Ultra-Low Temperature Freezer Performance and Energy Use Tests

Stirling Ultracold SU78UE
Eppendorf Cryocube 570h
Thermo Fisher TSX600

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Gratitude

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I. Introduction

The energy intensity of laboratories has come into focus over recent years due to increased costs of electricity and an awareness of the large carbon footprint associated with their operations. Building designers are looking for new ways to reduce building plug loads and as well as cooling needs from equipment reject heat. Most cascade (compressor-based) Ultra Low Temperature (ULT) freezers consume as much power as typical household. They also generate heat and noise, need a significant amount of electricity, and require frequent maintenance. Because space in university laboratories is at a premium, the footprint of such equipment will be discussed as well.
New energy efficient units are now available on the market and provide 50% energy reduction, as well as less heat production and less noise.
During fall 2015 and winter 2016, staff and students from the Office of Sustainability tested three Ultra Low Temperature Freezers (Table 1). A Stirling, with assorted racks for sample storage, was purchased for testing purposes through funding from the University of California Office of the President as part as the University's Carbon Neutrality Initiative. The Thermo Fisher and Eppendorf freezers, and racks for both units, were loaned to the campus for three months. The Thermo Fisher was sold to a campus lab after the testing was completed and the Eppendorf was returned to the manufacturer at the end of the loan period. The characteristics of each unit are described below.

Table 1: Tested freezer's dimensions and capacities

Distributor	Stirling Ultracold	Thermo Fisher	Eppendorf
Manufacturer	Stirling Ultracold[1]	Thermo[2]	Eppendorf
Model	SU78UE	TSX600	Cryocube 570h
Cubic Feet	27.5	28.8	20.1
Storage Capacity: number of 2" Boxes	600	600	400
Voltage	120V (can be plugged in 208V but tested with a 120V outlet)	208V	120V
Amperage	15 Amps	15 Amps	20 Amps
Picture			

[1] The Stirling freezer does not use typical compressor but a free-piston Stirling engine previously used by NASA. This engine does not require oil lubrication and works continuously, opposed to the stop-start operation of a typical cascade compressor. The engine is located at the top of the unit and it has the size of can. By taking less space than 2 compressors, it provide a large storage capacity without occupying a large floor space.

[2] The Thermo Fisher TSX600 can operate in two different modes, as described below, and both modes were tested:

- Standard Mode – by default. This setting can be used in most applications and is more energy efficient. Standard Mode is for researchers who do not require maximum temperature uniformity.
- High Performance Mode optimizes temperature uniformity in the freezer and should be used when validation protocols require tight temperature uniformity. In addition, this mode should be used when operating in ambient temperatures higher than 80°F (27°C), humidity levels above 50% RH, or dew points of 65 or higher.

II. ULTs at UCR: audit and cost analysis

In 2014, UCR began documenting the number and condition of Ultra Low Temperature Freezers (ULT) on campus. An inventory listed 175 ULTs in research labs across campus. The office of Sustainability audited ~70% of them. The ULTs ranged in age from less than one year to more than twenty years old.
As part of the audit, 11 ULTs were monitored to gather data on energy consumption (Table 1). The energy consumption data collected varies from 15kWh/day to 32kWh/day per ULT. Energy used by all ULTs on campus represents 1.3% of the total electricity use for the campus.

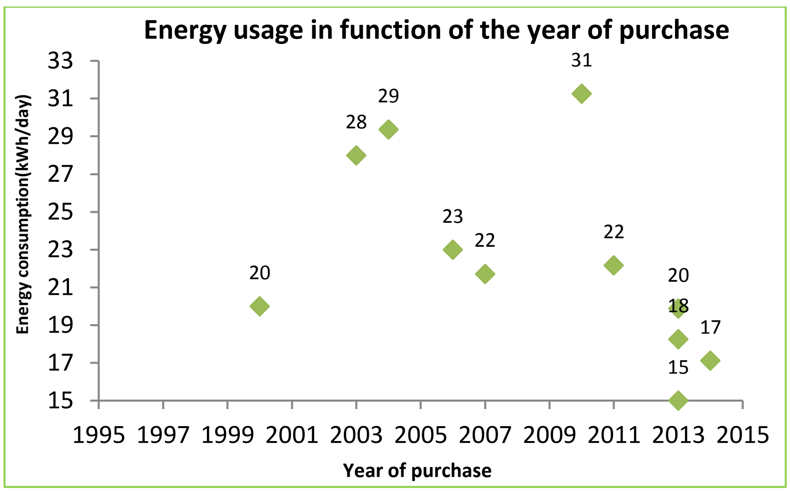

Figure 1: Energy usage of monitored Freezer during the freezer audit in 2014-2015

Because energy savings can be significant for ULTs, UCR decided to investigate and compare ULTs marketed as being energy efficient. These models included the Stirling, Thermo TSX and the Eppendorf Cryocube (Table 2).
From vendors' data and onsite monitoring, we have approximated the energy use for *regular new ULT* and *half-life regular ULT*.

Table 2: Energy usage and operational cost comparison between regular ULTs and EE ULTs

	Average consumption (kWh)/day	Average consumption (kWh) /year	cost $/kWh in 2015	Yearly operational cost ($)	kWh difference for 1 year	$ difference for 1 year
Energy Efficient freezer[3]	8.86	3,233		$ 323		
Regular half-life freezer[4]	24	8,760	0.10	$ 876	5,527	$ 552
regular NEW freezer[5]	17	6,205		$ 620	2,972	$ 297

[3] The energy consumption for Energy Efficient ULT comes from the average of onsite monitoring presented in Table 3.
[4] The energy consumption for half-life ULT comes from the average of freezer monitored on site.
[5] The energy consumption for regular new ULT comes from vendors' data.

III. Testing methods

1. Energy tests

A WattsUp Pro Meter was used to measure ULT energy consumption. Wattage and voltage were measured simultaneously. The data were reported in Watts/day.
The freezers were given 24 hours once they reached the set temperature to stabilize before and between each tests, then energy measurements were logged at 10 minute intervals and added up for a 24-hour period.
For each test, all freezers were full. Racks were used first and Styrofoam coolers were used to complete empty space when the number of racks available did not suffice to occupy the full freezer. Rack contains cardboard boxes that were empty.

2. Temperature Uniformity tests

On the recommendation of Allen Doyle, Sustainability Manager at UC Davis, type J thermocouple (TC) wire for temperature sensing were selected. Fifteen TCs were placed inside the freezer, which were inter-calibrated for accuracy and precision in a methanol bath with dry ice chunks. The measurements were logged at 10 second intervals continuously for 2 weeks. All 15 TC's were logged simultaneously using two Omega TC-08 panels. For consistency, uniformity is often measured on empty freezers, yet this is not like field conditions and it does not challenge the cooling system or air circulation. Previous work (Todd Davis and Kathi Shea citation) has shown marked difference between completely and partially full freezers, and at different temperatures. Thus, for each freezer, temperature uniformity was tested with 4 different conditions described below (see also Figure 7 and Figure 8):

- 80°C, freezer filled to capacity
- 80°C, freezer with one rack removed per shelf to increase air circulation
- 70°C, freezer filled to capacity
- 70°C, freezer with one rack removed per shelf to increase air circulation

Doors opening tests were conducted as well. For each condition, three replicates of 30 second door openings and three replicates of 90 second door openings were conducted.
For all temperature uniformity tests, the Thermo Fisher was set to High Performance mode. Due to lack of time, the Standard mode has not been tested.

3. Thermocouple installation

The drawing representing the TC (red circles) distribution for the Thermo Fisher freezer is shown in Figure 2. The three freezers were tested following the same distribution model.
One TC was installed next to the temperature probe, one on each corner at the top and the bottom of the freezer, and one on each side, and under each shelf. TC's were bent so that the tips did not touch any surfaces and were about 1 cm) from the walls.

On the top front right corner and bottom front right corner, the TCs were placed inside a plastic vial (micro-centrifuge tubes), which was located inside a 2" cardboard box (Figure 4 and Figure 6). These locations were identified as sensitive to temperature change during door openings. Measuring air temperature with a bare TC would not realistically indicate sample conditions, so enclosing the TCs in tubes and standard box simulated what samples experience.

The blue squares represent the freezer probes installed by the manufacturer. They are present in all units.

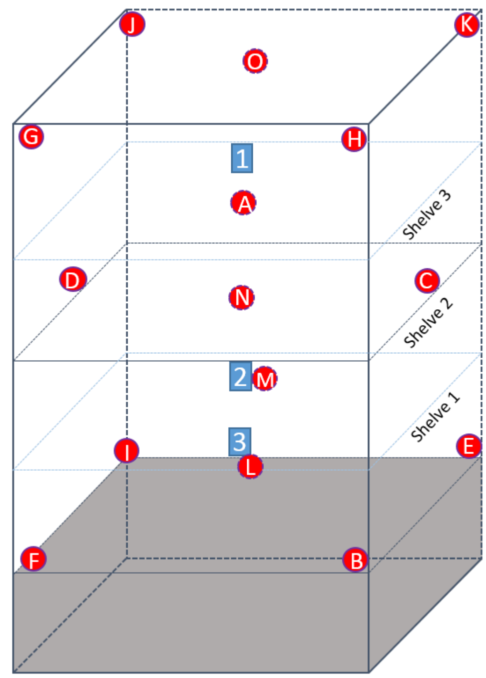

Figure 2: Thermocouple repartition inside the Thermo freezer

Figure 3: TC installation 1

Figure 4: TC inside a plastic tube, inside a box

Figure 5: Putty around TCs at the exit of the freezer

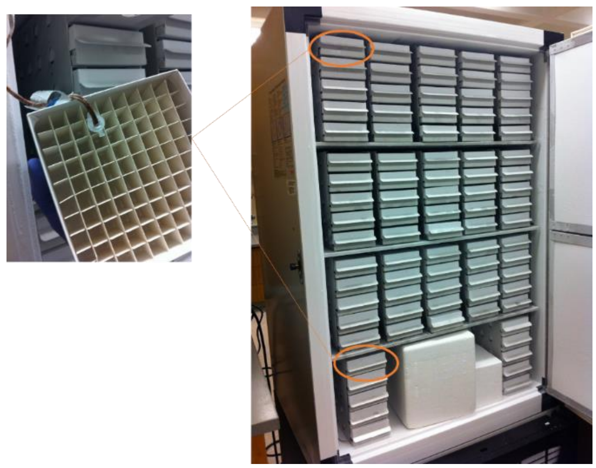

Figure 6: Front top and bottom corner with TC in real sample condition - inside a tube, inside a box.

Figure 7: Freezer full of racks and coolers

Figure 8: One rack removed per shelf to increase air flow movement

4. Noise test

To measure the noise produced by the freezer, a Brunel & Kjaer type 2230 sound meter was used. It was placed 1 meter from different part of the freezer (3.3 feet).
The noise was measured from the front, back and sides of the freezer whenever possible.

5. Heat test

To estimate the heat produced by the freezer, an U8865 Infrared Thermometer Caterpillar was used. The temperature was measured from the front, back and sides of the freezer whenever possible.

IV. Results

1. Energy

1.1 Energy consumption at different temperatures

The energy consumption for each freezer was measured at -80°C with no door openings and with the freezers full of racks, as shown in Table 3.
The electricity cost per year was calculated at a cost per space for storing one 2” box at -80°C.

Table 3: Energy consumption at the set point -80 °C. Measurements made using a WattsUp Pro meter.

	Stirling	Eppendorf	Thermo TSX – High Performance mode	Thermo TSX – Standard mode
Energy Use kWh/d at -80°C	7.55	9.35	9.82	8.74
Electricity Cost/year (0.1 $/kWh)	$ 275	$ 341	$ 358	$ 318
Electricity Cost/Box/y	$ 0.46	$ 0.85	$ 0.60	$ 0.53

The energy consumption results for each freezer at three different temperatures: -80°C, -70°C, and -60°C are shown below in Figure 9 and Table 4.

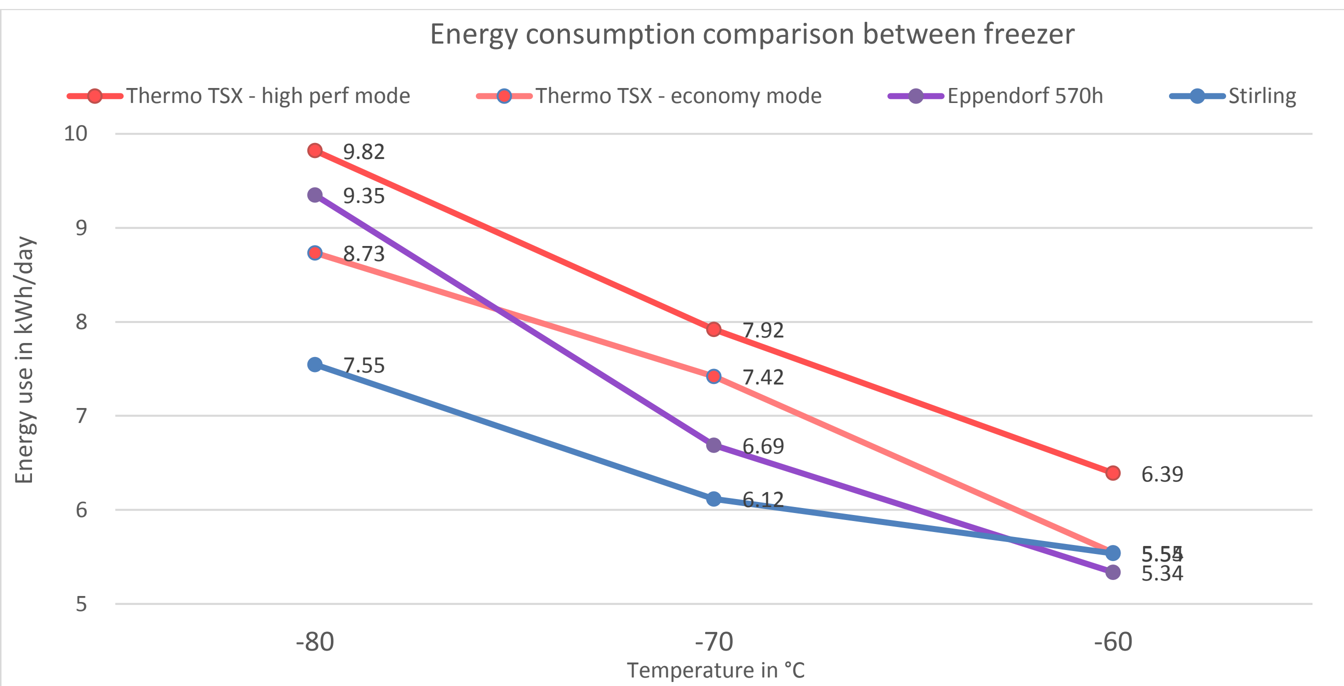

Figure 9: Energy consumption comparison between freezers

All freezers used less than 10 kWh per day at all temperature and performance settings.
The Standard mode of the Thermo freezer used less energy than the High Performance, as advertised by the company. At -80°C and -70°C, the Stirling consumes the least amount of energy as compared to the Thermo and the Eppendorf, and they all converged on the same value at -60 °C.

The savings between the different temperatures are presented in Table 4. There is a clear savings potential when adjusting the temperature set point by 10°C or 20°C.

Table 4: Saving by increasing the temperature

	Stirling	Eppendorf	Thermo TSX – High Performance mode	Thermo TSX – Standard mode
Savings from -80°C to -70°C	19%	29%	19%	15%
Savings from -80°C to -60°C	27%	43%	35%	48%

1.2 Energy Consumption as a function of storage capacity

Two measures of volume were used to compare volumetric energy consumption, the listed cubic feet, and the number of standard 2" boxes they could hold when full (Figure 10 and Figure 11).

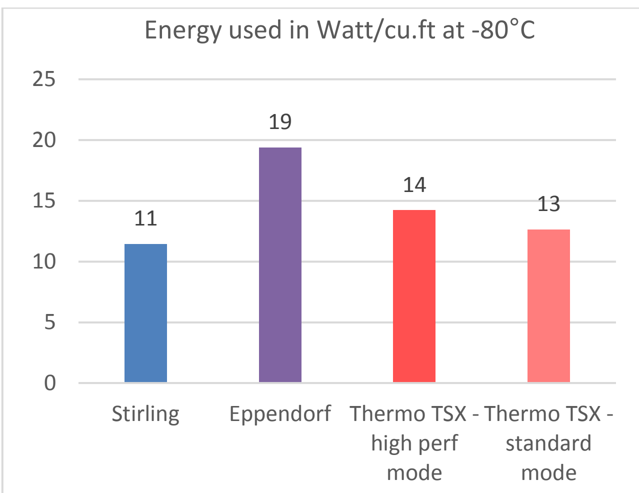

Figure 10: Energy used in Watt/cu.ft at -80°C

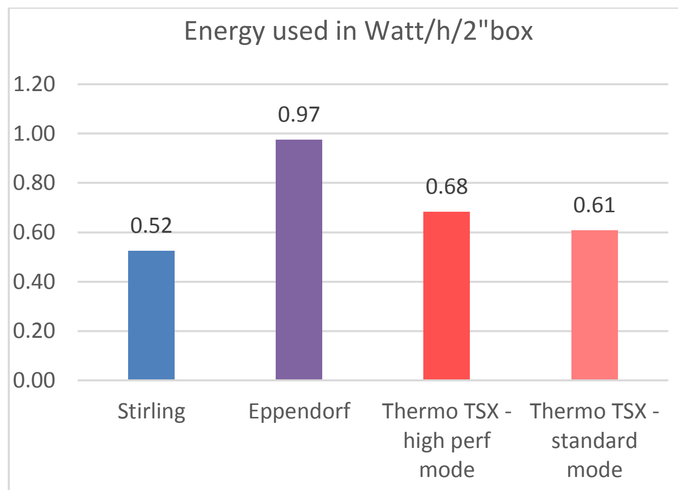

Figure 11: Energy used in Watt/2"box at -80°C

Because the interior of ULT freezers has so few obstructions or compartments, the volumetric comparisons gave the same results, and all freezers were efficient compared to values reported in a rebate calculator published in 2012 (Doyle, EERE ULT guide). The Stirling used the least amount of energy when compared on the basis of storage capacity, about 15% less than the Thermo at standard (economy) mode, and 22% less at high performance mode. Because of its smaller size, the Eppendorf volumetric energy consumption was much worse than the Stirling and Thermo.

1.3 Cost of operation

Based on their energy consumption, the cost of operating these ULTs per year is compared in Figure 12. The electricity price used for calculation was $0.1/kWh.

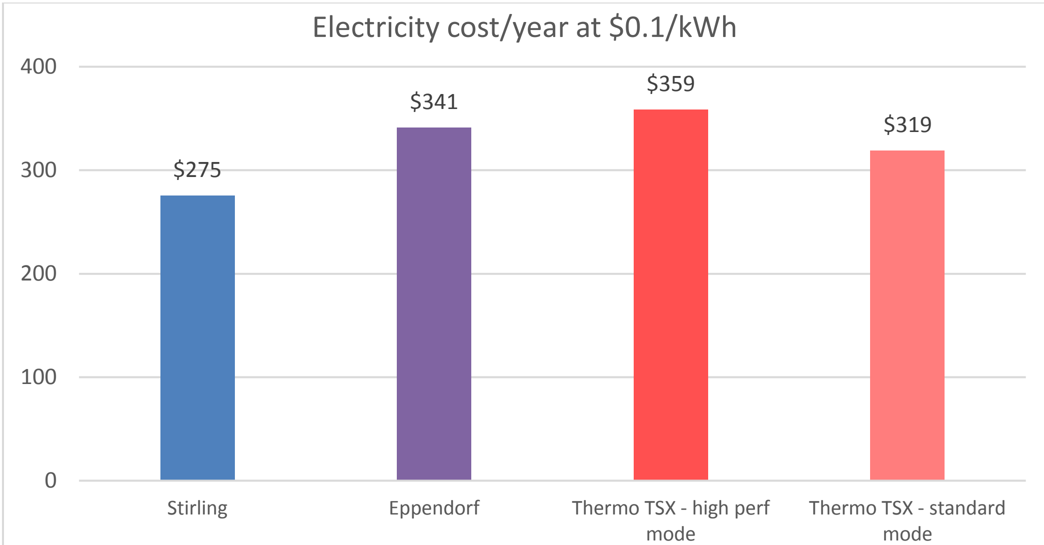

Figure 12: Electricity cost/year at $0.1/kWh

The electricity cost is lower when operating the Stirling freezer, between 14% and 23%.

2. Footprint

The three tested freezers have different dimensions as well as different storage capacities. Scientists are motivated to purchase unitary freezers to maintain control and minimize their individual first costs, and buildings quickly fill up with individual freezers without an overall strategy. Because space in laboratories is at a premium, a space management approach to storage and energy efficiency would be indicated, and the footprint of such equipment should be part of a decision process (Figure 13). It is also interesting to link this information to the storage capacity (Figure 14). While square footage is often compared, freezer depth is rarely limiting as corridors are relatively wide, so horizontal wall length is the limiting dimension. [For a given room, 20-40% more storage capacity can be achieved with larger freezers (Allen Doyle, UC Davis)].

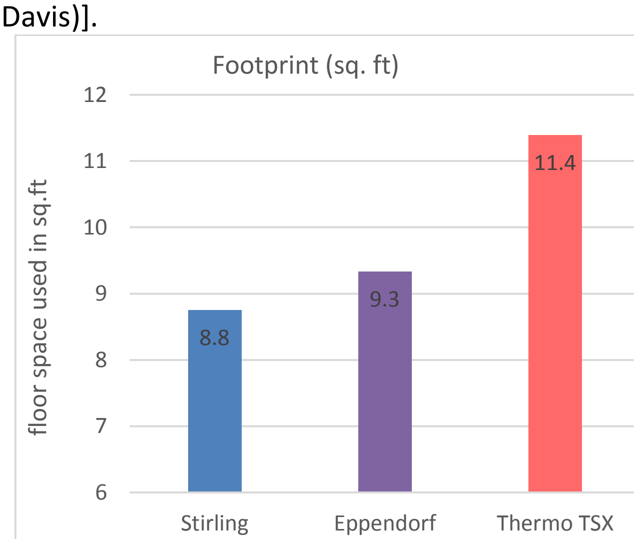

Figure 13: Square footage of each freezer

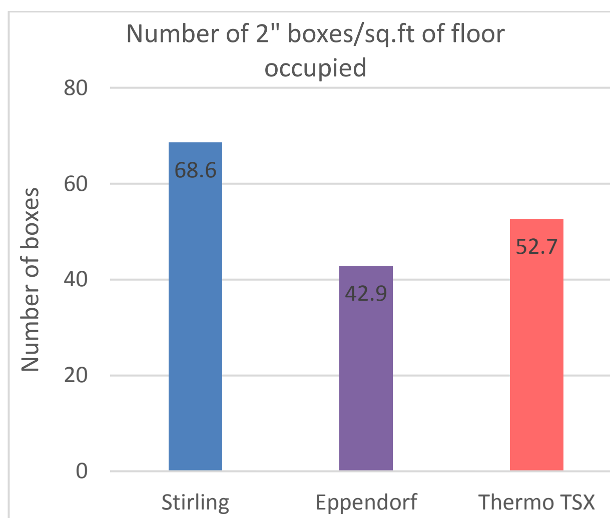

Figure 14: Number of 2" boxes per square feet of floor occupied

The Stirling has a smallest footprint and allows for the most number of boxes to be stored per 1 square foot of floor space occupied.

3. Performance: average internal freezer temperature

Several TCs – or temperature probes – were installed inside the three freezers.
The average temperature for set points at -80°C and -70°C is presented in Figure 15 . The temperature set point is fixed in the unit in set point menu, which used the internal temperature probe. UCR did not calibrate the freezers' probes, so the freezer set points are relative value.
This figure shows the comparison between a full freezer and a freezer with one rack removed (see Figures 7 and 8 above for details).

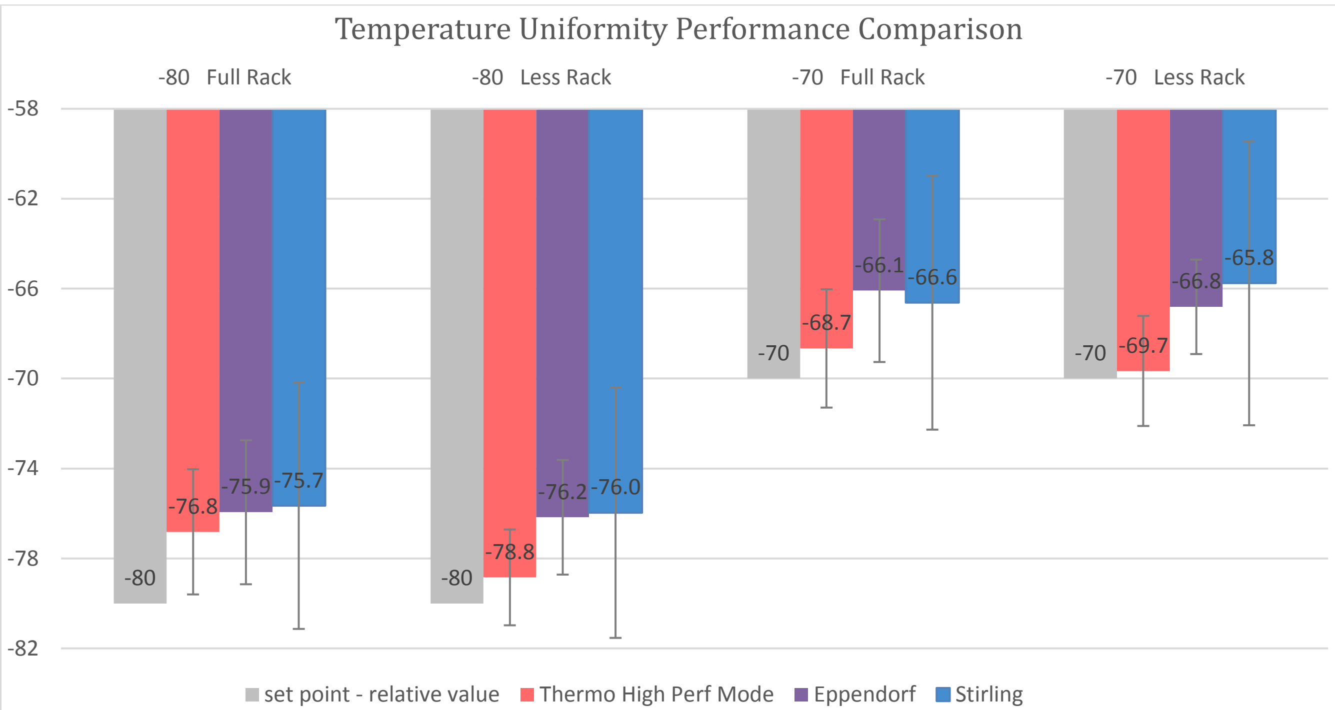

Figure 15: Temperature Uniformity comparison between freezers

At -80 °C and when full of racks, all three freezers were comparable—about 3-4 degrees above set point. At -70 °C or when one rack was removed, the Thermo freezer was closest to set point.
This is seen through the average temperature reading values measured inside compared to the relative temperature set point.
Also, most of the freezers perform slightly better when one rack per shelf was removed (denoted "Less Rack" in Figure 15 above). This can be explained by the improvement of air circulation inside due to more open space. More details can be found in the section Temperature Uniformity, which presents the variability and range of temperature for each condition in more details.
Also, the detailed temperature profile for each freezer can be seen in Appendix 2.

4. Performance: pull down and warm-up time

The pull down time is the time needed for the freezer to reach set point from room temperature.

The results are presented in Figure 16 below and calculated using the average of all the TCs installed inside the freezer, or an average of 14 points. The freezers were all full of racks and boxes. While pull down from room temperature only happens rarely in the lifetime of a freezer, the rate of pull down at the coldest temperatures is the most relevant comparison, as that is the condition after door openings.

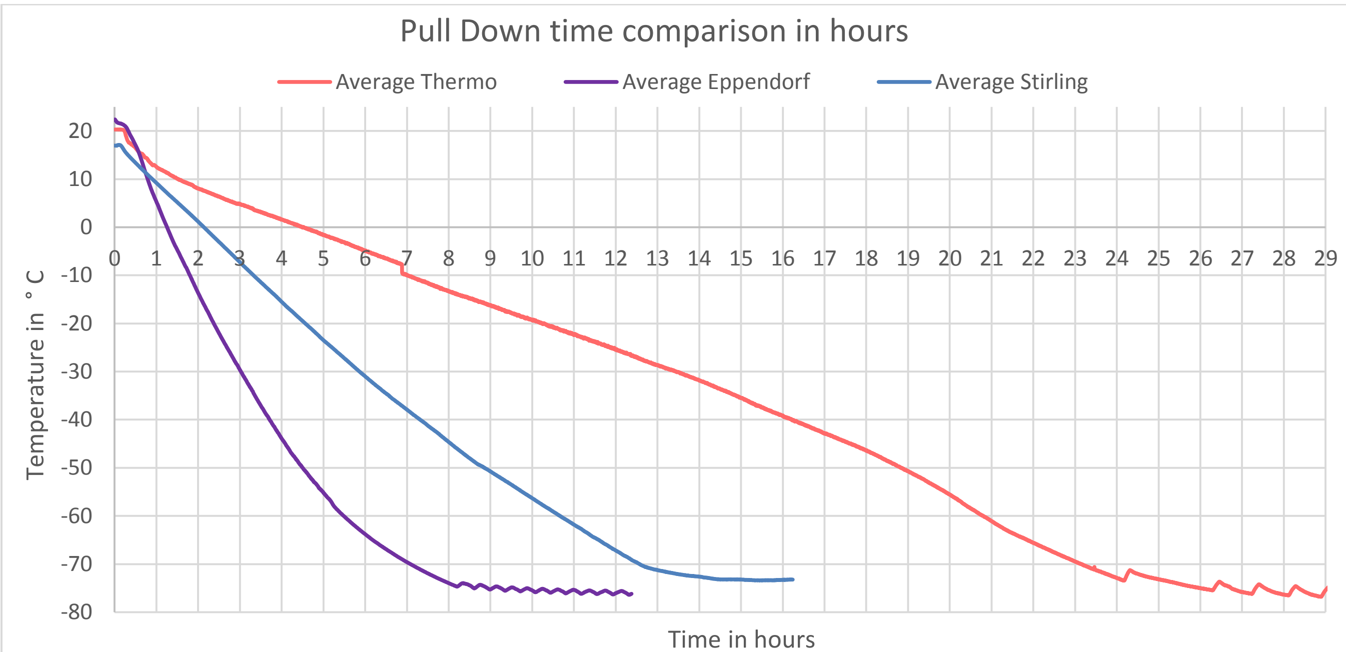

Figure 16: Pull down time in hours

It takes 9 hours for the Eppendorf to reach its -80 set point, 15 hours for the Stirling and close to 26 for the Thermo Fisher in Standard Mode.
This information will be valuable when you set up your freezer and need it ready in a short period of time.

The warm up time is the time needed to reach ambient temperature from -80°C (Figure 17). All three freezers were full of racks/coolers when tested. This is particularly valuable data in the case of a power outage or freezer malfunction.

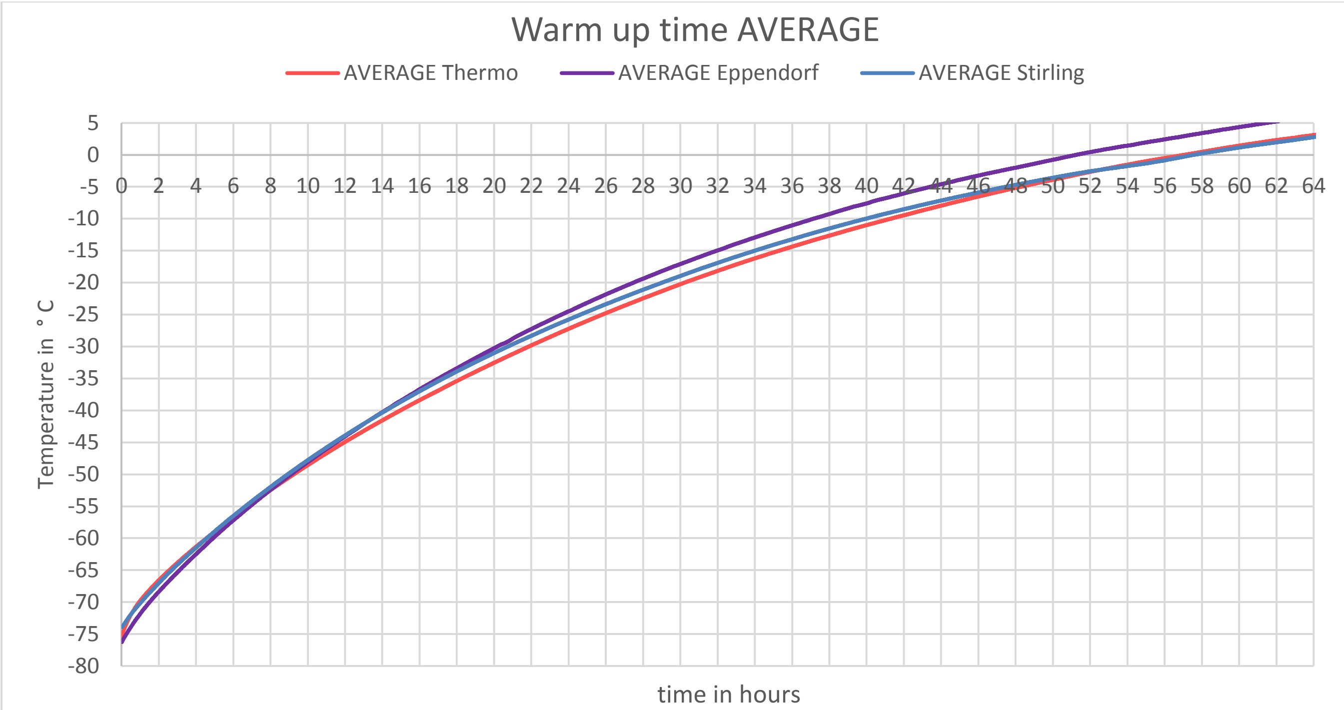

Figure 17: Average Warm up time from -80 to ambient

The three freezers behave similarly in case of power outage or freezer failure.
The literature states that most biological samples can be stored for a few hours at -50°C.
In case of power outage or freezer failure, if the door is maintained closed at all time, the scientists have ~9hours (Table 5) to find a backup freezer before their samples reach -50°C and 2 days before they reach 0°C. This time should allow researchers to save their samples if the issue happen when people are present in the lab.

Table 5: Average warm up time from -80 to -50.

	Stirling	Thermo	Eppendorf
Time to reach - 50°C in hours	8.9	9.2	9.1

Zooming in on the graph above (Figure 18), it can be seen that when the freezers are set to -80°C, the average temperature inside the freezer is higher, between -76°C and -74°C.
The warm-up time difference between a freezer set to -80°C versus -70°C was found to be between 1.5 to 2.8 hours. A common argument is made when changing the temperature set up from -80°C to -70°C, which is the time lost in case of power/freezer failure. The answer to that question can now be discussed and the researcher can make their decision knowing that they might have an additional 1.5 to 3 hours with no door opening to move their samples in case of failure.

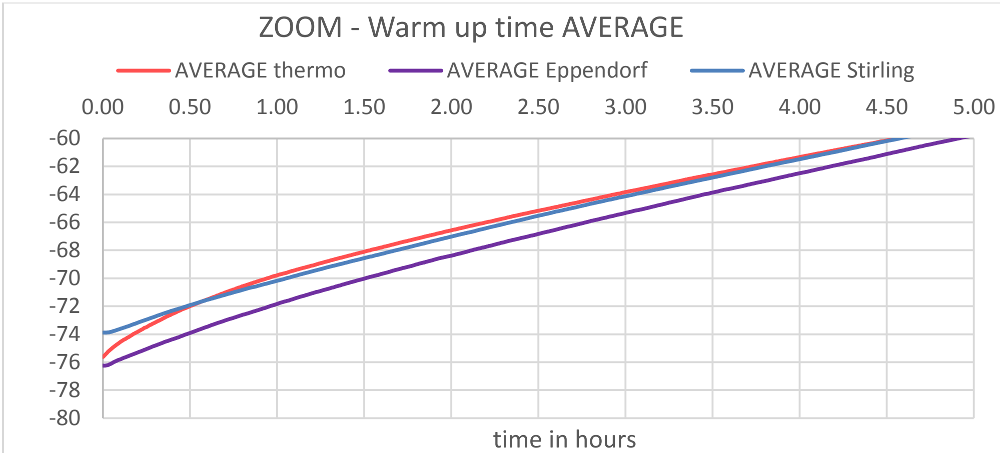

Figure 18: Zoom on Warm up time

5. Temperature Uniformity

5.1 General Comparison

For all temperature uniformity tests, the Thermo Fisher freezer was set up in High Performance mode. The totality of the TC functioning was averaged for each test condition. The standard deviation was calculated and is represented in the figure below. The Thermo and Eppendorf freezers had excellent uniformity and were about the same at 2-3 degrees, while the Stirling freezer had a standard deviation of 5-6 degrees.

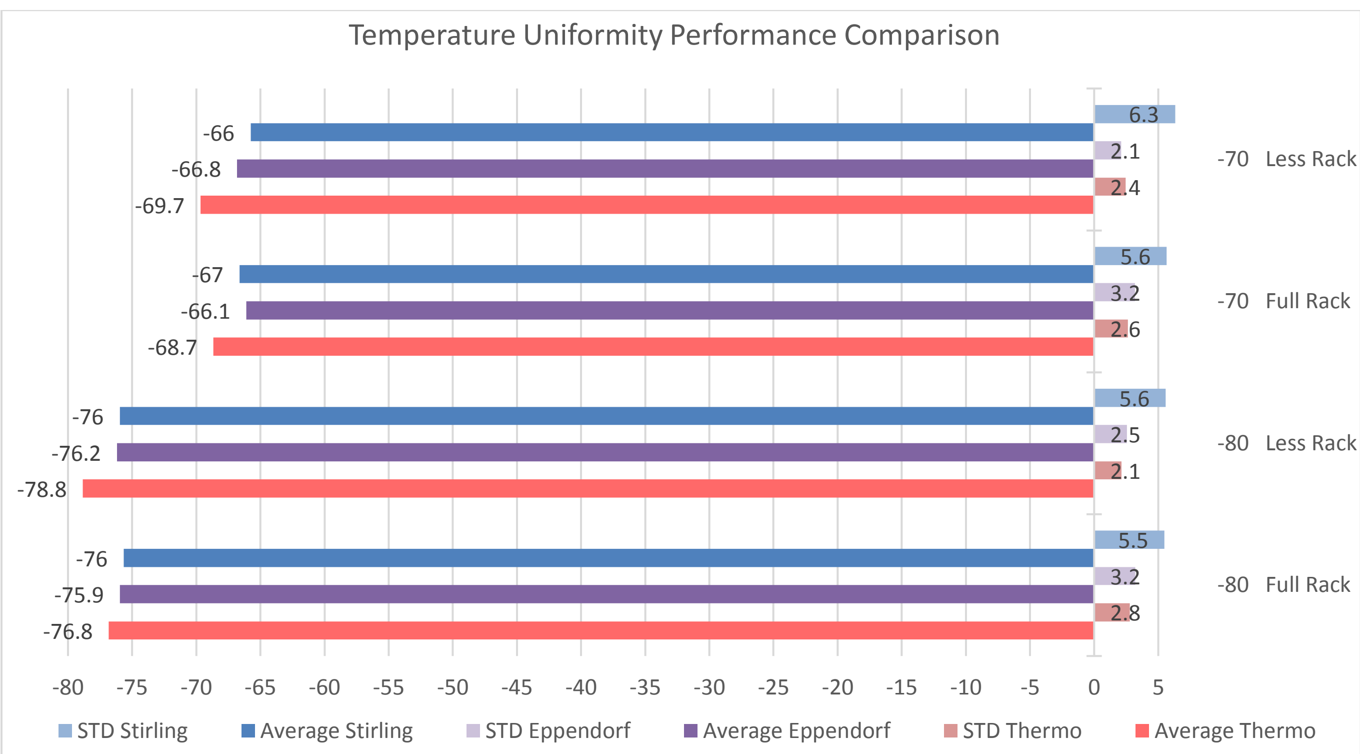

Figure 19: Temperature Uniformity Performance Comparison with standard deviation

The range of temperature uniformity at -80 is presented in section 5.2 below. More temperature profiles at both -80 and -70 are compared in Appendix 2.

5.2 Temperature uniformity: Stirling at -80, freezer at capacity

The color code follows the rule explained below:

< -78°C	<-75°C and >-78°C	> -75°C	Not functioning

The Stirling freezer presents some variability in temperature.
Five points are below -78°C, 3 are situated between -75°C and -78°C and 5 are above -75°C.
The temperature repartition shows a pattern with the cold air coming from the middle between shelves 2 and 3, which then disperses up and down in the freezer.
The warmer temperatures are at the top and bottom.
The top seems likely to be warmest.

Figure 20: Stirling Temperature Uniformity

5.3 Temperature uniformity: Thermo at -80, freezer at capacity

The Thermo freezer, set up in High Perf mode, presents some variability in temperature.
Six points are below -78°C, 6 are situated between -75°C and -78°C and 2 are above -75°C.
The warmer points are located at the top along the door.

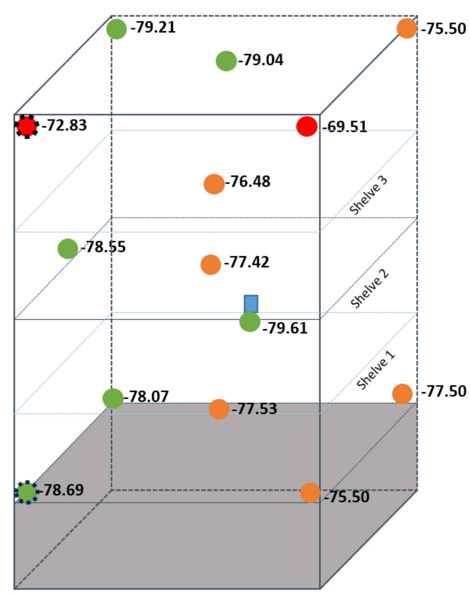

Figure 21: Thermo Temperature Uniformity

5.4 Temperature uniformity: Eppendorf at -80, freezer at capacity

The Eppendorf freezer presents some variability in temperature. Six points are below -78°C, 3 are situated between -75°C and -78°C and 5 are above -75°C.
The cold air seems to come from the bottom and back of the unit. The warmer temperatures are found at the top part. Thermocouples located along the door measure warmer temperatures.

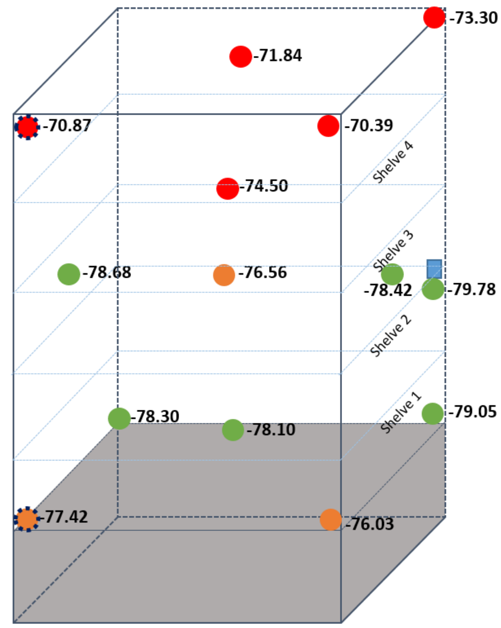

Figure 22: Eppendorf Temperature Uniformity

5.5 Temperature variability at -80 versus -70

Temperature variability is a measure of consistency over time. To better understand the differences between -80°C and -70°C, Figure 23 compares the average inside temperature for the three freezers when they are at capacity (noted FR for Full of Rack in the figure below) at both temperatures.

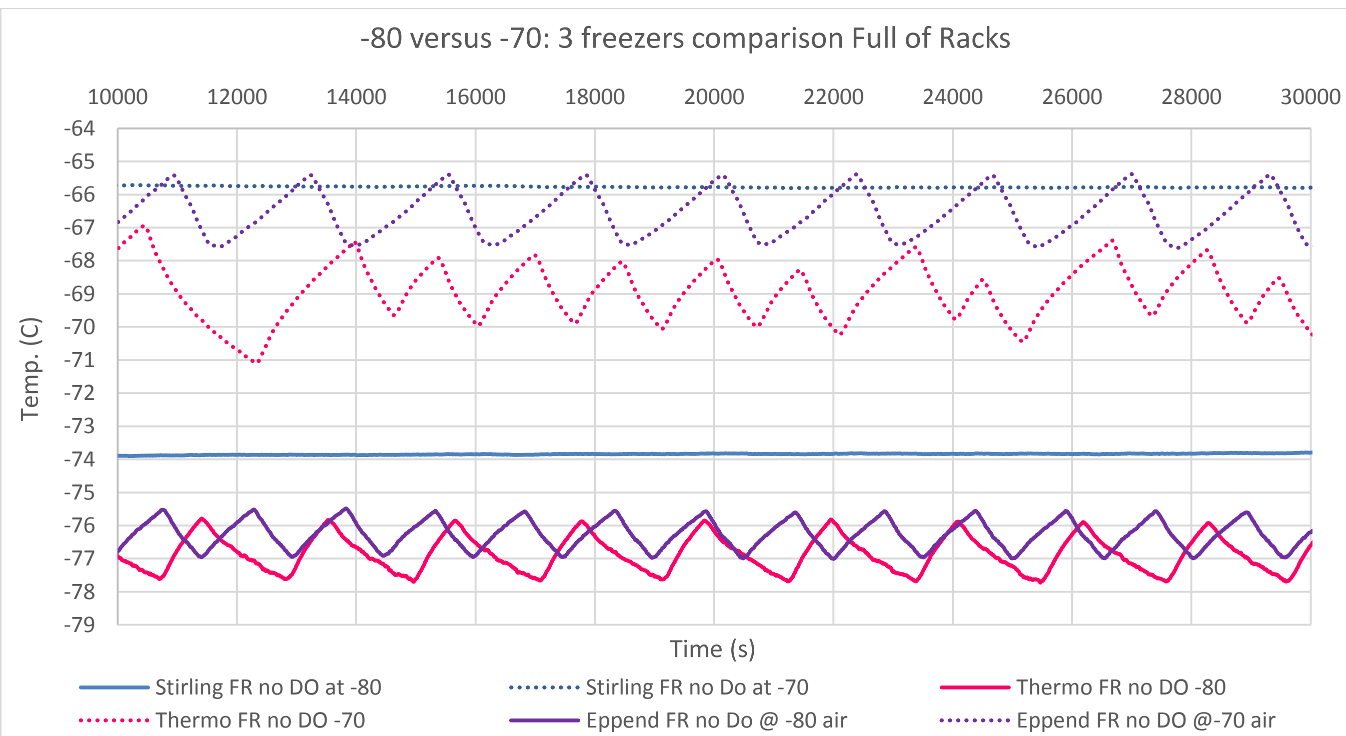

Figure 23: Inside temperature comparison at -70 and -80

The Stirling has a constant profile because the Stirling engine runs constantly while cascade compressors cycle. As the cascade compressors cycle, temperature fluctuation over time is more important than the Stirling Engine. Thermo and Eppendorf have a similar profile at -80°C but the Thermo unit is slightly more variable at -70°C.

5.6 Air circulation and capacity

Freezer capacity can also impact the temperature repartition. Indeed, a freezer full will allow less air circulation and might impact the uniformity. Figure 24 presents the results of these tests for the three freezers at -80°C when not filled to capacity (note LR for Less Rack inside, at the opposite of FR for Full of Racks).

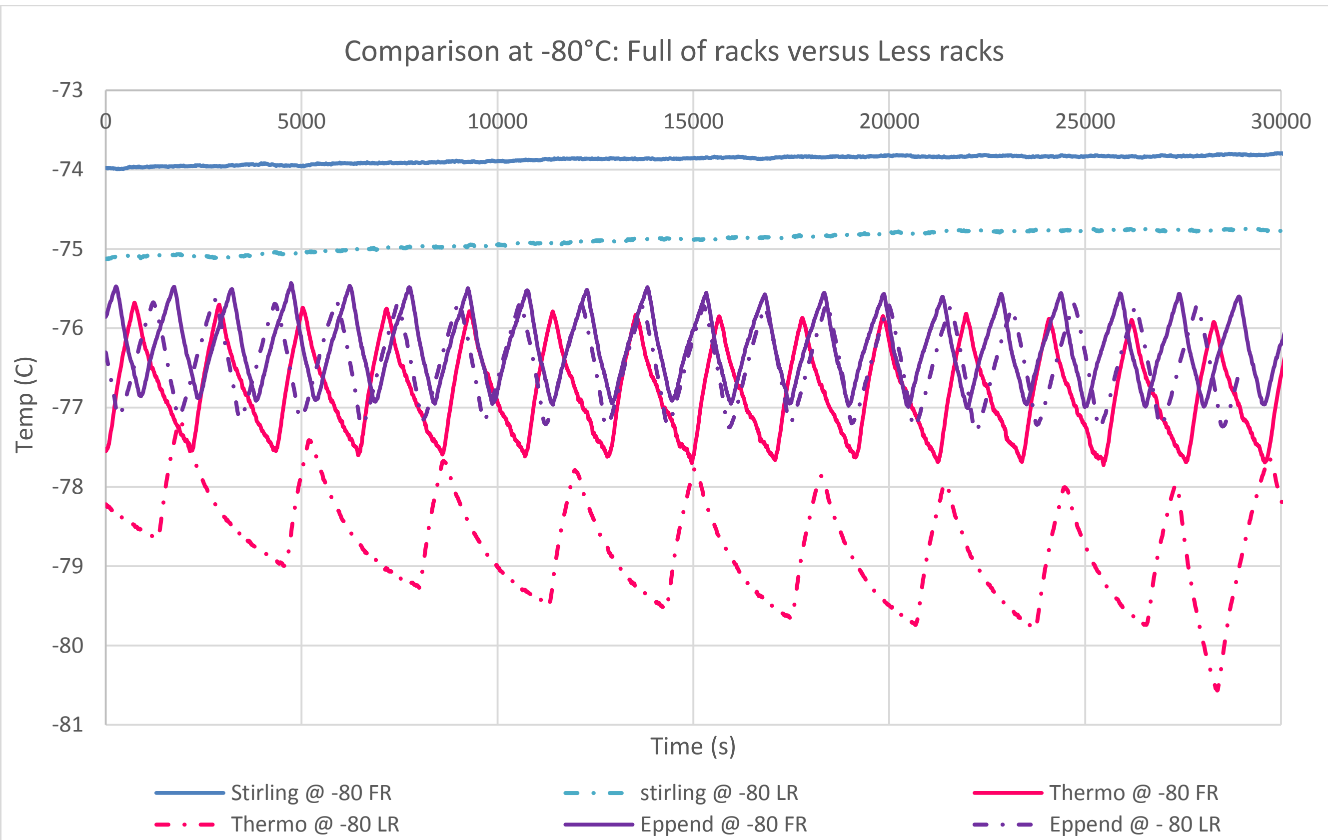

Figure 24: Inside temperature comparison between a unit full of rack and not full of racks

For both Stirling and Thermo, the average temperature is closer to the set point when the freezer is not full. The Eppendorf seems to perform the same way whether it is full or not.

5.7 Temperature Uniformity: Sample versus air

Two TCs were placed inside plastic centrifuge tubes, which were then placed inside 2" boxes. Figure 25 shows the average temperature for the "air" –a bare TC in contact with the air in the freezer- and the "sample" -the TC placed in micro-centrifuge tube. These conditions were not tested with the Thermo Fisher.

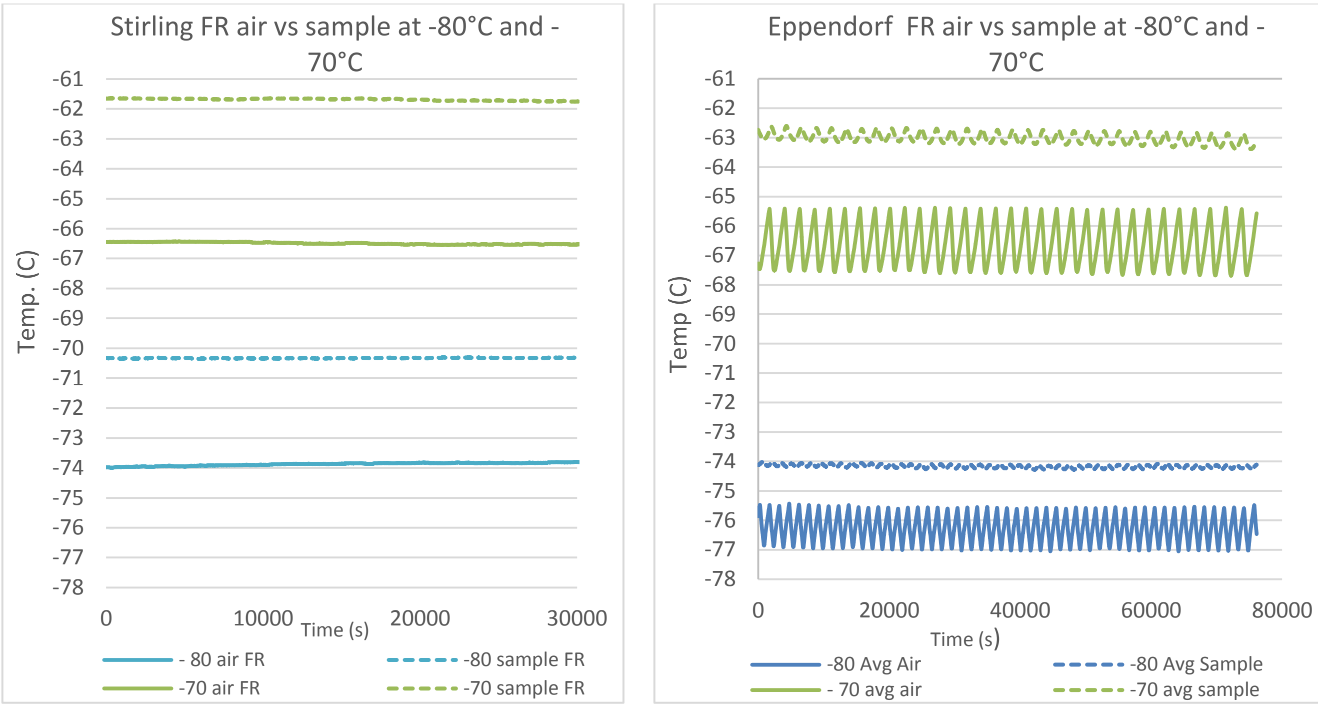

Figure 25: Comparison between air and sample temperature at -70 and -80

In the Stirling, the samples are warmer than the air 3°C - 4°C. In the Eppendorf, the variation of temperature due the compressors going on and off is largely diminished in the sample TC and a difference of 2°C - 3°C is noticeable.

6. Noise

Figure 26 shows the noise produced by each freezer.

The background noise in **the laboratory was 54 decibels**, and may have compromised noise measurements from the freezers. The lab has two fumehoods, and general ventilation are responsible for this value. The noise produced by the freezer comes from the compressors, located at the bottom on the Thermo and Eppendorf, and the engine at the top on the Stirling.

Figure 26: Noise production by each freezer

The noise produces by the three freezer is similar, even though it doesn't come from the same location (top or bottom of the unit).

7. Heat production

Figure 27 shows the heat produced by each freezer.
The temperature **in the laboratory was 64°F**. The heat produced by the freezer comes from the engine, located at the bottom on the Thermo an Eppendorf, and at the top on the Stirling. This explains why the values are higher in these locations.

Figure 27: Heat production by each freezer

The Thermo and Eppendorf show a lot of variation at the back bottom. This is due to the tool used to measure the heat exhausted; the heat gun was pointed at hot surfaces of the freezer, and some areas were hotter than others behind the protective grill.

8. Amperage used

For circuit load purposes, the amperage was measured when the freezer were turn on (Figure 28). Their different needs in volt and amps is indicated in the legend of the figure below.

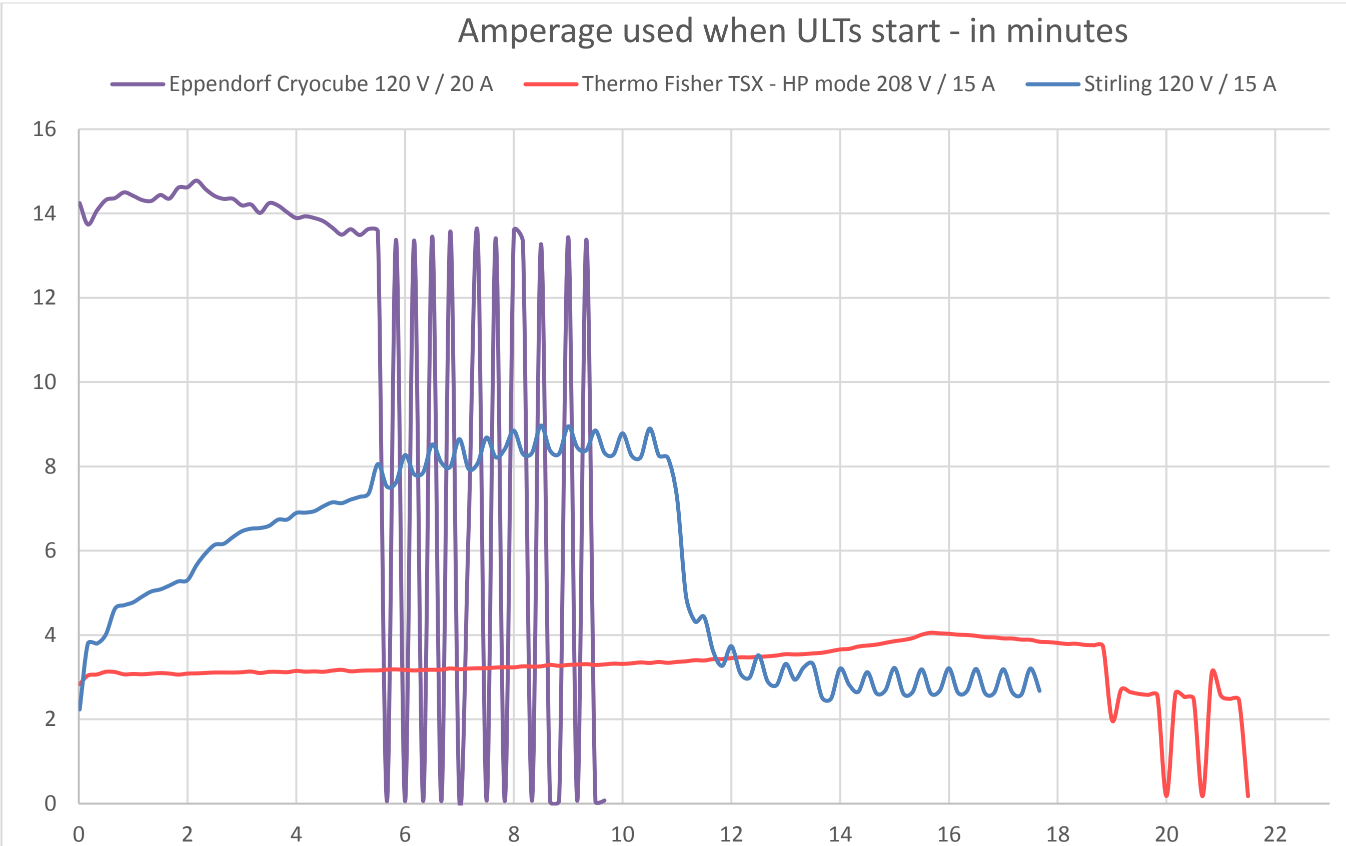

Figure 28: Amperage drawn when the freezers start during the first 20 minutes

The manufacturers generally recommend one freezer per circuit. A 20 Amp, 208 V circuit could potentially support two freezers made by either Thermo or Stirling. A 20A, 120V circuit could support two Thermo, but might be near capacity with the two Stirlings.

V. Conclusion

First of all, these tests validated the vendor's data that the three units tested are energy efficient, using less than 10kWh/day.
The three freezers have similar levels of performance, but a few points can be considered when making a procurement decision:

- Operational cost, thanks to the energy efficiency, you can save between $297and $552 (48% to 63%) at the minimum per year, solely from plug load.
- Energy consumption: all freezers used less than 10kWh/day, but the Stirling used the least amount of electricity, costs the least to operate and offers the smallest operational cost per cu.ft.
- Space: the Stirling offers the larger storage capacity while occupying the least floor space.
- Temperature uniformity: the Thermo remained closest to the temperature set point and showed the best internal temperature uniformity.
- By design, the Stirling engine offers less temperature variability than cascade compressors.
- Heat exhaust: located at the bottom for the Thermo and Eppendorf, versus the top of the unit for the Stirling.
- Finally, if you already have racks, the large internal dimensions of the Stirling and Thermo might allow you to reuse your existing racks.

Once the freezer is purchased, here are some considerations:

- Chilling up your freezer can reduce between 15 and 30% of energy consumption.
- In case of power outage, you will have ~2hours less to move your samples if your freezer is set up at -70°C.

APPENDIX

Appendix table of contents:

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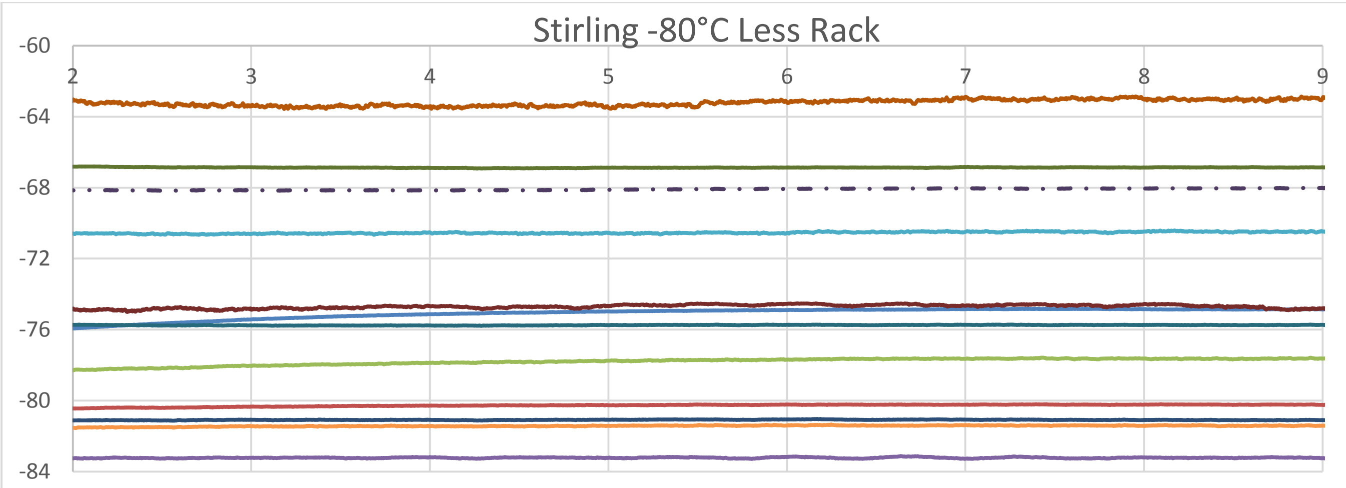
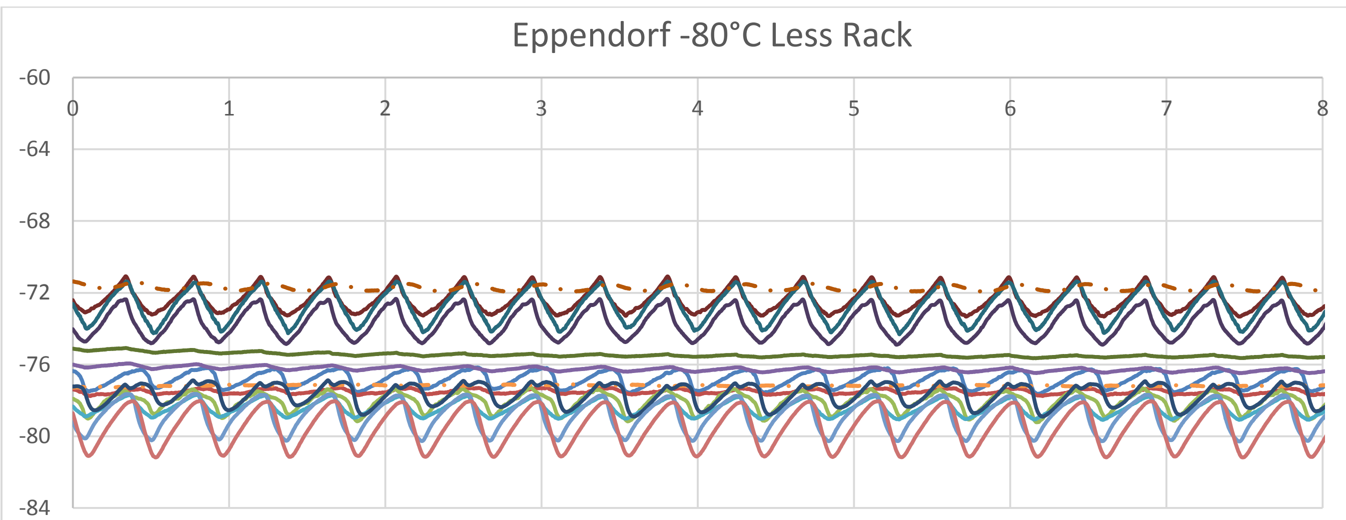
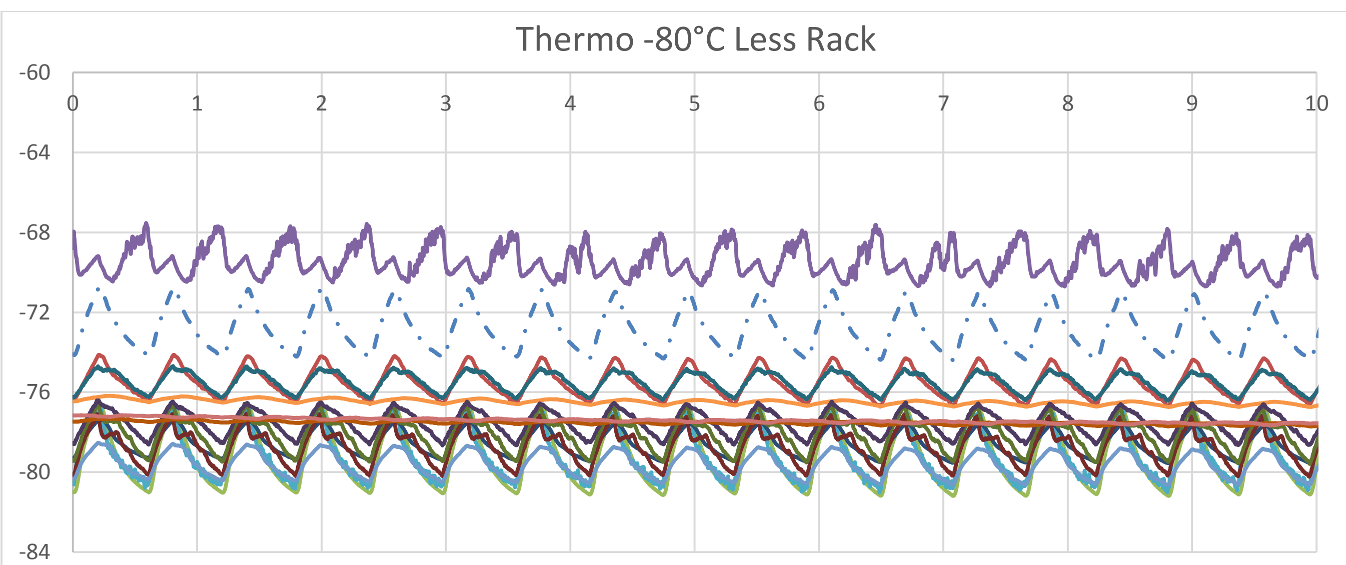
APPENDIX 1: Freezer profiles at -80°C with no door openings and one rack removed per shelf







APPENDIX 2: Temperature uniformity profiles at -80°C and -70°C

Legend:

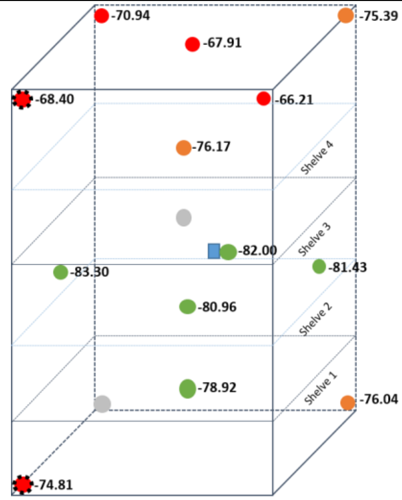
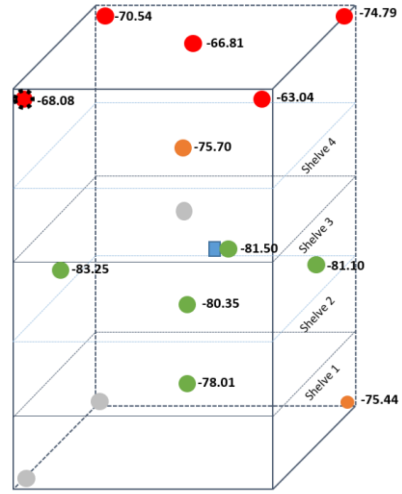
: Indoor freezer probe

Freezer set point at -80°C:

< -78°C	<-75°C and >-78°C	> -75°C	Not functioning

Freezer set point at -70°C:

< -68°C	<-65°C and >-68°C	> -65°C	Not functioning

<table>
<tr><th>-80°C</th><th>Full of Racks</th><th>One rack removed per shelf</th></tr>
<tr><td>Stirling</td><td>
</td><td>
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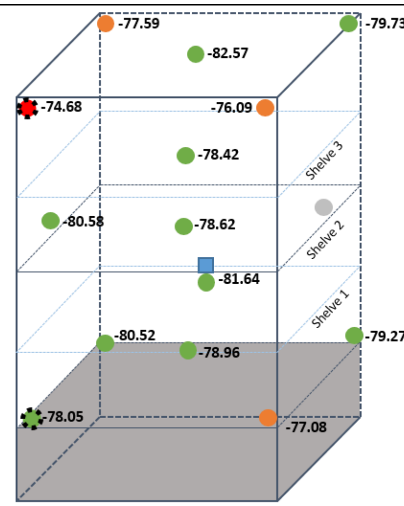
</td><td>
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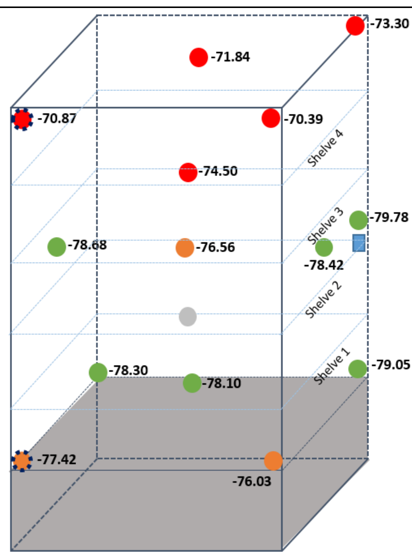
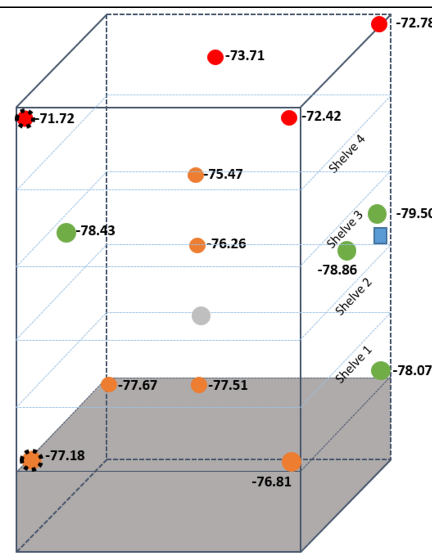
<tr><td>Eppendorf</td><td>
</td><td>
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<table>
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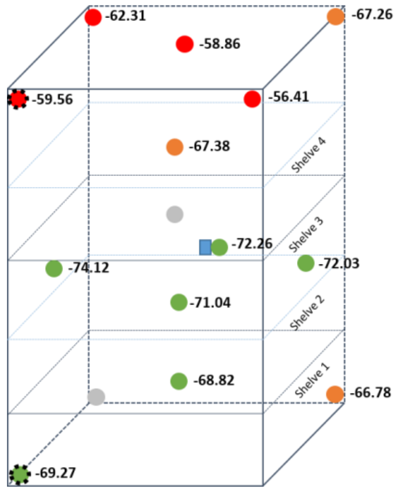
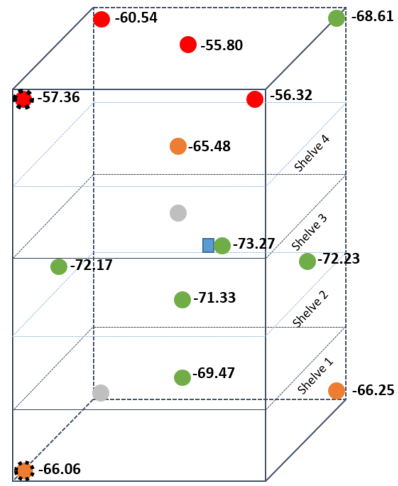
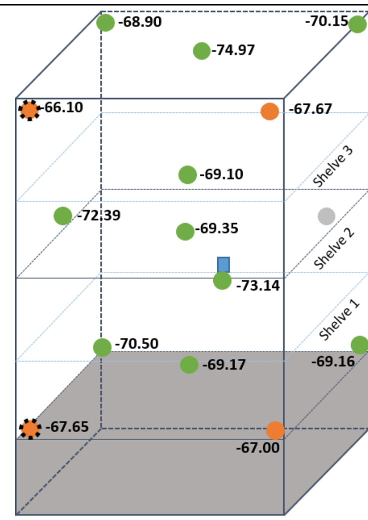
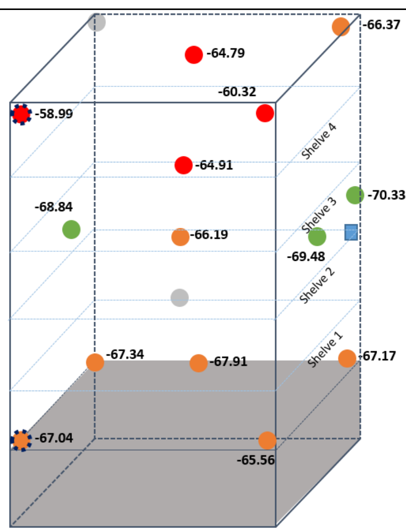
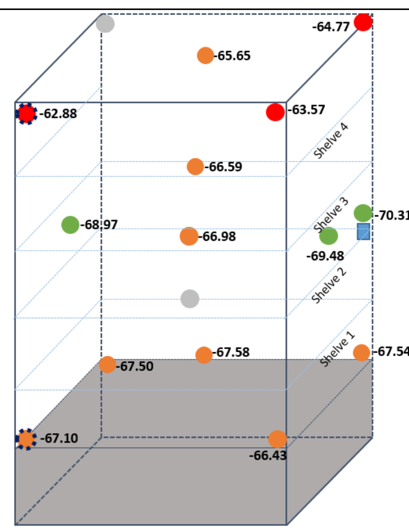
<tr><td>Stirling</td><td></td><td></td></tr>
<tr><td>Thermo</td><td></td><td></td></tr>
<tr><td>Eppendorf</td><td></td><td></td></tr>
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