# Commercialization Status of Free-piston Stirling Machines

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## ABSTRACT

After many years of engineering and market development some free-piston Stirling machines are now available commercially. These successes presage other such products based on free-piston Stirling machines that will likely enter the market over the coming years. This paper describes Sunpower's beta type free-piston machine technology, its attributes relative to kinematic and other free-piston machines, and its commercialization status. Some typical performance data for such machines is presented.

## BACKGROUND

In response to the short-comings of the conventional kinematic Stirling engine, William Beale invented the free-piston Stirling engine (FPSE) in 1964[1]. All kinematic Stirling machines, no matter what the arrangement, face a number of very significant engineering design challenges which may be so great as to prevent any commercial success. These challenges include the requirement for long-lived non-contact bearings and seals, the difficulty of sealing and pressurizing the machine, the need for lubrication and to separate the lubricant from the heat exchangers, modulation and control. The promise of the free piston machine has been a hermetically sealed, near fixed-frequency device operating in a non-contact mode providing very long life, with no need for lubricants, and direct alternating current output from an integral linear alternator. A representative schematic of a free-piston Stirling machine is shown in Figure 1.

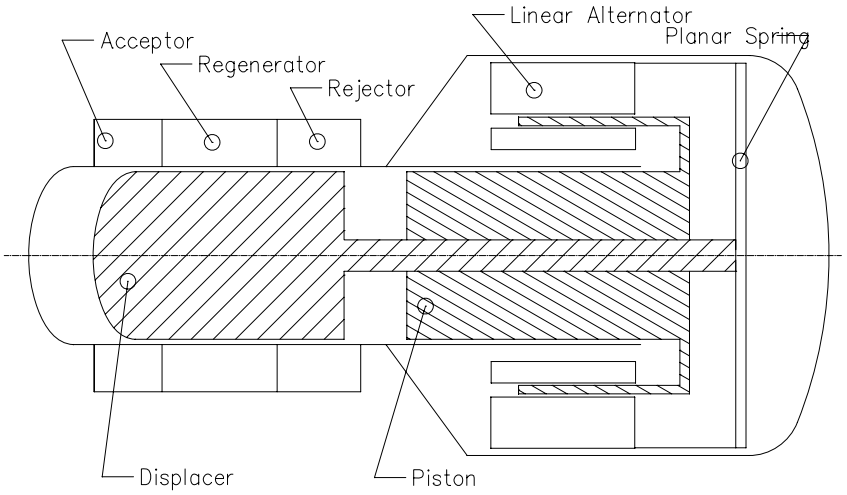


**Figure 1.** Free-piston Stirling Machine Schematic



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Sunpower was founded in 1974 to commercialize the free-piston Stirling engines. This effort has continued for more than 30 years, over which time the FPSE technology evolved to include free-piston Stirling coolers and cryocoolers, and linear compressors. Significant work on free-piston machines was also done at Stirling Technology Company (STC) which recently became Infinia[3].

Sunpower and Infinia's machines, while both free-piston devices, employ quite different approaches, particularly to achieve non-contact operation and in the linear alternator design. Sunpower's machines use a combination of compliance and hydrostatic gas bearings to achieve non-contact operation while Infinia uses mechanical flexures. Sunpower's machines use a moving magnet alternator design[2] while Infinia use a moving iron design[4,5,6].

There are many challenges to commercial success, and operating machines in a "proof of concept" demonstration is a relatively small step on the path to a volume manufactured commercial product. Figure 2 describes the road map to commercialization for some of Sunpower's technology. It is clear that the specification of a viable product and the design for manufacture are, in combination, by far the longest elements along the path to product launch. Not surprisingly these activities also require the greatest funding, typically requiring 10 to 100 times more capital than that required for a successful proof-of-concept demonstration.

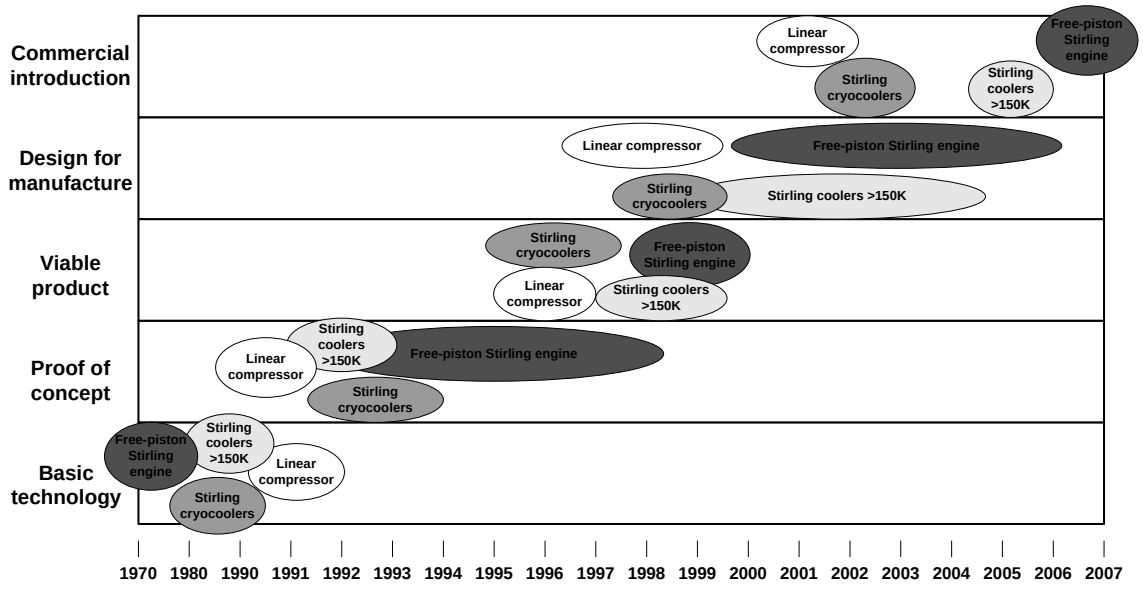


**Figure 2.** Free-piston Machine Commercialization Roadmap

Note in Figure 2, that while linear compressors are derivatives of the basic free-piston Stirling technology and the basic linear compressor technology was invented 20 years after the FPSE, compressors nevertheless reached the market in 2001 before any of the Stirling machines. These compressors are drop-in replacements for conventional compressors in Rankine systems in household refrigerators. They offer higher performance but do not in general require re-engineering of the refrigerator. They are used to enhance the performance of a well-established existing consumer product and do not require the creation of a new product and market such as a household-sized cogeneration system. The barriers to commercialization are still very large and the household refrigerator compressor business is extremely cost-competitive, but the barriers faced by compressors are much lower than for Stirling machines, either engines or coolers. The commercialization of the linear compressor by LG Electronics [7] validates much of the basic free-piston technology in an extremely cost sensitive market and other manufacture will bring similar products to market over the next two years.

Over three decades passed between the invention of the free-piston Stirling engine and the first commercial Stirling product. Significant barriers were overcome during this period. Initially the basic engineering elements of workable machines were developed and the promise of high thermodynamic performance realized. Thereafter product development challenges were revealed and solved as end-user products were developed. Finally, design-for-manufacture at low cost of both the Stirling device and the product it enables consumes far more effort and capital than any of the previous steps. It is an exceedingly long path from an idea about a new heat engine arrangement to a product that end-users purchase and employ. In hindsight, solving the engineering challenges of the basic technology was a small part of the overall challenge.

Free-piston Stirling machines are now achieving commercial success and this paper is a report of the commercialization status of Sunpower's machines.

## STIRLING CRYOCOOLERS

Free-piston Stirling cryocoolers operating at less than 150 K are available commercially and are employed in wireless, pharmaceutical, sensor, bio-preservation and medical applications. These small cryocoolers offer unmatched performance and reliability, and are available at dramatically lower costs than competing technology. Such machines are currently flying in space and are slated for further space missions in the future.

Sunpower started the development of small scale Stirling coolers in the early 1990's with the introduction of laboratory-built M223 and the M77[8]coolers. Following the success of these coolers in various applications for NASA and for prototype product development, Sunpower introduced a designed-for-manufacture version of a cryocooler known as the M87. The M87 was produced in limited quantities at Sunpower's manufacturing facility as the heart of an oxygen liquefaction device invented by In-X, a medical products company. To meet needs in the industrial and telecommunication industry, Sunpower built on the new M87 design and cryocooler manufacturing capabilities, partnering with LG Electronics to introduce the CryoTel™ family of cryocoolers, which initially included the CT (Figure 3) and the MT.


**Figure 3.** CryoTel™ CT Cryocooler

The CT and MT are now in manufacture and achieve unmatched cooling performance for a cryocooler of similar size and input power[9]. Over 800,000 hours of operation have been accumulated during in-house testing[10] of these machines and they are available at commercially reasonable prices. In sufficient volumes, we expect prices-per-unit lower than $2000.

A summary of the features of Sunpower's CryoTel™ family of free-piston Stirling cryocoolers is shown in Table 1.

**Table 1**: Specifications and Performance CryoTel™ Cooler Family

| | **CT** | **MT** | **LT** | **GT** |
|---|---|---|---|---|
| **Mass** | 3.1kg | 2.0kg | 3.1kg | 3.1kg |
| **Lift** | 10.0W at 77K | 5.0W at 77K | 1.5W at 25.5K | 15.0W at 77K |
| **Operating Temperature** | 35°C | 35°C | 32°C | 35°C |
| **Input Power** | 160W | 80W | 235W | 240W |

## HIGH TEMPERATURE STIRLING COOLERS

Through Sunpower spin-off company and licensee Global Cooling,[11] free-piston Stirling coolers for high temperature application above 150 K such as food preservation cool boxes have been introduced to the market in consumer products both in Japan and the USA by Twinbird[12] and Coleman[13]. These machines offer dramatic advantages over competing cooling technologies of this size such as thermoelectrics. The specifications for the Twinbird TB-SCUC04 are given in Table 2.

**Table 2.** Twinbird TB-SCUC04 Specifications

| System | Free Piston Stirling Cooler |
|---|---|
| Refrigerant | Helium |
| Power Consumption | 40W (max) |
| COP | ~1.1 (23.3 cold side, 35ºC warm side |
| Size | D=86mm, L=245mm |
| Weight | 1.7kg |
| Operating temperature range | 0-50ºC |

Larger free-piston coolers are being evaluated for other applications such as beverage vending machines[14].

## FREE-PISTON STIRLING ENGINES

Commercial development of a cogeneration product built around Sunpower's engine technology is well advanced by Microgen[15], part of the BG Group. Successful early generation field trials are completed and manufacturing activities are well underway. The Microgen wall-mounted domestic micro combined heat and power unit combines a FPSE with the latest condensing boiler technology. The unit (Figure 4) will save UK householders £150 per year on energy bills and will reduce carbon dioxide emissions by 1.5 tonnes per household per year. "Microgen expects to launch the product in 2007 when it will be rolled out in the UK by Microgen itself and by other selected distribution partners." [16]

**Figure 4.** Microgen FPSE Combined Heat and Power Unit

Significant US federal funding is being directed toward nuclear space power systems, small scale battlefield power and wearable soldier power systems based on FPSEs[17,18,19]. Commercial products derived from the military fuel-fired battery replacement programs are being pursued.

Typical performance of Sunpower's current generation engines is shown in Figures 5, 6, and 7 for the EE35, EE80 and EG 1000 engines respectively. Note in all cases that efficiency is defined as AC electric out divided by heat into the acceptor.

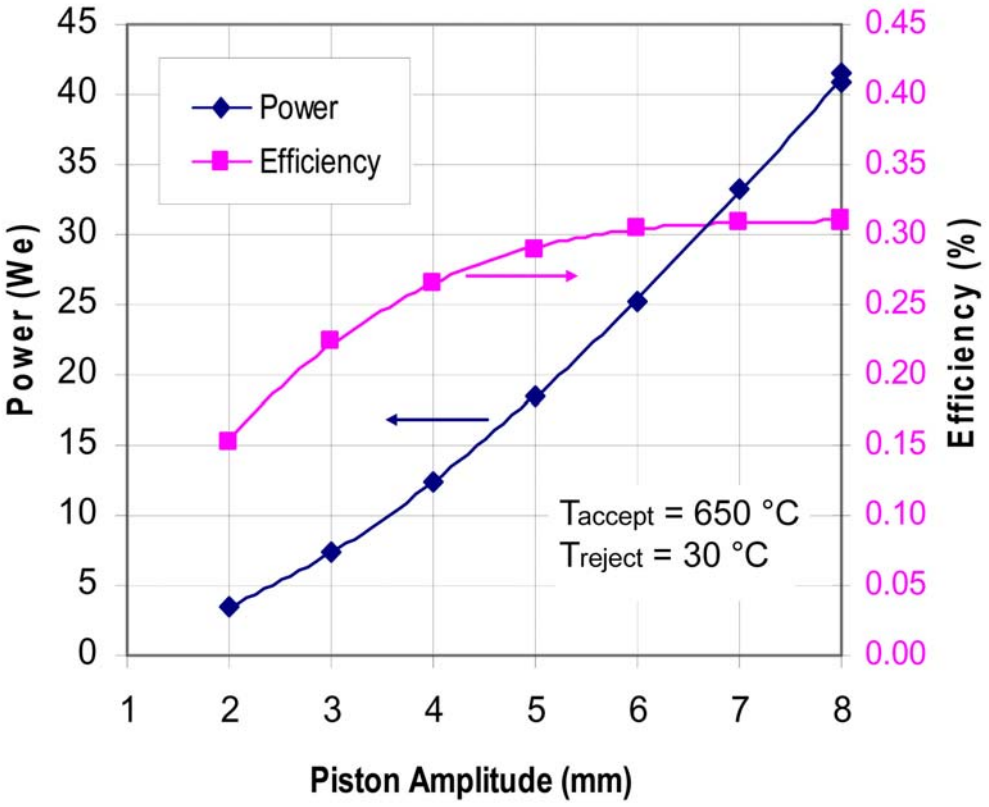


**Figure 5.** EE35 FPSE Performance

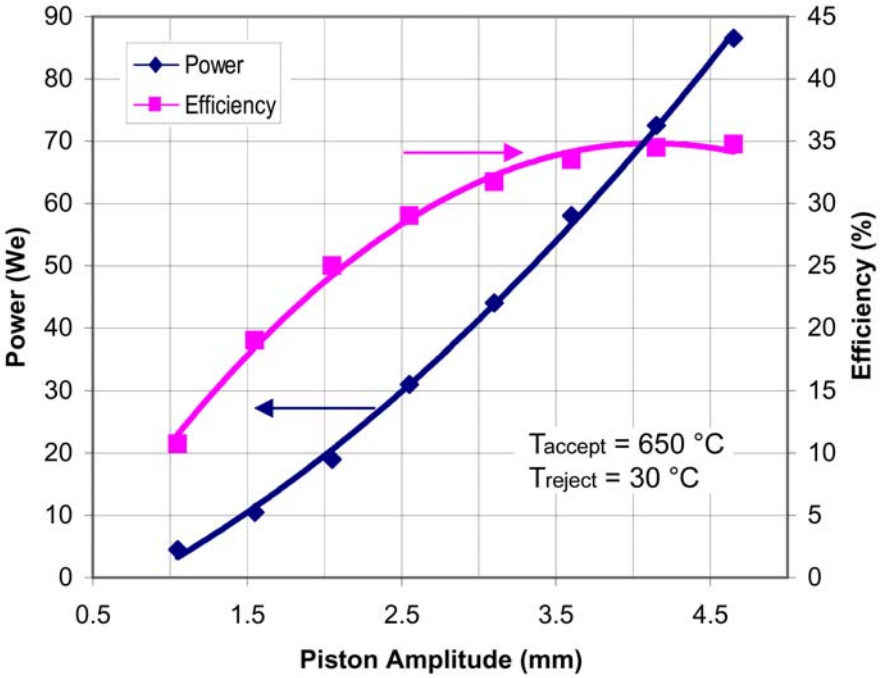


**Figure 6.** EE80 FPSE Performance

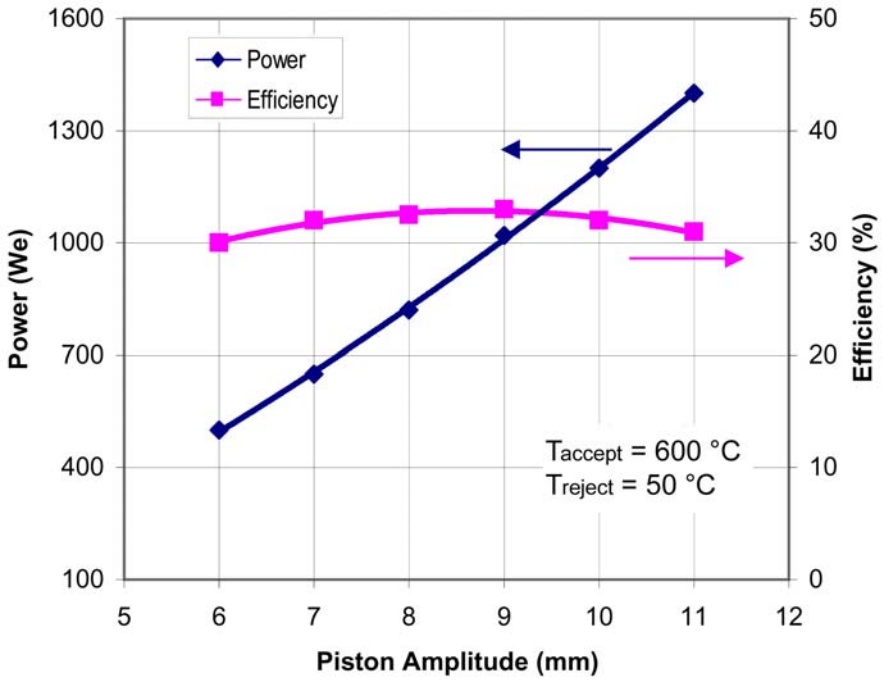


**Figure 7.** EG1000 FPSE Performance

## CONCLUSIONS

After a development period of more than thirty years, free-piston Stirling machines are now available in the market both in consumer devices and in more specialized applications. These initial products employ Stirling coolers and cryocoolers; however the engine technology is similar in principle, and free-piston Stirling engine-based products such as domestic combined heat and power systems and fuel-fired battery replacements will enter the market from 2007 on.

## ACKNOWLEDGMENTS

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## REFERENCES

[1] Beale, William, "Power Piston Actuated Displacer Piston Driving Means for Free-Piston Stirling Cycle Type Engine," U.S. Patent No. 3,937,018, February 10, 1976.
[2] Redlich, Robert, "Electromechanical Transducer Particularly Suitable for a Linear Alternator Driven by a Free Piston Stirling Engine," U.S. Patent No. 4,602,174, 22 July 1986.
[3] http://www.infiniacorp.com/about/docs/6_2_05_stc_becomes_infinia.pdf
[4] Wood, J.G., Lane, N., "Advanced Small Free-Piston Stirling Convertors for Space Power Applications, Space Technology and Applications International Forum – STAIF 2005, AIP CP699, edited by M.S. El-Genk, American Institute of Physics, Albuquerque New Mexico, February, 2005, pp. 440-444.
[5] Wood, J. G. and Carroll, C., "Advanced Stirling Convertor Program Update," Proceedings of the 2nd International Energy Conversion Engineering Conference (IECEC 2004), Providence, RI, August 16-19, 2004.
[6] Wood, J.G, Lane, N., "Development of the Sunpower 35 We Free-Piston Stirling Convertor," Space Technology and Applications International Forum – STAIF 2005, AIP CP746, edited by M.S. El-Genk, Issue 1, American Institute of Physics, Albuquerque New Mexico, February 6, 2005, pp. 682-687.
[7] http://www.lge.com/products/component/compressor/ref/ref.jsp
[8] Berchowitz, D. M. "Free Piston Stirling Coolers", International Refrigeration Conference – Energy Efficiency and New Refrigerants, Purdue University, July 1992.
[9] Unger, R. U., Keiter, D. E. "The Development of the CryoTel Family of Coolers", Cryogenic Engineering Conference and the International Cryogenic Materials Conference (CEC-ICMC), Anchorage, Alaska, September 2003.
[10] LT 24 Paper
[11] http://www.globalcooling.nl/
[12] http://www.stirlingcooler.com/en/index.html
[13] http://www.coleman.com/coleman/colemancom/detail.asp?product_id=5726-750&categoryid=8570
[14] http://www.refrigerantsnaturally.com/pps/SHARP_Fuji.pps
[15] http://www.microgen.com/main2.swf
[16] http://www.microgen.com/news12.htm
[17] Kim, S.Y., Huth, J., Wood, J.G., "Performance Characterization of Sunpower Free-Piston Stirling Engines" Proceedings of the 3rd International Energy Conversion Engineering Conference (IECEC 2005), San Francisco, CA, August 2005, currently in process of publication.
[18] Wood, J.G., "Advanced 80 We Stirling Convertor Phase II Development Progress," Proceedings of the 3rd International Energy Conversion Engineering Conference (IECEC 2005), San Francisco, CA, August 2005, currently in process of publication.
[19] M. Hendrickson, T. Podlesak, J. Huth, H. Brandhorst, and F. Rose, "Stirling Engines for Military Applications", IECEC 2005, San Francisco, CA August 2005, currently in process of publication.