a wood log- or wood chunk-fueled Stirling system may act as a remote, stand-alone power station for hospitals or schools in developing countries. There may also be similar off-grid, commercial and industrial applications in the United States.

EP also plans to enter the European residential combined heat and power (CHP) market with Stirling systems fueled by wood pellets. The company also plans to form strategic partnerships to introduce individual Stirling systems for natural gas-fueled residential (on-grid) cogeneration applications (using forced-air heating) in the US.

External Power is currently testing a prototype engine at the WM headquarters facility in Indianapolis, but the company has not yet field tested its Stirling system in its intended application. EP hopes to receive an additional phase of funding from the DOE to build several integrated Stirling systems for testing at several field trial sites. The company also claims that it has received commitments from unidentified strategic partners in the US and Canada to test a total of 100 Stirling engine systems.

EP has completed the production design of the “twin-opposed” engine and has tooling in place for a continuous production rate of 10,000 “twin-opposed” engines per year. The company estimates that it will take approximately 4-5 years to reach these production levels. EP will complete integration of the engines with the biomass burner (which will additionally be offered by Wood-Mizer as a separate product). The target specifications of the External Power “twin-opposed” Stirling engine are shown in Table A-5. Table A-6 provides target specifications for the company’s planned product.

Table A-5
External Power Target Specifications – 2.7-kW$_e$ Engine

Product	Engine
Product Status	Design/Lab Stage, May Have a Single Unit in Testing
Engine Type	Free-Piston
Cylinders / Power Pistons	Two
Working Fluid	Helium
Generator / Alternator	Linear Alternator
Power Output	2.7 kW$_e$ AC
Phases	Single-Phase
Voltage/Frequency	120 or 240 VAC @ 50 or 60 Hz
Usable Heat Output	12.3 kW$_{th}$ @ 650 °C plus 9.6 kW$_{th}$ @ 50 °C
Fuel	Fossil, Biomass, Solar
Electrical Efficiency	11% (LHV Fuel In to AC Electricity Out)
Physical Size (w x d x h)	39.4 x 9 x 9 in 1,000 x 230 x 230 mm
Weight (dry)	165 lbs 75 kg
Servicing Interval	None
Product Lifetime	10 years
Price to Distributor	$1,000/kW$_e$

Table A-6
External Power Target Specifications – 15-kW_e System

Product	Integrated System
Product Status	Design/Lab Stage, May Have a Single Unit in Testing
Engine Type	Free-Piston
Cylinders / Power Pistons	Twelve
Working Fluid	Helium
Generator / Alternator	Linear Alternator
Power Output	15 kW_e AC
Phases	Single-Phase
Voltage / Frequency	120 VAC @ 60 Hz
Usable Heat Output	250 kW_{th}
Fuel	Undensified Biomass
Electrical Efficiency	7% LHV Fuel In to AC Electricity Out
Overall Efficiency	85% LHV Fuel In to AC Electricity and Usable Heat Out
Physical Size (w x d x h)	114 x 39.4 x 90.6 in 2,900 x 1,000 x 2,300 mm
Weight (dry)	2,425 lbs 1,100 kg
Emissions	< 100 ppm CO < 200 ppm NO_x <3 g/h particulates at 15% O2
Servicing Interval	Yearly
Product Lifetime	10 years

EPRI Perspective

The External Power Stirling engine system is relying on the same proven Sunpower technology as the BG Group product. If External Power can successfully incorporate an efficient gasification burner for a variety of biomass fuels, the system could find a niche market where biomass fuels are available at low cost. The company also has a significant distribution network already in place through Wood-Mizer. However, it remains to be seen if there is a large enough market for a biomass-fueled Stirling product to be commercially successful.

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Role: Engine Developer, Engine Manufacturer

Kockums of Malmö, Sweden is a developer and manufacturer of naval technology. Kockums (through its former subsidiary United Stirling) has been involved in kinematic Stirling engine development since the 1960s. Kockums is focused on the installation of its 75-kW Stirling engine, air-independent propulsion (AIP) system into submarines. The company has also licensed a 25-kW engine to Stirling Energy Systems, Inc. for solar-fueled stationary power generation applications. SOLO Kleinmotoren of Germany has been granted a license to utilize the core Kockums engine technology in a 10-kW$_e$ Stirling system.

Company Background

Kockums has developed two four-cylinder engines based on its V-160 design: the 25-kW 4-95 for stationary power generation and the 75-kW 4-275 for naval applications. The company is divided into two divisions: an advanced submarine unit in Malmö and a surface vessel division in Karlskrona. Kockums is a subsidiary of the Germany-based HDW Group.

Kockums began work on Stirling engines in the 1960s and established a daughter company for its Stirling work, United Stirling AB, in the 1970s. United Stirling was then later dissolved back into Kockums in 1988. The company presently has approximately 25 full-time employees devoted to Stirling engines. Kockums also has available the technical resources of 200 engineers. Most of the funding for the company's Stirling research comes from internal sources and government contracts.

Technology Overview

Kockums became involved in kinematic Stirling engine development in the late 1960s with a technology license from Philips in Holland. The company was initially focused on the V-160 engine design for three application areas when its Stirling development began: submarines, bus engines, and auxiliary power units (APU). The company has now modified its Stirling engine design and narrowed its focus to submarines and stationary power generation applications.

Kockums has developed two four-cylinder engines: the 25-kW 4-95 for stationary power generation and the 75-kW 4-275 for naval applications. The engines operate at a hot-end temperature of 700-750 ºC. Due to the confined and sealed space of a submarine, helium is the working fluid of choice for sub applications. On the other hand, hydrogen is employed for solar power generation applications in order to achieve higher efficiencies. Kockums has achieved efficiencies (LHV fuel to shaft power) as high as 42% for the hydrogen engine and 39% for the helium engine.

Kockums' key strength lies in the durability of its Stirling engines. This is due to the high standards set by Kockums' military clients. The company has built over 200 engines in total. During testing, its submarine engines have operated for 18,000 hours without maintenance. The company also had a recent milestone when one of the solar Stirling systems installed by Stirling Energy Systems, Inc. (SESI) reached 10,000 hours.

Technology Status

In the late 1970s, Kockums became a subcontractor to Mechanical Technology, Inc. (of Albany, New York) in a $100 million project supported by the U.S. DOE and managed by NASA to develop a Stirling automobile engine. Kockums' primary role was to transfer its Stirling technology from Sweden to the U.S. The project lasted through 1986, during which time Kockums received a total of approximately $25 million in funding.

Kockums began development of solar Stirling engines in 1980. The company signed a contract with McDonnell Douglas (MD) in 1983 in order to integrate MD's concentrated solar collector technology with Kockums' Stirling engines. The collaborative effort was dropped in 1987. At that time Kockums sold the manufacturing technology developed as part of the program, while MD sold a license to Southern California Edison for the solar concentrator technology.

In 1995, Kockums revived its development of solar Stirling engines through its relationship with Stirling Energy Systems, Inc. (SESI) of the U.S. Kockums has granted SESI rights to use its 25-kW 4-95 Stirling engine for solar applications exclusively in North America and nonexclusively throughout the rest of the world. SESI also holds rights to the MD solar collector technology.

Specifications for the 25-kW 4-95 for stationary power generation and the 75-kW 4-275 for naval applications are shown in Table A-7.

Table A-7
Kockums Specifications – 4-95 and 4-275 Engines

	Product	
	4-95 Engine	4-275 Engine
Product Status	In Production	In Production
Engine Type	Kinematic	Kinematic
Cylinders / Power Pistons	Four	Four
Working Fluid	Hydrogen	Helium
Hot End Temperature	1,300-1,400 °F 700-750 °C	1,300-1,400 °F 700-750 °C
Generator / Alternator	Induction Generator	Synchronous Generator with Rectifier (connected to submarine main battery)
Power Output	25 kW_{shaft}	75 kW_{shaft}
Phases	3-Phase	n/a
Voltage/Frequency	440 VAC @ 50 or 60 Hz	n/a
Fuel	Solar Radiation	Cryogenic Liquid Oxygen
Electrical Efficiency	42% (LHV Fuel In to Shaft Power Out)	39% (LHV Fuel In to Shaft Power Out)
Servicing Interval	Up to 18,000 Hours	Up to 18,000 Hours
Price to Distributor	\$4,000/kW_e @ low production (current price)	n/a

Kockums is also known for its development of the Stirling Air Independent Propulsion (AIP) system. As shown in Figure A-4, the Stirling AIP system generates electricity by burning cryogenic liquid oxygen (LOX) with exhaust gases and conventional fuel (i.e., diesel) in a pressurized combustion chamber. When utilized in a submarine, the Stirling AIP system provides power for propulsion and operation of electronic equipment (e.g., sonar, computers, etc.), permitting extended periods of submersion and extremely quiet operation. The combustion pressure is higher than that of the surrounding seawater, allowing the exhaust products to be filtered and dissolved into the water undetected (i.e., no bubbles) without using a compressor.

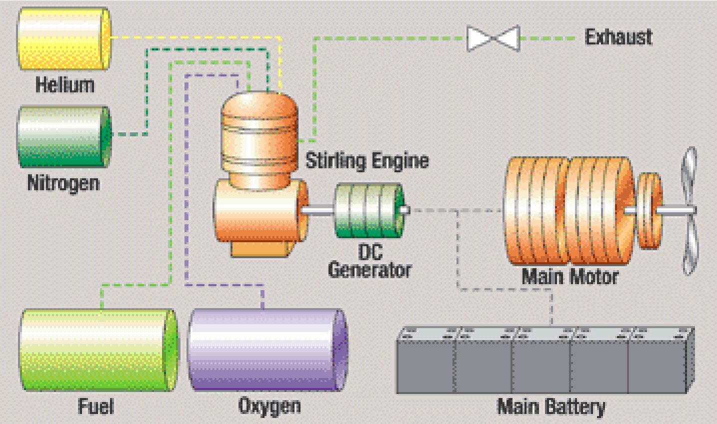

Figure A-4
Kockums Air Independent Propulsion (AIP) System

There are five AIP systems in operation on submarines today: three Swedish vessels, one Danish submarine, and one Japanese sub. The Swedish navy is in the process of fitting two more submarines with the Kockums AIP system for operation next year. Kockums is also a partner in the Viking Project to supply and install AIP systems for ten submarines from Scandinavian countries. The AIP is based on Kockums 75-kW 4-275 Stirling engine (shown in Figure A-5.).

There are two solar Stirling systems operating in the U.S. through Kockums' partnership with SESI. The 25-kW 4-95 engine prototypes utilized in the solar Stirling systems have a price of approximately $100,000. Kockums estimates that a production level of about 500,000 units per year would be required to reduce the price to a level that is comparable to conventional technologies.

Kockums has also licensed rights to its Stirling engine design to SOLO Kleinmotoren of Germany. SOLO has developed a 10-kW_e Stirling engine based on the core technology of Kockums. This 10-kW_e engine will be integrated into complete systems for stationary cogeneration applications. Kockums does not have plans to develop and commercialize its own consumer product, but is open to granting additional technology licenses for other parties to do so.

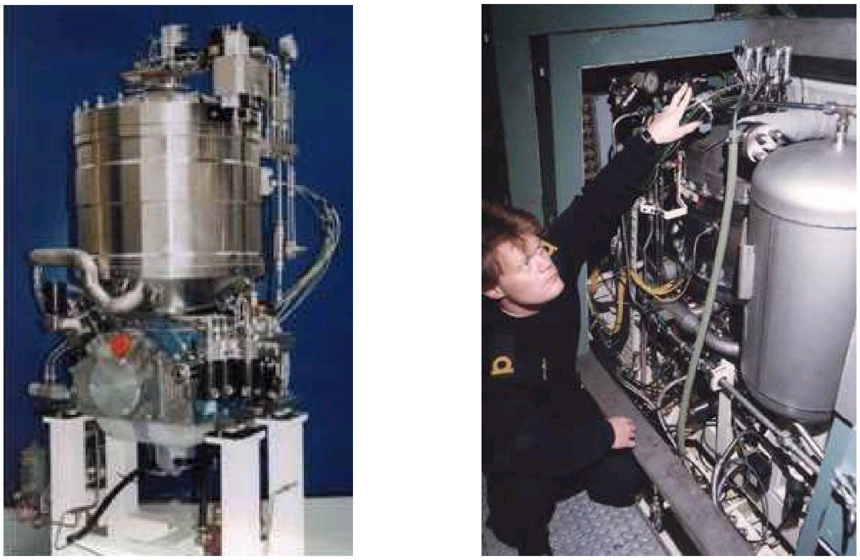

Figure A-5
Kockums 75-kW 4-275 Stirling Engine (left) and AIP System (right)

EPRI Perspective

The Kockums Stirling engines have been designed and developed around stringent military standards, resulting in highly durable machines. However, these stringent standards have also led to extremely high prices. While a high price may not effect installation of Stirling engines for naval applications, it can certainly hinder the commercialization of consumer products based on Stirling technology. It will be up to the Kockums technology licensees (currently Stirling Energy Systems, Inc. and SOLO Kleinmotoren) to modify designs and develop manufacturing processes that lead to cost reduction

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Role: Engine Developer

Quiet Revolution Motor Company (QRMC) was founded in 1999 to build and demonstrate a Stirling engine based on the patented HydraLink™ technology of the company's founders. The company utilizes hydraulic technology to overcome traditional stumbling blocks in Stirling engine design. A 100-hp "proof-of-concept" engine is scheduled for completion by the end of 2002. QRMC ultimately plans to license its Stirling engine technology to users and/or manufacturers for use in distributed generation, auxiliary power, and power tool applications.

Company Background

The founders of Quiet Revolution Motor Company (QRMC), engineers Phil Hodge and Darryl Phillips, began their involvement in Stirling engine technology in the mid-1970s. As pilots, the gentlemen were initially in search of a quiet engine to power small airplanes. The duo set out to identify the common hurdles in Stirling engine development that have traditionally forced designers to compromise performance or cease development. Once these stumbling blocks were identified, Hodge and Phillips began to work on the design of a Stirling engine that would eliminate them. In the late 1990s, Hodge and Phillips developed the now patented HydraLink™ mechanism (U.S. Patent #6,065,289) and applied it to their Stirling engine design. QRMC was formed in January 1999 to build and test a prototype of the HydraLink™ Stirling engine.

QRMC is funded by its founders, in addition to "friends and family" investments. There is presently one full-time employee (Darryl Phillips) and five other part-time contributors. The company has also established a relationship with the University of Oklahoma to assist with theoretical research and fabrication needs.

Technology Overview

QRMC has incorporated its unique, patented HydraLink™ technology into a three-piston Stirling engine design (shown in Figure A-6). While a short power piston stroke theoretically leads to less aerodynamic loss, it also requires that a large cross-sectional area of gas be displaced (i.e., larger bore) and increases the force on the bearings. Through the use of hydraulics, the QRMC Stirling engine will be able to maintain a short piston stroke, while achieving high efficiencies and quiet operation.

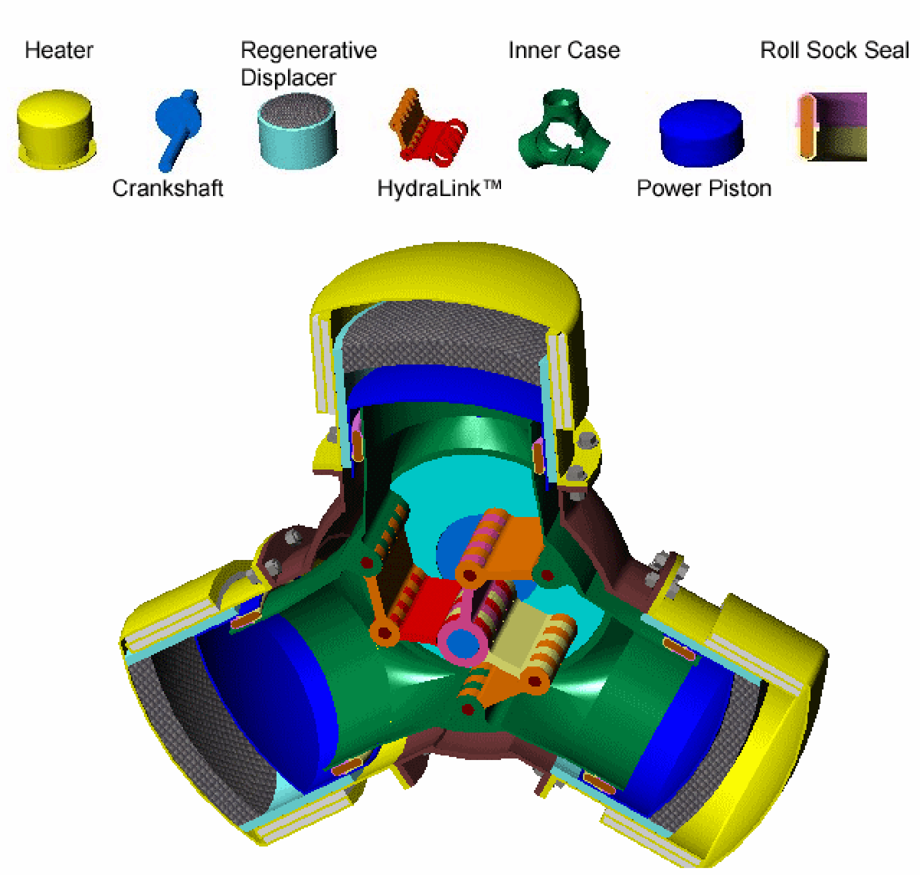

Figure A-6
QRMC Three-piston Stirling Engine Design

Technology Status

QRMC is in the process of building its first "proof-of-concept" Stirling engine, which will incorporate the HydraLink™ technology in a three- or four- cylinder design. The proof-of-concept engine will operate on natural gas or propane fuel to provide approximately 100 hp of mechanical output. It is expected that the proof of concept will operate at a minimum net thermal efficiency of 45% (LHV fuel in to mechanical output). The proof-of-concept is scheduled for completion by the end of 2002. The target specifications for the QRMC proof-of-concept engine are shown in Table A-8.

Table A-8
QRMC Target Specifications – 100-hp Proof-of-Concept Engine

Product	Engine
Product Status	Design/Lab Stage, May Have a Single Unit in Testing
Engine Type	Free-Piston
Cylinders / Power Pistons	Three or Four
Working Fluid	Helium
Power Output	75 kW_{shaft} 100 hp
Fuel	Natural Gas or Propane
Electrical Efficiency	45% (LHV Fuel In to Shaft Power Out)
Physical Size (w x d x h)	20 x 20 x 20 in (not including radiator) 510 x 510 x 510 mm

The burner, engine core, and crankshaft designs of the QRMC Stirling engine are independent of one another. This unique design feature permits the operation of the QRMC engine on a variety of fuels by simply changing the burner type. The QRMC design also uses readily available materials and has few moving parts. The company does not foresee any natural limitations to the sizing or power output of its engine design.

QRMC intends to attract financial investments through the successful demonstration of the proof-of-concept engine. The company will then use the funding to finalize the Stirling engine design and to obtain the necessary intellectual property protection. The source of funding will also likely determine the future goals of the company. QRMC ultimately plans to license its Stirling engine technology to users and/or manufacturers. The QRMC Stirling engine is best suited to applications that require a constant engine speed. The company believes that distributed generation, auxiliary power units, power tools, and direct-drive compressors are attractive markets and applications.

EPRI Perspective

The unique incorporation of the HydraLink™ technology into a “hydraulic” Stirling engine design sets QRMC apart from other developers. The true test for the company will be the completion and successful operation of the proof-of-concept engine. QRMC must demonstrate its 45% efficiency target (LHV fuel in to mechanical out) in order to secure strategic partners for commercialization of its unique Stirling engine technology.

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Role: Engine Developer

Sanyo Electric Company, Ltd. is based in Osaka, Japan and has operations worldwide. The company has been involved in Stirling engine development since the 1980s. Sanyo has designed and built several kinematic engine prototypes for power generation and heat pump applications. However, the company believes that cost reduction of its engines is a difficult task, especially in markets like power generation where the Stirling engine must compete with the internal combustion engine. Sanyo has thus chosen to focus its immediate attention on a 300 W Stirling cooler for specialized or niche refrigeration applications.

Company Background

Sanyo Electric Company, Ltd. was established in 1947 and incorporated in 1950. It employs more than 20,000 employees in Japan, and has more than 100 affiliated manufacturing and sales companies in over 26 countries. Sanyo manufactures a wide range of electronic products across many industries, including energy, communications, and home appliances.

Technology Overview

Sanyo has been awarded with a number of patents in the U.S. related to its Stirling technology. The company became involved in Stirling engine development in the 1980s as part of a national research project in Japan sponsored by the Ministry of Economy, Trade and Industry (formerly Ministry of International Trade and Industry). By 1987, Sanyo had developed a 46-kW, 1,800-rpm engine unit using helium as the working gas. The system utilized a 4-cylinder kinematic design and achieved a maximum thermal efficiency of 38%. This engine was later tested as part of an integrated power generation system, which produced 27 kW_e at an efficiency of 28%.

After extensive research and development, Sanyo determined that the Stirling technology was too expensive for broad commercialization in power generation applications. Thus, no further development has taken place on this power generation unit. Sanyo has, however, identified the high-temperature heat exchanger and the regenerator as two key areas for cost reduction.

The company moved on to develop a Vuilleumier Heat Pump in the 1990s. The specifications of the Sanyo Vuilleumier heat pump are summarized in Table A-9. In the Vuilleumier Cycle essentially two Stirling engines are interconnected. An illustration of the concept of the Vuilleumier cycle heat pump, which is capable of producing both hot and cold fluids simultaneously, is shown in Figure A-7. All chambers of the Vuilleumier system are connected by heat exchangers and ducts, and therefore the pressure inside the engine is equalized, which reduces wear and fatigue. Although it is often called a “piston” configuration, the moving elements have only a small pressure differential and are generally referred to as “displacers.”

Table A-9
Sanyo Specifications – Vuilleumier Heat Pump

Capacity (cooling / heating)	4 kW / 6 kW
Coefficient of Performance (cooling / heating)	0.7 / 1.3
Physical Size (w x d x h)	13.8 x 31.5 x 29.5 in 350 x 800 x 750 mm
Weight	220 lbs 100 kg

Sanyo developed several prototypes of these heat pumps in cooperation with Japanese gas companies. Once again the company decided that the initial cost of the Stirling technology was too high for commercialization, although the Vuilleumier heat pump has the following advantages:

- Waste heat augments the heating capacity, increasing the coefficient of performance (COP) of the unit. The waste heat is easier to capture than in conventional IC engine systems.
- In small-sized systems, such as residential and small commercial applications, the efficiency of the unit surpasses that of comparable IC gas engine heat pumps.
- The unit has intrinsically low levels of noise and vibration and is comparable to electric heat pumps in that regard.

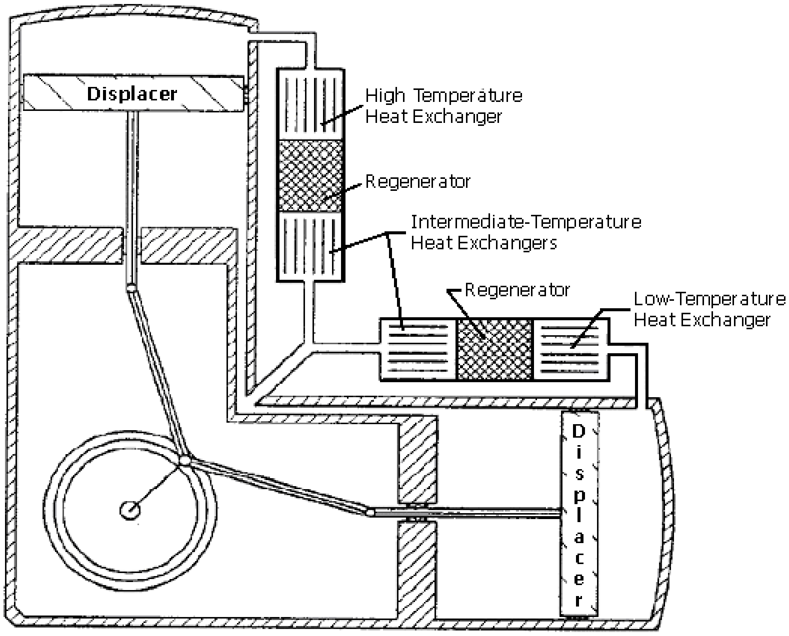

Figure A-7
Sanyo Vuilleumier Heat Pump

Sanyo has presently shifted its focus to the development of kinematic Stirling coolers for use in industrial applications, such as food distribution, environmental testing, medicine, and semiconductor manufacturing. The company believes that buyers in this niche market may be willing to pay high costs for a product that will meet their specialized cooling needs (i.e., as low as -100ºC).

Over the years, Sanyo has worked on its basic Stirling technology to reduce costs, improve reliability, and determine the feasibility of making the product. One of the difficult technological problems that Sanyo has tried to solve involves sealing issues, such as oil seals and piston seals. Sanyo has also developed a design modification that moved components for the general compressor into the drive in order to reduce costs.

Technology Status

The Sanyo Stirling cooler in development today utilizes a kinematic engine with helium working fluid. It employs a radiating heat exchanger and a cooling heat exchanger for use in cooling applications in the ultra-low temperature range of -100 to -60 ºC. Specifications for this cooler are shown in Table A-10. The Stirling cooler uses electricity to provide power to the drive and it emits no fluorocarbons.

Sanyo has built several sample units of this Stirling cooler. The company is currently running durability tests on these units and is planning to put several units into field demonstration. The intended niche market for this product is specialized cooling applications at commercial and industrial facilities. Specific commercialization plans were not available.

Table A-10
Sanyo Specifications – Stirling Cooler

Cooling Capacity	300 W
Cooling Temperature Range	-148 to -76 °F -100 to -60 ºC
Electrical Input	1.7 kW
Physical Size (w x d x h)	8.3 x 16.5 x 23.2 in 210 x 420 x 590 mm
Weight	165 lbs 75 kg
Product Lifetime	50,000 hours
Servicing Interval	Yearly

EPRI Perspective

Sanyo has not completely ruled out the possibility of commercializing a Stirling engine for power generation applications, although it is unlikely to happen in the near future. The company is presently more focused on a cooperative effort with a Japanese gas company to develop residential cogeneration systems based on proton exchange membrane (PEM) fuel cell technology. Sanyo will revisit development of Stirling engine power generation systems only if its ongoing research leads to significant cost reductions in engine design and production.

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Role: Engine Developer, Engine Manufacturer

Sigma Elektroteknisk is a wholly owned subsidiary of Ocean Power Corporation. Sigma has developed a single-cylinder kinematic Stirling engine called the Personal Combustion Powerplant (PCP™) that produces 3 kW_e and 9 kW_{th}. The company has secured a strategic relationship with Baxi UK Limited to integrate and package the PCP™ into micro combined heat and power (MCHP) systems that will be sold as a replacement for traditional residential boilers. It is anticipated that these products will be available in 2003 or 2004. Sigma is presently seeking to build similar relationships with system integrators in the U.S. and Japan.

Effective August 9, 2002, Sigma Elektroteknisk AS, the wholly-owned subsidiary of Ocean Power Corporation, a Delaware corporation ("Ocean Power") was placed under administration of the Ytre Follo Bankruptcy Court in Norway. Effective July 31, 2002, Ocean Power, owner of Sigma Elektroteknisk, laid off most of its employees due to a severe cash-flow shortage. Ocean Power's operations continue with the remaining employed staff.

Company Background

Sigma Elektroteknisk is a Norwegian company that was founded in 1994 for the sole purpose of commercializing a Stirling engine to be used in micro combined heat and power (MCHP) products. On August 10, 2000, Ocean Power Corporation of the United States acquired Sigma for $5.5 million in stock. Sigma is now a fully owned subsidiary of Ocean Power. Ocean Power's goal is to become the first distributed power and seawater desalinization company, with an emphasis on developing and utilizing renewable energy resources. The company has two offices in the U.S. and two offices in Europe, including the Sigma facility in Norway.

Ocean Power is publicly traded over the counter (OTC) under ticker symbol PWRE. The company sought funding in 2001 to continue on schedule its Stirling engine commercialization plans. As a result of the events of September 11, 2001, Ocean Power was unable to close $10 million in funding from Malaysian investors. However, Ocean Power has confidence that it will close a $20 million funding round in early 2002.

As an aside, in April 2000 – before its acquisition of Sigma – Ocean Power signed an exclusive license agreement with STM Power for the use of its solar-Stirling hybrid technology in desalination systems. Ocean Power claims that the solar-Stirling hybrid systems offered by STM proved to be too expensive for near-term commercialization. Therefore, Ocean Power renegotiated the agreement to a non-exclusive license, which is still in effect today.

Technology Overview

Sigma's kinematic Stirling engine technology is based on design and development work conducted by United Stirling of Sweden throughout the 1970s and 1980s. The United Stirling engine, in turn, was a derivative of previous Stirling work done by Philips in the Netherlands. Sigma acquired exclusive technological rights from Sweden to develop a small, single cylinder Stirling engine based on the core United Stirling technology. Sigma has internally advanced and developed this base technology.

While Sigma believes that STM Power has the best Stirling engine design for variable load applications (i.e., automobiles and grid-independent stationary applications), the company also believes that STM's multi-cylinder design will not prove to be cost-effective in small stationary power generation applications. Sigma feels that its single cylinder design is less expensive and more likely to succeed in commercialization. The cylinder volume is 133 cm^3 with a bore stroke of 65 mm x 40 mm.

Sigma calls its Stirling engine the Personal Combustion Powerplant (PCP™) energy converter. The PCP™ (shown in Figure A-8)) is a hermetically sealed engine. One of the unique design features of this engine (cutaway shown in Figure A-9) is that it includes two generators. Each is sealed in the crankcase and run in a helium atmosphere, which is expected to facilitate cooling. The engine requires a helium recharge about once every two years. The engine contains permanently-lubricated bearings, eliminating the need for oil.

The current model employs 230 V units, but 24 V DC units can also be made available. The engine subsystem comes ready for integration into a complete MCHP system, including all equipment necessary for a cogeneration installation except for the cooling system heat exchanger.

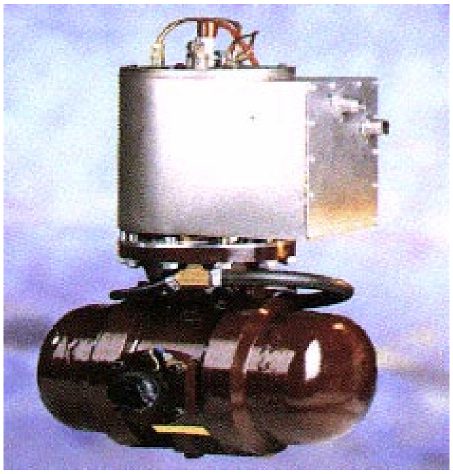

Figure A-8
Sigma Elektroteknisk PCP™

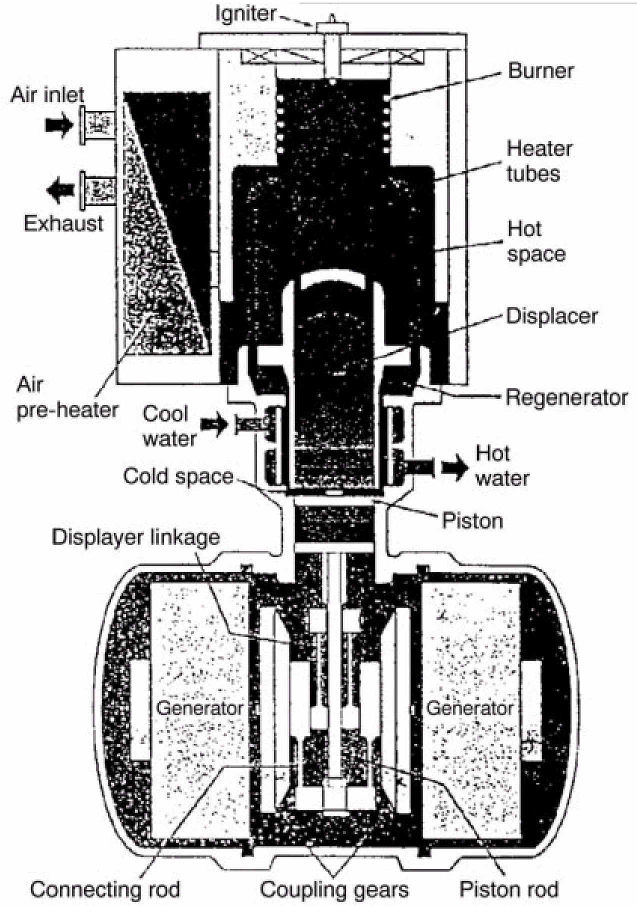

Figure A-9
Sigma Elektroteknisk PCP™ Cutaway

Sigma believes that the distinguishing factor between different Stirling engines is the hot end design, which generally accounts for about 50% of the total engine cost. The company has developed a platelet hot end design, which it believes is a radical leap in this area. The platelet design was originally developed for rocket engines. It will increase the number of burners from one to 890 (each 2.4 mm high), and eventually permit higher operating temperatures, and thus higher efficiencies. The new flat plate design will be able to accommodate any fuel, including solar. Sigma estimates that this drastic design change will reduce the cost of the hot end to 5% of the total engine cost. The company plans to demonstrate the new design in mid-2002. It is anticipated that Sigma will manufacture these platelets at a facility in Asia.

In November 2000, Sigma and Kockums, A.B. of Sweden signed a cooperation agreement to optimize the Sigma PCP™ Stirling engine. It is also anticipated that Sigma will provide some services to Kockums. Kockums was quoted in describing Sigma's hot end design as a "revolutionary" achievement, as opposed to an "evolutionary" development.

Technology Status

During the lengthy transfer of technology from Sweden (United Stirling) to Sigma, Sigma completed its first Stirling engine prototype in 1998. Sigma also conducted economic and viability studies in cooperation with EA Technology (UK) and McKinsey & Co. (Norway), among others, in order to verify the potential market for MCHP systems based on Stirling engine technology. Sigma particularly claims to have done considerable work to assess and understand the implications of MCHP products to energy service companies.

The specifications of the PCP™ Stirling engine are shown in Table A-11. The PCP™ is designed to have an electrical output of 3 kW_e and a thermal output of 9 kW_{th}. It is specifically designed to operate on natural gas or propane. It has a natural gas consumption of about 0.33 kilogram per kilowatt of electricity generated.

The PCP™ presently has an energy conversion efficiency of 30% (natural gas to mechanical work). Sigma believes that the efficiency of the first commercial product will be higher. The company is targeting an operational life of more than 50,000 hours. The PCP™ does not have dynamic response capabilities (e.g., the two operating modes are "on" and "off"). The operation of the PCP™ is heat-led; thus, a MCHP system based on this technology will not likely operate during the summer months. Sigma estimates that the average annual operating time of a MCHP system will be in the range of 2,000-3,000 hours.

Sigma has tested its PCP™ engine subsystems for many years. In December 2000, Statoil announced the testing of a MCHP system based on the PCP™ technology at its refinery in Mongstad, Norway. This system has now operated for more than one year. In total, Sigma has approximately six MCHP systems in operation: four at the Sigma facilities, and two in the field. Sigma intends to launch its next demonstration phase of 30 systems in mid-2002.

Table A-11
Sigma Elektroteknisk Target Specifications – PCP™ Engine

Product	Engine (Including Burner and Generator)
Product Status	Multiple (<10) Early Units in Testing (alpha)
Engine Type	Kinematic
Cylinders / Power Pistons	One
Working Fluid	Helium
Pressure	1,160 psi
Engine Shaft Speed	1,600 rpm
Generator / Alternator	Two Generators
Power Output	3 kW_e AC
Voltage/Frequency	230 VAC @ 50Hz
Usable Heat Output	9 kW_{th}
Fuel	Natural Gas, Propane
Electrical Efficiency	30% (LHV Fuel In to Shaft Power Out)
Physical Size (w x d x h)	26.2 x 10.2 x 33.1 in 665 x 260 x 840 mm
Weight (dry)	165 lbs 75 kg
Emissions	3.5-4.0 ppm NO_x, 25-50 ppm CO, 0.3-1.0 ppm HC at 15% O_2
Servicing Interval	5,000 hours or 2 years
Product Lifetime	50,000 hours
Price to Distributor	\$333/kW_e @ 100,000 units per year

Sigma's sales strategy is to supply its PCP™ Stirling engine prime mover to original equipment manufacturers (OEMs) for integration into branded MCHP products. The company originally planned to focus on three national markets in Europe where MCHP is developing as a novel energy concept: the U.K., Germany, and The Netherlands. In European countries, the MCHP products will be introduced as a replacement for gas boilers. By installing a MCHP system instead of a new boiler when the existing boiler has broken down, the effective capital cost for a MCHP system based on the PCP™ technology is reduced to the marginal capital cost (e.g., the difference in price between a MCHP system and a new gas boiler).

Since its acquisition by Ocean Power, Sigma has geographically expanded its sales plans to include the U.S. and possibly Japan in the introduction of the PCP™ products. New construction and multi-family homes (i.e., apartments, condominiums, etc.) will make up the majority of Sigma's initial market in the U.S.

In November 2000, Sigma signed an engineering contract with Ricardo, Inc. to prepare the PCP™ for volume manufacturing and integration into MCHP systems. Ricardo will design a prototype manufacturing/assembly process and initially produce up to 2,000 of the Sigma engine sub-systems in order to troubleshoot the process. Sigma will then seek to partner with a manufacturer for large-scale production of the engine subsystems (similar to automotive industry strategy).

Sigma also plans to enter into joint ventures or equity agreements with OEMs that have the capability to integrate the engine subsystem with the other components required in the MCHP system (i.e., tanks, valves, heat exchangers, enclosure, etc.). Sigma has already established one such relationship with Baxi UK Limited. The companies entered into a collaboration agreement in April 2001 to bring to market a MCHP product based on the PCP™ technology. Baxi will engineer the packaged system for domestic use across Europe.

It is anticipated that Sigma will launch the first commercial generation of the PCP™ engine subsystem product by 2003 or 2004. Sigma estimates that PCP™-based MCHP systems will be made commercially available around the same date. At a production volume of more than 100,000 units per year, the PCP™ will be made available to OEMs at a price of approximately $1,000.

EPRI Perspective

While Sigma claims to have developed “revolutionary” and cost-effective Stirling engine technology, the company has yet to prove the operational characteristics of MCHP systems based on the PCP™ technology. The company has been unable to secure the funding necessary to aggressively pursue commercialization plans. In addition, the availability date for demonstration units has been pushed back several times. Although Sigma has secured a relationship with Ricardo to develop a manufacturing process, the company has not yet partnered with a manufacturer. This, and the recently-announced bankruptcy filing, call into question Sigma’s plans to have proven engines ready for Baxi UK Limited to package and distribute in 2003.

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Role: Engine Manufacturer, Product Packager, Product Distributor

The German company SOLO Kleinmotoren GmbH is a manufacturer of gardening and landscaping equipment. With a technology license from Kockums of Sweden, SOLO began development of a 10-kW$_e$, kinematic Stirling engine in 1990. Since then, SOLO has demonstrated more than one hundred of its Stirling engines and dozens of integrated combined heat and power (CHP) systems operating on solar heat and natural gas. The company is now planning to commercialize CHP systems based on its Stirling technology for multi-family homes in Europe (e.g., apartment complexes).

Company Background

SOLO Kleinmotoren GmbH (SOLO), founded in 1948, is a German manufacturer of gardening and landscaping equipment (e.g., chainsaws, lawnmowers, air blowers, etc.) based on SOLO’s own two- and four-stroke internal combustion (IC) engines. The company became involved in kinematic Stirling engine development in 1990 under a contract with the civil engineering firm, Schlaich Bergermann und Partner (SBP) to assemble six Stirling solar systems at the Platforma Solar de Almeria in Spain (shown in Figure A-10).

Figure A-10
SOLO/SBP Stirling Solar Systems at the Platforma Solar de Almeria

SOLO continues to internally fund the development of its own Stirling engine, which is a modification of the Kockums V-160 engine technology. The company has eight full-time employees devoted to Stirling engine work at its facility in Stuttgart.

Technology Overview

As part of the project with SBP in 1990, SOLO was granted a license to modify the Kockums V-160 Stirling technology in the design of a 10-kW_e engine. SOLO calls its modification the V-161 (shown in A-11). It is a two-cylinder design that uses helium as the working fluid. The engine's electric output may be adjusted between 2 and 10 kW_e by varying the working gas pressure between 30 and 150 bar. SOLO plans to commercialize a combined heat and power (CHP) system based on the V-161 Stirling engine technology.

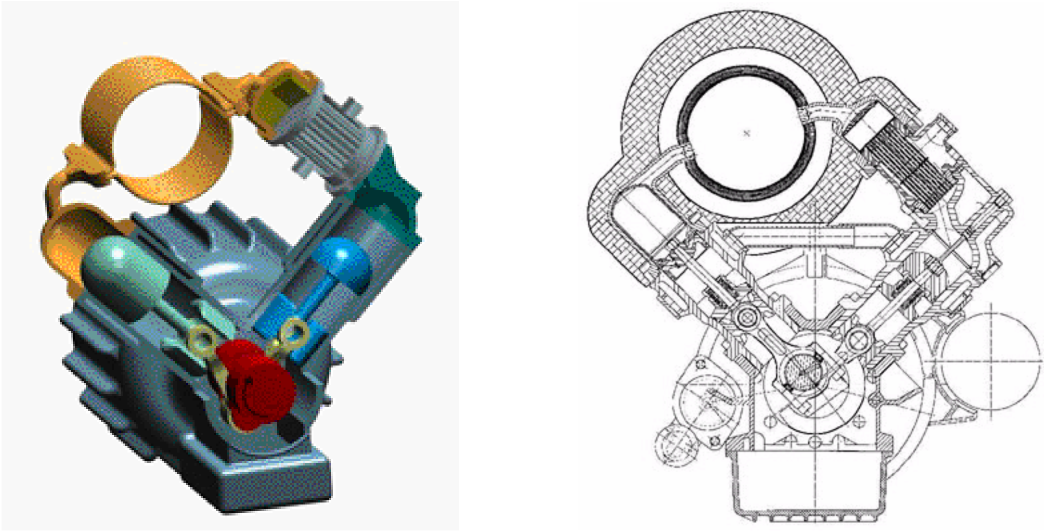

Figure A-11
SOLO V-161 Stirling Engine

Technology Status

In addition to the solar Stirling development project with SBP in 1990, SOLO has delivered five engines to Sandia National Laboratory for integration with advanced solar collector technology developed at the laboratory. SOLO has built and tested a total of 150 V-161 engines to date. These engines have accumulated a total of more than 150,000 hours of operation. Individual engines have operated for more than 20,000 hours, with up to 6,500 hours maintenance-free.

SOLO integrated its first CHP system prototype based on the V-161 engine in 1995. The company conducted a field demonstration program to test its CHP systems (shown in Figure A-12) between 1996 and 2000. While SOLO has not secured direct partnerships for the commercialization of its systems, many small European electric, gas, and energy service companies have participated in testing and demonstrations.

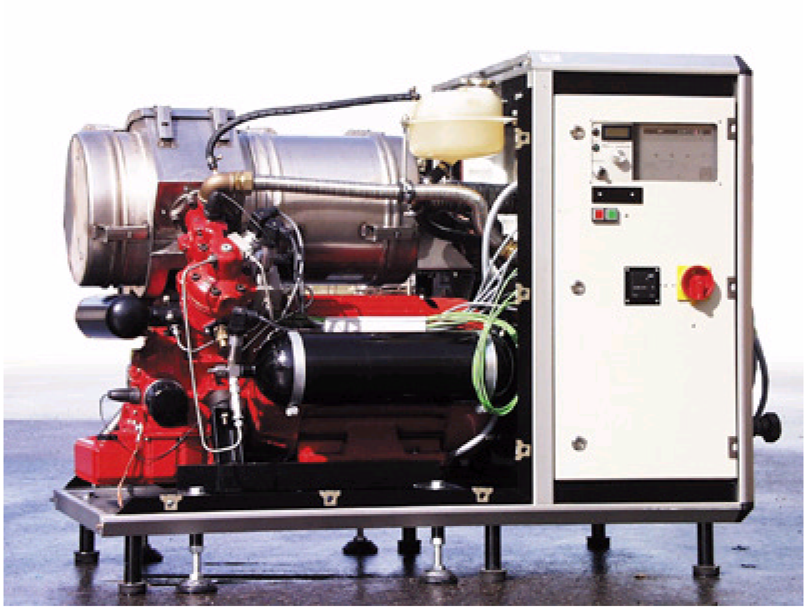

Figure A-12
SOLO Stirling CHP System

SOLO is presently testing 16 CHP prototype systems operating on natural gas fuel and an additional 15 systems in solar and cryocooling applications. The CHP system is heat-load following and intended for indoor installation in multi-family home applications in Europe (e.g., a unit of 25-50 apartments). Any excess electricity generated by the system will be fed to the electric grid. SOLO estimates that its CHP system will have to operate 5,000 hours out of the year in order to be cost-effective. The company anticipates a yearly maintenance call to replace items like the helium bottle (required for recharging the working fluid), piston rings, and seals. SOLO ultimately plans to distribute its systems through electric and gas utilities and energy service companies. Specifications for the SOLO CHP system are displayed in Table A-12, SOLO Target Specifications – CHP System.

SOLO plans to build a total of 60-70 Stirling engines in 2002. Most of these engines will be integrated into natural gas-fired CHP systems, while a few will operate on solar heat. The company also anticipates the testing of a biomass-fired prototype system near the end of 2003. The SOLO facility in Stuttgart has a Stirling engine system production capability of approximately 2,000 units per year. At that level, SOLO estimates a unit price of about €16,000-18,000 (~$14,000-16,000).

Table A-12
SOLO Target Specifications – CHP System

Product	Integrated System
Product Status	Many (10-20) Pre-Production Prototypes in the Field (beta)
Engine Type	Kinematic
Cylinders / Power Pistons	One
Working Fluid	Helium
Hot End Temperature	1,200 °F 650 °C
Pressure	435-2,175 psi
Engine Shaft Speed	1,500 rpm
Generator / Alternator	Asynchronous Generator
Power Output	2-10 kW_e AC (varied by pressure)
Phases	3-Phase
Voltage/Frequency	400 VAC @ 50 Hz
Usable Heat Output	8-24 kW_{th}
Fuel	Natural Gas
Electrical Efficiency	24% (LHV Fuel In to AC Electricity Out)
Overall Efficiency	90% (LHV Fuel In to AC Electricity and Usable Heat Out)
Physical Size (w x d x h)	51.2 x 27.6 x 38.6 in 1300 x 700 x 980 mm
Weight (dry)	1,000 lbs 450 kg
Noise Level	< 60 dbA at 3.3 ft
Emissions	< 50 ppm NO_x, CO at 15% O_2
Servicing Interval	Yearly (3 hours downtime)
Warranty	2 years (in Europe)
Price to Distributor	$14,000-16,000 per system @ 2,000 units per year $20,000 per system @ low production (current price)

EPRI Perspective

While SOLO claims to have demonstrated CHP systems with several small European utility companies, the company has not yet secured any significant strategic relationships with distribution partners. On the other hand, SOLO has built and tested more Stirling engines than any other developer. In addition, the company has a great deal of know-how in manufacturing and sales of consumer products. SOLO will likely be a strong competitor in the European market. The company’s success in the U.S. will be dependent upon the formation of a strong partnership or joint venture to modify and sell the system in the U.S. market.

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Role: Engine Developer, Engine Manufacturer, Product Packager

Stirling Advantage, Inc. (SAI) has designed a low-temperature, low-frequency Stirling engine system that operates with a hydraulic drive. The company is presently building a 25-kW_e free-piston engine for testing and demonstration purposes. SAI ultimately plans to commercialize a 200-kW_e system for a variety of applications, including industrial waste heat, inexpensive or free fuel, and commercial cooling.

Company Background

Stirling Advantage, Inc. (SAI), previously MicroPhotonics, Inc., was formed in 1995 to develop and commercialize promising technologies. One of the technologies developed by the company was a manufacturing process for thin “microglass” to be used in flat panel displays. While assessing the market for this technology, SAI had discussions with Stirling Energy Systems, Inc. about the possibility of utilizing the “microglass” in solar collector applications. Rather than commercializing the “microglass” technology as a result of these discussions, SAI instead took a strong interest in Stirling engine operation. In 1998, the company committed to developing its own Stirling engine, based on the following criteria:

- Long Life (100,000+ hours)
- High Efficiency (38+ %)
- Low Maintenance (< $0.01/kWh)
- Competitive Capital Cost (< $500/kW)

SAI presently has five employees, three of which are located at the company’s machine shop facility in Athol, Massachusetts. Five investors have combined for over $1 million in funding for SAI over the past two and half years. Four of the funding parties are individuals, and the fifth investor is Massachusetts company Water Recovery Systems. SAI is presently seeking funding to complete and test a prototype engine.

Technology Overview

Since turning its focus to Stirling technology in 1998, SAI has completed the conceptual design of a complete 200-kW$_e$ Stirling engine system. This system is based on a low-temperature (525 ºC), low-frequency (10-15 Hz) free-piston design and will produce 2,100 Btu/kWh (~123 kW$_{th}$) of useable heat output. The four-cylinder engine (50 kW$_e$ per cylinder) is hermetically sealed and uses hydrogen as the working fluid. The four cylinders are arranged in a coaxial configuration (i.e., looks like a square from above), and each cylinder is 12-14" in diameter. SAI believes that its Stirling engine is the first multi-cylinder, free-piston design. Due to the tremendous torque that exists in a large engine with low frequency, SAI opted to utilize a hydraulic drive system. SAI has filed to receive patent protection on its unique Stirling engine design. The company expects to be granted the 53-claim patent by mid-2002.

Although low-temperature Stirling engine operation theoretically signifies low thermodynamic efficiency, SAI claims that its engine has several benefits to counterbalance this negative effect. First, low-temperature operation permits the use of less expensive (i.e., less specialized) design materials. Second, creep stress (i.e., degradation) is significantly reduced as operating temperatures are lowered, thus increasing the lifetime of the engine. Third, operation at low temperatures produces less NO_X emissions. Fourth, low-frequency operation dramatically reduces viscous losses, hence increasing engine efficiency. Finally, slow operation also permits novel sealing methods and decreases wear on the engine.

Technology Status

SAI's 200-kW$_e$ Stirling engine system was designed to meet market demands. The company believes that smaller systems (i.e. < 25 kW) will meet great difficulties in cost reduction, whereas larger systems generate enough electricity to obtain a more rapid return on investment. Returns are even faster if free or inexpensive fuels are available. SAI has identified several attractive markets for its 200-kW$_e$ system:

Waste Industrial Process Heat – Many industrial facilities generate a considerable amount of waste heat that could be used to operate a Stirling engine. SAI believes that this is a large market without a significant amount of competition. The company hopes to first build name recognition and a positive track record in this market and then expand into other markets:

- Inexpensive Fuels – Biomass, landfill gas, digester gas, etc. offer a free or inexpensive source of fuel for the SAI Stirling engine.
- Commercial cooling – Air conditioning at office buildings and shopping malls creates a high demand of electricity at peak times. A single 200-kW$_e$ SAI system can provide 400 tons of chilling. The unit may also be configured to operate in "power" mode for part of the day and "cooling" mode for another part of the day.

SAI is presently undergoing the fabrication of a 25-kW$_e$ single-cylinder engine for testing purposes. The company plans to demonstrate the viability of low-temperature, low-frequency, free-piston operation with this half-scale prototype (i.e., the 200-kW$_e$ system will have four cylinders of 50 kW$_e$ each). The performance of the materials, sealing, and other system subcomponents will be demonstrated with the 25-kW$_e$ engine. SAI estimates that it will require an additional $300,000 to $400,000 and four to five months (once funding is available) to complete fabrication of the engine.

Upon completion of the 25-kW$_e$ engine, SAI plans to build a single 200-kW$_e$ system prototype. The company estimates that about $2 million and nine to twelve months will be required build and test the 200-kW$_e$, full-scale system. The next step will be to manufacture and demonstrate an additional 20 systems at an estimated cost of $6 million over two years.

Following field demonstrations, production levels will be increased. SAI will either choose to ramp up production in house or to secure a manufacturing partner, based on the less expensive option. Completed systems will likely be sold through distributors. SAI believes that 8,000 units per year is an optimal production level. At half that level, the company anticipates a price of $450 per kilowatt to a distributor. Target specifications for the 200-kW$_e$ Stirling engine system are shown in Table A-13.

Table A-13
SAI Target Specifications – 200-kW$_e$ System

Product	Integrated System
Product Status	Design/Lab Stage, May Have a Single Unit in Testing
Engine Type	Free-Piston
Cylinders/Power Pistons	Four
Working Fluid	Hydrogen
Hot End Temperature	1,000 °F (575 °F for waste heat engine) 525 °C (300 °C for waste heat engine)
Engine Shaft Speed	1,800 rpm
Generator / Alternator	Synchronous Generator
Power Output	200 kW$_e$ AC
Voltage/Frequency	480 VAC @ 60 Hz
Usable Heat Output	123 kW$_{th}$ (hot water at 160 °F)
Fuel	Natural Gas
Electrical Efficiency	38% (20% for waste heat engine) (LHV Fuel In to AC Electricity Out)
Overall Efficiency	76% (LHV Fuel In to AC Electricity and Usable Heat Out)
Physical Size (w x d x h)	96 x 72 x 96 in (skid) 2,440 x 1,830 x 2,440 mm
Weight (dry)	9,500 lbs (skid) 4,300 kg
Emissions	< 0.13 g/bhp NO$_x$
Servicing Interval	4 inspections per year
Product Lifetime	100,000+ hours
Price to Distributor	$450/kW$_e$ @ 4,000 units per year
O&M Cost	$0.01/kWh (incl. 1 engine overhaul, parts, labor, and 4 inspections per year)

EPRI Perspective

SAI has a unique design approach that incorporates low-temperature and low-frequency operation with a hydraulic drive system as a means to improve efficiency and decrease cost. Although the company has completed a conceptual, multi-cylinder Stirling engine design, it has not yet proven this design through operation of an engine. SAI may have solved a number of Stirling design issues, but it will have to sell these developments to investors if it plans to prove its design.

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Role: Product Packager, Product Distributor

Stirling Energy Systems, Inc. (SESI) is a developer of utility-scale renewable energy power plants. The company has a testing and demonstration facility in Huntington Beach, California, in addition to its headquarters facility in Phoenix, Arizona. SESI holds patents for a solar concentrator technology originally developed by McDonnell Douglas. The company has also been granted a license by Kockums of Sweden to manufacture, market, and sell its 25-kW Stirling engine as part of a solar dish Stirling system.

Company Background

Stirling Energy Systems, Inc. (SESI) was formed in 1996 to develop utility-scale renewable energy power plants. The Phoenix-based company is a project developer and marketer of Vestas wind turbine systems. SESI also develops projects for solar dish Stirling (SDS) systems, based on the Kockums Stirling engine technology. The company's engineering and technical demonstration facilities are located at the Boeing Aerospace Campus in Huntington Beach, California.

David Slawson, Chairman and CEO, succeeded in raising $6 million in SESI's first round of private equity funding. The company is presently seeking up to $25 million for its second level of funding. SESI has 18 full-time employees: 5 in Phoenix and 13 in Huntington Beach. SESI also utilizes the resources of more than a dozen outside consultants for specialized areas of discipline. In addition, there are more than ten students who are trained and paid by the University of Nevada at Las Vegas (UNLV) to maintain an SESI solar Stirling system that is installed on the campus.

Technology Overview

SESI holds two key patents, in addition to trade secrets and technical and manufacturing know-how, on a solar concentrator system that was originally developed by McDonnell Douglas (now Boeing). SESI integrates this solar collector with the Kockums 25-kW 4-95 Stirling engine. In 1997, Kockums granted SESI with an exclusive license to manufacture, market, and sell this engine in the U.S. and Mexico. SESI holds a similar license agreement that gives it non-exclusive rights worldwide. Kockums has worked closely with SESI to optimize the design of the 4-95 engine to meet the SDS system requirements. The specialized Stirling engine (shown in Figure A-13) operates on a working fluid of hydrogen. The heater head uses Inconel® seals and operates at a hot end temperature of 720ºC.

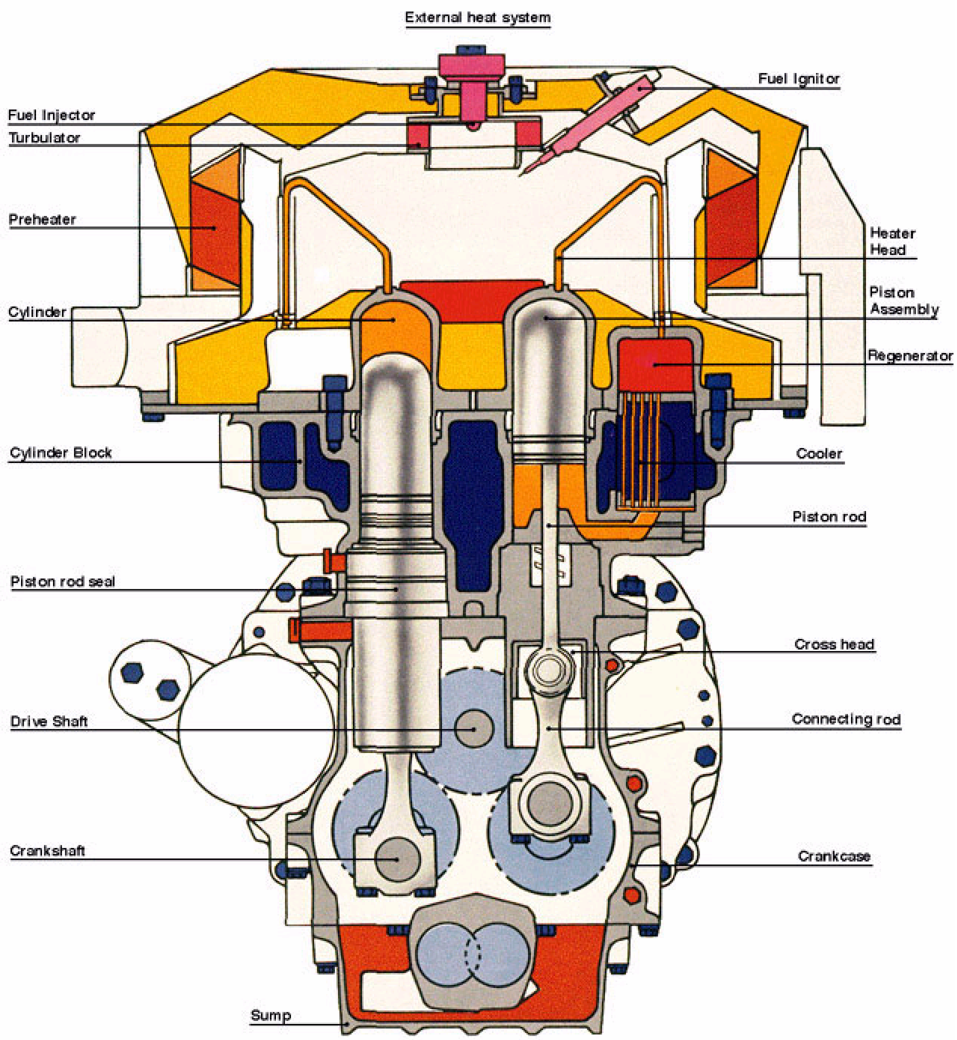

Figure A-13
SESI – Kockums 4-95 Stirling Engine

Technology Status

SESI's business plan is built on the philosophy that the earth's most vast energy source is the sun. The company estimates that a "solar Stirling farm" with an area of 100 square miles could meet the electricity needs of the entire U.S. It is SESI's goal to develop solar Stirling projects up to 1,000 MW (i.e., 40,000 SDS systems). The company calculates that a power plant of that size could provide electricity at a price of $0.06 per kWh.

SESI fabricates its 89-facet parabolic solar concentrator in five subassembly units at its Huntington Beach facility. The subassemblies are then taken to an installation site where they are integrated with the Stirling engine (presently manufactured by Kockums in Sweden). The entire installation takes about three hours, and electricity is supplied to the grid the next day.

The SESI assembly facility in Huntington Beach has a production capacity of 6 units per year. SESI will either expand the production capacity on its own or will secure a strategic relationship with a company that has assembly capabilities. SESI has already established a partnership with an undisclosed Canadian automotive supplier to mass manufacture the Stirling engines. The Canadian company presently has a production capability of 50 engines per day (i.e. 300 MW per year) on one production line in a single shift. SESI's target is 1,000 MW per year.

The specifications of each individual SESI SDS system are listed in Table A-14. The units have an expected lifetime of 30 years. An annual check-up is required and may involve changing lubrication and seals or replacing the hydrogen bottle that is used to recharge the engine with working fluid. It is anticipated that the yearly maintenance call will take three man-hours and cost $100 in parts.

SESI presently has two "first-generation" SDS systems in operation: one at the company's test site in Huntington Beach and one at UNLV. Both demonstrations are part of a U.S. Department of Energy (DOE) Dish Engine Critical Components (DECC) contract awarded to SESI and Boeing in 1999. In Phase I, the team was awarded $1million (50% cost share) to demonstrate the successful operation of an SDS system in Huntington Beach (shown in Figure A-14). Under the $6.2-million Phase II project, the team joined forces with Nevada Power and is presently conducting a demonstration of a second system at UNLV.

SESI plans to demonstrate additional SDS systems later this year. The company has signed a letter of intent with Gamesa Energia, S.A. of Spain for a $1.5 million demonstration project. Arizona Public Service has also signed a $250,000 agreement with SESI for the opportunity to test an SDS system. A third agreement has been signed with an undisclosed company to test an SDS system beginning in late 2002. In addition, SESI plans to demonstrate up to 40 systems (i.e., 1 MW capacity) in the El Dorado Valley (just outside of Las Vegas) as part of a DOE-sponsored project. It is anticipated that the DOE will release an RFP for this project soon. Likely competitors include the solar-Stirling teams of STM/SAIC and SOLO Kleinmotoren/WG Associates.

Table A-14
SESI Target Specifications – Solar Dish Stirling System

Product	Integrated System
Product Status	Multiple (<10) Early Units in Testing (alpha)
Engine Type	Kinematic
Cylinders / Power Pistons	Four
Working Fluid	Hydrogen
Hot End Temperature	1,330 °F 720 °C
Engine Shaft Speed	1,800 rpm
Generator / Alternator	Induction Generator
Power Output	25 kW_e AC
Phases	3-Phase
Voltage/Frequency	480 VAC @ 60 Hz
Fuel	Solar Radiation
Electrical Efficiency	32-33%* (Solar Energy In to AC Electricity Out)
Servicing Interval	Yearly
Product Lifetime	30 years
Price to End User (Retail)	$250,000 per system (current price)
O&M Cost	$0.008/kWh

* SESI has demonstrated an efficiency of 29.4% - a world record for a solar-Stirling system.

SESI ultimately plans to develop projects through power purchase agreements (PPA). It is anticipated that these PPAs will have durations of 18-24 months. The most likely arrangement would involve equity investors to own the actual equipment, while a separate operating company would be set up to provide ongoing maintenance and support. The company has identified the southwest U.S. (7 states), South Africa, and Australia as attractive initial markets. SESI has also received interest from utility and energy companies in several European countries, including Spain and Italy.

Figure A-14
SESI Solar Dish Stirling System

EPRI Perspective

SESI has a strong Stirling technology partner in Kockums and has demonstrated a world record efficiency for a solar Stirling system. However, with only two systems in operation and no long-term power purchase agreements in place, it will likely take many years and significant financial investments for the company to turn a profit on its solar Stirling systems. SESI is a strong advocate of renewable energy and may benefit in the long run from government subsidies and legislation that promotes the use of solar energy for electricity generation and hydrogen production. The company's success is dependent upon its financial abilities to make it to the "long run."

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Role: Engine Developer, Engine Manufacturer

Stirling Technology Company (STC) was formed in 1985 to develop and commercialize Stirling engine technology with a long, maintenance-free life. Applications for STC's engines fall into two distinct product lines. First are the RemoteGen™ electrical generators, ranging in size from 55-3,000 watts. STC plans to make these engine subsystems available to OEMs for integrations into combined heat and power systems. The second product line includes the BeCool™ cryocoolers based on Stirling technology. STC introduced this family of Stirling cryocoolers in 1996 for commercial use. Originally designed for computer cooling and laboratory applications, these coolers have found broader uses in laser cooling, high-temperature superconductor cooling, and biomedical freezing.

Company Background

Stirling Technology Company (STC) evolved from the McDonnell Douglas energy research and development (R&D) lab of the mid-1960s and 1970s. The lab was originally sanctioned to develop space power systems based on Stirling engine technology. The lab then received a contract from the National Institute of Health to develop an implantable Stirling power source for artificial hearts that operated on a radioisotope heat source. The lab successfully developed a Stirling technology with a long, maintenance-free life that incorporated flexure bearings and compensated bellows into the design.

When the McDonnell Douglas energy R&D lab was closed in the late 1970s, the Stirling engine technology developed there was transferred to the University of Washington graduate program for further research. After many more years of academic development, the technology was spun off from the university into Stirling Technology Company (STC), which was incorporated to perform contract R&D work that could ultimately lead to the commercialization of products that utilize the Stirling cycle. Technology transfer from the university to STC occurred through 1988. Since its founding in 1985, the company has more than $40 million invested from commercial and government contracts.

Today, the founders and the current and former employees own over 90% of STC. The University of Washington, Westinghouse, and a local development fund share ownership of the remaining portion of the company. STC's revenues were close to $6 million in 2001. In addition, the company has received funding through government contracts. In order to accelerate commercialization efforts, STC is presently seeking private equity funding through strategic relationships. The company anticipates that it will make an initial public offering in three or more years.

STC is focused on the development of Stirling engine products for a wide variety of applications, including space power, specialized remote power, off-grid residential power, micro-cogeneration, and self-powered appliances. The company has over 30 employees at its Kennewick facility.

STC is gearing up for low-volume manufacturing and has recently purchased production equipment worth $750,000. The facility will allow for manufacture/assembly of hundreds of Stirling engine subsystems per year. As demand increases, the company will upgrade or purchase new production facilities.

Technology Overview

The key strength of the STC Stirling engine technology is long, maintenance-free life. This characteristic is a direct result of one of the original applications that initiated the research at McDonnell Douglas: power for artificial human hearts. Although the artificial-heart market may appear remote from current interest, the challenge of producing an engine that would have the reliability necessary for such an application led to the key developments that distinguish STC's technology.

The problem of crankcase sealing (e.g., sealing the power piston to avoid mixing of the working gas and lubricating oil) has perennially plagued Stirling engine developers and remains a concern today in building long-life, service-free equipment. In the STC concept, pressure fluctuations on the primary bellows are internally balanced by use of a second compensating bellows (shown in Figure A-15). This also alleviates the tendency of such sealing systems to gradually undergo stress-induced failure.

The use of flexural bearings (shown in Figure A-16) instead of thrust bearings in free-piston Stirling engines and linear alternators marked another important development in STC technology. STC holds several patents in the area of flexural bearings. The flexural bearing is a similar solution to a problem in any reciprocating system, which needs to maintain critical axial alignment. STC has used flexural bearings in its Stirling engine systems for both power generation and cooling applications.

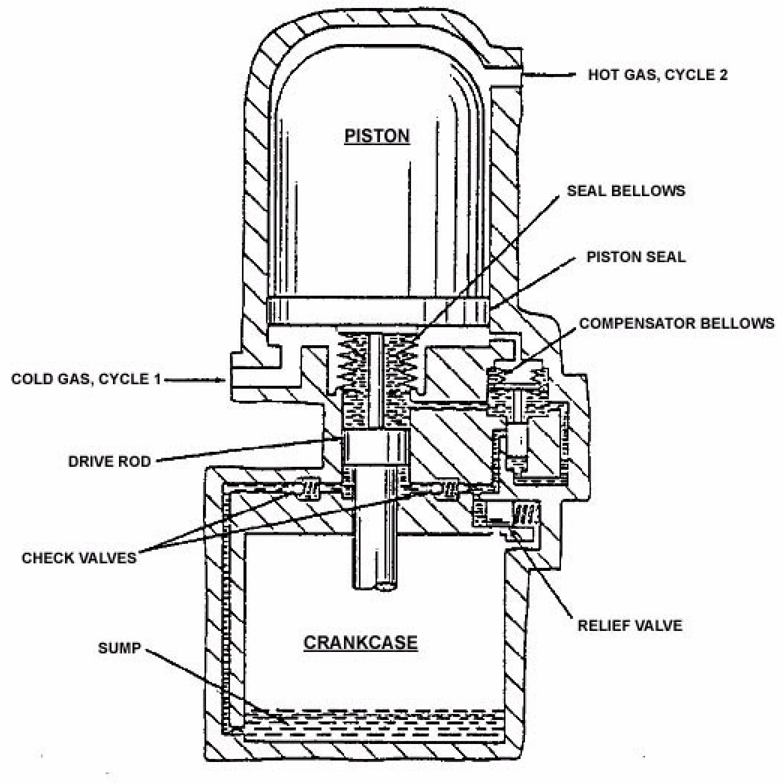

Figure A-15
Stirling Technology Company – Compensated Bellows Piston Seal

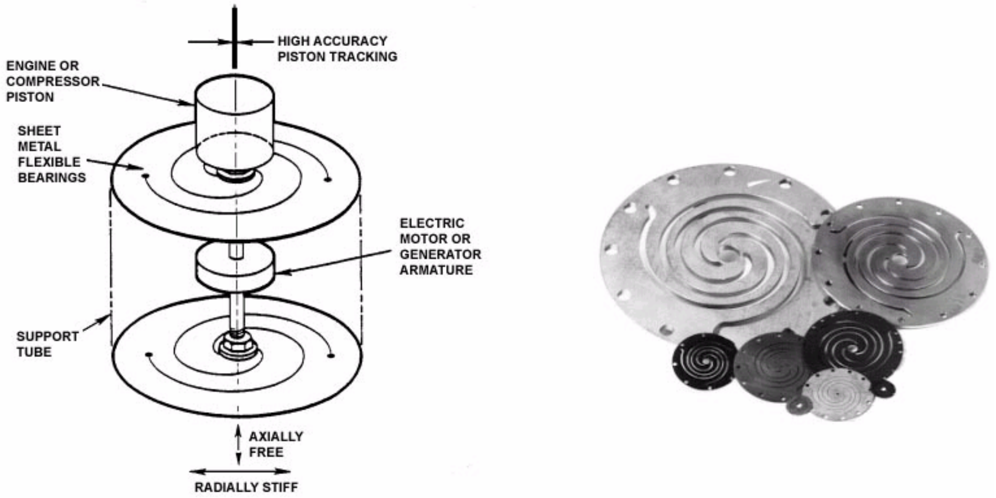

Figure A-16
Stirling Technology Company – Flexural Bearings

STC has designed and built both kinematic and free-piston Stirling engines. The company has distinguished the free-piston design as superior, due to its mechanical simplicity and absence of external dynamic seals. The free-piston engine was designed with flexural bearings, which combine radial stiffness with axial motion, to avoid all rubbing parts, eliminating the need for lubrication. This, in turn, allows the engine to be hermetically sealed, which prevents pressure loss and minimizes maintenance. However, the prototype engines in production now for demonstration will not be hermetically sealed; rather, they will be sealed with o-rings and require a helium charge every three to four months. Although, as the company moves to mass manufacture, all of its engines will be hermetically sealed. STC's latest engine design includes three pistons (shown in Figure A-17).

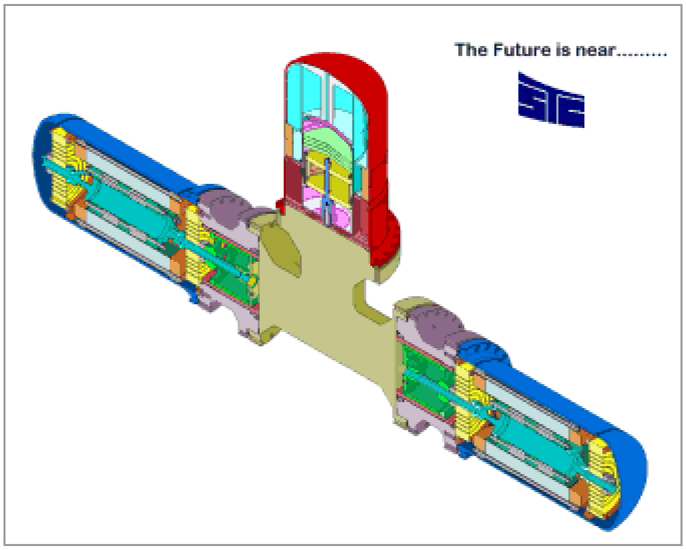

Figure A-17
Stirling Technology Company – Three-Piston Engine Design

Helium is the working fluid in STC's Stirling engines. The radiant matrix burner utilized in the STC engines radiates energy from the burner element to the heater head and permits fuel-flexible designs. The burner contains a flame quencher that prevents the combustion temperature from climbing too high, thus also controlling emission levels. In order to meet its longstanding goal of low-cost production, STC has designed its Stirling systems to utilize conventional machining and assembly techniques using common materials such as steel and copper.

Technology Status

STC has demonstrated the maintenance-free, degradation-free operation of a single 10-W Stirling engine for more than 67,000 hours. In addition, many other engines and power generation systems have accumulated tens of thousands of hours of operation without warranted failure. A large portion of this testing has been accomplished at third party test sites. STC has developed two distinct product lines: the RemoteGen™ engines for power generation applications and the BeCool™ product line for cooling applications.

The company has successfully operated RemoteGen™ units on a variety of fuels, including natural gas, propane, biomass, solar energy, diesel, and radioisotope fuel sources (for space applications). The RemoteGen™ product line consists of five Stirling cycle generators, ranging from 60 W to 3,000 W, for stationary power applications. The products include the burner, engine, linear alternator, controllers, and water jacket cooling.

STC's Stirling engines are designed with a continuous duty cycle and for a minimum maintenance-free lifetime of 50,000 hours. The RemoteGen™ systems have also demonstrated quiet operation (e.g., 53 decibels at 1 meter) and low emissions (e.g., less than 10 ppm CO and less than 5 ppm NO_x, SO_x). The RemoteGen™ specifications are shown in Table A-15.

The RG-55 product is currently in limited production. The radioisotope-fueled version of this product, developed under a U.S. DOE contract, has been selected by NASA to power future deep space and planetary lander missions. NASA plans to replace traditional electric generators with Stirling engines due to the technology's higher efficiency. The radioisotope fuel is the primary cost of electricity in space. Therefore, NASA will be able to save money by employing a more efficient generating technology, like Stirling engines.

STC anticipates that funding for the NASA project will shift in the spring of 2002 from the DOE to a four-year contract with a system integrator. The integrator will package the Stirling engine, alternator, and assembly supplied by STC into a product that will be used by NASA. The first demonstration of the RG-55 in a space application will be in the Mars long-distance rover deployed from the advanced smart lander, planned for 2007.

There are more than 20 beta RG-350 units located at different facilities around the world to demonstrate the low-maintenance and high-reliability features of the STC Stirling engine design. This system is ideally suited for auxiliary power applications in boats or recreational vehicles. STC has installed one RG-350 in a prototype hydronic heating system boiler unit in Europe, while another RG-350 has successfully operated on biomass fuel using an advanced low-tar gasifier. STC has also integrated a complete power generation system with an RG-350 engine, a battery buffer system, and other necessary components. This system is undergoing testing at the STC facilities in Kennewick.

Table A-15
STC Specifications – RemoteGen™ Product Line

Product	RG-55 Engine (Incl. Burner and Generator)	RG-350 Engine (Incl. Burner and Generator)	RG-450 Engine (Incl. Burner and Generator)	RG-1000 Engine (Incl. Burner and Generator)	RG-3000 Engine (Incl. Burner and Generator)
Product Status	In Production	Many (10-20) Pre-Production Prototypes in the Field (beta)	Multiple (<10) Early Units in Testing (alpha)	Multiple (<10) Early Units in Testing (alpha)	Multiple (<10) Early Units in Testing (alpha)
Engine Type	Free-Piston	Free-Piston	Free-Piston	Free-Piston	Free-Piston
Cylinders / Power Pistons	One	One	One	One	One
Working Fluid	Helium	Helium	Helium	Helium	Helium
Generator / Alternator	Induction Generator	Induction Generator	Induction Generator	Induction Generator	Induction Generator
Power Output	60-80 We	350 We	550 We 450 We	1.25 kW$_e$ 1 kW$_e$	3 kW$_e$
Voltage / Frequency	120 VAC @ 60 Hz 240 VAC @ 50 Hz	120 VAC @ 60 Hz 240 VAC @ 50 Hz	120 VAC @ 60 Hz 240 VAC @ 50 Hz	120 VAC @ 60 Hz 240 VAC @ 50 Hz	120 VAC @ 60 Hz 240 VAC @ 50 Hz
Fuel	Radioisotope	Natural Gas Propane Biomass	Natural Gas Propane	Natural Gas Propane	Natural Gas Propane
Electrical Efficiency *	29%	23%	30%	23%	39%
Physical Size (l x dia)	13.8 x 5 in 350 x 130 mm	23 x 8 in 580 x 200 mm	24 x 7.5 in 600 x 190 mm	28 x 9 in 710 x 230 mm	34 x 10 in 860 x 250 mm
Weight (dry)	7.7 lbs 3.5 kg	80 lbs 36 kg	100 lbs 45 kg	130 lbs 59 kg	160 lbs 73 kg
Noise Level	53 dbA at 3.3 ft	53 dbA at 3.3 ft	53 dbA at 3.3 ft	53 dbA at 3.3 ft	53 dbA at 3.3 ft
Emissions	< 10 ppm CO < 5 ppm NO_x < 5 ppm SO_x at 15% O_2	< 10 ppm CO < 5 ppm NO_x < 5 ppm SO_x at 15% O_2	< 10 ppm CO < 5 ppm NO_x < 5 ppm SO_x at 15% O_2	< 10 ppm CO < 5 ppm NO_x < 5 ppm SO_x at 15% O_2	< 10 ppm CO < 5 ppm NO_x < 5 ppm SO_x at 15% O_2
Servicing Interval	None	None	None	None	None
Product Lifetime	50,000 hours	50,000 hours	50,000 hours	50,000 hours	50,000 hours
Production Cost	n/a	n/a	n/a	$1,000 per system @ 100,000 units per year	n/a

* Heat in to AC out – not including burner efficiency

The RG-450 was specifically designed for micro-cogeneration systems, remote power applications, and self-powered appliances. STC has granted a license to an undisclosed company for the manufacture, integration, and sale of products that incorporate the RG-450 engine in Europe.

The RG-1000 (shown in Figure A-18) is undergoing testing in Europe for use in micro-cogeneration systems. It has entered into limited production with natural gas- and propane-fueled versions. The Dutch consortium, ENATEC micro-cogen B.V., has been granted a license by STC to integrate and sell products based on the RG-1000 engine in Europe. ENATEC shareholders include ENECO Holding N.V., ATAG Verwarming, B.V., and the Energy Research Centre of the Netherlands (ECN). ENATEC is presently testing three micro-cogeneration systems that utilize the RG-1000 engine. The consortium is planning a 100-unit field trial program. Although ENATEC has obtained rights to manufacture the engine, the group has approached STC to possibly manufacture/assemble the one hundred engines for demonstration.

Figure A-18
Stirling Technology Company RG-1000

The RG-1000 has also operated successfully on solar power at the National Renewable Energy Laboratory in Golden, Colorado. The same unit also operated on propane and underwent a successful integration and demonstration with gasified biomass fuel (e.g., wood pellets) as part of a DOE Small Business Innovative Research (SBIR) grant.

The RG-1000 unit was designed by STC to permit low-cost mass production. STC intends to sell its engine subsystems to original equipment manufacturers (OEMs). The OEMs will then integrate the engine into a complete power generation system for a variety of applications. This sales strategy will permit STC to mass-produce its engines for a wide variety of applications, rather than focusing its efforts on packaging entire systems for specific applications.

STC's ultimate goal is to produce 100,000 RG-1000 units per year. At this production level, parts for the RG-1000 engine will cost $250-500, while the entire manufacturing cost of the RG-1000 Stirling engine subsystem will be $1,000 (or $1,000 per kW). STC plans to leverage its experience with the RG-1000 into production of additional engine systems (i.e., the RG-3000) for many other possible applications.

STC presently has six RG-1000 units in prototype production. The company plans to make these units available for demonstration, either as engine subsystems or completely integrated power generation systems, in the spring of 2002. The completely integrated system includes a battery buffer system. The operation of the integrated system is relatively simple, automatically turning on to charge the batteries and turning off to drain them. It is anticipated that a demonstration of this type of system would cost $40,000-50,000, including a few days of training. STC has an integrated power generation system, based on the RG-1000 engine, in operation at its facilities in Kennewick.

STC anticipates that micro-cogeneration applications in the United States may be met by its RG-3000 system (shown in Figure A-19). Although this engine was originally developed for naval applications, STC believes it may also be utilized in stationary power generation applications. This product is in the early stages of demonstration. Limited production runs are scheduled for early 2002.

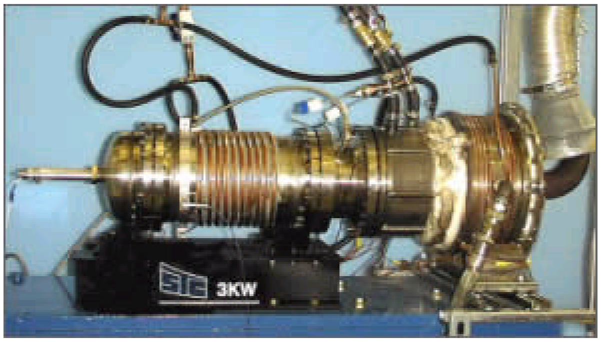

Figure A-19
Stirling Technology Company RG-3000

In addition to the RemoteGen™ product line, STC has developed the BeCool™ line of cryocoolers based on the Stirling cycle. The three coolers in the line provide cooling over a wide range of cryogenic temperatures with a nominal cooling capacity of 15 watts at 77 Kelvin. Each of the BeCool™ units features the long, maintenance-free, flexural bearing design utilized in the RemoteGen™ products.

EPRI Perspective

STC has a strong patent position and claims that their machines are superior to the Stirling technology of competitors. Although the company has tested a sub-scale engine for more than 67,000 hours without maintenance or performance degradation, STC has not demonstrated the same type of durability on its larger engines. It may prove to be true that the STC engines are much more durable and reliable than others, but they are also currently very expensive. MCHP systems based on STC Stirling engines have the potential to lead the market for boiler replacement in Europe if the company is able to reach their targeted production level and prices.

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Contact: Craig Kinzelman, Director of Stirling Technology

Role: Former Engine Developer, Engine Manufacturer

Stirling Technology, Inc. (STI) was formed in 1983 by former Sunpower employees. The company originally set out to develop Stirling engines that operate on biomass fuels for power generation in remote areas and developing countries. After a series of failed partnerships, STI has stalled the development of its ST-5 engine, which produces 3.5 kW_e and up to 25 kW_{th}. STI has shifted focus to its energy recovery ventilation product.

Company Background

Former employees of Sunpower established Stirling Technology, Inc. (STI) in 1983 in Athens, Ohio. In addition to its office space, STI has a 36,000 ft2 research, development and manufacturing facility. The company began its business with the development of small, biomass-fueled Stirling engines. STI produced approximately 100 engines several years ago in India, but the joint venture that had been established in that country disbanded due to political issues. STI also worked with Stirling Engine, Co., of Japan, until that company chose to progress with a different type of engine technology.

STI presently does not offer any Stirling engine products. The company has made several attempts to resurrect its Stirling engine program; however, the project is stalled due to lack of strategic partners. STI is instead focusing on another technology. The only product that STI currently offers is an energy recovery ventilation system called the RecoupAerator®.

STI is a privately held company, with policy driven by its few stockholders and management. Sunpower did own equity in STI in the past, but STI has since bought back that equity. The company is currently a completely separate entity from Sunpower.

Technology Overview

Stirling Technology, Inc. developed a 5-hp kinematic Stirling engine (the ST-5) for stand-alone operation in rural areas. The engine was developed to use a wide range of fuels, including impure natural gas, crude oil, and biomass (i.e., rice husks and chaff, wood, wood pellets, peanut shells, weeds and hay, cotton waste, etc.). The ST-5 (shown in Figure A-20) was billed as a multipurpose engine that could be used in applications where there is no access to electricity from a grid.

Figure A-20
Stirling Technology, Inc. – ST-5 Engine

STI has a variety of patents and patent applications pending in the U.S. and abroad, the majority of which appear to be related to the company's ventilation product.

Technology Status

The ST-5 engine is sized to provide up to 3.5 kW_e, which is generated by attaching an AC alternator to the engine. The ST-5 offers up to 25 kW_{th} of recoverable waste heat for space heating, domestic hot water heating, electric power generation, and shaft power for water pumps or compressors. The engine has a cold start time of about 10 minutes. Specifications for the ST-5 are shown in Table A-16. One potential application of the ST-5 engine is to provide domestic baseload power (i.e., appliances, washers, freezers, etc.) for up to six hours a day. At the same time, excess power may be used to charge batteries for use when the engine is not in operation. By connecting the ST-5 to a centrifugal water pump, it may also be used in applications that require pumping water.

The ST-5 is a kinematic type Stirling engine, fitted with sealed bearings and dry-lubricated cylinders. There is no oil used in lubrication of the engine. The ST-5 uses air as its working fluid, and is pressurized to 5 bar (~73 psi). The engine is self-pressurizing; therefore, leakage is not a problem and the engine does not require hermetical sealing. However, the seals will likely require replacement periodically. The engine's speed is set to operate at 650 rpm, with an electric frequency of 60 Hz. The ST-5 is a large engine, approximately half the size of a large office desk (shown in Figurre A-21).

Table A-16
Stirling Technology, Inc. Specifications – ST-5 Engine

Product	Engine
Product Status	Inactive
Engine Type	Kinematic
Cylinders / Power Pistons	One
Working Fluid	Air
Hot End Temperature	950 °F 510 °C
Pressure	73 psi
Engine Shaft Speed	650 rpm
Power Output	3.5 kW_e AC
Usable Heat Output	Up to 25 kW_{th}
Fuel	Natural Gas, Propane, Crude Oil, Biomass

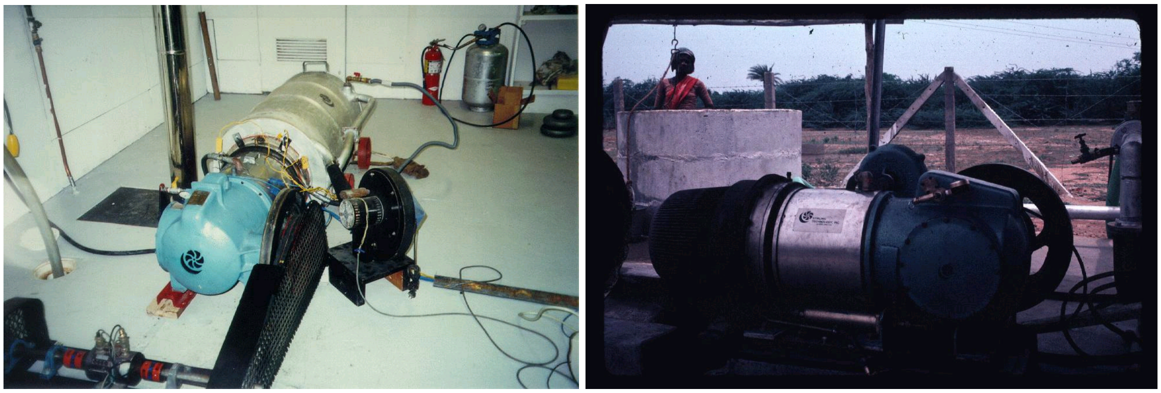

Figure A-21
ST-5 Engine: At STI Facilities and Testing in India

There are two burner options for the ST-5: a cyclone burner for small particle fuels and a two-stage wood burner. The fuel can be fed into the burner either manually or through a hopper. The use of gaseous fuels would require modification to the intake orifice of the cyclone burner. High temperatures are necessary to run the engine, and both burners employ a forced-air blower to reach these temperatures. Before the engine starts running, the blower must be operated either by hand or by battery for ten minutes, or until the desired heater head temperature of 950ºF is reached.

The coolant for the engine is either water or a water-glycol mixture, which is circulated throughout an automotive-type radiator by a small pump. A fan blows air across the radiator, and all waste heat exits into the atmosphere.

Stirling Technology, Inc. has had previous relationships with Stirling Dynamics of India, Stirling Engine Company of Japan, and Stirling Technology of Korea. Unfortunately these partnerships are no longer in existence. STI has been unable to resurrect its ST-5 program thus far due to lack of support.

At the time when the ST-5 engines were being produced in India, the manufacturing cost was $3,000 per engine. The higher capital cost to the end user may be offset by the ST-5's fuel flexibility, as opposed to conventional gasoline or diesel-powered internal combustion engines. Several 50-Hz, 3-kW_e ST-5 engines were sent to China in the mid-1980s for testing over a period of two or three months.

EPRI Perspective

The ST-5 would have been an optimum product for less-developed countries where biomass fuels are abundant but access to electricity is not. The design of the engine is such that maintenance would have been similar to that of internal combustion engines. Since the engine is not hermetically sealed and the working fluid is air, relatively simple tools could be used to maintain the ST-5. Unfortunately, the lack of funding and interest in the product has led to its abandonment.

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Role: Engine Developer, Engine Manufacturer, Product Packager

STM Power, Inc. (formerly Stirling Thermal Motors) is a developer of Stirling engines and power generation systems for stationary applications. The company plans to make its first PowerUnit product commercially available in the second half of 2003. It will provide up to 44 kW_{th} at a rated power output of 25 kW_e. STM is configuring this system to operate on a wide variety of fuels and waste heat. In addition, STM has developed the SunDish Solar hybrid product that combines the PowerUnit system with a solar collector licensed from Scientific Applications International Corporation (SAIC).

Company Background

STM Power, Inc. is a developer of Stirling engine systems for on-site power generation applications. The company was originally founded as Stirling Thermal Motors more than a decade ago. STM's corporate headquarters and manufacturing facilities are located in Ann Arbor, Michigan, and a satellite office is located in Arlington, Virginia. The company's early development work (particularly related to solar and renewables) was funded through contracts with the Department of Energy. In recent years, STM has secured a significant amount of private equity and venture capital funding. Current shareholders include Singapore Technologies, DTE Energy, The Beacon Group, Nth Power, Arete Corporation, and several individual European investors.

Technology Overview

STM has developed a proprietary four-cylinder Stirling cycle engine called the STM 4-120 (design shown in Figure A-22). Due to its swashplate driven rotary shaft, the output torque of the Stirling engine is nearly constant (i.e., more like an electric motor than an IC engine). The working gas utilized in the engine is hydrogen. The company's design is scalable, allowing integration of the engine design into power generation products that range in size from 2 kW_e to

500 kW_e. STM estimates that its Stirling engines have 50% fewer moving parts than traditional reciprocating internal combustion engines.

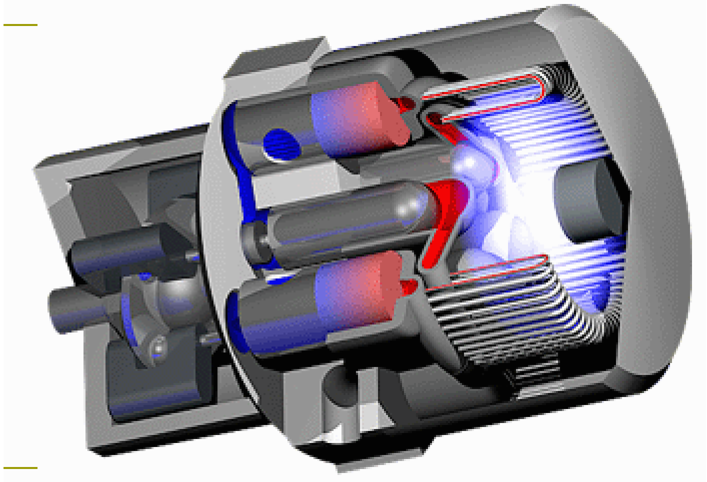

Figure A-22
STM 4-120 Stirling Engine Design

In order to minimize cost, the company has designed the STM 4-120 engine (shown in Figure A-23) to utilize parts and materials that are readily available through current automotive and industrial suppliers. In the hermetically-sealed STM design, the engine pistons are isolated from the combustion gases, which in turn increases the lifetime of the unit and reduces the life cycle cost of the system. The STM 4-120 engine has a gross power output of 30 kW_e at a speed of 1,800 rpm.

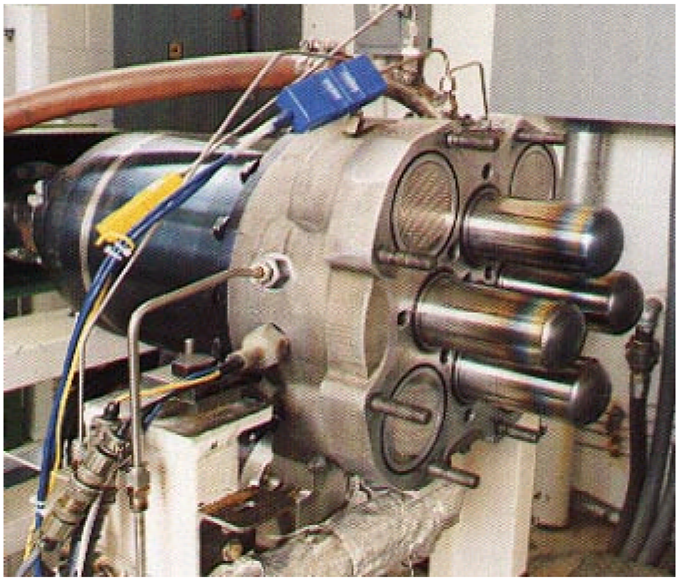

Figure A-23
STM 4-120 Engine on Test Stand

Technology Status

STM's first product, the 25-kW_e PowerUnit, is a fully integrated power generation system based on the STM 4-120 Stirling engine. The PowerUnit produces up to 150,000 Btu/hr (44 kW_{th}) of usable heat at its rated power capacity of 25 kW_e. The PowerUnit's net fuel energy consumption is approximately 11,500 Btu per each kilowatt-hour of electricity delivered by the system. This equates to a demonstrated electrical efficiency (LHV) of about 30%. STM believes that the efficiency of the 25-kW_e PowerUnit can be improved to greater than 34% in the mid- to long-term. Efficiency measurements and projections of the PowerUnit are shown in Table A-17.

Table A-17
STM 25- kW_e PowerUnit – Efficiency Measurements and Projections

	Demonstrated (Prototype)	Near-Term (Production)	Mid-Term (Enhancement)
Net Electric Fuel Efficiency			
LHV	29.6%	30.9%	34.3%
HHV	26.9%	28.2%	31.3%
Heat Rate (Btu/kWh)			
LHV	11,530	11,040	9,950
HHV	12,690	12,100	10,900

The standard 25-kW_e PowerUnit (shown in Figure A-24) is intended for grid-parallel operation. However, the product will also be made available with a grid-independent option. This option permits the system to load follow and gives it black-start capability.

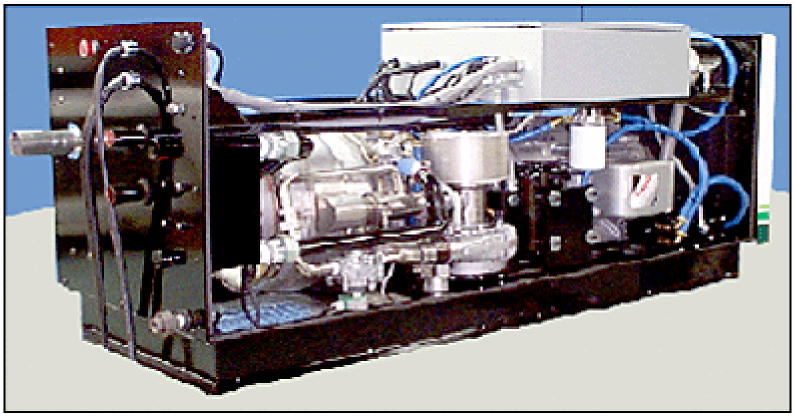

Figure A-24
STM 25- kW_e PowerUnit

The STM PowerUnit may be designed to operate on a variety of available fuels, including natural gas, propane, diesel fuel, and gasoline. A fuel compressor is not required, as the system operates at a low pressure. Renewable fuels, such as solar, biomass, hydrogen, landfill gas, and waste heat, may also be employed in STM products. Additionally, STM's Stirling engines can be powered with light crude oil flare gas without compression. The STM PowerUnit consumes natural gas at a rate of approximately 315 scf/hr. The system has a cold start up time of 1 minute for positive power and 3-5 minutes to full load. While in idle mode, the system can reach full load in 1/3 second.

As an external combustion engine, STM's 25-kW_e PowerUnit is controlled to have low emissions. The commercially available units will meet all future distributed generation air regulations, such as those imposed by the California Air Resource Board (CARB) and the Texas Natural Resource Conservation Commission (TNRCC). The NO_X regulations established by these agencies are currently at 0.5 lb/MWh and 0.47 lb/MWh, respectively.

STM also considers the low noise level of the 25-kWe PowerUnit an advantage. The system falls within OSHA standards, measuring 68 dB at 3 feet and 47 dB at 33 feet (~10 meters). The company anticipates that its PowerUnit systems will operate for 40,000 hours prior to major engine overhaul. Target specifications of the STM PowerUnit are shown in Table A-18.

Table A-18
STM Target Specifications – 25-kWe PowerUnit

Product	Integrated System
Product Status	Multiple (<10) Early Units in Testing (alpha)
Engine Type	Kinematic
Cylinders/Power Pistons	Four
Working Fluid	Hydrogen
Engine Shaft Speed	1,800 rpm
Generator / Alternator	Induction Generator
Power Output	25 kW_e AC
Voltage/Frequency	480 VAC @ 60 Hz
Usable Heat Output	44 kW_{th}
Fuel	Natural Gas, Propane, Diesel, Gasoline
Electrical Efficiency	30.9% (29.6% demonstrated) (LHV Fuel In to AC Electricity Out)
Overall Efficiency	80% (LHV Fuel In to AC Electricity and Usable Heat Out)
Physical Size (w x d x h)	79 x 30 x 42 in 2,000 x 760 x 1070 mm
Noise Level	< 68 dbA at 3 ft (OSHA standard)
Emissions	< 0.47 lb/MWh NO_x (TNRCC standard)
Servicing Interval	Yearly (filters, lubricating oil, etc.)
Product Lifetime	40,000 hours
Price to End User (Retail)	$1,000/$kW_e$ (projected for 2003)

In addition to the conventional PowerUnit product, STM plans to offer the WasteHeat PowerUnit. It will be an adaptation of the 25-kW$_e$ PowerUnit that will be fueled from waste heat produced by industrial processes, such as furnaces, kilns, thermal oxidizers, incinerators, and other high-temperature equipment. Figure A-25 shows a possible configuration of four heat-fired PowerUnits to produce 100 kW$_e$.

Figure A-25
STM WasteHeat PowerUnit

STM presently has ten alpha PowerUnit systems in operation at its Ann Arbor facility. These units have been configured to demonstrate engine operation on a variety of fuels, including natural gas, propane, and waste heat. STM plans to deploy several beta PowerUnit systems for field demonstration in the summer of 2002. These systems will not include a warranty, however it is anticipated that full engineering support will be provided to complete the initial start up and to monitor the operation of the unit. The 25-kW$_e$ beta units are priced at approximately $60,000 per system, depending on the configuration.

STM plans to make the first 25-kW$_e$ PowerUnit product commercially available in the second half of 2003. At this time, it is estimated that the retail price of the final product will be competitive with that of microturbines (i.e., $1,000 per kW$_e$). STM has contracted with Ricardo plc to design and build a manufacturing and assembly process for the PowerUnit product. The initial manufacturing plant will be located in Ann Arbor and will have a production capacity of thousands of units per year.

STM also has plans to manufacture and distribute the hybrid SunDish Solar system (shown in Figure A-26). The SunDish product incorporates a 25-kW$_e$ PowerUnit with a 16-facet solar collector licensed from Science Applications International Corporation (SAIC). The system permits both solar and solar-hybrid applications. Specifications of the SunDish product are listed in Table A-19.

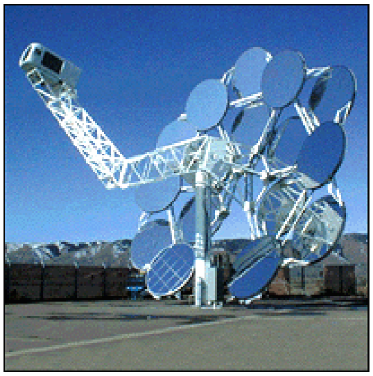

Figure A-26
STM SunDish Solar Product

Several SunDish Solar systems have been deployed for demonstration throughout the U.S. One system was previously installed at the Pentagon in Washington, D.C. There are currently three SunDish systems in operation: one at the University of Nevada at Las Vegas (UNLV) and two within the service territory of Arizona Public Service. A fourth SunDish solar system is undergoing testing at the National Renewable Energy Laboratory (NREL) in Golden, Colorado.

Table A-19
STM Specifications – SunDish System

Solar Insolation	1,000 W/m^2
SunDish Installation Density	10 units/acre (200 kW/acre)
Power Output	20 kW$_e$ AC (solar only) 25 kW$_e$ AC (solar-hybrid)
Usable Heat Output	44 kW$_{th}$ (hot water at 130 °F)
Reflective Area	113 m^2, 16 facets
System Height/Diameter	50 ft

One of the unique features of the PowerUnit and SunDish product lines is the inclusion of a small hydrogen generator within the Stirling engine. The miniature hydrogen generator, based on electrolysis technology, is supplied by Proton Energy Systems under a 10-year exclusive agreement with STM. The electrolyzer is controlled to recharge the pressurized hydrogen working fluid of the Stirling engine as needed.

STM has also completed designs of the STM 4-70 and the STM 4-20 Stirling engines, both of which are scaled-down versions of the STM 4-120 engine. While product development for these engines is presently inactive, it is possible that they may ultimately be utilized in future 10-kW$_e$ and 2-kW$_e$ PowerUnits for light commercial and residential markets.

STM currently has distribution agreements with DTE Energy Technologies and Singapore Technologies. DTE Energy Technologies sells the 25-kW_e PowerUnit product as the ENE 250 under DTE's energy|now brand name (packaged system shown in Figure A-27). The ENE 250 is specifically targeted to remote, flare gas applications where the available fuel may be sour. STM intends to secure a small number of additional strategic distributors for its Stirling engine power generators. In the near-term, STM also plans to handle product orders directly from its factory in Ann Arbor

Figure A-27
energy|now ENE 250

EPRI Perspective

STM is a leader in Stirling technology. STM units utilize standard parts and materials available through the automotive industry. The company has also demonstrated an efficiency of nearly 30% at their facility. STM has several SunDish Solar systems at demonstration sites throughout the US. The company has been involved with Stirling development for over 10 years and has the financial backing and strategic relationships to meet their commercialization goals.

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Role:	Engine Developer

Founded in 1970, Sunpower has become one of the recognized leaders in free-piston Stirling engine technology. The company has made cryocooler products available that utilize this technology. In addition, Sunpower has licensing agreements with several companies worldwide to manufacture, package, and sell its Stirling engine for heating and power applications. Most notably, BG Group of the U.K. is planning to introduce a micro combined heat and power (MCHP) product based on Sunpower's Stirling technology. This MicroGen product is being designed for boiler replacement in the European residential market.

Company Background

Sunpower was established in 1970 by Professor William Beale. It began as a sole proprietorship with income primarily from large industrial and government research and development funds. Sunpower received the first of over thirty Stirling engine government contracts from NASA in 1974. The bulk of Sunpower's funding currently comes from a variety of international private sector partners. Neill Lane assumed control of Sunpower in 1998 following the retirement of William Beale.

Sunpower is located in Athens, Ohio. Sunpower's facilities include offices, laboratories and a machine shop, with a 6,000 ft^2 cryocooler factory. The company currently employs approximately fifty people.

Technology Overview

William Beale invented the free-piston Stirling engine in 1964. In the years since, Sunpower has further developed free-piston Stirling engine generator technology. The company has also developed a Stirling cryocooler and linear compressors. Sunpower's technology is protected by more than 30 U.S. patents, and by more than 80 foreign patents and applications. Sunpower's compressor technology is currently being used in a refrigerator sold in Korea, while its power generation technology is undergoing field testing in Europe.

One of the common obstacles to the widespread acceptance and application of Stirling engines is the myriad of problems related to kinematic technology, including decreased lifetime (due to the high number of moving parts) and bulkiness of the engine. There are few companies worldwide that are actively pursuing free-piston Stirling technology, with Sunpower at the forefront of this research and development. Sunpower is a small company entirely devoted to free-piston Stirling technology. Sunpower is not only developing this technology, but has also developed its own software to test and evaluate its Stirling products.

Sunpower is mainly a research and development company, licensing its free-piston Stirling technology to manufacturers around the world. Sunpower has facilities to manufacture Stirling cycle cryocoolers, but on a small scale using batch production techniques. Sunpower is also a strategic and funding partner in External Power, which was created in 1996 by Wood-Mizer after it received a license for the Sunpower free-piston technology.

All of Sunpower's products are hermetically sealed, which means they are classified as pressure vessels. A problem with the design of the machine that could influence lifetime of the system includes thermal-stress induced creep of the heater head. Over time, the high temperatures involved in heating the head can irrevocably damage the part, and the selection of material for the heater head will greatly affect the lifetime of the engine, as well as the cost for production.

Technology Status

Sunpower produces and sells a small engine that demonstrates the operation of their free-piston Stirling engine technology. The B-10B (shown in Figure A-28) is supplied with a simple alcohol burner-ring, starts easily, and runs quietly. It can be adapted to operate on any source of adequate heat, including solar energy. The B-10B Stirling engine is capable of producing 1 watt of power, suitable for educational demonstrations.

Figure A-28
Sunpower B-10B Stirling Engine Demonstrator Product

Sunpower has granted an exclusive license to Global Cooling, B.V. for use of its high-temperature cooling technology for food preservation applications. The M100A Free-Piston Stirling Cooler is a fully modular cooling unit, capable of being used in DC, solar, or AC applications. The maximum cooling capacity for the unit is 100 W, which makes it suitable for use in small domestic refrigerators, recreational vehicles, or for solar-powered cooling applications. The cooler is manufactured both in Athens, Ohio and at Global Cooling's facilities in the Netherlands.

Sunpower's other cryocooler products are currently available for performance evaluation and testing, but are not available for widespread consumer use. The M77 cryocooler can be adapted as needed for given applications. It has a cooling capacity of 4 W at a temperature of 77 Kelvin. For critical applications, vibration can be suppressed via an active balance motor, and for less-critical applications, a passive mass balance can be used. The M77 employs helium as its working fluid in a hermetically sealed container. The components within the engine move in a linear fashion, operating on gas bearings. This reduces friction and wear within the engine and theoretically extends the life of the engine. The M77 sells for approximately $33,000 per unit.

Sunpower also offers the M87 cryocooler, which uses the same technology as the M77. The M87 is available in sample quantities, at a cost of $10,000 per unit. The cooling capacity of the M87 is 7.5 Watts at 77 Kelvin, and it operates at a frequency of 60 Hz. The estimated life of the M87 is 40,000 hours. These cryocoolers are capable of extremely quiet operation through the use of either highly effective vibration absorbers, or twin opposed coolers to counteract vibration.

Sunpower also offers a 1-kW$_e$ free-piston Stirling engine. The specifications of this engine are shown in A-20 . At present, only prototypes of the engine are available for evaluation and development purposes at a cost of $35,000 per unit. As with the company's cryocoolers, the power generating engine uses helium as its working fluid. The engine operates at a frequency of 50 Hz, and has an average electrical efficiency of 28%.

Twenty-eight of the 1-kW$_e$ engines are currently undergoing field trials at BG Group in the U.K. BG is a worldwide licensee of the Sunpower Stirling engine technology for use in domestic (i.e., residential) combined heat and power applications. BG has integrated and packaged the Sunpower engine into a complete natural gas-fired MCHP system, called the MicroGen. The engine is currently at the design-for-manufacture stage, and BG Group recently announced a partnership with Rinnai of Japan for mass-production of the Stirling engine.

External Power is another licensee of the Sunpower engine technology. The companies are working together to develop BioWatt™, a line of biomass-fueled combined heat and power systems. These products will use a free-piston Stirling engine to convert various wood fuels (such as wood, wood pellets, sawdust, chips, and biomass waste) to electricity and heat for residential, small commercial, and agricultural applications. The BioWatt™ systems are capable of generating between 500 We and 10 kW$_e$. The fuel is first pyrolyzed to generate a wood gas, which is burned to heat the Stirling engine. At full capacity, the system can generate a minimum of 4 kW$_{th}$ per kW$_e$. Biomass-to-electricity conversion efficiencies will depend on the amount of heat recuperated, but in general range from 12% to 17%.

Table A-20
Sunpower Specifications – Engine for Power Generation Applications

Product	Engine
Product Status	Many (10-20) Pre-Production Prototypes in the Field (beta)
Engine Type	Free-Piston
Cylinders / Power Pistons	One
Working Fluid	Helium
Hot End Temperature	1,022 °F 550 °C
Cool End Temperature	122 °F 50 °C
Generator / Alternator	Linear Alternator
Power Output	1 kW_e AC
Voltage/Frequency	240 VAC @ 50 Hz
Fuel	Natural Gas, Propane, Biomass
Electrical Efficiency	28% (Heat to Head to AC Electricity Out)
Price to Distributor	\$35,000/kW_e @ low production (current price)

External Power and Sunpower are currently generating pre-production prototypes to be tested and altered prior to the larger-scale prototype production, where the product will be demonstrated by prospective strategic partners. The companies do not anticipate commercial availability of the biomass-fueled 1-kW_e free-piston Stirling engine until 2003. After initially launching the 1-kW_e version, the companies intend to produce a range of systems, with electrical output capacities up to 18 kW_e.

Sunpower does not currently have any engine programs specifically concentrated on solar applications of Stirling technology.

EPRI Perspective

Sunpower is a development leader in Stirling technology, with an experienced team of highly qualified professionals working on a variety of products. Sunpower also has many licensing relationships with companies worldwide, and with products ranging from medical equipment to residential heat and power generators. Sunpower's technology will be put to the test as these products hit the market in the coming years. If Sunpower can successfully manage the transfer of its know-how and technology to its licensing partners, their Stirling technology business may become highly successful.

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Contact: Drummond Hislop, President

Role: Engine Developer

Sustainable Energy Systems Limited was founded in the late 1980s to develop a simple, standard Stirling engine design that can be the basis for all sizes and applications. The small U.K. company is presently in the early testing phases of its 10-kW_e prototype. If the current engine design proves to be successful in the laboratory and in field demonstrations, SES will seek investment to complete the development. It is likely that the company will eventually sell its intellectual property rights.

Company Background

In the late 1970s, engineer-turned-economist Drummond Hislop was involved in the development of rural energy systems in areas of India and Africa. Traditionally, diesel-pumping systems were utilized because oil and electricity were not available in such rural areas. The only viable alternative to diesel was biomass. Mr. Hislop assessed the needs to develop a rural energy system that utilized biomass fuel for applications from 5 kW_e to 1 MW_e.

The favored biomass technology at that time involved the gasification of the biomass fuel in order to burn it in an internal combustion engine. However, in practice this was difficult to do in a cost-effective manner. The primary reason for this is that the biomass fuel is generally very dirty, so it must be cleaned and cooled before it enters the IC engine. It was at this point in his assessment that Mr. Hislop identified the potential opportunity for Stirling engine technology in rural applications.

Because it is an external combustion engine, the Stirling is ideal for applications that utilize biomass fuel. Mr. Hislop researched the engines available in the early 1980s, only to find that after lengthy periods of development, Stirling engines were still not widely commercially available. Stirling Technology, Inc. ST-5 engines were operating in rice mills in Bangladesh in the late 1980s; however, the design was too basic to succeed in a system fueled by biomass.

Mr. Hislop turned to a university in the U.K. for help. The university was able to design a 20-kW_e system, and with the help of Mr. Hislop and his partners an “academic” Stirling system was built. When the system failed in the intended application, it became clear to Mr. Hislop and his partners that there must be reasons why Stirling engines continue to fail in the pursuit for commercialization. The group determined that there are technical reasons for the failure. The problem was deemed to be that Stirling engine developers have never developed the primary design of an engine for a specific application. Rather, old engine designs are carried over, although an engine utilized in an automotive application may not be appropriate for residential cogeneration applications.

At this point in the late 1980s, Sustainable Energy Systems Ltd. (SES) was established to develop an "ubiquitous" Stirling engine design that can be the basis for all applications and sizes. Today the company includes two to three full-time employees, with a number of associates called on as needed. SES has received funding from the Department of the Environment in the U.K. under a program that supports development of 5- to 30-kW_e combined heat and power (CHP) systems. The European Commission's biomass program has also funded the Stirling engine development at SES.

Technology Overview

SES has designed a 10-kW_e Stirling engine (concept shown in Figure A-29) that is capable of running on biomass, as well as other fuels. The company has designed its engine with four potential markets in mind:

- 5- to 30-kW_e gas-fired CHP
- 0.5- to 3-kW_e residential CHP
- Renewables (solar and biomass)
- Trigeneration (heating, cooling, and power)

One of the key features of the SES engine is that air is used as the working fluid. The company decided that this feature was most practical, as many developing nations don't have readily available access to hydrogen or helium. In addition, air molecules are much larger than those of hydrogen or helium, which simplifies the sealing mechanisms utilized in the SES Stirling engine. Using air also coincides with SES's goal to develop a single engine design that may be used in any type of application.

Figure A-29
SES Conceptual Stirling Engine Design

Technology Status

SES has begun testing at its own facilities on the first 10-kW$_e$ prototype (target specifications shown in Table A-21). The company has an additional four units in production. These four systems will be available for demonstration in the fourth quarter of 2002. Once the engine's operation is proven, SES intends to attract investments in order to complete the development and patenting of the unit. SES plans to sell rights to the engine once the development work is complete.

Table A-21
SES Target Specifications – Conceptual Engine Design

Product	Engine
Product Status	Design/Lab Stage, May Have a Single Unit in Testing
Engine Type	Kinematic
Cylinders / Power Pistons	One
Working Fluid	Air
Power Output	10 kW$_e$ AC

EPRI Perspective

SES has an interesting philosophy to Stirling engine development. While the company is small and trails behind the leaders in the field, SES may have a great deal of intellectual property to offer in the future as a means to simplify and standardize Stirling engine designs. The progress of the company's engine demonstrations bears watching.

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Role: Engine Developer, Engine Manufacturer

Tamin is a small, private company that has been involved in the development of Stirling engines since the early 1990s. The company is presently developing the CAM002, a hermetically-sealed, 10-kW_e engine that utilizes a cam-drive design. Tamin believes that the CAM002 will initially be employed in auxiliary power units for recreational vehicles. It is anticipated that the first engineering model of the CAM002 Stirling engine will be operational at the Tamin facility in the fall of 2002.

Company Background

Don and Mary Isaac founded Tamin Enterprises in 1983 to design and produce technical-, engineering-, and job-related counted cross-stitch kits. The company has since evolved and expanded to include machine design, metal sculpture, and kinematic Stirling engines. Mr. Isaac was originally introduced to Stirling cycle coolers during his employment at Lockheed Martin. As a hobbyist, he built his first Stirling engine based on the design of an alcohol-burning, Stirling- powered table fan developed by Professor Senft at the University of Wisconsin.

Stirling engines became an integral part of the company in the early 1990s when Tamin Enterprises was awarded a contract by a Canadian housing developer to design and build a Stirling engine combined heat and power system for an energy efficient home in Toronto. Although the housing developer eventually lost funding from the Canadian government, Mr. Isaac continued with the development of Stirling engines. In 2001, a separate company, Tamin, was formed to design and commercialize a 10-kW_e Stirling engine for recreational vehicles and other generator set applications. Tamin presently has a staff of six and is funded by its founders. Its facilities in Half Moon Bay, California include an engineering office and a machine shop.

Technology Overview

Tamin originally designed the TESE001 Stirling engine in the early 1990s as part of the contract to develop a cogeneration system for a residential application in Canada. Although the engine was never built, the 1-kW TESE001 was designed to be a rhombic-drive, single-cylinder, air-charged Stirling engine with a life of 5,000 hours. Tamin downsized the original engine design in the development of the TESE002. The TESE002 (shown in the left-hand side of Figure A-30) was tested at Tamin facilities and eventually led to the development of the CAM001 Stirling engine (shown in the right-hand side of Figure A-30).

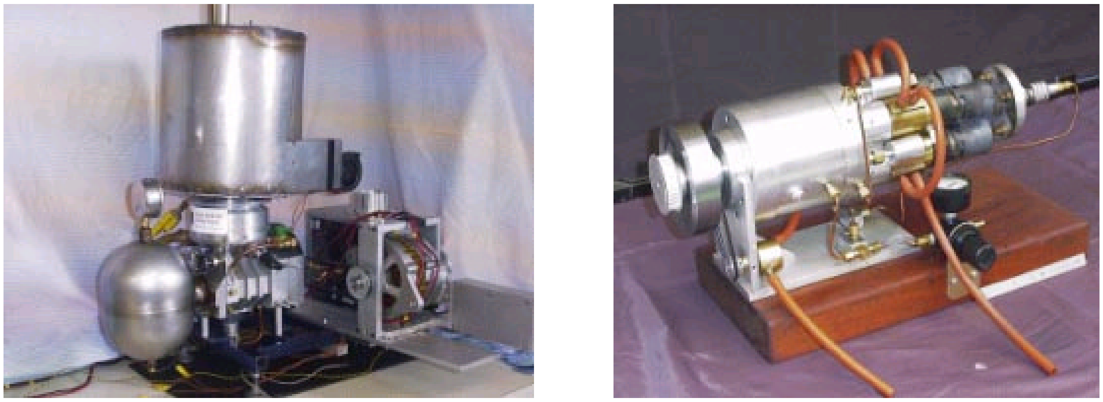

Figure A-30
Tamin Stirling Engines: TESE002 (left) and CAM001 (right)

The CAM001 is a proof-of-concept engine based on the company's unique cam-drive design. The three co-inventors of this cam-drive Stirling engine technology are presently in the early stages of the patent filing process. By locating the generator within the hermetically-sealed crankcase of the CAM001, Tamin was able to design a relatively compact engine, while eliminating the need for an output shaft seal. The company is expanding upon the design of the CAM001 to develop and build the 10-kW CAM002 engine for use in recreational vehicles and stationary gensets. Tamin believes that its competitive advantage lies in the intellectual property related to the cam-drive and heater head designs of the CAM002 Stirling engine. The CAM002 design is intended to reduce manufacturing cost and increase reliability of the engine.

Technology Status

Tamin plans to build the first CAM002 engine for testing that will be performed at its California facility in the fall of 2002. Experience yielded from the operation of the first CAM002 unit will be utilized to refine the design of the final product. It is also anticipated that success of the CAM002 demonstration will lead to funding and other demonstration opportunities. Tamin plans to offer gensets based on the CAM002 Stirling engine available for demonstration by early 2003. The demonstration gensets will operate on propane and have a power output in the range of 7.5-8.0 kW. Pricing for the demonstration units has not yet been determined, however it is likely that initial engineering support will be included as part of the program.

Tamin's intended customers will ultimately be generator manufacturers (i.e., Kohler, Honda, Generac, etc.). The first application for the CAM002 engine will be in auxiliary power units for recreational vehicles. Tamin has also identified users of high-end diesel gensets as a potential early market. Other future markets may include combined heat and power systems for residential applications, as well as power generation for remote locations.

Tamin recently began the search for a manufacturing partner to progress with large-scale production of the CAM002 Stirling engine. Once a partner is found, Tamin anticipates a three-year development phase, during which time the company will build prototypes and conduct testing and demonstrations. At a production level of 10,000 units per year, it is estimated that Tamin will sell the CAM002 to its customers for roughly $2,000 per engine. The long-term, anticipated target specifications of the CAM002 (listed in Table A-22) are subject to change.

Table A-22
Tamin Target Specifications – CAM002 Engine

Product	Engine
Product Status	Design/Lab Stage, May Have a Single Unit in Testing
Engine Type	Kinematic
Cylinders / Power Pistons	One
Working Fluid	Helium
Hot End Temperature	1,200 °F 650 °C
Pressure	300 psi
Power Output	10 kW_{shaft}
Phases	Single-Phase
Voltage/Frequency	120 VAC @ 60 Hz
Fuel	Natural Gas, Diesel
Electrical Efficiency	35% (LHV Fuel In to AC Electricity Out)
Physical Size (l x dia)	20-24 x < 14 in 508-610 x < 355 mm
Weight (dry)	50 lbs 23 kg
Noise Level	< 50 dbA at 3.3 ft
Servicing Interval	As needed (burner, filters, seals, etc.)
Product Lifetime	50,000 hours
Price to Distributor	$2,000 per engine @ 10,000 units per year

Although Tamin utilizes titanium in the design of the CAM002, it is not anticipated that this material choice will significantly affect the pricing of the engine. The low thermal conductivity of the titanium displacer will, however, improve the performance of the engine relative to the use of standard metal materials.

EPRI Perspective

Tamin’s cam-drive Stirling engine design may be sound, but it lacks testing and remains unproven. The company’s ultimate fate will rely upon the timing and outcome of the CAM002 demonstration. The performance of the CAM002 will also determine the likeliness that the company will find a manufacturing partner and secure customers. At this point, Tamin’s plans appear ambitious and overly optimistic, considering that the first CAM002 has not yet been built and tested.

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Role:	Engine Developer, Engine Manufacturer

Uwe Moch manufactures and sells the gamma-type Stirling engine that was developed by Dieter Viebach. Individual parts for the ST 05 G engine are also available from Uwe Moch for "do-it-yourself" assembly. The engine, which presently sells for approximately $3,400, has a shaft power output of 500 W and an expected lifetime of 1,000 hours. Individuals that buy the engines share operating results in order to improve the future design of other Stirling engines. While Mr. Uwe Moch is not active in further development of the ST 05 G, some of his partners are aggressively pursuing alternative engine designs as well as integrated combined heat and power (CHP) systems.

Company Background

Mr. Uwe Moch is one of several partners involved in a project initiated by Mr. Dieter Viebach to develop and produce kinematic Stirling engines that are capable of energy production. Mr. Viebach developed a "gamma-type" Stirling engine and a casting to produce it. Mr. Moch's role is to manufacture and sell the gamma-type engine and its individual components. Other project partners include Mr. Helmut Schefers (for electrical control) and Mr. Bernd Kammerich (development and organization). Alpha- and beta-type Stirling engines have also been designed and tested thus far as a result of the project collaboration.

Any person who purchases a casting set from Uwe Moch becomes a member of a user group called the "Study Group Stirling." The members of the group share problems, solutions, developments, and other information with one another in order to progress the commercialization of Stirling technology. More than 70 of the "gamma-type" Stirling casting kits have been sold, and over 40 engines are in operation.

Technology Overview

The gamma-type kinematic Stirling engine (ST 05 G) developed by Mr. Viebach has a shaft power output of 500 W and does not require oil or other lubrication. The engine (shown in Figure A-31) may operate with a working fluid of air or nitrogen at a working pressure of 10 bar (~9.9 atm or 145 psi) and a heater temperature of 650°C (~1,200°F). The three basic parts of the ST 05 G engine are:

- Aluminum case
- Crank-mechanism, piston, and flywheel
- Heat-exchanger, cooler, and regenerator

An electric generator may be integrated with the engine for the conversion of shaft power to electricity. In addition, the gamma-type Stirling engine may be integrated with a furnace or heat source fueled by gases, liquids, biomass, solar, or wood.

Figure A-31
Gamma-type Viebach Stirling Engine (ST 05 G)

The beta-type Stirling engine (shown in Figure A-32) is similar to the gamma-type engine in that a power piston and displacer operate in a single cylinder. The beta-type engine designed by Mr. Bernd Kammerich operates at a pressure of approximately 15 bar with a hot side temperature of 500-550°C and a cold side temperature of 50°C. Nitrogen is the preferred working fluid, although air may also be utilized. However, oxygen from the air may react with the plastic material on the surface of the piston, having a negative effect on the performance of the engine.

The alpha-type Stirling engine (also shown in Figure A-32) consists of two working cylinders and requires compression and decompression of helium working fluid. The higher compression ratio in the alpha-type engine also translates to higher temperatures. However, it also makes this engine suitable for applications that require a small physical design with higher electric outputs.

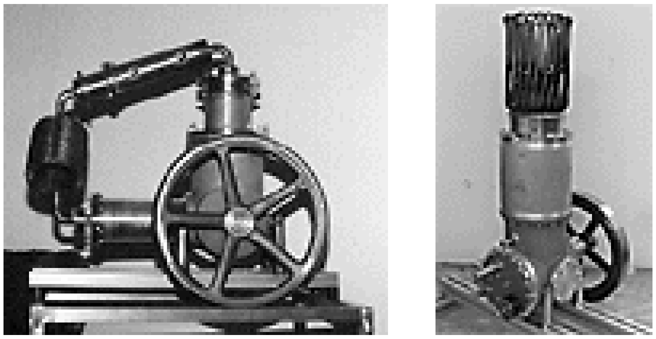

Figure A-32
Alpha- and Beta-type Stirling Engines

Technology Status

Uwe Moch presently sells the ST 05 G Stirling engine for 8500 German Deutschmarks (approximately U.S. $3,400), excluding sales tax and shipping costs. Each engine is made individually by hand and is pre-tested for a running time of five hours. The gamma-type engine has a running life of approximately 1,000 hours. After that time, there is usually leakage of the working gas and loss of pressure. Also, issues with the "dry" aspects (no lubrication) of the engine affect the performance. The specifications of the Viebach gamma-type engine are listed in Table A-23.

Table A-23
Uwe Moch Specifications – Viebach Gamma-type Engine (ST 05 G)

Product	Engine Kit
Product Status	In Production
Engine Type	Kinematic
Cylinders / Power Pistons	One
Working Fluid	Nitrogen or Air
Hot End Temperature	1,200 °F 650 °C
Pressure	145 psi
Engine Shaft Speed	600 rpm
Power Output	0.5 kW_{shaft}
Physical Size (w x d x h)	14 x 12 x 28 in 350 x 300 x 720 mm
Weight (dry)	60 lbs 27 kg
Price to End User (Retail)	$3,400 per system (current price)

Alternatively, individual components of the engine may be purchased from Uwe Moch and assembled by the consumer. Over 70 gamma-type engines have been sold and more than 40 are in operation. The operating results from these engines, which were fabricated either by Mr. Uwe

Moch or other members of the Study Group Stirling (e.g., consumers), are utilized in ongoing development work by Mr. Kammerich.

Since the late 1990s, Mr. Kammerich has completed a significant amount of work with the beta-type Stirling engine. With assistance from the grid or a small generator, the beta-type engine requires about one minute to start and reaches full power within ten minutes. Mr. Kammerich has successfully integrated his beta-type engine with an electrical generator and a standard wood-fired furnace (supplied by Hoval), which operates in a thermal output range of 12-25 kW. A picture of this system is shown in Figure A-33. The engine is approximately 400 mm (~16") in diameter with a length of 800 mm (~32") and a height of 500 mm (~20"). As of January 2002, the system had operated for more than 1,400 hours with an electrical output of 900-950 W. The efficiency of the beta-type engine is near 30%, while the generator has an efficiency of 75%. Thus, the combined efficiency is in the range of 20-22% (see specifications in Table A-24).

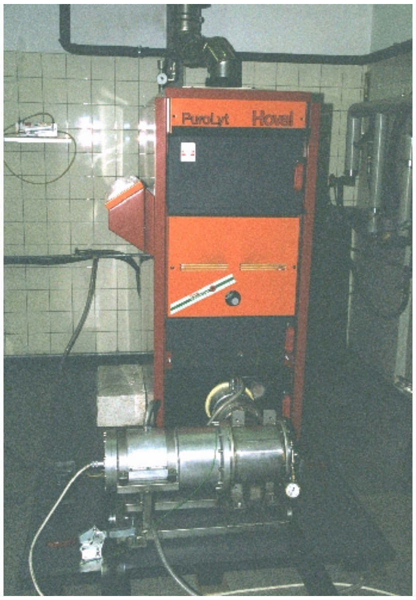

Figure A-33
Kammerich Beta-Type Stirling Engine Integrated with a Hoval Wood-Fired Furnace

Mr. Kammerich plans to integrate and test a second wood-burning system with an electrical output of 1.5 kW, also based on his beta-type engine technology. If this testing is successful, it is likely that 10-20 units will be produced and deployed as part of a field demonstration program. It is possible that Hoval, the burner manufacturer, will consider an integrated system as a future product.

Mr. Kammerich believes that the wood-burning furnace with a Stirling engine add-on or option would be an attractive product in Europe. The long-term goal is to develop a small, inexpensive beta-type Stirling engine that operates without maintenance on heat from the wood furnace for 10,000 hours. It will also be necessary to overcome the issues of low-temperature, ash contaminated flue gases, as well as corrosion- and ash-layers on the hot side heat exchanger. Mr. Kammerich plans to continue with this development until a design is finalized for large-scale production. If successful, it is possible that rights to the technology will be sold to a manufacturer or system integrator/packager.

Presently, a hand-made 1-kW$_e$ beta-type Stirling engine would sell for a price between $9,000 and $10,000. Mr. Kammerich estimates that at a production level of 100-500 engines, the price would fall to $3,000-$4,000. The remainder of the system, including the Hoval wood-burner, heat exchanger, electronics, and other balance of plant items would increase the cost by another $6,000 to $9,000.

Table A-24
Kammerich Specifications – Beta-type Stirling Engine Demonstration System

Product	Integrated System
Product Status	Design/Lab Stage, May Have a Single Unit in Testing
Engine Type	Kinematic
Cylinders / Power Pistons	One
Working Fluid	Nitrogen or Air
Generator / Alternator	Asynchronous Generator
Power Output	900-950 W AC
Phases	3-Phase
Voltage/Frequency	230 VAC @ 50 Hz
Fuel	Wood
Electrical Efficiency	20-22% (LHV Fuel In to AC Electricity Out)
Physical Size (l x h x dia)	32 x 20 x 16 in 800 x 500 x 400 mm
Price to Distributor	$15,000-19,000 per system (current price)

EPRI Perspective

Uwe Moch and his partners will not likely be major players in the demonstration and mass-production of Stirling engines for stationary applications. However, it is possible that the Study Group Stirling will make important developments that could assist the rest of the industry. Dieter Viebach, the developer of the engine sold by Uwe Moch, is known for his openness regarding intellectual property. The wood-fired system in development by Bernd Kammerich may also supply the industry with valuable information.

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Role: Engine Developer, Engine Manufacturer, Product Packager

Whisper Tech, based in New Zealand, is a developer of Stirling engine systems for cogeneration applications. The company's WhisperGen DC system is available as a CE-marked product for marine and remote power applications. It provides 1 kW_e and 6 kW_{th}. The AC version of the WhisperGen product is presently in the demonstration phase. It is anticipated that this system will be made commercially available in 2003 for European residential boiler replacement.

Company Background

Whisper Tech was founded in 1995 to develop, manufacture, and distribute Stirling engine systems suitable for micro combined heat and power (MCHP) applications in single-residence homes. The company's core technology is based on a Ph.D. thesis conducted by Dr. Donald Clucas to design a commercially viable and practical Stirling engine. Whisper Tech is a privately owned company based in New Zealand. It currently employs 60 people in New Zealand, Amsterdam, and the U.K.

Whisper Tech's two major shareholders are Orion Limited (formerly Southpower), an electricity network company, with 35% and Meridian Energy Limited, a government-owned generator of electricity, with 25%. An individual "angel" investor from the U.S. has a 10% stake in the company, and the staff holds the remaining 30%. While Orion and Meridian are presently the principal cash-funding parties, Whisper Tech would eventually like a wider spread of stockholders.

Technology Overview

Through 1999, Whisper Tech continued the development of a four-cylinder, double-acting kinematic Stirling engine technology that utilizes a unique “wobble yoke” linkage. The wobble yoke (shown in Figure A-34) is a patented engine mechanism that converts the linear piston motion to rotating motion for a conventional electricity generator. It prevents side motion of the piston, thereby reducing wear on the seals.

Whisper Tech has chosen to utilize nitrogen as the working fluid in its engines due to its larger molecular size (relative to hydrogen and helium). Although electrical efficiency suffers with the use of nitrogen, the larger molecules eliminate the need for hermetical sealing and permit use of conventional sealing techniques. The burner used in the Whisper Tech Stirling engine is specifically designed to operate on gas or liquid fuels, such as natural gas, propane, or diesel. The company has not established plans to develop an engine fueled by solar heat or solid fuels. Whisper Tech has integrated its Stirling engines into small combined heat and power systems called WhisperGen Personal Power Stations (PPS).

Whisper Tech has designed a total of four PPS products:

- DC – liquid fuels
- DC – gaseous fuels
- AC – liquid fuels
- AC – gaseous fuels

The systems that utilize liquid fuel can accept kerosene or diesel. Natural gas, propane, and butane are intended for use in the gaseous-fueled systems.

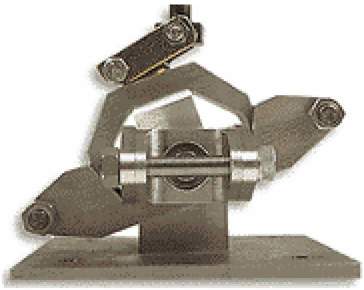

Figure A-34
Whisper Tech Wobble Yoke

Technology Status

In the late 1990s, Whisper Tech made its first product, the WhisperGen PPS16 DC System (formerly the WG800), available for use in marine applications. The initial commercial application for the PPS16 DC system (shown in Figure A-35) is as a battery charger for yachts, houseboats, and remote homes. The PPS16 DC product is CE marked in Western Europe. In addition, the product has been approved for sale in Australia and New Zealand.

Whisper Tech distributed the PPS16 DC product through International Business Factory (IBF) in Japan and Victron Energie in Europe. The DC systems have demonstrated run times of over 10,000 hours. The systems require an annual maintenance call that involves checking consumable parts such as spark plugs, fuel evaporators, and water and fuel filters. It is expected that the burner and heat exchanges may also require cleaning. Whisper Tech estimates that this yearly maintenance check will take one to two hours of labor and cost less than $200.

Figure A-35
WhisperGen PPS16 DC System

The Whisper Tech PPS16 DC product presently retails for about $11,000 and comes with a 3-year/10,000-hour warranty. For the company's 2001 fiscal year (ending March 2002), Whisper Tech anticipates that it will have sold 450 of the PPS16 DC systems. There are presently about 500 DC systems on back order. The company plans to sell approximately 1,500 of the DC units in its 2002 fiscal year.

The system produces 1 kW_e (12 VDC or 24 VDC) and 6 kW_{th} available for water heating. The PPS16 DC includes batteries for electric start and an intelligent control system for battery bank management and staged charging. The WhisperGen DC system is also available on a trial and demonstration basis for other markets and applications. Specifications for the DC unit are shown in Table A-25.

Table A-25
Whisper Tech Specifications – WhisperGen PPS16 DC System

Product	Integrated System
Product Status	In Production
Engine Type	Kinematic
Cylinders / Power Pistons	Four
Working Fluid	Nitrogen
Power Output	1.0-1.1 kW_e DC
Usable Heat Output	6 kW_{th}
Fuel	Diesel, Kerosene
Electrical Efficiency	12% (LHV Fuel In to DC Electricity Out)
Overall Efficiency	90% (LHV Fuel In to DC Electricity and Usable Heat Out)
Physical Size (w x d x h)	18 x 20 x 25 in (molded FRP enclosure) 450 x 500 x 640 mm
Weight (dry)	200 lbs 90 kg
Noise Level	48 dbA at 3.3 ft (with no vibration)
Servicing Interval	Yearly or 2,000 hours
Product Lifetime	30,000 hours (major overhaul predicted)
Warranty	3 years or 10,000 hours
Price to End User (Retail)	$11,000 per system (current price)
O&M Cost	$200/year

Whisper Tech chose the DC system as its initial product for several reasons. First, the company believes that there are a number of niche applications for the PPS16 DC system, in which the customer will not be hugely demanding on the system but will still be willing to pay a premium, allowing Whisper Tech to make a margin on early sales. One example of a niche market for the WhisperGen DC system is a marine application (shown in Figure A-36). Second, the DC unit is versatile and has received CE marking, allowing the company to place many units in the field.

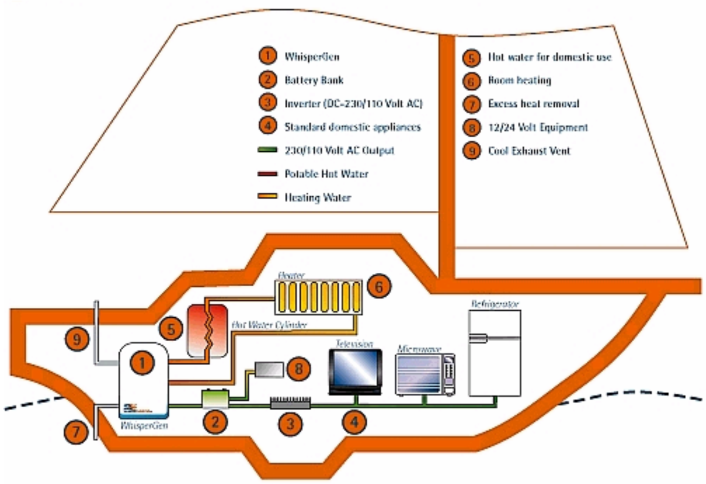

Figure A-36
Configuration of WhisperGen PPS16 DC in a Marine Application

The AC version of the WhisperGen product utilizes the same engine as the DC product. It is designed to replace the conventional central heating boiler in a home, as shown in Figure A-37. The WhisperGen AC system operates in a grid-parallel mode with a heat load-following control strategy. Excess electricity generated by the system may either be exported to the grid or converted to heat. Shutdown of the AC system is automatic in the case of grid failure. Whisper Tech plans to develop an AC system by early 2003 that will permit stand-alone operation in stand-by or emergency situations. Ongoing development work also includes increasing the power output of the AC system from 950 W to 1,000 W.

The AC version of the WhisperGen system is presently available on a trial and evaluation basis. A total of approximately 50 AC systems are currently undergoing testing and demonstration at a number of sites in the U.K., France, Germany, The Netherlands, Denmark, Switzerland, New Zealand, Korea, Japan, Canada, and the U.S. One of the systems operating in the U.S. has run for 6,000 hours over a fifteen-month period. The WhisperGen AC demonstration systems are available with a four-week lead time at a cost of about $13,000. This price excludes shipping and insurance, but includes up to five days of engineering support.

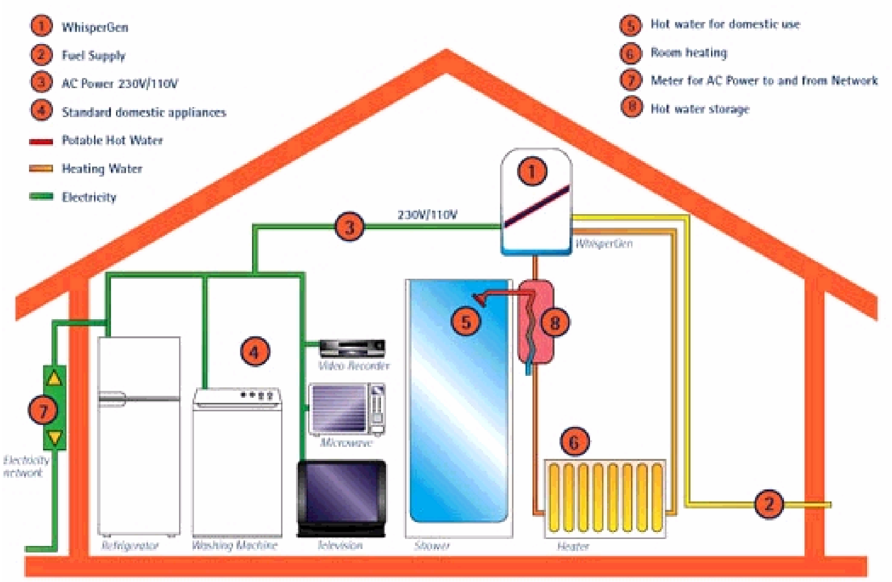

Figure A-37
Configuration of WhisperGen AC System in a Residential Application

Twenty-five of the current AC demonstration systems are operating in residences in the U.K. This testing program is being conducted through a strategic joint venture between Whisper Tech and a U.K. utility. The U.K. utility is also planning the launch of a 400-unit WhisperGen AC demonstration program in late 2002. Whisper Tech estimates that the WhisperGen AC system will receive CE marking by summer 2002 and that its U.K. partner will take the product to market in the U.K. by early 2003. The final WhisperGen AC product will comply with European emissions standards for conventional residential boilers. This standard is in the range of 70-80 ppm NO_x (at 3% O2). Specifications for the WhisperGen AC system are shown in Table A-26.

Development for mass manufacture and cost reduction are two of Whisper Tech's priorities. The company presently manufactures the core engine for the DC and AC WhisperGen systems at its New Zealand facilities, although this will not continue for the long term. The maximum production level with existing equipment is 2,000 units per year. Whisper Tech is actively seeking manufacturing facilities in the Northern Hemisphere (i.e., North American, Europe, Asia) in order to increase production capabilities and lower costs. It is likely that Whisper Tech will establish a joint venture to manufacture the core Stirling engine.

Table A-26
Whisper Tech Specifications – WhisperGen AC System

Product	Integrated System
Product Status	Many (10-20) Pre-Production Prototypes in the Field (beta)
Engine Type	Kinematic
Cylinders / Power Pistons	Four
Working Fluid	Nitrogen
Generator / Alternator	Asynchronous Generator
Power Output	950 We AC
Phases	Single-Phase
Voltage/Frequency	230-240 VAC @ 50/60 Hz
Usable Heat Output	6 kW_{th}
Fuel	Natural Gas, Propane
Electrical Efficiency	12% (LHV Fuel In to AC Electricity Out)
Overall Efficiency	90% (LHV Fuel In to AC Electricity and Usable Heat Out)
Physical Size (w x d x h)	15.7 x 21.7 x 31.5 in (insulated metal box) 400 x 550 x 800 mm
Weight (dry)	220 lbs 100 kg
Noise Level	48 dbA at 3.3 ft (with no vibration)
Servicing Interval	Yearly or 2,000 hours
Product Lifetime	30,000 hours (major overhaul)
Price to Distributor	$2,500-3,000 per system @ 100,000 units per year

Whisper Tech anticipates that it will be able to manufacture the core engines for less than $1,000 each at a production level of 100,000 units per year. This will equate to a WhisperGen system cost to the end user of approximately $2,500-3,000 per unit. At this price, the customer will have to pay about a 30% premium above the cost of a new conventional boiler. It is anticipated that there will be a simple payback of about three years on this “marginal” capital cost over a WhisperGen product life of 12-15 years.

Whisper Tech also plans to develop additional strategic relationships with product packagers/integrators for distribution of the WhisperGen system. Potential DC system integrators will be chosen based on applications (i.e., marine product integrator, telecommunications product integrator, etc.). On the other hand, AC system integrators will be geographically-specific because the product is best suited to MCHP applications (i.e., U.K. utility for Western European market, etc.).

EPRI Perspective

Whisper Tech is a strong player in the Stirling technology industry. WhisperGen systems have been undergoing demonstration in the field since 1999. Unfortunately, the company does not currently have plans to develop a larger product that is more suitable for the U.S. market. Unless Whisper Tech finds a strong strategic partner in the U.S., it is unlikely that the company will design and manufacture a Stirling engine with a higher power output.

Target:

Emerging Distributed Resource Technologies

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