Ultra-Low Temperature Free-Piston Stirling Engine Freezers

By Neill Lane,
President and CEO, Stirling Ultracold,
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Author Bio

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Abstract

This paper describes a new class of ultra-low freezer which uses a unique Stirling cooling engine. These Stirling freezers are described in comparison to competing cascade compressor freezers – the only ultra-low freezers available until now. The following major conclusions are drawn.

Independent field test have shown Stirling freezers to save between 35% and 59% in energy use over the best available freezers. These savings directly contribute to lower operating costs. Even at a 20% initial price premium the total costs of a Stirling freezer will be 30% less expensive over the freezer lifetime.

Stirling freezers do not have a current surge associated with start-up. This reduces the electrical infrastructure and back-up power requirements. Therefore, if a bio-repository is built to take advantage of these benefits the total cost of freezers, HVAC systems and electrical infrastructure can be 10% less if Stirling freezers are used.

Stirling freezers are able to modulate continuously to meet the load – enabling constant internal temperatures during steady state operation – unlike the on-off operation of cascaded compressor freezers.

These Stirling freezers and the cooling engines are manufactured in the USA by a single manufacturer. Unlike the compressors used in cascade systems the Stirling cooling engine is not outsourced to a third party manufacturer. Free-piston Stirling engines of this design have been proven in numerous applications. More than 3500 Stirling engines have been incorporated in laboratory equipment and more than 800 Stirling freezers have been built and sold to pharmaceutical and biotech companies, to hospitals, and to universities and research laboratories around the world.

The Stirling cooling engine technology offers fundamental technology and field proven reliability benefits over cascade compressors. The cooling engines are designed to be replaced in the unlikely event of failure and the manufacturer's warranty on the Stirling engines is longer than any warranty offered on cascade compressors.

The Stirling freezers have industry leading pull-down and temperature recovery from door openings. The Stirling freezer cools to -80°C 18% more quickly than the cascade system and 34% more quickly to -86°C. When recovering from a 2 minute door opening the Stirling freezer recovers to the -80°C setpoint 29% faster than the leading cascade freezer.

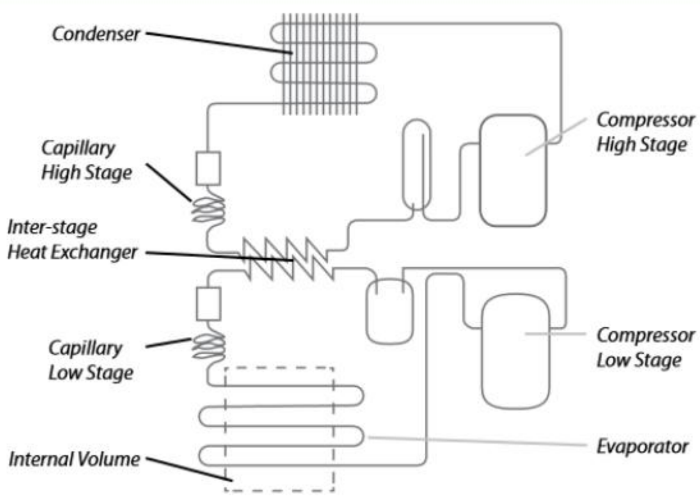
In the event the cooling system fails or the power is cut the Stirling freezer's warm-up rate is only 57% of the rate of a typical cascade compressor system. This reduced warm up rate allows significantly more time to find or repair back-up systems, or to find alternative freezers.

The Stirling freezers have a number of sustainability benefits over cascade compressor freezers including lower energy use, less refrigerant, no oil and less raw material. The combination of these advantages is that a Stirling freezer with produce 52% of the CO_2 of a cascade freezer during its manufacture and operation.

Current Ultra-Low Freezer Cascade Compressor Technology

Almost all current ultra-low freezers on the market use similar cascade compressor cooling technology. In all these systems two compressors are used in a cascade arrangement where one compressor cooling loop, the 1st stage, operates between ambient and an intermediate temperature and a 2nd stage compressor loop operates between the intermediate temperature and the freezer cabinet – Figure 1. Typically for cascade systems around 700 liter (25 cu. ft.) internal volume, each compressor is a 1000W (approximately 1.3 HP) class compressor. The system evaporator is a copper tube that surrounds the internal volume while the condenser is a forced air finned tube construction. The inter-stage heat exchanger serves as the evaporator of the first stage and the condenser of the second stage. In addition, there are expansion devices, typically capillary tubes, oil separators and dryers in the circuit. Auto-cascade systems use only a single compressor and a mix of refrigerants to enable both the 1st and 2nd stage loops and in some cases even more than two stages; in other respects they are similar to cascade systems.

Figure 1: Cascade Compressor System[1]

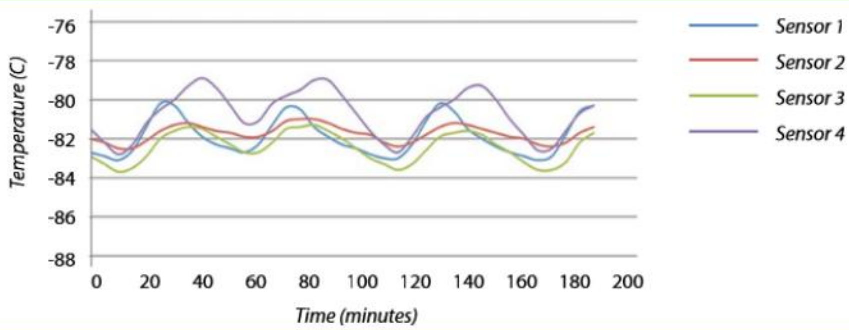


Ultra-low freezer manufacturers typically do not make their own compressors. They are sourced from compressor manufacturers whose primary markets are typically household refrigeration, air conditioning and supermarket display case cooling. These compressors are not originally designed for specific use in ultra-low temperature cabinets. They are modifications of existing compressors designed for other applications.

A typical ultra-low freezer used in the United States uses synthetic refrigerants such as R-508B (DuPont SUVA®95) in the low stage and R-407D in the high stage. In Europe natural hydrocarbon refrigerants are more widely used, including R-170 (ethane). In a 700 liter (25 cu. ft.) freezer the combined weight of the high and low stage refrigerants is about 0.9 kg (2 lbs).

[1] "Environmental Profiles of Stirling-Cooled and Cascade-Cooled Ultra-Low Temperature Freezers", David M. Berchowitz and Yongrak Kwon, to be published in *sustainability* www.mdpi.com/journal/sustainability

Figure 2: Temperature Variation Over Time – Cascade Freezer Brand P (Source - independent bio-repository test)



Cascade compressors are lubricated with synthetic oil which mixes with the refrigerant. Over time this oil migrates into capillary and evaporator tubes, coalesces on the tube walls and increases the potential for "oil clogging" where refrigerant flow is restricted and the compressor has insufficient oil to lubricate the moving parts. Ultimately this can lead to failure of the compressor(s).

The interior temperature of a cascade freezer is maintained at setpoint by cycling one or both of the compressors on and off in response for cooling demand from the temperature control sensor. This control scheme creates a "saw-tooth" temperature profile where the temperature at any point in the freezer moves up and down around the setpoint as the compressor(s) turn on and off – Figure 2. At each start up there is a current surge and a period during which the oil lubrication film must develop. In a well-maintained freezer this current surge has been measured at 13 amps[2]. With three on-off cycles per hour an ultra-low freezer compressor stops and restarts 24,000 times per year. This control scheme also places significant stress on the compressors and impacts the compressor life

Conventional cascade compressor systems have compressor motors which run synchronously with the power grid. This means that a freezer is designed and specified to work with a specific grid voltage and frequency. Cascade compressor manufacturers must offer numerous models for combinations of 50 and 60Hz and 110 or 220V operation[3] and the correct configuration must be used and specified at point of purchase

Conventional cascade compressor systems have as many as 24 moving parts; they are expected to fail one or more times over the life of the freezer resulting in a complicated and costly repair. *"All freezers fail at some point. Mechanical freezers fail much more frequently [than LN_2 units], and the required response time is much, much less. For mechanical -80°C freezers, the recommended quantity of spare freezers held at temperature is 5-10% of the total freezers."*[4]

Specialized training is required for cascade freezer maintenance and repair. In the repair process, the compressor, all refrigerant and oil must be removed and recovered. The interstage heat exchanger, common to all cascade systems, is often embedded in cabinet foam insulation must also be removed for service.

In all current upright ultra-low freezers the compressors and heat rejection heat exchanger(s) are housed in a mechanical compartment at the base of the freezer. Cooling air is drawn in from floor level and rejected at floor level, adding to dust build-up on condensers causing diminished cooling efficiency.

[2] "Factors affecting the performance, energy consumption, and carbon footprint for ultra low temperature freezers: case study at the National Institutes of Health", Leo Gumapas and Glenn Simons, World Review of Science, Technology and Sustainable Development, 2013 Vol.10, No.1/2/3, pp.129 – 141 http://www.inderscience.com/info/inarticle.php?artid=50786#

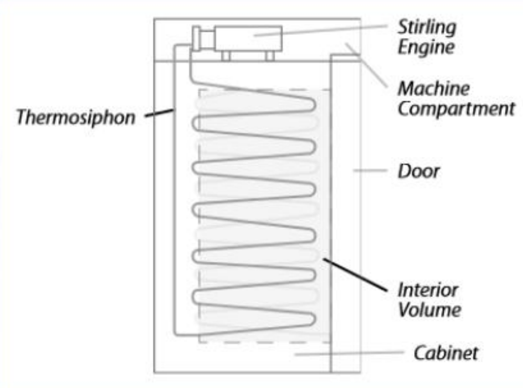
[3] Thermo Scientific™ Forma™ 900 Series Ultra-Low Temperature Upright Freezers http://www.thermoscientific.com/ecomm/servlet/productsdetail_11152_L10587_80523_14018589_-1

[4] Phil Baird ("Large-Scale Repository Design" Philip M. Baird and Richard J. Frome, Cell Preservation Technology, Volume 3, Number 4, 2005) ISBER News Vol. 12, No. 3, August 2012

Stirling Ultracold Freezer Technology

The Stirling freezer uses no compressors. The cooling system is a combination of an electrically driven free-piston Stirling engine[5] which provides the cooling and a thermosiphon[6] which transports the energy from the interior of the freezer to the Stirling engine – Figure 3.

Figure 3: Stirling Engine Cooled Freezer



The Stirling cooling engine uses environmentally benign helium as the working fluid. The engine is hermetically sealed at manufacture and requires no maintenance. There is no phase change of the helium working medium during operation. The cycle compresses and expands the gas in segregated areas providing a cold heat *acceptor* and a warm heat *rejecter*. The Stirling engine is a free-piston beta configuration with two moving parts – a piston and a displacer. The two moving components are supported on gas bearings enabling non-contact operation and therefore there is no wear during normal operation of the engine. The engine requires neither oil nor any other form of lubrication. The piston is driven at a fixed frequency by an integral permanent magnet linear motor

Free-piston Stirling engines of this design have been proven in numerous applications, have flown on the Space Shuttle[7] and continue to cool the instruments on the Rhessi satellite[8]. More than 3000 Stirling engines have been incorporated in laboratory equipment and more than 600 Stirling freezers have been built and sold to customers.

The Stirling engine cold head is connected to a thermosiphon, a sealed copper tube that wraps around the cabinet interior, insulated from ambient by a combination of vacuum panel insulation and polyurethane foam. The helium in the engine and the cooling medium in the thermosiphon do not mix. The working medium of the thermosiphon is either R-508B or R-170 depending upon the user preference. There is no difference in the freezer performance with either refrigerant. The total mass of refrigerant is less than 20% of the mass required in cascade refrigeration systems and no oil is used.

The thermosiphon has no moving parts. In a continuous, gravity driven process the cooling medium flows down the length of the tube as a liquid, absorbs energy (heat) from the freezer interior, transitions to a vapor, travels up the tube and condenses back to a liquid at the cold head of the engine. This process is isothermal; there is virtually no temperature gradient in the tube or interior cabinet walls.

5 "Commercialization Status of Free-piston Stirling Machines", Neill W. Lane, 12th International Stirling Engine Conference, Durham, UK September 2005, published by Kluwer Press

6 US Patent 6,550,255, Stirling refrigeration system with a thermosiphon heat exchanger, Arthur G. Rudick and David M. Berchowitz

7 "Stirling Refrigerator for Space Shuttle Experiments". McDonald K.; Berchowitz, D.; Rosenfeld, J.; Lindemuth J. (1994) http://www.sunpowerinc.com/library/pdf/publications/Doc0057.pdf

8 RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager) https://directory.eoportal.org/web/eoportal/satellite-missions/r/rhessi

The free-piston Stirling engine operates at a constant frequency. Cooling capacity is modulated by changing the piston amplitude on demand from the temperature control sensor. The control electronics provide the fixed frequency and varying amplitude AC voltage required by the Stirling engine. Ignoring any interruptions in power, the Stirling freezer has only one start up during its operating life and there is no current surge at that or any other start-up such as after a power failure. This modulation capability means that the temperature at any point in the freezers remains within less than a half of a degree of the setpoint during steady state operation – Figure 4.

Figure 4: Temperature Variation Over Time – Stirling Freezer SU780U 27.5 cu. ft. (Source - independent bio-repository test)

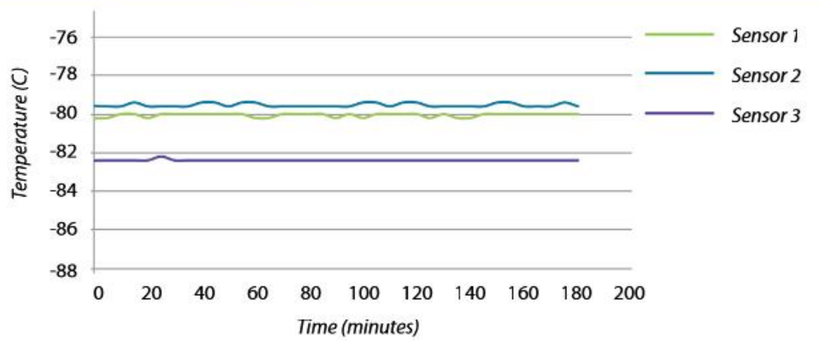
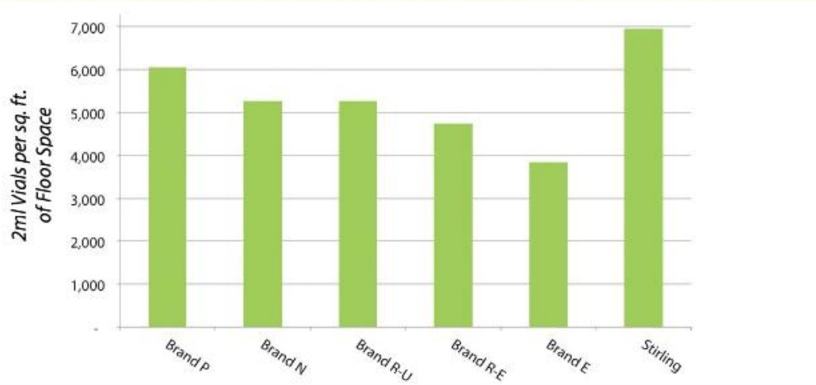


Figure 5: Stirling Freezer Engine Module

Figure 6: Stirling Freezer Showing Mechanical Compartment at the Top

Stirling Ultracold Model SU780U Freezer shown with optional inventory racks and three additional shelving units (not included).

Figure 7: Vial Density per Unit of Floor Space (Source - manufacturers' specifications)



The Stirling cooling engine module is shown in Figures 5. The Stirling cooling engine and electronics are housed in a mechanical compartment at the top of the freezer – Figure 6. Cooling air is drawn in over the top of the door and the Stirling engine is designed for easy field replacement if needed. No cascade refrigeration experience is required. There is no oil to remove. Clip-on flexible insulation is easy to remove and replace.

The entire Stirling freezer, including the free-piston Stirling engine, controls and cabinet, is manufactured by a single manufacturer in the USA ensuring quality control and performance of each component.

The freezer can plug into any outlet and can use a range of input voltages from 108V to 264V at either 50 or 60Hz. The unit automatically adjusts for the input voltage and frequency with no action required by the user.

The freezer has an ergonomic touch screen controller with a graphical user interface providing secure, PIN number access to setpoints and alarm parameters. Through-wall access ports permit easy integration with facility alarm and monitoring systems. Third party alarm, monitoring and recording systems on the market are easily accommodated. LN_2/ CO_2 backup systems and water cooled freezers are available. The SU780U freezer has adjustable shelves to fit a wide range of rack or sample storage requirements.

Energy use Stirling versus Cascade Freezers

The energy consumption of a number of full size 780 liter (27.5 cu. ft.) Stirling freezers have been field tested and directly compared to the latest model cascade compressor freezers at customers' sites In all cases customers independently chose which cascade comparison model was used. There was no freezer manufacturers' input, from Stirling Ultracold or cascade compressor freezer manufacturer companies. These customers included private biotech companies, universities, private research laboratories and government laboratories.

When these customer field tests were performed the Stirling freezer energy use specification was less than 12 kWh/day at -80°C. Currently Stirling freezers of this size use less than 9 kWh/day at -80°C setpoint.

Energy consumption data on the basis of kWh/day from testing at a research laboratory, at both -70°C and -80°C, is shown in Figure 8. This data at -80°C shows the Stirling using 41% and 49% of the energy of the competing cascade freezers. At -70°C the energy use is 52% and 38% of the competing cascade freezers. Other independent tests at a biorepository and a research facility indicate savings of between 34% and 55% on energy use *per unit of storage volume* over the best competing products.

There is no industry standard testing for ultra-low freezers and no widely accepted independent testing . Some data is available from manufactures' marketing material. Labs21 has documented some end user testing and UC Davis has tested some freezers[9]. UC Davis has also tested Stirling freezers[10]. Figure 9 shows a summary of this data from these various sources. Note that significantly lower energy consumption of Stirling freezers independently tested at UC Davis versus other freezer manufacturers' specifications. (Note: Since original UC Davis testing, the electrical energy consumption specification for the Stirling freezer has been reduced from 12 kWh/day to 9 kWh/day, further improving the already substantial difference between the Stirling freezer and the cascade units.)

Figure 8: Stirling Freezer Energy Consumption Compared with Current Model Cascade Freezers (Source – research laboratory testing)

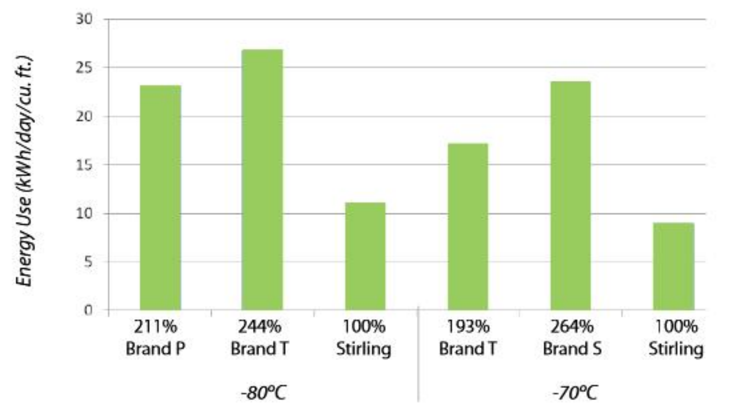
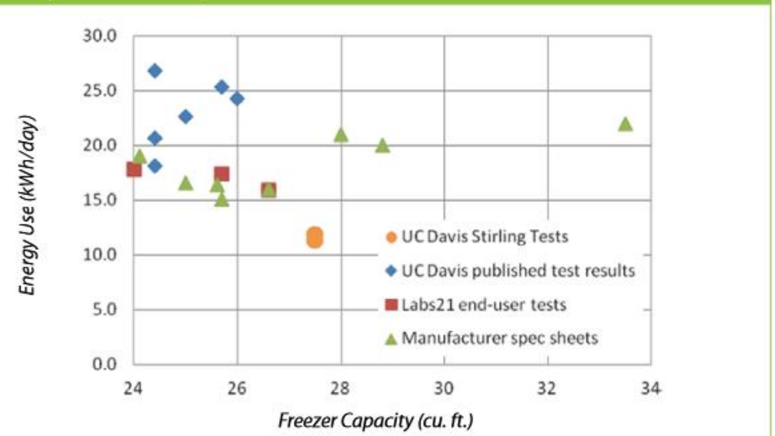


Figure 9: Freezer Energy Consumption (Source - manufacturers' specifications and independent test data)



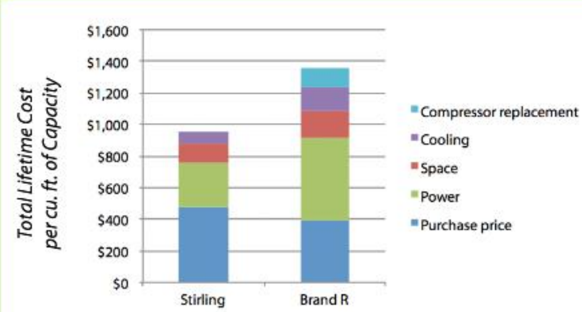
[9] Labs21 Laboratory Appliance website, http://labs21.lbl.gov/wiki/equipment/index.php/Category:Refrigerators_and_Freezers

[10] UC Davis SU780 Test report, http://labs21.lbl.gov/wiki/equipment/index.php/Stirling_Ultracold_SU780U

The Lifetime Cost

The total lifetime cost of an ultra-low freezer is the sum of the purchase price, plus the costs for energy, cooling, floor space and the usual compressor replacement. Using cascade manufacturer's energy use data, assuming discounted prices from list price and a 20% price premium on the Stirling, a life of 12 years, 16c/kWh electric costs, and with cooling and space costs as reported independently[11], the Stirling freezer's total cost is 30% less than a current model cascade compressor freezer.

Figure 10: Total Lifetime Cost - Stirling Versus Current Model Cascade (Source - see text)



Infrastructure Costs

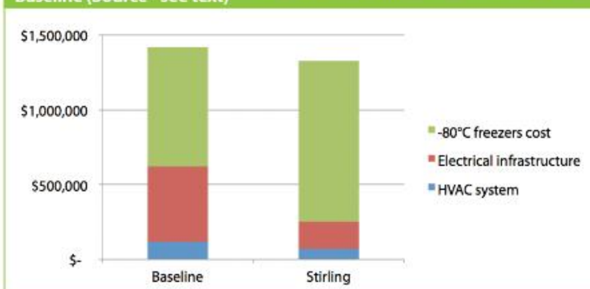
Ultra-low freezers create two distinct burdens for a facility's infrastructure. All the power consumed by a freezer is rejected into the facility as heat which then has to be removed, usually with air conditioning. The power used by a freezer is all rejected to the room as heat, so a freezer which consumes 22 kWh/day of electric power rejects 22 kWh/day (75,117 BTU/day) of heat which must be removed from the building. The peak current requirements of a freezer determine the size of the electrical infrastructure and the size of the back-up power systems. Table 1 shows the energy use and peak current draw for a Stirling freezer and a current model competitor product tested at a research laboratory.

Table 1: Power and Peak Current Measurements (Source - research laboratory tests)

	Power consumption		Peak current	
	kWh/day	%	Amps	%
SU/80U	10.8	57%	2.6	37%
Latest Brand T	19.0	100%	7.0	100%

For a biorepository the costs of HVAC and electrical infrastructure are very significant. For an eighty freezer facility these HVAC and electrical infrastructure costs are estimated at $120,000 and $500,000 respectively[12]. If these estimate are scaled by the lower energy use of the Stirling for the HVAC and for the lower peak current draw of the Stirling for the electrical infrastructure, these costs are reduced to $186,000 for the electrical infrastructure and $68,000 for the HVAC system. As can be seen in Figure 11 the total cost of freezers, electrical infrastructure and HVAC system is lower if a facility is designed with Stirling freezers specified at the outset. Even though Stirling freezers have a 30% price premium over cascade freezers in this example, the facility is still nearly 10% less expensive to build. In this example the superior vial density per floor space is not considered but will also contribute to lower initial infrastructure costs. The operational benefits are still to come.

Figure 11: Bio-Repository Capital Costs - Stirling Versus Cascade Freezer Baseline (Source - see text)



[11] "Cold Storage Strategies for Energy Efficiency While Improving Sample Access and Freezer Performance", Allen Doyle and Kathy Ramirez-Aguilar, 12th CDC International Symposium on Biosafety – 2012 Sustainability, February 11-15, 2012

[12] Large-Scale Repository Design, Philip M. Baird and Richard J. Frome, Cell Preservation Technology, Volume 3, Number 4, 2005

Life and Reliability

As described above conventional ultra-low temperature freezers are not reliable. All cascade compressor freezers are expected to fail. User perceptions of freezer reliability are a combination of the real reliability of the freezers combined with the CO_2 or LN_2 back-up systems in place, reserve freezers available at temperature, ease and cost of service and warranty offered. A user whose freezer fails with no back-up system or reserve units available will have a very different perception of the freezer than a user whose freezers fails while there is a back-up freezer running at temperature immediately available.

The Stirling cooling engine offers fundamental technology and field-proven reliability benefits over cascade compressors. The Stirling cooling engines are designed to be field replaceable in the unlikely event of failure, and the warranty on the engines is longer than any warranty offered on cascade compressors (7 year Stirling engine warranty).

The various factors which influence life and reliability and its perception for traditional cascade compressors and free-piston Stirling engines are summarized in Table 2.

Table 2: Life and Reliability Factors

Cascade Compressor	Stirling Engine
Technology Differences	
Oil lubrication with wear	Gas bearings with non-contact operation and no wear
Stop-start operation	Continuous operation with modulation
Surge current at start-up and during on-off cycling	No surge current
Field Experience	
Failure expected • Running spare freezers • CO_2 and LN_2 back-up systems • Well-developed service infrastructure	Failure not expected • Flown on the Space Shuttle • >10 year operation on satellite • Thousands of engines built for critical applications
Repair Difficulty	
Compressor replacement – complicated by oil and rigid insulation	Stirling engine designed for replacement – modular design, clip on insulation, no oil, 80% less refrigerant
Warranty	
5 year warranty best available	7 year warranty standard

Freezer Cooling Performance

The Stirling freezers have industry leading pull-down and temperature recovery from door openings.

Figure 12 shows the pull-down comparison of the Stirling freezer compared with an industry leading cascade system. Pull-down is from an ambient temperature of 25°C ± 2°C with the freezers empty. The Stirling freezer cools to -80°C 18% faster than the cascade system and 34% faster to -86°C. Note also the details as the freezers approach the -86°C setpoint. In the case of the cascade system the cooling system is clearly at the limits of its capability and can only just reach the setpoint. In the case of the Stirling freezer it is clear that the control system intervenes to hold temperature at the setpoint. The Stirling cooling system has the clear capability to go to lower temperatures.

Figure 13 shows the recovery from door openings for the Stirling freezer compared with an industry leading cascade system. The inner and out doors of both freezers are opened for two minutes in this comparison and the ambient is 25°C ± 2°C. Both freezers are empty – the most challenging condition for this test. The Stirling freezer recovers to the -80°C setpoint 29% faster than the cascade freezer.

Figure 12: Pull-Down Comparisons with Cascade Freezer

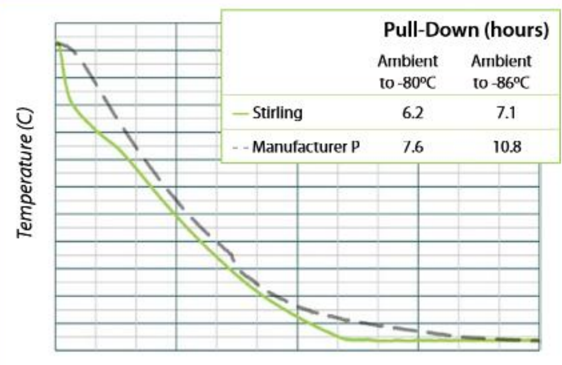
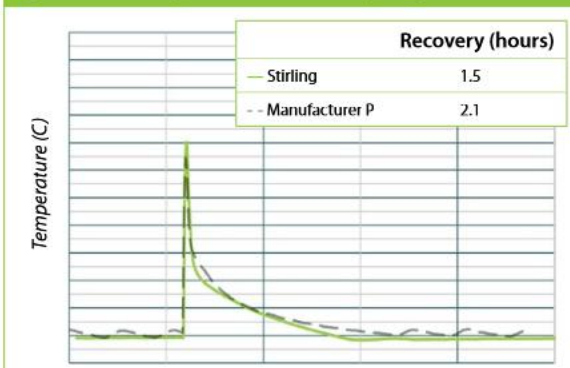


Figure 13: Recovery from 2 Minute Door Opening



Power Outage Warm-up

When the power is interrupted to an ultra-low freezer or there is a refrigeration system failure the interior of the freezer starts to warm up as heat leaks into the interior and is not removed. There are three paths which allow heat to leak in a closed freezer; the cabinet, the gasket and the non-operating cooling system. The Stirling freezer has very similar cabinet and gasket heat leakage performance to best available competing freezers. The Stirling freezer thermosiphon, however, moves heat in only one direction, from the interior of the freezer to the cold head of the Stirling engine. When the Stirling engine is not operating the thermosiphon does not transfer heat. The cascade freezer evaporator operates differently. When the compressors are not operating, the high and low stage refrigeration loops can move heat from the mechanical compartment at the base of the freezer into the interior cabinet. The net effect of this phenomenon is that when there is no cooling the Stirling freezer warms up much more slowly, 57% of the rate to -40°C, than a typical cascade compressor ultra-low freezer – Figure 14. This slower warm up allows significantly more time to find or repair back-up systems, or to find alternative freezers.

Figure 14: Power Outage Warm-Up Performance to -40°C (Source - internal data)

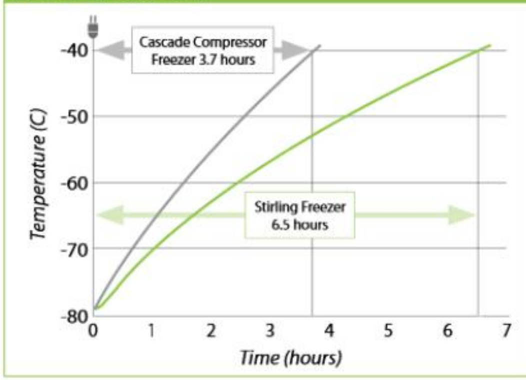
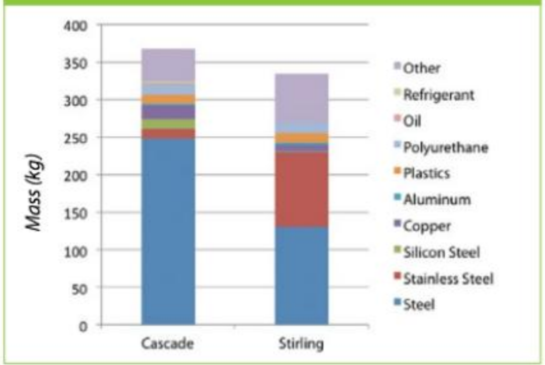


Figure 15: Material Use Comparison



Sustainability Benefits

The Stirling freezers have comprehensive sustainability advantages over cascade freezers. These benefits are described in "Environmental Profiles of Stirling-Cooled and Cascade-Cooled Ultra-Low Temperature Freezers"[13]. The largest of these advantages is the lower lifetime energy use and consequently the lower carbon footprint. This is not the only advantage. The Stirling freezer is lighter than a comparable cascade unit and therefore uses less raw material – Figure 15. However, the carbon footprint of the raw material and manufacturing process is dominated by the use of R-508B (SUVA 95) which has a global warming potential (GWP) of 13,396[14]. Therefore the CO_2 associated with the manufacture of the product is very much larger for the cascade freezer than for the Stirling – Figure 16. This data includes the GWP of the materials used in the freezer as well as the CO_2 costs to transform the material into the final product and to ship it. Use of R-170 (ethane) as a refrigerant in the Stirling system thermosiphon improves this GWP even further. Cascade freezers cannot use R-170 (ethane).

Due to the high energy demand of ULT freezers, the embodied CO_2 generation during freezer manufacture is much smaller than is generated during its use. As a consequence, the environmental impact of operating efficiency is dominant. Figure 17 clearly illustrates the total CO_2 generation associated with operation, air conditioning and manufacture. The advantage of Stirling over cascade – 48% less CO_2 – is predominantly a consequence of lower energy use during operation.

Figure 16: CO_2 Associated with Material Transformation and Product Manufacture

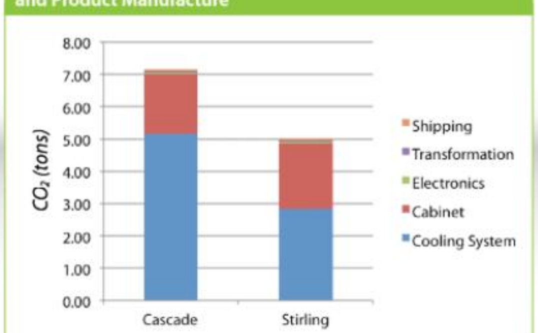
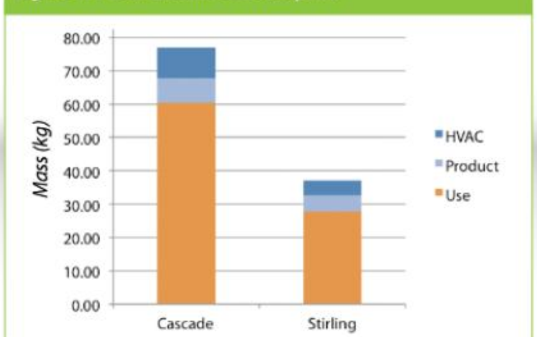


Figure 17: Total Lifetime CO_2 Footprint



[13] "Environmental Profiles of Stirling-Cooled and Cascade-Cooled Ultra-Low Temperature Freezers", David M. Berchowitz and Yongrak Kwon, to be published in sustainability, www.mdpi.com/journal/sustainability

[14] SAFETY DATA SHEET DuPont™ SUVA® 95 refrigerant, http://msds.dupont.com/msds/pdfs/EN/PEN_09004a2f806a2e87.pdf

Conclusions

With the exception of Stirling freezers all other ultra-low freezers on the market use cascade compressors to cool the cabinet. These cascade compressor freezers use large amounts of energy, more than 22 kW/day in some cases. Independent customer field test have shown Stirling freezers to save between 35 and 59% in energy use over the best available freezers. These savings directly contribute to lower operating costs. Even at a 20% initial price premium the total costs of a Stirling freezer will be 30% less expensive over the freezer lifetime.

Stirling freezers do not have a current surge associated with start-up, have reduced heat output as result of reduced energy use, and can plug into any outlet. These factors reduce the electrical infrastructure and back-up power requirements. Therefore, if a bio-repository is built to take advantage of these benefits, the total cost of freezers, HVAC systems and electrical infrastructure will be 10% less if Stirling freezers are used.

Stirling freezers modulate continuously to meet the cooling load, enabling constant internal temperatures during steady state operation, unlike the on-off operation of cascaded compressor freezers.

These Stirling freezers and the cooling engines are manufactured in the USA by a single manufacturer. Unlike the compressors used in cascade systems the Stirling cooling engine is not outsourced to a third party. Free-piston Stirling engines of this design have been proven in numerous applications including ultra-low temperature freezers.