A Personal History in the Development of the Modern Stirling Engine

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ABSTRACT

My involvement in the development of modern Stirling engines spans more than 40 years – from an early introduction to computational simulation with the Rallis-Urieli team at the University of the Witwatersrand, to design optimization and development with leading companies such as Mechanical Technology Inc., Sunpower Inc., and the company that I founded, Global Cooling Inc. Over this period some twenty-five designs have been implemented into hardware, all of which have been free-piston types. These designs are discussed chronologically and are broadly summarized in terms of the state of the technology and intended application. Though these designs were each seen as having the potential for meeting a specific need very few were successfully commercialized. This was in some cases due to business circumstances but more often due to the level of technical development. This presentation focuses on the evolution of the technology through numerous iterations that eventually achieved a maturity that allowed commercialization.

1. INTRODUCTION

The beginning of the development of the modern Stirling engine may be attributed to the rediscovery of these machines by the Dutch company Philips just before the Second World War [1]. As is well known, Philips were able to substantially improve the performance of Stirling engines, a good example being a portable 200W air-engine generator set. My exposure to Stirling engines comes much later when I had the opportunity to experiment with the Philips 200W engine under the watchful eye of Professor Costa Rallis in 1975. It was obvious to us that the oiled crank mechanism presented a significant contamination issue. Professor Rallis pointed out at least two designs that solved this problem. The first was a diaphragm engine by Cooke-Yarborough [2] at Harwell in the UK and the other the free-piston configuration by Beale in Ohio, USA [3]. We were able to obtain a small Beale-type engine which provided a great vehicle for applied mechanical dynamics studies.

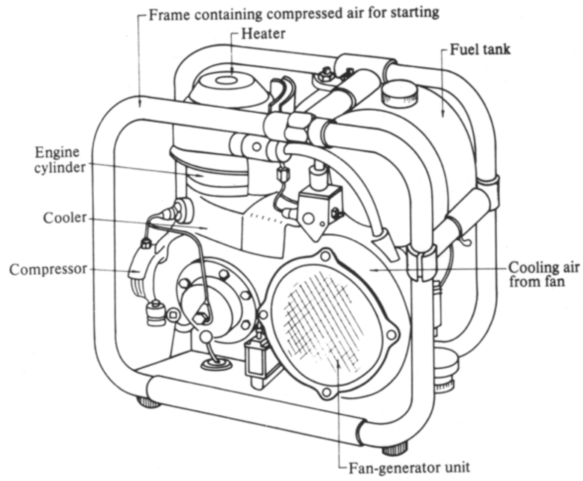

Figure 1. Philips 200W Air Engine

Aside from the arguments relating to mechanical arrangements, the cyclic gas flows in the Stirling were not then well understood. On this front, Professor Rallis and his

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graduate student Issy Urieli, had been working on a relatively complete simulation of the gas dynamics associated with Stirling engines [4]. After completing my BSc, I joined the Rallis-Urieli team as a graduate student in 1976 and in the same year attended an extension course at UCLA offered by Finkelstein, Walker and Beale, then the doyens of the Stirling rebirth. These people inspired my young mind and I returned to South Africa determined to make an impact in this field. My first task was to construct a test rig that subjected a mass of gas to the Stirling cycle with provision to measure pressures and temperatures. This provided an opportunity to validate Urieli's simulation but also taught me that simulation was nothing more than a numerical equivalent of an experiment [5]. As useful as that may be, it is not conducive to effective design and I quickly moved to a linearized representation that naturally morphed into a phasor representation – a much more intuitive and more easily exercised analysis. One enormously valuable side-product of the phasor representation was that it led so naturally to a clear understanding of free-piston machines.

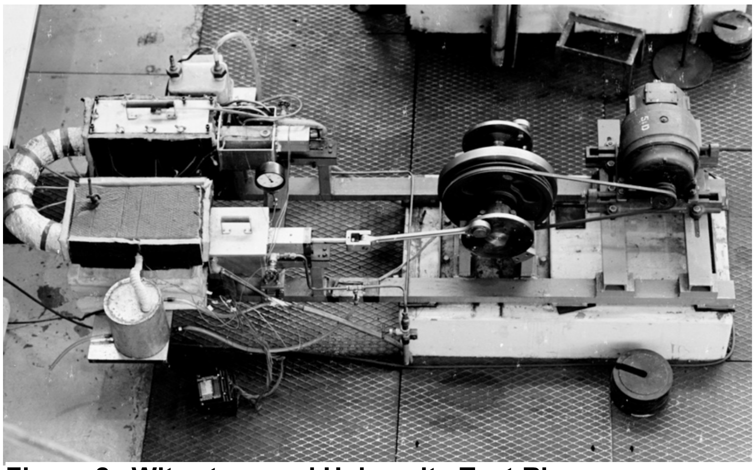


Figure 2. Witwatersrand University Test Rig

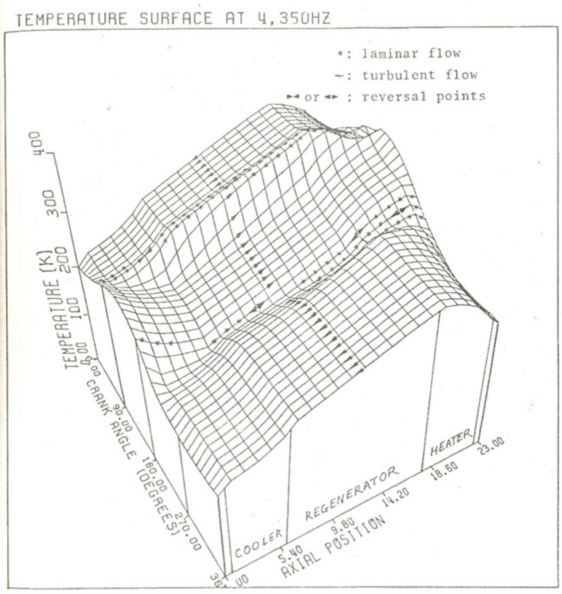


Figure 3. Simulated Temperature Surface

In 1978, Professor Rallis and I were approached to model the Harwell TMG machine. This opportunity allowed us to investigate high frequency / small displacement engines and further refine the linear analysis [6]. After completing the consulting job on Cooke-Yarborough's engine, I took up employment at Mechanical Technology Inc. and joined the group that was developing an automotive Stirling [7]. The two years that I spent there inoculated me against crank machines and I resolved to work on free-piston machinery from then on out. This took me to Sunpower Inc., where I designed several engines. While each of these were interesting machines that I believe moved the technology forward, none were a commercial success. In 1995 I left Sunpower and founded Global Cooling with the express desire to commercialize Stirling technology. At Global Cooling we first focused on being a licensing company and more recently switched to become a manufacturer of deep temperature freezers cooled by free-piston Stirling engines.

In this presentation I will describe and contrast various of the machines that I have been involved with over the years – their failings and their successes. Today, a number of Stirling machines are manufactured routinely. Aside from a few toys and demonstrators, all the machines doing serious work are the free-piston type.

2. SUNPOWER PERIOD

Aside from research and consulting work, my first exposure to design was a 2.5kW free-piston machine in 1981 shortly after arriving at Sunpower [8]. The engine was to provide power through a common piston to a Stirling cryocooler to liquefy natural gas. I was therefore tasked to design both an engine and a cryocooler. The engine was largely based on the RE-1000 that preceded it [9]. Aside from the interesting dynamics, this machine shared a common problem with previous designs in that it was extraordinarily sensitive to the clearances between the moving parts. This issue was of such importance to the practicality of Stirling engines that it led to a study to find out how to reduce or ameliorate this sensitivity. The results of this study suggested low-pressure / high-frequency machines and a series of 1kW machines following these principles were built in the early to mid 1980s (AT1000 and SPIKE engines) [10].

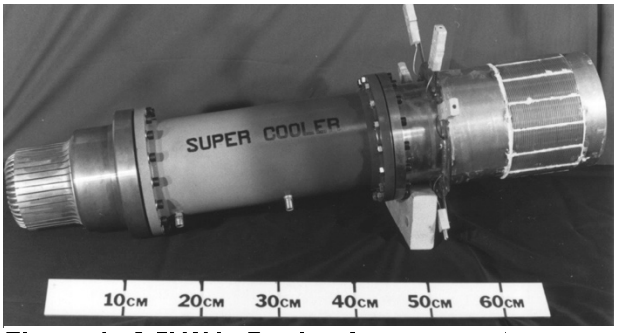


Figure 4. 2.5kW in Duplex Arrangement

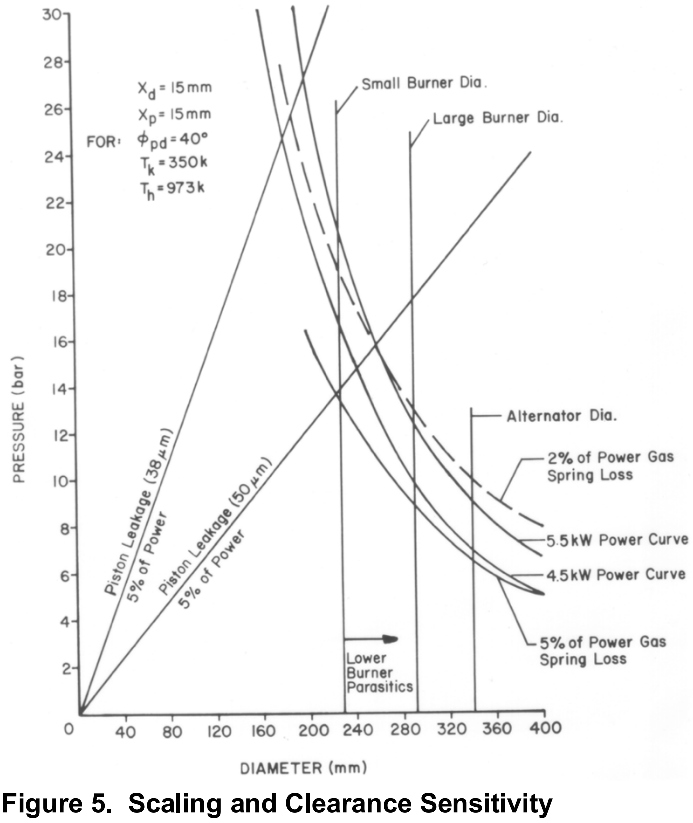


Figure 5. Scaling and Clearance Sensitivity

Improved understandings of gas dynamics and scaling opened the design space to consider all kinds of configurations such as high frequencies, different gases and size [11]. A direct consequence was a 60Hz 3kW free-piston air engine that was routinely operated at Sunpower in the 1985 time-frame [12]. Though this machine was designed to use air as the working gas, oxidation problems were too overwhelming, and nitrogen was used instead. Even so, the performance of this machine was almost identical to similar helium engines. The larger diameter, monocoque construction, provided lower heat fluxes through the walls of the machine and therefore improved heat exchanger effectiveness. In this regard, the method of entropy minimization was found to be very useful in the optimization of the heat exchangers [13] [14].

In about 1987 the high-frequency concept was further extended to build a compact 2kW engine operating at 120Hz referred to as SHARP [15]. This machine employed a sodium heat pipe for its heat source and demonstrated that a high-power density free-piston Stirling engine was possible. By way of contrast, the casing for this machine formally served as the displacer for the 3kW air engine. This machine was used later in an opposed configuration as a solar power converter.

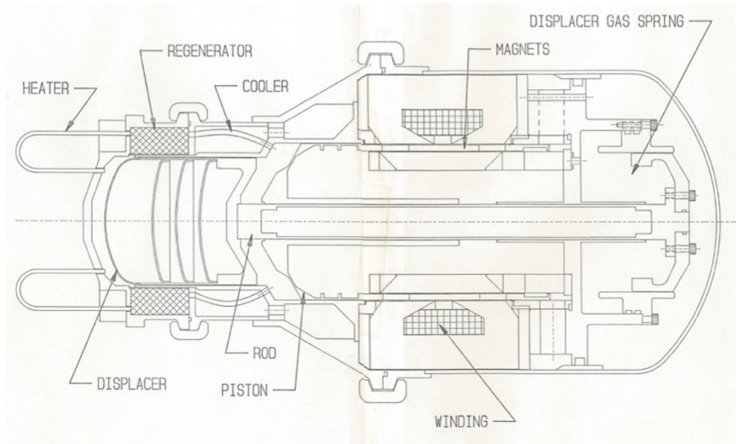


Figure 6. 2kW 120Hz SHARP Engine – Casing Dia. 194mm

The principles of high-frequency / low pressure applied to sub-kilowatt power levels suggested that a low-cost engine might be possible. These ideas were applied to a 150W free-piston machine for an appliance manufacturer that saw great utility in small power generators that could operate quietly. Two or three versions of this machine were demonstrated around 1988 to 1990.

Though all these engines discussed so far were technical successes insofar that they all performed thermodynamically, none were truly durable despite the low side-loads expected of the free-piston arrangement. It became clear that some form of bearing or lubrication would be necessary. In addition, axial vibration was not controlled, and this contributed to noise and difficulties in integrating the engines with end-uses.

The first machine to successfully utilize gas bearings was the M223, a small cooling engine designed for keeping an Intel Pentium microprocessor at -50°C. Cooling to this temperature allowed for much greater processor clock-speeds. In addition, vibration in this application needed to be at extremely low levels and a simple tuned mass damper was found to be suitably effective. A small batch of about fifty units was built for durability testing, which allowed further refinements. The M223 form factor was compact and reliable and led to several variants including an opposed unit flown on space shuttle *Discovery* and the M77 cryocooler that continues to provide deep temperature cooling for the *Rhessi* space mission [16].

Around 1993, a demonstration cooling engine was built for domestic refrigeration applications [17]. This unit employed a magnetic spring for displacer resonance and was able to show potential for improved performance over compressor technology [18]. A version of the M223 was also installed in a non-battery solar powered domestic refrigerator using a thermal store for night-time and no-sun cooling [19].

3. GLOBAL COOLING PERIOD

In 1995 I spun off from Sunpower to form Global Cooling Inc. to commercialize free-piston Stirling machinery for cooling applications. The first machine developed by our new company was the M100 which became the first serially produced free-piston Stirling engine. A version of this machine, the M150 is still in production as the cooling device for deep temperature freezers. Several cooling machines have been developed over the years for intermediate temperature cooling. These range from lifts of 40W to 600W over some six versions. The first consumer product to utilize a free-piston cooling engine is the portable cool box manufactured by Global Cooling's licensee, the

Twinbird company in Japan [20]. This unit has a lift of 40W and has been in production since 2000.

One difficulty of the Stirling engine alluded to earlier is related to the high heat fluxes necessary through the walls of the machine. To address this, a two-phase thermosiphon was successfully applied to solve this problem [21]. The use of multiple cylinders is another means to reduce the heat flux. In 2004 alpha type multi-cylinder free-piston engines were developed and successfully demonstrated [22].

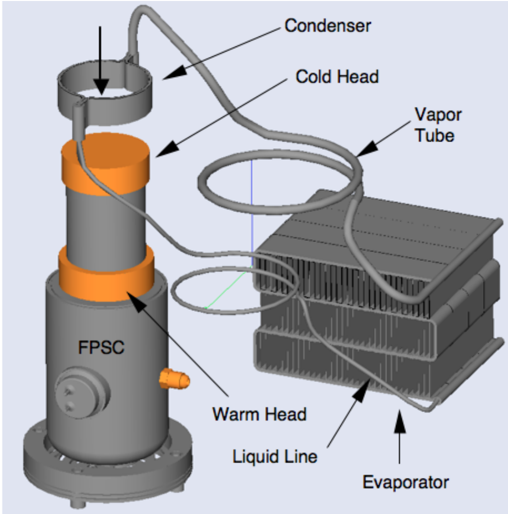


Figure 7. Thermosiphon and M100

A project that illustrates the free-piston Stirling's wide possibilities is the heat pump developed by the Terra Therma consortium from 2006 to 2012 [23]. Warm temperature heat pumping has long been an intriguing application for Stirling machines. Early efforts using the duplex arrangement resulted in much larger machines compared to compressor systems [24]. Various efforts were also tried where a Stirling driver was used to provide input to a Rankine cycle. These all failed due to the complexity of separating the working fluids. By using CO_2 as the combined working fluid of both the engine and the heat pump, the problem of separating the working fluids is avoided and a simple one-gas system can be configured.

By this time, Global Cooling had decided that licensing would not succeed as a business model and in 2008, remade itself as a manufacturer of ultra-low temperature freezers. The first product was a portable -80°C freezer using the M150 unit followed shortly by a 100 liter freezer using the same engine. In 2012, a large 780 liter -80°C freezer was launched using the M600, a high-capacity free-piston cooling engine. The M600 utilizes all the key developments discussed here; high-frequency, low pressure, gas bearings, dynamic balancing and two-phase external heat transfer.

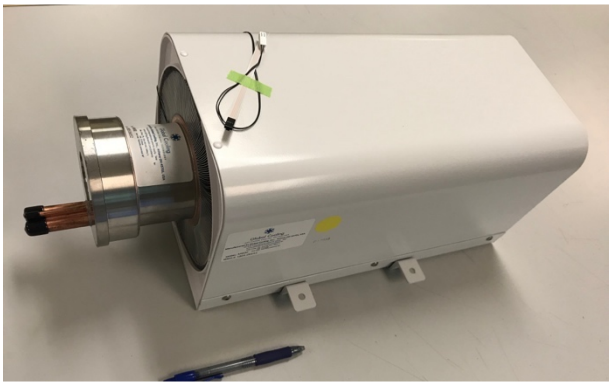


Figure 8. M600 Engine Used in Large Freezer

4. DEVELOPMENT CHRONOLOGY

In Table 1, I have chronologically collected the major machines with which I have been involved with over the years. As a measure of the evolution of free-piston engines, in 1978 the specific power was about 0.003 kW/kg. by 1983 this had improved by an order of magnitude to 0.03 kW/kg while charge pressure dropped from 70 bar to around 12 bar. Even the air-charged engine came in at close to 0.04 kW/kg (based on power from the alternator). By the end of the 1980s, specific power had about doubled again to 0.07 kW/kg. To compare cooling engines by a similar measure, the M600 currently used in deep temperature freezers is about 0.06 kW/kg based on input power.

Energy conversion efficiencies have not changed much over the period considered here though there have been improvements. Recuperative burners have demonstrated efficiencies of 80% to slightly above 90% and are essential for obtaining good overall efficiency for engines. For cooling applications, the two-phase thermosiphon has been the key for effectively removing heat from cabinets.

Aside from the primary invention of the free-piston machine by Beale and Cooke-Yarborough, there were many secondary items vital to its success as a practical machine. These follow roughly:

- Comprehensive simulation – 1977 [4]
- Initial linear analysis – 1978 [6]
- High efficiency recuperative burner development – 1979
- Scaling rules – 1981 [11]
- Entropy minimization method – 1981 [13]
- Linear motor / alternator – 1982 [25]
- High frequency / low pressure designs – 1983 [10] [12] [26]
- Adaptive control demonstrating power modulation – 1983
- Improved understanding of parasitic losses – 1984 [27]
- Linear dynamics leading to phasor representation – 1985 [28]
- Dynamic balancing – 1987
- Gas bearings – 1991
- Planar springs – 1991
- External two-phase heat transfer – thermosiphon and heat pipe – 1989, 2000

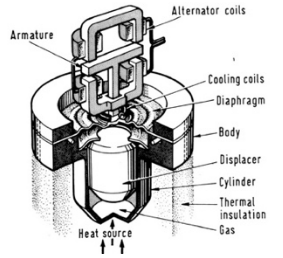
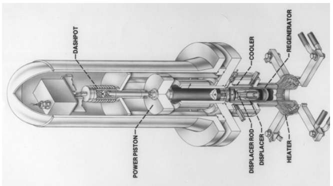
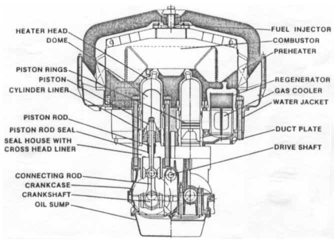
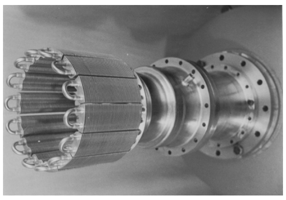
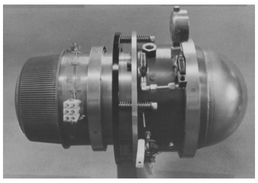
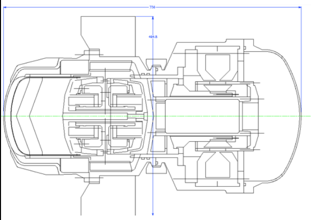
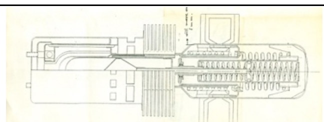
5. THE FUTURE

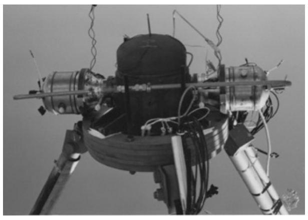
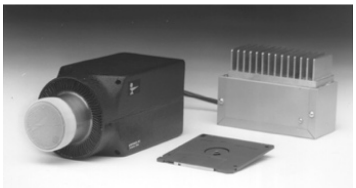
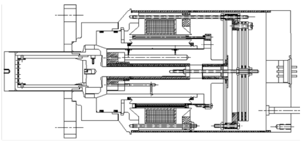
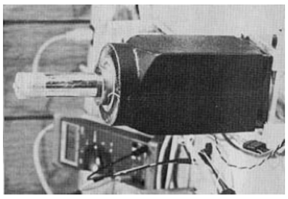
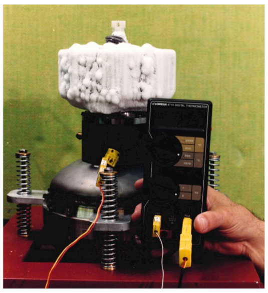
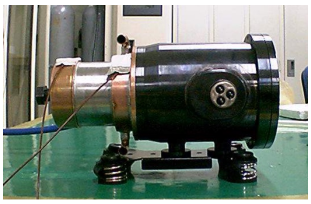
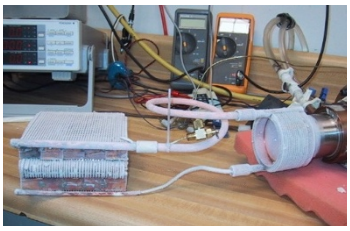
In a presentation such as this, one is obliged to look into the crystal ball despite the pitfalls associated with such activities. In the niche of high reliability, long-lived and small to moderate power levels, there seems to be no technology that offers sufficient promise to challenge the free-piston Stirling. High power machines will eventually run into the costly difficulty of transferring the heat across the walls of the heat exchangers. The upper level power of single cylinder machines is probably limited to sub one or two kW at best, and most improvements will be incremental. An example of such an application is the fueled heat pump mentioned before. The modern Stirling engine attributes are well matched to this application. Moderate power levels with modulation, high energy utilization, quiet operation, high reliability and long lived.

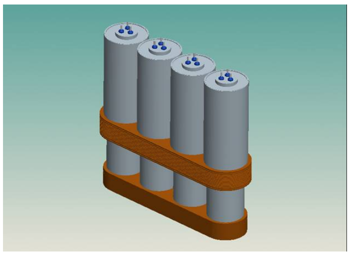
In applications where Stirling machines are replacing compressor-based systems there is a requirement that the Stirling casing be tested to five times the operating pressure. This safety requirement is a holdover from refrigeration compressor requirements and does not make engineering sense when applied to Stirling machines. An improvement in cost would result with agency relaxation of this five times pressure requirement. This single item has proved burdensome and results in much heavier engines than is necessary for safely managing the pressurized gas.

On the other hand, almost everything with Stirling gets better at smaller powers. How small this technology can go is an interesting question but before that would be worth spending too much time on, it may be better to ask to what applications or products such machines can be applied. To that question I do not have a clear answer.

Table 1. Design and Development Chronology

	LAYOUT	DATE	DESCRIPTION	DEVELOPMENT	DISPOSITION OR CONSEQUENCE
1	SEE TEXT	1978	WITWATERSRAND TEST RIG 5.35 Hz 1 bar	PRESSURE PHASE AND REGENERATOR TEMPERATURE DISTRIBUTION.	VALIDATION OF URIELI SIMULATION MODEL
2		1978	HARWELL TMG 110 Hz 2 bar 80 kg 150 W	SIMULATION OF TEMPERATURE DISTRIBUTION IN EXPANSION AND COMPRESSION SPACES	INITIAL DEVELOPMENT OF LINEAR MODEL. HIGH FREQUENCY OPERATION
3		1979 - 1981	RE-1000 30 Hz 70 bar 350 kg 1 kW	1kW FREE-PISTON ENGINE	A NUMBER OF THESE MACHINES WERE BUILT FOR RESEARCH PURPOSES. WELL DOCUMENTED DATA. APPLIED TO LINEAR MODEL
3		1979 - 1981	MTI AUTOMOTIVE STIRLING 200 bar 75 kW	HIGH POWER DENSITY HYDROGEN CHARGED ENGINE	PRACTICAL DIFFICULTIES ASSOCIATED WITH LUBRICATION AND SEALING. VERY HIGH INDICATED THERMAL EFFICIENCIES.
4		1982	2.5 KW FREE-PISTON ENGINE SERIES 45 Hz 70 bar 100 kg	HIGH PRESSURE - LOW FREQUENCY. DUPLEX ARRANGEMENT. FURTHER DEVELOPMENT OF LINEAR DYNAMICS	SENSITIVITY TO CLEARANCES. REQUIREMENT OF HIGH PRECISION. HIGH EFFICIENCY RECUPERATIVE BURNER
5		1983	1 KW FREE-PISTON SERIES, AT AND SPIKE MODELS 60 Hz 11 bar 40 kg	LOW PRESSURE – HIGH FREQUENCY. REDLICH ALTERNATOR	SCALING RULES. REDUCED SENSITIVITY TO CLEARANCES. MONOCOQUE HEAT EXCHANGERS. REDLICH LINEAR ALTERNATOR
6		1985	3 KW FREE-PISTON AIR ENGINE 60 Hz 25.5 bar 110 kg	HIGH-PERFORMANCE FREE-PISTON AIR ENGINE.	DEMONSTRATION OF HIGH PERFORMANCE USING NITROGEN AS WORKING GAS. USE OF ALUMINUM CASTING FOR CASING
7		1988	150W FREE-PISTON ENGINE 100 Hz 20 bar 2 kg	LOW COST DESIGN FOR APPLIANCE USE	PREMATURE WEAR-OUT OF BEARING SURFACES. CERAMIC COMBUSTION CHAMBER. EXTERNAL LINEAR ALTERNATOR

8		1989	2KW SHARP ENGINE 120 Hz 25 bar 28 kg	HIGH-SPECIFIC POWER FREE-PISTON ENGINE	HIGH-FREQUENCY OPERATION – 120HZ. SOLAR CONVERSION. OPPOSED SYNCHRONOUS OPERATION
9		1990	-50°C FREE-PISTON COOLER AND DERIVATIVES [12] 60 Hz 17 bar 1.5 kg 35 W lift	COMPACT LOW-VIBRATION DEEP COOLING FOR MICROPROCESSOR. 140K CRYOCOOLER. SPACE SHUTTLE REFRIGERATOR	DYNAMICALLY BALANCED OPERATION. GAS BEARINGS DEVELOPED. RELIABLE, LOW-NOISE CONFIGURATION DEMONSTRATED. MOVING IRON MOTOR
10		1992	CRYOCOOLER STUDIES	ANALYTICAL STUDY INVESTIGATING SMALL TO LARGE CAPACITY FREE-PISTON MACHINES	NO HARDWARE
11		1993	77K CRYOCOOLER 60 Hz 17 bar 1.5 kg 4 W lift	HIGH-RELIABILITY CRYOCOOLER DEVELOPMENT	SERIES PRODUCTION FREE-PISTON CRYOCOOLER
12		1993	250W LIFT COOLER 60 Hz 10 bar 4 kg	COOLING UNIT FOR DOMESTIC REFRIGERATORS	LOW COST / HIGH RELIABILITY COMBINATION / COMPETITIVE TO COMPRESSOR SYSTEMS. NON-CFC-COOLING
13		1995	M100 SERIES 60 Hz 20 bar 2.8 kg 100 W lift	COOLING UNIT FOR SOLAR POWERED REFRIGERATOR	NON-BATTERY SOLAR POWERED OPERATION WITH THERMAL STORE FOR NO-SUN PERIODS. SERIES PRODUCTION.
14		1996	S100 AND S200 SERIES 60 Hz 24 bar 3 kg 100 to 200 W lift	COOLING UNITS FOR DOMESTIC REFRIGERATOR	FIRST THERMOSIPHON IMPLEMENTATION
15		2000 TO 2007	MA100 AND MA200 SERIES 70 Hz 33 bar 7 kg 300 W lift	COOLING UNITS FOR DOMESTIC REFRIGERATORS	CO_2 THERMOSIPHON. MASS PRODUCTION DESIGN

16		2000	TB40 -TB80 SERIES 79 Hz 26 bar 1.6 kg 40 W lift	COOLING UNIT FOR PORTABLE REFRIGERATORS. THERMOELECTIC DISPLACEMENT	LOW-COST MANUFACTURE. FIRST CONSUMER PRODUCT UTILIZING FREE-PISTON STIRLING TECHNOLOGY
17		2002	EM600 60 Hz 25 bar 10 kg 600 W lift	COOLING UNIT FOR VENDING MACHINE	LOW-COST MASS PRODUCTION DESIGN. INTERNAL BALANCE MASS SYSTEM.
18		2006	ALPHA FREE-PISTON MACHINES 84 Hz 34 bar 5 kg 600 W lift	COMPACT ELECTRONIC COOLING AND POWER GENERATION	MULTIPLE CYLINDER DYNAMICS
19		2006 - 2012	TERRA THERMA PROJECT CO2 ENGINE 50 Hz 26.5 bar 1.9 kW ENTIRE SYSTEM 30 kg	NATURAL GAS FUELLED HEAT PUMP – INTEGRATED STIRLING AND TRANSCRITICAL CYCLE	EVALUATION USING CO2 AS A WORKING FLUID AND HELIUM – CO2 MIXTURES
20		2007	PORTABLE ULTRA-LOW FREEZER USING M150 UNIT M150 UNIT 70 Hz 25 bar 4.4 kg 50 W lift @ -50°C	LOW-TEMPERATURE THERMOSIPHON. COMPACT COOLING AND MOUNTING SYSTEM	IN PRODUCTION
21		2008	FREE-PISTON OPPOSED PISTON GAMMA ARRANGEMENTS 70 Hz 31 bar 5.6 kg 250 W	SINGLE DISPLACER – TWO OPPOSED PISTON ARRANGEMENTS	LOW-COST, EFFICIENT AND COMPACT LONG LIFE POWER GENERATOR

22		2009	100 LITER UNDER COUNTER ULTRA LOW FREEZER M150 UNIT	LOW POWER CON-SUMPTION, COMPACT, HIGH-RELIABILITY UL-TRA-LOW TEMPERA-TURE FREEZER	IN PRODUCTION
23		2012	780 LITER ULTRA LOW FREEZER M600 UNIT 60 Hz 30 bar 18.6 kg 270 W lift @ -100°C	LOWEST ENERGY CON-SUMPTION IN CLASS. HIGH-RELIABILITY	IN PRODUCTION

ACKNOWLEDGEMENTS

I have had the privilege of working with many inventive people over the years – far too many to give full justice to in a short presentation. Obviously, one does not work in a vacuum and success has many parents. Two people to whom I owe deep gratitude are Professor Costa Rallis who was able to provide me with learning skills that serve me to this day and Robert Redlich who provided many of the key insights that led to the practical realization of these machines. Others include Robi Unger who installed gas bearings on the M223 and nurtured the M77 into production, Yongrak Kwon who implemented a practical thermosiphon and designed the M600 and Neill Lane who as an enthusiastic young engineer on the SHARP engine, developed it for direct solar conversion and is now CEO of Global Cooling.

Imagination is of course an essential ingredient in a journey such as this. In this regard, I hope that I have given the proper credit to those who saw furthest.

REFERENCES

[1] C. M. Hargreaves, The Philips Stirling Engine, Amsterdam: Elsevier, 1991.

[2] E. H. Cooke-Yarborough, "The Thermo-Mechanical Generator: A Proposal for a Heat-Powered Non-Rotating Electrical Alternator," Harwell AERE, Harwell, 1967.

[3] W. T. Beale, “Free-Piston Stirling Engines - Some Model Tests and Simulations,” SAE, 1969.

[4] I. Urieli, “A Computer Simulation of Stirling Cycle Machines,” University of the Witwatersrand, Johannesburg, 1977.

[5] D. M. Berchowitz, “A Computer and Experimental Simulation of Stirling Cycle Machines,” University of the Witwatersrand, Johannesburg, 1978.

[6] D. M. Berchowitz and G. F. Wyatt-Mair, "Closed-Form Solutions for a Coupled Ideal Analysis of Free-Piston Stirling Engines," Boston, 1979.

[7] J. Corey and J. Meacher, “Advancements in Automotive Stirling Engine Developments,” in *20th IECEC*, Miami Beach, 1985.

[8] D. M. Berchowitz, “The Design, Development and Performance of a Duplex Stirling Natural Gas Liquefier,” in *17th IECEC*, Los Angeles, 1982.

[9] J. Schreiber, “Testing and Performance Characteristics of a 1kW Free-Piston Stirling Engine,” NASA-Lewis, Cleveland, 1983.

[10] D. M. Berchowitz, “The Development of a 1kW Electrical Output Free-Piston Stirling Engine Alternator Unit,” in *18th IECEC*, Orlando, 1983.

[11] D. R. Gedeon, “Scaling Rules for Stirling Engines,” in *16th IECEC*, Atlanta, 1981.

[12] D. M. Berchowitz and M. Richter, “3 kW Stirling Powered Generator Set,” in *20th IECEC*, Miami Beach, 1985.

[13] A. Bejan, “The Concept of Irreversibility in Heat Exchanger Design: Counterflow Heat Exchangers for Gas-to-Gas Applications,” *Jnl of Heat Transfer,* vol. 99, pp. 374-380, August 1977.

[14] A. Bejan, "The Method of Entropy Generation Minimization," *Energy and the Environment,* vol. 11, no. 12, 1999.

[15] N. W. Lane, D. M. Berchowitz, D. Shade and A. Karandikar, "Development of a High Frequency Stirling Engine Powered 3kW(e) Generator Set," in *24th IECEC, IEEE*, 1989.

[16] A. Karandikar and D. M. Berchowitz, "Low Cost Small Cryocoolers for Commercial Applications," in *Advances in Cryogenic Engineering*, Columbus, 1995.

[17] D. M. Berchowitz and R. Unger, "Experimental Performance of a Free-Piston Stirling Cycle Cooler for Non-CFC Domestic Refrigeration Applications," in *XVIII International Congress of Refrigeration*, Montreal, 1991.

[18] D. M. Berchowitz and W. F. Bessler, "Progress on Free-Piston Stirling Coolers," in *6th ISEC*, Eindhoven, 1993.

[19] D. M. Berchowitz, D. Kiikka and B. D. Mennink, "Recent Advances in Stirling Cycle Refrigeration," in *19th International Congress of Refrigeration*, The Hague, 1995.

[20] T. Nomizu and K. Sone, "Enhancement of the Lineup of the Next Generation Refrigerator FPSC and the Applications Thereof," in *5th Asian Conference on Refrigeration and Air-Conditioning*, Tokyo, 2010.

[21] D. M. Berchowitz, "Condenser, Evaporator and Cooling Device". US Patent 7,073,567 B2, 11 July 2006.

[22] D. M. Berchowitz and Y.-R. Kwon, “Multiple Cylinder Free-Piston Stirling Machinery,” *Journal of Power and Energy Systems,* vol. 2, no. 5, pp. 1209-1220, 15 August 2008.

[23] D. M. Berchowitz, M. Janssen, M. van Beek and A. Hagedorn, “CO2 Based Free-Piston Stirling Heat Pump with Ground Source Heat Reservoir,” in *14th ISEC*, Groningen, 2009.

[24] B. Penswick and I. Urieli, "Duplex Stirling Machines," in *19th IECEC*, San Francisco, 1984.

[25] R. W. Redlich, "Electromechanical Transducer Particularly Suitable for a Linear Alternator Driven by a Free-Piston Stirling Engine". US Patent 4602174A, 1 12 1983.

[26] N. W. Lane and W. T. Beale, “Stirling Engines for Gas Fired Micro-Cogen and Cooling,” in *Strategic Gas Forum*, Detroit, 1996.

[27] I. Urieli and D. M. Berchowitz, Stirling Cycle Engine Analysis, Bristol: Adam Hilger, 1984.

[28] R. W. Redlich and D. M. Berchowitz, “Linear Dynamics of Free-Piston Stirling Engines,” *Proc Instn Mech Engrs,* vol. 199, no. A3, pp. 203-213, March 1985.

[29] D. M. Berchowitz, "Operational Charateristics of Free-Piston Stirling Engines," in *23rd IECEC*, 1988.

[30] G. T. Smedley, R. G. Ross and D. M. Berchowitz, "Performance Characterization of the Sunpower Cryocooler," in *8th International Cryocooler Conference*, Vail, 1994.

[31] D. M. Berchowitz, "Free-Piston Stirling Coolers for Intermediate Lift Temperatures," in *27th IECEC*, San Diego, 1992.