

# DESIGN AND TESTING OF A 40 W FREE-PISTON STIRLING CYCLE COOLING UNIT

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## ABSTRACT

A 40W capacity free-piston Stirling cooler (FPSC) unit has been designed and fabricated for application to portable refrigerators. Calculations suggest that average power consumption for a well insulated 30 liter box would be about 8 W at fresh food temperatures and 15 W at freezing temperatures in a 30 °C environment. Performance curves for the cooling unit are presented so that system performance may be estimated for different applications. Total mass of the unit is about 1kg. Integration into portable cool boxes with a simple thermosyphon system is shown to operate with low temperature differentials. Initial test data for the prototype unit are included.

## 1. INTRODUCTION

Cooling unit requirements for portable or mobile refrigeration applications demand small size, low mass, rugged construction, low environmental impact, low noise and low cost. In addition many of these applications are used where low energy consumption is an important criterion. Small capacity FPSCs appear to be a natural match for portable refrigeration. The mass advantage of these devices becomes more favorable at lower capacities as is shown in Figure 1. A FPSC unit of 50 W capacity may be as much as one sixth the mass of a Rankine compressor. In addition, as shown by Mennink and Berchowitz (1994), the energy efficiency of the device is maintained to capacities as low as 10 W. This gives the FPSC a large advantage in battery or solar powered applications. In Figure 2 the estimated performance of a FPSC is compared to Peltier (thermoelectric) devices which are often employed in portable refrigeration. All else being equal, Stirling systems should be able to operate with one fifth or less of the input energy as compared to Peltier systems.

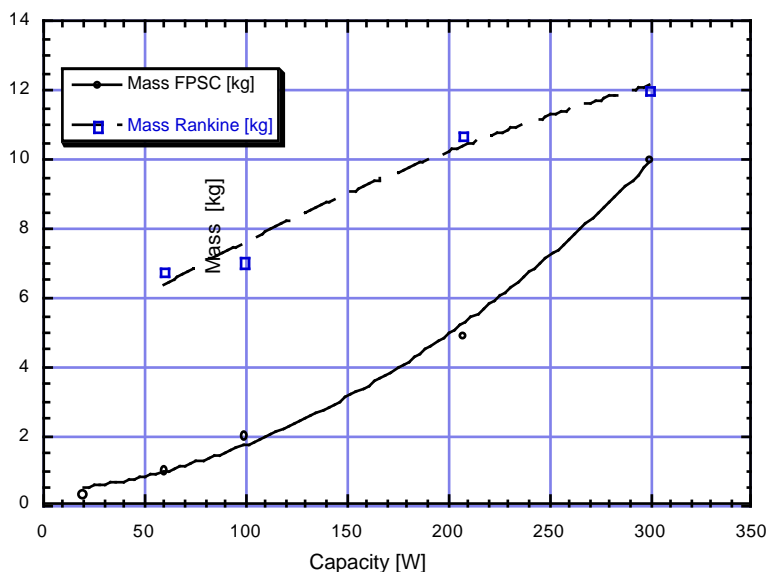


Figure 1 Mass of Rankine compressors and FPSCs. Taken from Berchowitz (1998).

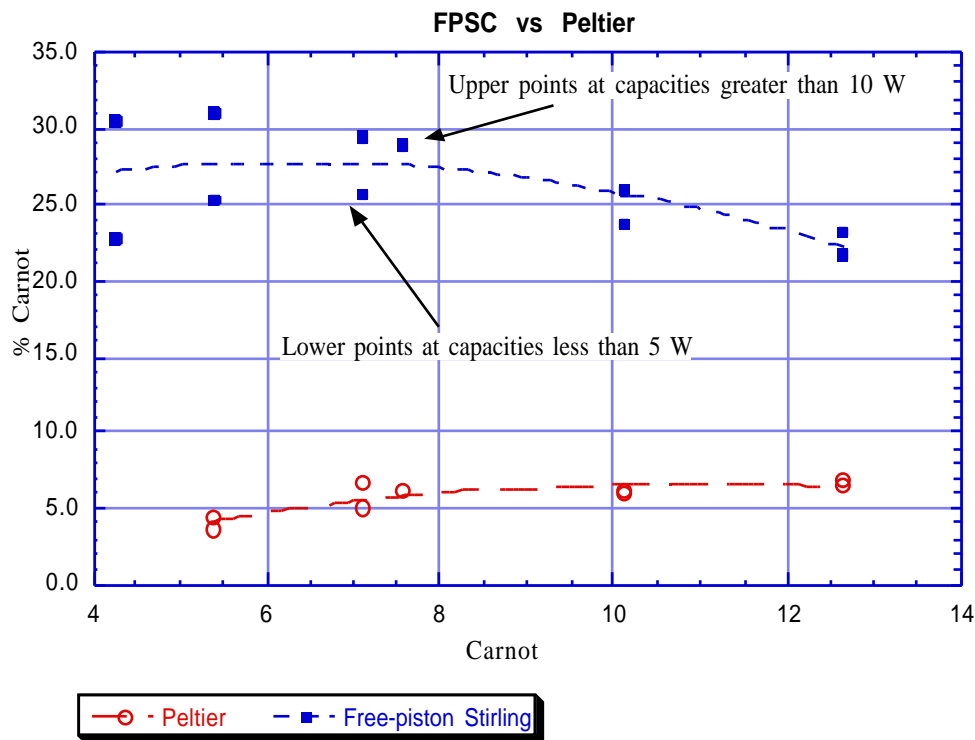


Figure 2 COP performance as a fraction of the Carnot COP

## 2. THE SYSTEM

### 2.1 Free-Piston Stirling Cooler

The Stirling cycle employs a small quantity of helium as its working medium in a closed regenerative cycle. The gas is expanded mainly in the cold side and compressed mainly in the warm side of the machine. The displacer shuttles the gas between the cold side and the warm side while the piston expands and compresses the gas. No phase changes occur during the cycle and therefore all heat transfer takes place over a finite temperature differential which must be kept as small as possible in order to maintain high COPs. The particular unit described here is a free-piston machine driven by a linear motor as is shown in Figure 3. In this machine all internal running surfaces are supported by gas bearings so that during steady operation no contact wear takes place. The entire unit is hermetically sealed to a leak rate of about  $10^{-9}$  std cc/s. An AC voltage source (which may be derived from a DC source) drives the unit and operational characteristics are such that the lift (or capacity) are easily modulated since the piston amplitude is directly proportional to the RMS drive voltage. A more complete description of Stirling cycle theory may be found in Walker (1983), Finkelstein and Polonski (1959) and Lundqvist (1993).

For the machine presented here emphasis has been placed on low cost while at the same time maintaining a competitive efficiency and size. Design for Manufacture (DFM) techniques have been used from the outset to ensure that common and widely available processes and materials are properly considered. Solid modeling techniques together with finite element models have been integrated with component testing to maintain a high degree of confidence in the design. The parts count is low compared to similar FPSC machines.

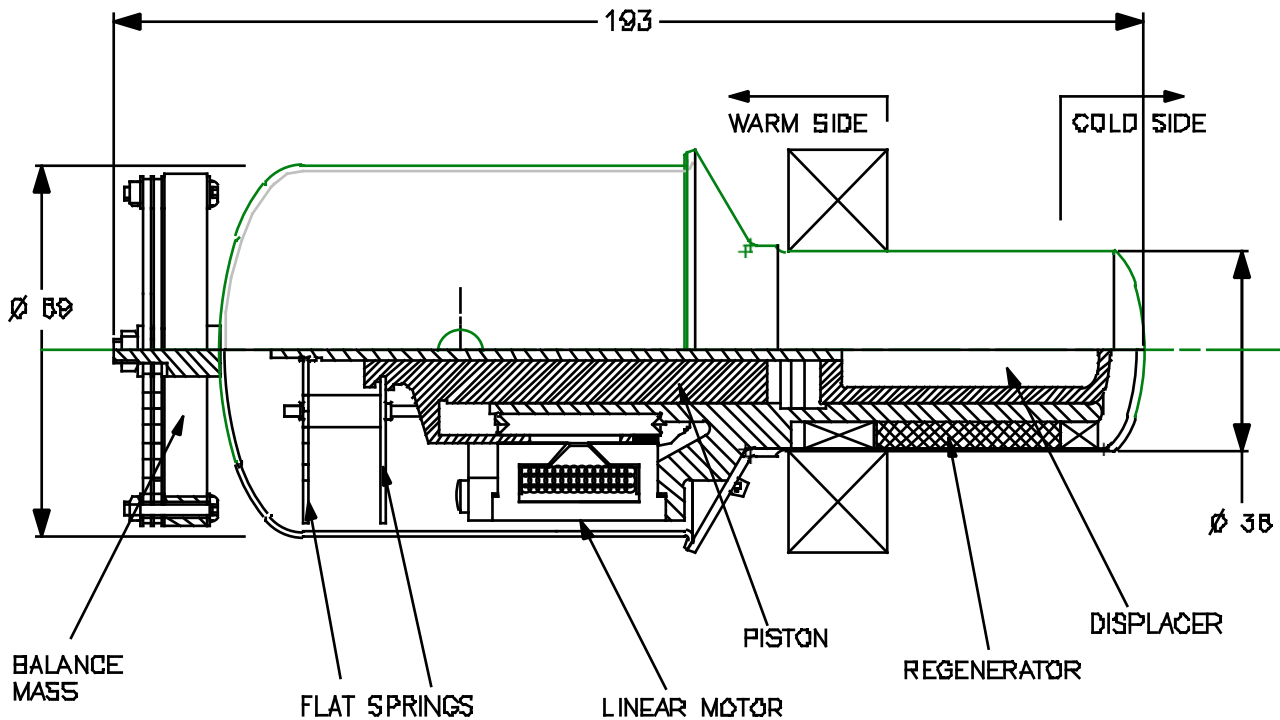


Figure 3 Small FPSC unit capable of lifting up to 40 W at freezing temperatures

## 2.2 Electronic Driver

Since portable refrigeration is generally powered by DC sources, it is necessary to convert the DC to AC power. This is done with a small converter which is integrated with the cooling modulation circuit. This electronic driver ensures that the cooler maintains the cabinet temperature by controlling the RMS drive voltage in response to an error signal derived from a user set temperature. Additionally, since the cooler may be easily modulated, the electronic driver contains logic that enables it to alter the cooler load on a solar panel in order to capture the maximum available energy Berchowit (1996). This latter procedure is sometimes referred to as peak power tracking.

## 2.3 Small Portable Cabinets

Typically portable refrigerators have a volume capacity of less than 30 liters though a few are available up to 40 liters. Construction is usually of ABS plastic with polyurethane foam insulation. Heat leak performance varies widely but the better 30 liter units achieve between 0.2 and 0.3 W / °C of temperature difference between the cold space and ambient. The lid gasket needs to be well designed in order to achieve low heat leaks. For the purposes of this paper, a heat leak of 0.3 W / °C will be assumed. Table 1 shows the expected steady state heat loads for various ambients. Typically freezer loads are not accommodated by Peltier cooled units.

**Table 1:** Heat loads at various ambient temperatures for a 30 liter cabinet

Ambient [C]	Freezer load at -18C [W]	Fresh food load at 3C [W]
25	12.9	6.6
30	14.4	8.1
45	18.9	12.6

## 2.4 Thermal Transport

The FPSC is connected to the cold space by way of a simple thermosyphon. Tests have been conducted on a 40 liter cabinet using carbon dioxide as the heat transfer fluid. In these tests the thermosyphon was fabricated from 3 mm inner diameter copper tubing. The condenser consists of a number of wraps of the tubing around the cold head of the FPSC while the evaporator consists of a few wraps of the tubing around the walls of the cold cavity. This is shown in Figure 4. Measured temperatures for the thermosyphon system are shown in Figure 5 using an M100A FPSC.

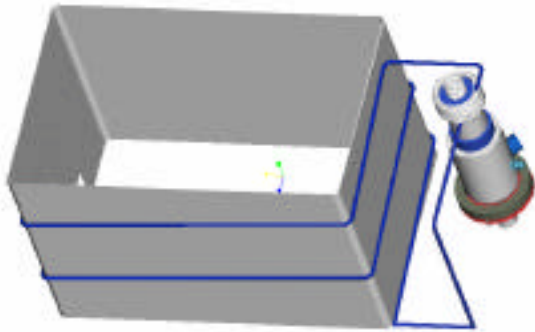


Figure 4 Thermosyphon and cold wall integration. FPSC on right side.

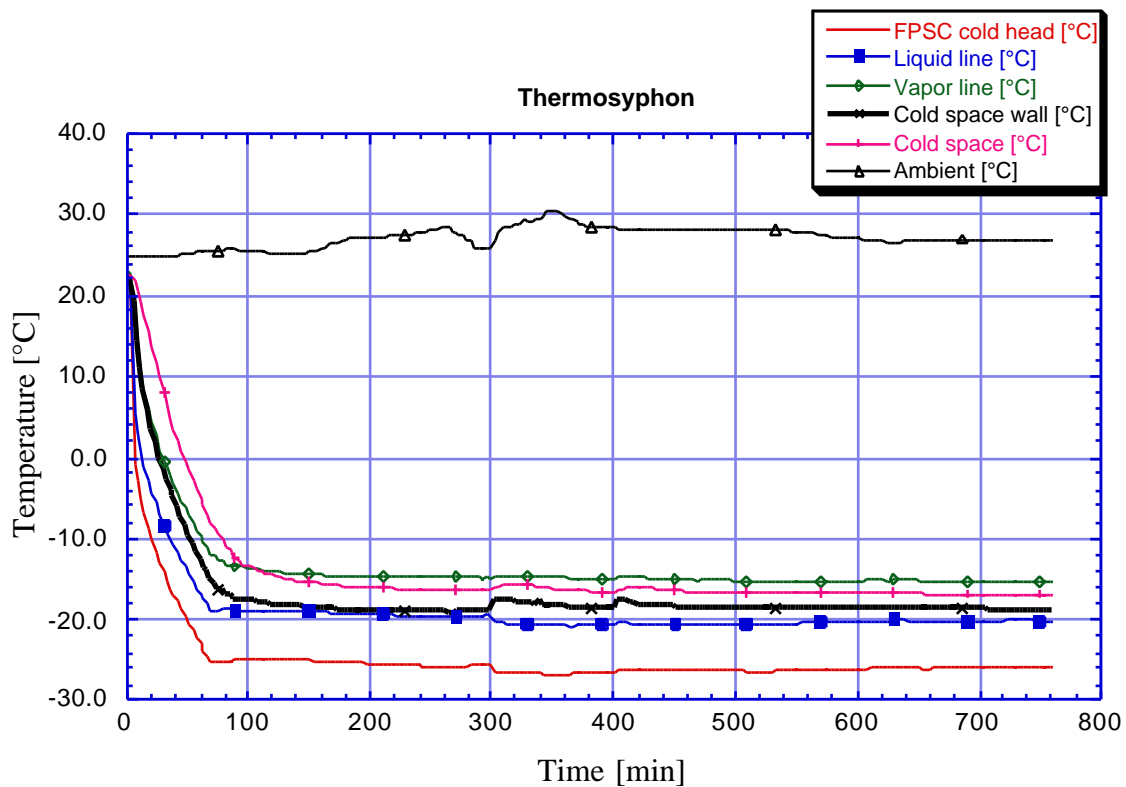


Figure 5 Thermosyphon results for a 40 liter cabinet with an M100A FPSC

### 3. PERFORMANCE

#### 3.1 Expected Performance

The expected performance for the FPSC is shown in Figure 6 for two lift temperatures corresponding to fresh and frozen food conditions. In an ambient of 30°C it is expected that the reject side will operate at around 35°C while the cold side would be about 0°C for fresh food conditions and -23°C for freezing conditions. Both these operating points are possible with the machine since the heat load will only be about 14.4 W at freezing temperatures in an ambient of 30°C. In fact the FPSC will be operating at less than 40% of its maximum rated capacity for the freezer point. From Figure 6, the average input to the cooling unit will be about 11 W when operating as a freezer. The electronics will add another 2 W and the reject fan also another 1.5 to 2 W for a total of about 15 W input. Of course during cool down the FPSC will draw whatever is available up to its maximum capacity. This could be up to 30 W. Power consumption for fresh food conditions would be a lot less. In this case the heat load is 8.1 W at 30°C which suggests an input of about 4 W to the cooler for a total system input of 8 W or less.

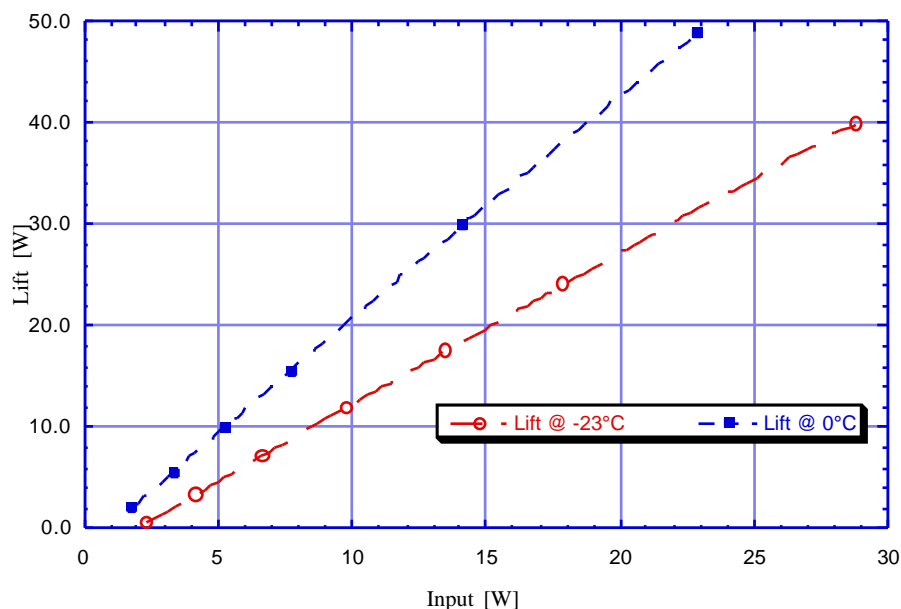


Figure 6 Performance estimation of FPSC (warm side at 35°C)

Performance estimation at warmer temperatures is shown for FPSC inputs of 10 W, 20 W and 30 W in Figure 7. For the purpose of simplification, the cold side is assumed constant at -23°C which in reality would vary depending on the load. The temperature differential between the FPSC and source or sink is also assumed constant at 5°C. A heat load line for a cabinet with 0.3 W /°C characteristic is included for reference. From this estimate, it appears that this FPSC would have no difficulty holding the cabinet at freezing conditions under extreme ambients. Actual input performance would be somewhat different than that estimated here since it depends on many things not fully accounted for. For example the design and implementation of the thermosyphon, heat rejector and reject fan have a significant effect on the operating point. Furthermore, the temperature differentials between the source and sink will be a function of the load too. As the design becomes better defined these factors will be easier to include. Parasitic losses associated with electronics and fan would add another 4 to 6 W depending on the load and ambient temperature.

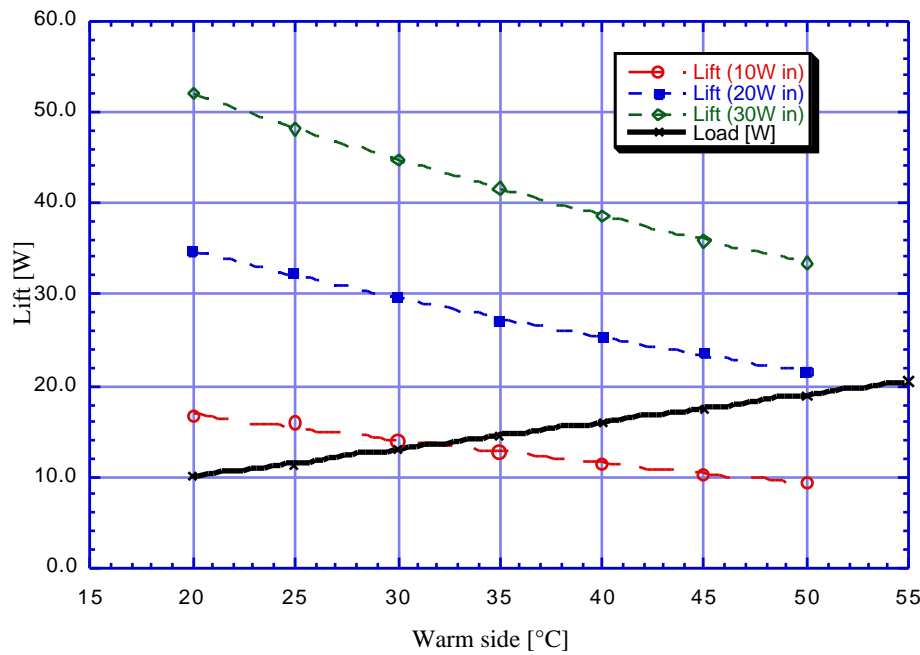


Figure 7 Effect of higher temperature conditions on freezer operation

### 3.2 Testing

Initial test points are shown in Table 2. At this time, performance is a little lower than expected but still much better than Peltier or small Rankine systems. It is expected that the performance will improve as familiarity with this machine develops. As presented by Berchowitz (1998), a larger FPSC with a maximum capacity of 100W easily exceeds the current COP performance of the 40 W machine. When the larger machine is run at reduced input conditions that reflect the inputs expected of the 40 W unit performance easily meets expectations. It therefore appears likely that the performance of the 40 W unit will eventually meet expectations.

Table 2: Initial test data

Warm side [C]	Cold side [C]	Voltage [V]	Current [A]	Input [W]	Lift [W]	COP
35.6	-22	6.86	2.95	18.2	17.1	0.939
28.4	-19.1	*	4.2	25.5	29.8	1.17
29.6	-17.1	*	*	19.5	24	1.23
30.3	-1.4	*	*	19.4	32	1.65

\* Voltage and / or current not measured.

## 4. CONCLUSIONS

The size and mass of the 40 W FPSC make it well suited to portable cooling applications. Integration with such applications is expected to be by way of a simple thermosyphon. This particular machine has been designed for low cost manufacture. To some extent that tends to compromise performance. Calculations and initial testing show that performance is very much better than current Peltier cooling systems. Potential for improvement in performance is high since the machine is only limited by the Carnot maximum COP. At this time, the fraction of Carnot achieved is about 22%.

## 5. ACKNOWLEDGEMENT

Many people are involved in making a project such as this successful. In particular, we would like to express our sincere thanks to the discussion and contribution from Mr. Kentaro Suzuki especially concerning Peltier devices and its application to portable refrigeration. And to Mr Dale Kiiikka who performed the essential tasks of prototype fabrication and testing.

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## L'ESSAIS ET L'ÉPREUVE D'UN RÉFRIGÉRATEUR STIRLING À PISTON LIBRE DE 40 W

### RÉSUMÉ:

Un réfrigérateur Stirling à piston libre (appelée FPSC) de quarante watt a été designé et fabriqué pour l'usage à un congélateur portative. Des calculations suggèrent que l'usage de puissance moyenne pour un caisson à très haute isolation de trente litres serait environ 8W aux températures pour aliments frais et 15W aux températures de congélation dans un environnement de 30°C. Des courbes fonctionnements pour le réfrigérateur sont présentées pour que le fonctionnement du système sera apprécié pour des applications diverses. La masse totale du bloc est environs 1K. Faites à un congélateur portative avec une système thermosiphonne simple est montré à opérer aux températures différentiels bas. Des premières données d'épreuves pour ce prototype sont compris.