

A Machine That Would Go of Itself:  
The History, Design, and Applications of the Stirling Engine

Grege Smyth

Brian Tonks

Senior Exhibition

23 March 2009

Without a doubt, energy is increasingly the most important concern in our modern world. There is now overwhelming evidence that carbon-based fuels damage the environment on which we all rely for survival and that we cannot continue to use them indiscriminately (Climate Change). Because of this, many are now realizing that it is vital to our future that we find ways to conserve energy and generate it sustainably. It is obvious that much of our infrastructure will have to change in order for us to meet these challenges, and many new technologies will need to be implemented to maintain our way of life. This may range from creating new sources of electricity (American Wind Energy . . . ) to developing new ways to fuel our automobiles (Tesla Motors). However, often overlooked are older technologies which, though not invented specifically to help remedy our current situation, have just as much potential. One such technology may well be one of the best ways to make our society more sustainable.

The Stirling engine, a device invented almost two hundred years ago as a replacement for the (at that time) more dangerous steam engines, is not well-known to most people. However, it holds a special significance to most in the engineering field. Often overlooked even in its own time, the Stirling engine is nonetheless one of the simplest and most versatile engines in existence. Able to generate motion from almost any difference in heat, the Stirling engine can be powered by any fuel source, from gasoline to wood to waste heat from a factory. Furthermore, it is vastly more efficient than any other type of heat-powered engine, reaching the theoretical limit for any such engine's efficiency in design.

This efficiency gives the Stirling engine incredible potential for use in the modern world, allowing it to help improve our machinery and reduce our pollution and carbon emissions in the process. The engine has applications in powering vehicles, improving scientific instruments, and

generating power far more efficiently than with any other device. Though a lack of awareness about the engine has prevented it from gaining any real success in most fields, it has the potential to revolutionize our way of life.

In the early nineteenth century, many industrial businesses made heavy use of steam engines, which supplied power for numerous applications. However, in 1816, a Scottish minister named Robert Stirling invented an alternative: what he patented as a “hot air engine” with what he called an “economiser”. Stirling was by no means the first to invent an engine that used heated air as a medium to generate motion, as inventors had been designing and even patenting similar engines since as early as the seventeenth century (History 1816-1937). However, Stirling’s device had one crucial improvement over these: the “economiser”, now known as a regenerator. This vital difference in Stirling’s design greatly improved the engine’s efficiency. In fact, the theoretical efficiency of the Stirling engine with a regenerator matches the theoretical limit to any heat engine’s efficiency (American Stirling Company FAQ), a value that would not be derived by Sadi Carnot until several decades later (History 1816-1937).

It is believed that Stirling invented his design of “hot air engine” in response to the many injuries caused by steam boilers. The only material available with which to build steam engines at that time was cast iron, a material that could not stand up to high temperatures well. Case failures would frequently result in the explosion of the high-pressure boilers, blasting scalding steam and iron shrapnel across the area. Stirling’s engine, by contrast, would simply glide to a halt when the casing failed. Robert Stirling soon built a full-size engine to replace the steam engine at the nearby Dundee Foundry Company, where his brother James worked. The company made use of the engine for several years, but the Stirling engine was more delicate than the older

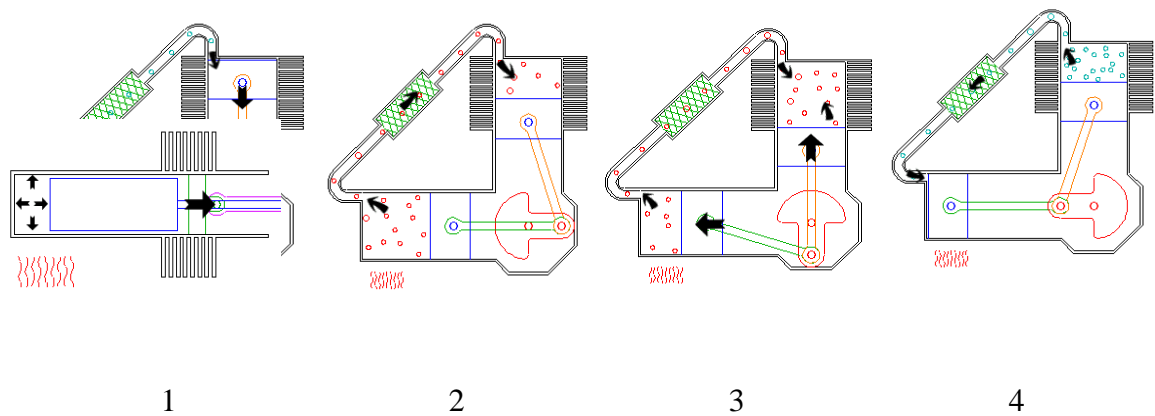
steam engine and its failures soon became too frequent for it to continue working. The foundry replaced it with a newer steam engine made of steel, which could now be mass-produced. With steam engines now safe, Stirling's seemingly redundant engine faded into obscurity (History 1816-1937).

The Stirling engine has remained in this relative obscurity since then. Though its reliability problems would have, likewise, been remedied by widely-available steel, the engine had other problems that kept this from happening. The main reason here was because of the Stirling engine's size. A Stirling engine is larger, heavier, and, due to the need for more material, more expensive than a steam or internal combustion engine of the same output (Norris). The increased availability of electric motors for many of the applications that could have used the Stirling engine only further continued to keep it in obscurity (Two-Cylinder Stirling). This has prevented the Stirling engine from reaching anywhere near its full potential in our modern technology.

There are many accepted configurations for a Stirling engine, but the simplest in theory is the alpha-type Stirling engine. Though it has the highest power-to-volume ratio of all of the designs, the alpha is also problematic in practice (Stirling Engines). An alpha-type Stirling engine is composed of two cylinders with pistons which are connected to a flywheel or crankshaft, usually ninety degrees off of one another. A pipe connects the two cylinders' sealed areas (the areas under the pistons), one cylinder is kept cool, usually through a passive heat sink, and the other cylinder is heated by whichever fuel has been chosen (Stirling Engine Configurations).

At the start of the alpha Stirling engine's cycle, most of the gas in the cylinders is in the hot cylinder. The gas in the cylinder is heated and begins to expand, powering the cylinder's

piston <1>. As the hot piston reaches its apex, the gas expands into the cold cylinder and begins to power the cold piston <2>. Flywheel momentum causes the hot piston to begin its return stroke <3>, forcing more of the gas into the cool cylinder and bringing the cold piston to the apex of its power stroke. The gas cools and contracts, completing the hot piston's return stroke and starting the cold piston's stroke. Flywheel momentum once more takes hold, completing the cold piston's return stroke and forcing the gas back to the hot cylinder <4>. This starts the hot piston's power stroke once more, which the heated gas will soon continue (Two Cylinder



Stirling  
ng).

However, though the alpha Stirling engine is relatively simple, it has one main drawback: the fact that the seal on the hot piston, naturally, wears out very fast. This problem makes the alpha Stirling difficult to implement in practice (Stirling Engine Configurations).

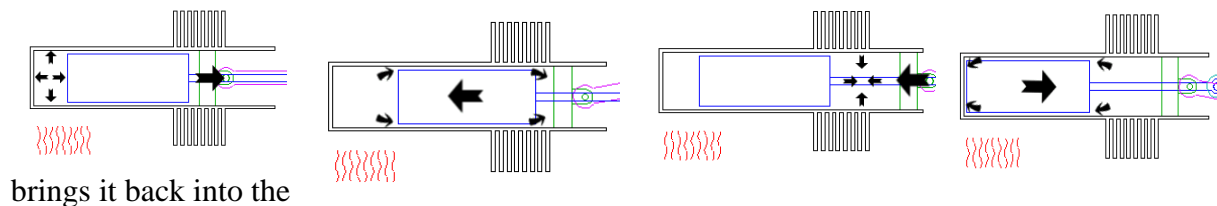
Though more complicated in theory than the alpha Stirling engine, the beta engine, the other of the two main Stirling engine configurations, can often work better in practice. The design used in Robert Stirling's original patent, the beta Stirling engine can be more difficult to build due to its more unusual configuration. Using only a single cylinder, one end of which is heated while the other end's sides are cooled, a beta engine still uses two pistons. However, only

one of these is the power piston (that is wide enough to reach the cylinder walls). The other is

Smyth 5

much longer, but narrow enough to allow the gas to move around it. This is a displacer piston, which forces the gas from one end of the cylinder to another (Beta Type Stirling Engines).

As the beta engine's cycle begins, the displacer is in the cold region of the cylinder. The gas, mostly in the hot end, is heated and expands, powering the power piston and in turn moving the displacer <1>. The displacer reaches its apex first, then flywheel momentum carries it back down to the hot end, forcing the gas into the cold end <2>. The gas cools and contracts, pulling back the power piston <3>, and the displacer is pulled by flywheel momentum back into a "power stroke". This



brings it back into the

cold region, forcing the gas back to the hot end <4>. From there, the gas will begin to expand, beginning the cycle anew (Single Cylinder Stirling).

1

2

The beta Stirling engine eliminates the need for a hot seal, reducing the frequency with which the engine will break down. It does have a lower power-to-volume ratio, but this is often made up for by the increased reliability (Stirling Engines -) Its only issue is the difficulty of powering the displacer *through* the power piston, but this can be solved without too much trouble (Beta Type Stirling Engines). Despite being nearly two hundred years old, the beta configuration is still the best-known Stirling engine.

Aside from the two main designs of Stirling engine, there are many other variations on

the engine. Though the actual configuration may vary greatly depending upon its application, one notable variation is known unofficially as the gamma Stirling engine. The gamma engine

Smyth 6

simplifies the beta Stirling engine by adding a smaller second cylinder, in which the power piston is held. The power cylinder is linked at the far end of the cold cylinder, essentially making the power cylinder part of the compression region. This design has the simple advantage of only having one piston per cylinder, which means that it is easier to build and any mass-production could be much less delicate work. This comes at the expense of some power, but for most applications this is acceptably small (Gamma Type Stirling Engines).

Despite the many types of Stirling engines, however, all contain one vital component: a regenerator. The distinctive piece in Robert Stirling's original patent in 1816, the regenerator (or economiser, as he called it) is a device that greatly increases the engine's efficiency. In theory, a regenerator is essentially the thermal equivalent of a capacitor; it will either hold a great deal of heat or will be left with little, depending on what part of the cycle the engine is in. When the heated gas moves from hot to cold in the engine, the regenerator absorbs a great deal of heat, and in doing so begins to cool the gas for the next step. When the now-cool gas returns to hot, the regenerator releases the heat, preparing the gas for the next stage of the cycle and ridding itself of a great deal of heat so that it is ready to absorb more from the next interchange. Most Stirling engines make use of layers of wire mesh for the regenerator, placed in the interchange pipe in an alpha-type and around the displacer in the beta-type. With the regenerator in place, the Stirling engine becomes one of, if not the most efficient engine possible (Two Cylinder Stirling Engine).

Some time after the invention of the Stirling engine, Sadi Carnot first calculated the maximum theoretical efficiency of any heat-powered engine. Analysis of the Stirling engine

itself shows that its maximum theoretical efficiency is the same, meaning that, in theory, no engine can have a higher efficiency. Though a perfect cycle is simply not possible in the real world, the real-

Smyth 7

world Stirling engines stay true to this (American Stirling Company FAQ).

The efficiency of the Stirling engine, as well as its flexibility in fuels, lends it the ability to work in many different applications. One of the first possibilities that might come to mind is the idea of new automobile engines. Current internal combustion engines, which are also some of the main culprits in the threat of global warming and climate change, are mostly limited to a single fuel, while Stirling engines could run off of any heat source and be more efficient in the process. Though this assumption is not entirely correct, Stirling engines may indeed have a part to play in aiding the automotive industry. During the oil embargo of the 1970s, NASA began work on a Stirling engine-powered car in an attempt to achieve better fuel mileage and run on other fuels (NASA Gets Spiritual . . . ). One main problem became apparent, though: Stirling engines are slow to start and designed to run at a constant speed, rather than the frequently stop-and-go driving experienced by many automobiles. The engines, which were also overly expensive and, due to the speed issues, not much more efficient than internal combustion engines, never had any success (American Stirling Company . . . ).

Recently, however, a new possibility has emerged that has revived the possibility of Stirling engines powering automobiles. DEKA Research and Development Corporation, headed by Dean Kamen and best known for the invention of the Segway scooter, the portable insulin pump and the home dialysis machine, has built a fully registered and street-legal automobile called the DEKA ReVolt. Based on an aborted Ford model called the Th!nk, the ReVolt is

mainly powered by electric motors. However, many of its nonessential functions are powered by a Stirling engine in a compartment under the trunk, increasing its range (Chapa). DEKA has already begun consulting with a European manufacturer on production, so Stirling engines may

Smyth 8

have a bright future in the automotive world.

The Stirling engine may not be suitable as a primary automotive engine, but it has great potential in the field of aeronautics. Where the need to run at a constant speed makes the engine too problematic for an automobile, such motion is perfect for the many non-jet aircraft used today. For obvious reasons, aircraft accelerate and decelerate much more smoothly than automobiles, and they certainly do not stop frequently! The efficiency of a Stirling engine is already higher than current engines, but the Stirling engine, unlike other engines, will not lose efficiency with altitude. In fact, were the cold end of the engine vented to the outside of the aircraft, its efficiency would increase as the temperature dropped with altitude. The engines would no longer need leaded fuel to deaden vibration, as with internal combustion engines, and the fuel used could be less volatile and safer. As a further benefit, airplanes powered by such engines would have virtually no engine noise, only the sound of the propellers themselves beating (AirSport Corporation Stirling Engine Page). However, there has been no real research done into this possibility, most of the effort having been focused on the automobile. The problem is not really one of sabotage, but of a mistaken direction for the research; had as much effort been focused on aeronautics, the research would likely have been much more successful.

Oddly enough, one of the few areas where Stirling engines are well-used does not use them as engines at all. Just as the application of a difference in temperature causes a Stirling engine to generate motion, the application of motion to a Stirling engine causes it to “pump” the

heat from one side to the other, generating a difference in temperature. Though some research has been done into using this for refrigeration, it is generally accepted that this is not the most efficient use of the engine. The Stirling engine is most efficient when generating a large amount

Smyth 9

of kinetic energy from a large temperature difference, so by the same token, it is far more efficient when applied to create a large temperature difference from a large amount of kinetic energy. This makes them perfect for low-temperature cooling devices in cryogenics applications.

Though many associate cryogenics with cryostasis, the rather strange procedure of preserving a human corpse at extremely low temperatures, cryogenics is a field encompassing all low-temperature cooling equipment. This equipment is used mainly to cool very sensitive computer components, which can be very easily damaged by heat. Unfortunately, this also includes many sophisticated weapons systems, but there are many more peaceful applications. By using the Stirling engines where a high temperature difference is needed, the engine reaches a much higher efficiency (SHI Cryogenics . . . ). This is one of the few places that the Stirling engine is used to its full potential.

The Stirling engine also has a great deal of potential for use in the field of micro-generation. In home, small business, and even in humanitarian needs for generation, the Stirling can prove very useful. Simply to generate power, a Stirling engine is more efficient than the internal combustion engines produced by many manufacturers and it is far less limited in its fuels than a gasoline-powered engine. Another interesting possibility is known as “micro CHP”, a term which refers to a water heater that produces Combined Heat and Power. In a CHP heater, the excess heat from heating the water is used to power a Stirling engine that generates electricity. As the heat would be unused anyway, this is a very efficient application (BBC News).

There are several efforts being made to introduce micro-generation using Stirling engines. For home use, in mid-2009 a European company called WhisperGen plans to launch a micro CHP heater that can generate 1kW (at 230v) while giving 8 to 12 kW of heat, as well as a portable one for travel (WhisperGen). The home generator would produce a total of 24 kWh per day, which could account for much of the average American home's consumption of 30 kWh per day (Electricity FAQs). Meanwhile, a company called Stirling Biopower has been preparing a 43 kW generator that can also work for CHP. However, the status of its launch is uncertain (STMPower). Most interestingly, DEKA President Dean Kamen has been promoting a Stirling generator for use in developing nations, where it could be powered by methane from animal manure. The generator is designed to be very easy to operate. It is referred to by Kamen as the "black box" as it is a complete, independent unit that can be easily delivered to a remote village. There, it could help give the residents the benefit of electricity while reducing the village's greenhouse footprint (as methane is 23 time more powerful a greenhouse gas than carbon dioxide). However, Kamen has yet to find any funding for his project. Kamen has said that he feels the main problem is that the technology is not widely-known enough, and that the organizations that he has approached simply do not have the right mindset to accept the type of solution Kamen has proposed (Inventor Kamen Pitches Tech . . . ). Sadly, the potential of the Stirling engine once again goes unused due to its relative obscurity.

One of the newest applications for Stirling engines, however, and one of the more successful, may yet be one of the greatest potential. Recently, interest has grown in building solar power plants that make use of Stirling engines rather than photovoltaics. The generators are composed of an array of mirrors arranged in a parabolic dish around a Stirling engine connected

to a generator. The heat focused by the dish is enough to drive the engine, and the dish tracks the sun through the day to maximize efficiency. The main reason for the concept is that, once again, the Stirling generator is far more efficient than the current technology. Tests at the Sandia

Smyth 11

National Laboratories have shown the collectors to be nearly twice as efficient as other technologies, including photovoltaics and even the more exotic parabolic troughs which focus the sunlight on a conductive liquid to heat a steam engine. They are also cheaper, thanks to the lack of expensive photovoltaics or a complicated piping structure (Allan). The result is a more cost-effective and efficient method of generating power from the sun.

Currently, the proponent of this technology is a company called Stirling Energy Systems, which has designed and prototyped collectors with a capacity of 25kW each. They will soon be conducting a large-scale test, and have purchase agreements for two solar farms. When completed, the two farms will have a capacity of 1.7 GW, and Gil Alexander, one of those working on the project, has said that “While [for confidentiality reasons] we cannot give out precise dollar amounts . . . We do not need any subsidies to make this work” (Allan). Assuming that the plants could work for twelve hours per day, the plants could generate 20 GWh each day. There are approximately 128 million homes in the United States (United States) and the average home uses 30 kWh each day (Electricity FAQs), which means that these two plants alone could power over 660,000 homes, over half of one percent of the United States’ residential use. This could offset a huge amount of coal-fueled energy, in turn preventing 15,000 tons of carbon dioxide from being released every day (Hinrichs and Kleinbach). Therefore, fewer than four hundred such solar farms could power every home in the United States! Perhaps the most unusual and revolutionary technology where the Stirling engine could be implemented, this new

type of solar collector nonetheless has incredible potential to improve our way of life and to protect it for our descendants.

The Stirling engine is one of the most incredibly useful and most versatile inventions ever

Smyth 12

conceived. As the highest-efficiency engine in existence and with the ability to run off of nearly any type of fuel, the Stirling engine has numerous applications throughout our modern world.

Robert Stirling could likely not have conceived of many of the uses that are now possible for the engine when he patented it in 1816, but now his invention gives us immense potential to improve our lifestyle and protect the environment on which we rely for survival. The engine could make future cars more efficient and allow many airplanes to fly faster and farther. It already helps make better computers for scientists and researchers in an application for which it was not even designed. The engine could usher in a home-generating revolution and could also supply all the power we need from the grid. This potential has only gone untapped due to one problem.

The sole barrier standing in the way of the Stirling engine's immense potential is the simple fact of its obscurity. Because of its early failures and apparent obsolescence, the Stirling engine has been overlooked by those searching for an efficient, versatile source of power. Despite this, it is still possible to implement the Stirling engine in all manner of technologies that can help us now and protect our future if its obscurity can be lifted. The great potential of the Stirling engine can be tapped, but only if it can become known. Once this happens, we can reap the benefits of the miracle of engineering that is the Stirling engine.

## Works Cited

- "AirSport Corporation Stirling Engine Page." AirSport Avionics - Altitude Alerters/Transponder Monitors. 03 Mar. 2009 <<http://www.airsport-corp.com/stirling.html>>.
- Allan, Sterling D. "Http://www.pureenergysystems.com/news/2005/08/11/9600147\_Edison\_Stirling\_largest\_solar/index.html." Pure Energy Systems News (PESN). 2005. Pure Energy Systems Network, Inc. 04 Mar. 2009 <[http://pesn.com/2005/08/11/9600147\\_Edison\\_Stirling\\_largest\\_solar/](http://pesn.com/2005/08/11/9600147_Edison_Stirling_largest_solar/)>.
- "American Stirling Company FAQ." Stirling Engines, Waste heat recovery, Sterling Engines-American Stirling Company Home Page. 2002. American Stirling Company. 09 Mar. 2009 <[http://www.stirlingengine.com/faq/one?scope=public&faq\\_id=1](http://www.stirlingengine.com/faq/one?scope=public&faq_id=1)>.
- American Wind Energy Association. 2009. American Wind Energy Association. 17 Mar. 2009 <<http://www.awea.org/>>.
- "BBC NEWS | Programmes | Working Lunch | Power from the people." BBC NEWS | News Front Page. 31 Oct. 2003. British Broadcasting Corporation. 03 Mar. 2009 <[http://news.bbc.co.uk/2/hi/programmes/working\\_lunch/3231549.stm](http://news.bbc.co.uk/2/hi/programmes/working_lunch/3231549.stm)>.
- Berger, Eric. "Coal -- affordable, available and clean? Maybe." Weblog post. SciGuy. 17 June 2006. 17 Mar. 2009 <[http://blogs.chron.com/sciguy/archives/2006/06/coal\\_affordable\\_1.html](http://blogs.chron.com/sciguy/archives/2006/06/coal_affordable_1.html)>.
- "Beta Type Stirling Engines - updated 11/11/2006." Russ College of Engineering and Technology at Ohio University. Ohio University. 04 Mar. 2009 <<http://www.ent.ohiou.edu/~urieli/stirling/engines/beta.html>>.
- Chapa, Jorge. "Deka Revolt Zero-Emission Hybrid Runs on Any Fuel! | Best of the GREEN

WEB - Join the Discussion for a Greener World." Best of the Green Web. 11 Nov. 2008.

Federated Media Publishing. 03 Mar. 2009

<<http://greenweb.federatedmedia.net/archives/658>>.

"Climate Change - Impacts of climate change and global warming: Feel the heat." The Nature Conservancy - Protecting Nature, Preserving Life. 2009. The Nature Conservancy. 17 Mar. 2009 <<http://www.nature.org/initiatives/climatechange/issues/>>.

"Electricity FAQs - Energy Information Administration." EIA.gov. 2007. United States Department of Energy - Energy Information Administration. 15 Mar. 2009 <[http://tonto.eia.doe.gov/ask/electricity\\_faqs.asp](http://tonto.eia.doe.gov/ask/electricity_faqs.asp)>.

Energy Information Administration - EIA - Official Energy Statistics from the U.S. Government. 2008. United States Department of Energy - Energy Information Administration. 15 Mar. 2009 <<http://www.eia.doe.gov/emeu/steo/pub/gifs/fig20.gif>>.

"Gamma Type Stirling Engines (updated 12/02/07)." Russ College of Engineering and Technology at Ohio University. Ohio University. 04 Mar. 2009 <<http://www.ent.ohiou.edu/~urieli/stirling/engines/gamma.html>>.

Hinrichs, Roger A., and Merlin Kleinbach. Energy: its use and the environment. 3rd ed. Fort Worth: Harcourt College, 2002.

"History 1816-1937." Stirling Engine Society USA. 2002. Stirling Engine Society USA. 07 Mar. 2009 <<http://www.sesusa.org/history.1816.htm>>.

"Inventor Kamen pitches tech for world's poor | Green Tech - CNET News." Technology News - CNET News. 21 Oct. 2008. CBS Interactive Inc. 03 Mar. 2009 <[http://news.cnet.com/8301-11128\\_3-10071457-54.html?tag=mncol;title](http://news.cnet.com/8301-11128_3-10071457-54.html?tag=mncol;title)>.

"NASA gets Spiritual and drops Stirling engines in some odd vehicles." Weblog post. Hemmings

Auto Blogs. 27 Jan. 2009. 3 Mar. 2009 <<http://blog.hemmings.com/index.php/2009/01/27/nasa-gets-spiritual-and-drops-stirling-engines-in-some-odd-vehicles/>>.

Norris, Michael. "Correspondence with Michael Norris." E-mail interview. Mar. 2009.

"SHI Cryogenics Group." SHI Cryogenics Group - Home. 2007. SHI Cryogenics Group. 04 Mar. 2009 <[http://www.shicryogenics.com/index.php?option=com\\_content&task=blogcategory&id=22&Itemid=169&gclid=CJLr5O-LipkCFQQhnAodVF8DnA](http://www.shicryogenics.com/index.php?option=com_content&task=blogcategory&id=22&Itemid=169&gclid=CJLr5O-LipkCFQQhnAodVF8DnA)>.

"Single Cylinder Stirling." Animated Engines. 2009. 10 Mar. 2009 <<http://www.animatedengines.com/stirling.shtml>>.

"Stirling Engine Configurations - updated 12/02/2007." Russ College of Engineering and Technology at Ohio University. Ohio University. 04 Mar. 2009 <<http://www.ent.ohiou.edu/~urieli/stirling/engines/engines.html>>.

"Stirling engine - Stirling engines into three distinct types." Stirling engine - Made in Germany. 15 Mar. 2009 <[http://www.stirlingshop.com/html/stirlingengines\\_types.html](http://www.stirlingshop.com/html/stirlingengines_types.html)>.

STMPOWER.COM. 2007. Stirling Biopower. 07 Mar. 2009 <<http://www.stmpower.com/>>.

Tesla Motors. 2009. Tesla Motors, Inc. 17 Mar. 2009 <<http://www.teslamotors.com/>>.

"Two Cylinder Stirling." Animated Engines. 2009. 10 Mar. 2009 <<http://www.animatedengines.com/vstirling.shtml>>.

United States of America. Census Bureau. State and Country QuickFacts. 20 Feb. 2009. U.S. Census Bureau. 17 Mar. 2009 <<http://quickfacts.census.gov/qfd/states/00000.html>>.

WhisperGen™ heat and power systems. WhisperGen, Ltd. 07 Mar. 2009 <<http://www.whispergen.com/>>.