Efficient ULT Freezer Storage

An Investigation of ULT Freezer

Energy and Temperature Dynamics

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Abstract

ULT freezers are one of the most ubiquitous pieces of equipment found in today's research environments and can be extremely energy intensive. A variety of factors can affect their efficiency including operating temperature, door openings, racking, and more. This study investigates such factors and their impact on internal temperature and energy consumption, as well as examines how ULT freezers warm in the event of power failure. Notable results include validating 28% energy savings associated with operating at -70 °C instead of at -80 °C, evidencing temperature differentials due to door openings, and minimal warm-up time differences between -70 °C and -80 °C operating temperatures post power failure.

Introduction

Cold storage is crucial to the continuity of research; it permits retrospective examination of results through the preservation of samples. This facilitates accountability for findings, resilience in research, and long-term re-examination or progression of conclusions. Such pillars of scientific method rely though on one of the more generic cold storage devices: the freezer (albeit liquid nitrogen and refrigerators also play crucial roles). Freezers employed for research purposes are typically set to either -20 °C or -80 °C, although the long-term continuation of this cold storage study will contest -80 °C[1], and have had significant improvements in terms of energy consumption and insulation[2]. Such improvements derive from the recognition of the high-energy demand particularly of ultra-low temperature freezers (ULT's for short).

ULTs are utilised typically for -70 °C or -80 °C storage, and despite their importance in research have had only a limited number of studies conducted on their dynamics of operation. In 2014 a comprehensive comparison of several models was conducted by the

U.S. Department of Energy[3]. This study focused on energy consumption under varying conditions as well as associated costs and demonstrated the significant variations in efficiencies between manufacturers. Beyond the choice of a manufacturer, freezer users must consider the effects of maintenance on efficiency. A 2013 study by L.A.M. Gumapas studied the effects of ambient temperature and ice build-up on freezer performance[4], both factors under user control.

In further recognition of the growing issue of managing ULT freezer storage, good practice-guides amalgamating tips from across the sector have been created to aid research and facilities staff. For e.g. the 'Store Smart' freezer user guide[5] summarises many good practice techniques and provides expert management guidance. A similar document was produced by the University of Cambridge[6], which again touches on similar good practice topics. Such guides rely on studies to validate recommendations though. For example, while such guides recommend operating a ULT freezer at -70 °C to save on energy and permit the compressor to endure longer, no study can verify the comparative sample-viability under varying temperatures, and there are surprisingly few studies looking purely at energy consumption differences. The accompanying long-term cold storage study is aimed at investigating such questions in an attempt to permit evidence-guided efficient storage. This short-term study attempts to do the same with a subset of three pertinent questions.

1. *How does energy consumption vary with ULT operating set-point temperature?*

As noted in the U.S. department of Energy and Cambridge freezer guides cited above, limited studies have investigated the energy consumption associated with operating a ULT freezer at either -70 °C or -80 °C. This study sought to immediately verify the assertion that operating freezers at -70°C delivers substantial energy savings versus -80°C as this is crucial to the underlying reasoning for conducting the accompanying long-term study. A tour of a freezer room will show many freezers operating at a variety of temperatures beyond just -70 °C and -80 °C though. To better understand the energy implications of operating a ULT at various temperatures, -60 °C and -85 °C were also examined. -85 °C was examined as researchers will often operate their ULT as cold as possible in hope of increasing the endurance of their samples, or because of an expected increase in response/warm-up time in the case of power failure (see question 3), and yet energy data on such an operating temperatures is lacking. Some freezers will be set to operate warmer than -70 °C, for example emergency backups may operate at -60 °C, though the energy implications are poorly understood. This study aims to firstly verify the -70 °C reduction in energy consumption when compared to -80 °C, but also complement it with several more temperatures ULTs are commonly set to operate at.

2. *How much does temperature increase with single door openings?*

Any user with ULT experience will be familiar with the notable temperature increases associated with opening the door to search for samples. Sample management tools list one of their benefits as reduced time required to open the doors. While some of the good practice guides listed above will encourage users to only open the doors briefly, relaying the benefits in terms of costs and temperature variations to users' remains challenging due to the lack of investigation. One study previously cited actually included door openings in their methodology to reflect real-life settings[4], though the doors were opened once briefly over a course of many hours instead of examining only the opening itself. This study aims to examine exactly what kind of temperature increases samples are exposed to with varying door opening times (15 sec, 30 sec, and 60 sec).

3. *How quickly does the temperature rise if the power is cut at various operating temperatures?*

This short-term study is accompanying a 5 year study investigating whether warmer storage temperatures are appropriate for long-term storage (-70 °C in particular). Beyond sample viability, there is one valid concern for storage at a warmer temperature; a decrease in time in which responders can react to a ULT or power failure requiring transfer of samples. What is important though is exactly how much more time does operating a ULT at -80 °C afford you compared to warmer operating temperatures? This is crucial as, if -80 °C does allow responders an extra few hours over the course of a night to respond, this is a strong argument for continuing to operate ULTs at -80 °C as the potential loss of samples will outweigh energy concerns. This study's final short-term focus is to assess warm up times of 'full' (filled with ice and polystyrene instead of samples) ULT freezers to ensure -70 °C operating temperatures don't risk sample loss.

Methods

For all following studies the three ULT freezers were situated next to each other in identical ambient conditions. They are housed in a small building with natural and artificial ventilation and cooling options maintaining a temperature of 17-18 °C. This is verified by daily logging of ambient temperature by Roslin facilities staff. The three freezers are New Brunswick U570 HEF models all built in the same year (2012). Freezers were fitted with three shelves with equal spacing; though note this can vary with user instalment. Temperatures were assessed using Madgetech Cryo-Temp © loggers, though externally marked door temperatures were also utilised as the loggers (cryologgers) could record wirelessly but not transfer the data until physically linked with the docking station (this affected the protocols and outcomes as marked door temperatures are unreliable). Note all cryologgers were UKAS calibrated and accurate to 0.1 °C in the temperature range of -86 °C to +35 °C. Energy consumption was monitored using standard plug-in energy monitors at the socket, which had been previously calibrated to ensure possible variation between meters would not affect results.

1. Energy consumption at various operating temperatures

- ULT freezers were plugged into a power socket via an energy monitor – note: after unplugging each freezer is given 1-2 minutes before turning back on. Freezers contained polystyrene boxes only (equal sizes, shapes and quantities on shelves).
- Operating temperatures of each of the 3 freezers were set to -60 °C, -70 °C, and -80 °C, and left one night to acclimate to their settings.
- Energy consumption and time were then noted for each freezer the following day. Note: External temperatures marked matched their new settings.
- 24h later energy and exact time are noted again.
- kWh per day are then noted and plotted.
- Once completed, one ULT freezer was reset to operate at -85 °C and one was set to -75 °C, and the same method for acclimatising and evaluating kWh/day was carried out.
- Note: Energy consumption was examined +1 year on to assess for variation. Freezers at this point had samples though and thus -85°C could not be assessed.

2. Door opening times effect on internal temperature

- Again all three freezers are set to the three different operating temperatures: -60°C, -70 °C, and -80 °C
- Note that racking was provided for this experiment, but only in limited quantities. There was sufficient racking for one shelf in each of the freezers, and thus racking was placed in the centre shelf of each ULT freezer. All racking was metallic (aluminium). The sliding shelves of each rack were filled with polystyrene packing materials ("peanuts"). The top and bottom shelves of the freezers were left empty.
- Cryologgers were then activated and set to take readings every 5 seconds. Each ULT freezer received 3 cryologgers; 1 on the top shelf in the middle, 1 in the bottom shelf in the middle, and 1 in the central shelf of the central rack.
- Doors were then closed and freezers left to achieve their set temperatures (-60 °C, -70 °C, and -80 °C). Doors were not opened again until the experiment as this would have increased internal temperatures. Note: Sometimes this meant hours or even waiting until the next day.
- Doors were then opened for different lengths of time – 15, 30, and 60 seconds. Note: When a door is opened, all internal panels (mini doors) were also opened simultaneously.
- After a door opening temperatures again were allowed to achieve set temperatures. Again this could sometimes take hours (particularly in the -80 °C freezer).

- All three door opening times were conducted on all three ULT freezers.
- Once complete, cryologgers were removed from the freezers and docked and temperature increases were noted and plotted.

3. Warm-up rate at various operating temperatures post-power cut.

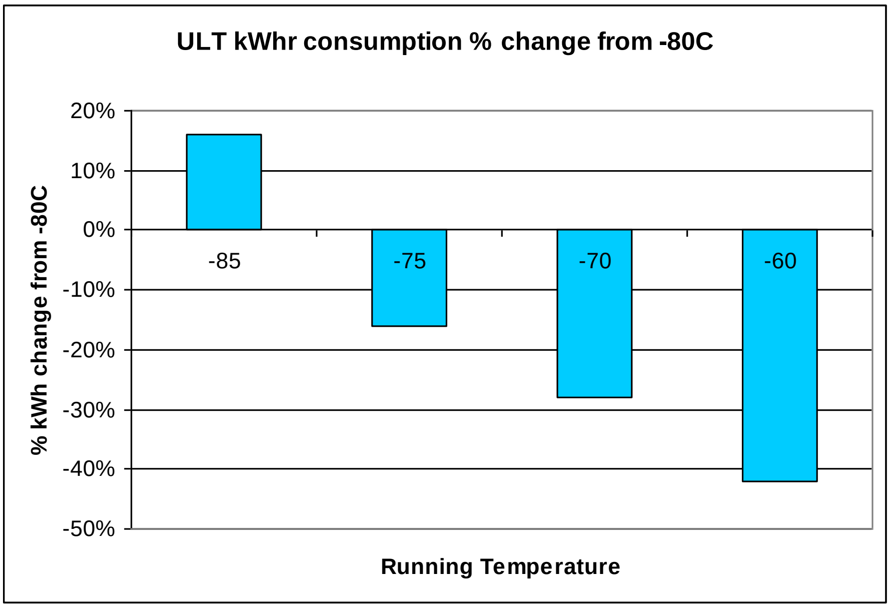
- Freezers kept their central racking which was still filled with polystyrene packaging. An approximation was calculated on the volume of liquids a ULT freezer may contain. This rough equivalent of volume of water was then poured into polystyrene boxes and placed in the bottom and top shelves of the freezers. This was done to imitate the thermal capacity of a real freezer, although the shortcomings of this strategy are recognised. Freezers were then left overnight to allow water to freezer and appropriate temperatures to be reached.
- Again racking was provided for this experiment, but only in limited quantities. There was sufficient racking for one shelf each of each freezers, and thus racking was placed in the centre shelf of each ULT freezer. The sliding shelves of each rack were filled with polystyrene packing material ("peanuts").
- Cryologgers (three for each freezer, again placed centrally in each shelf) were then activated to record temperature every 5 minutes. Again after door openings freezers were allowed several hours to acclimate back to set operating temperatures.
- Each of the three freezers was then turned off and the exact time was noted. Freezers were left to 'thaw' over one weekend. Note no one was allowed to access or open the freezers during these periods.
- After three nights (72 hours), freezers were opened and cryologgers removed. Temperature increase was noted and plotted.

Results

1. ULT Energy Consumption at various Operating Temperatures

Temperature	kWh/day	% Δ from -80 °C	+1 year (kWh)	% Δ from -80 °C
-60 °C	4.9	41.7%	5.5	36%
-70 °C	6	28.6%	6	30%
-75 °C	7.1	15.5%	X	X
-80 °C	8.4	X	8.5	X
-85 °C	9.6	14.3%	X	X

Table 1: Energy consumption/day for various ULT set operating temperatures and percentage variation from -80 °C



Graph 1: ULT energy consumption percentage variation from -80 °C

2. Door Opening Times Effect on Internal Temperature

-60 °C Freezer	Bottom Shelf △	Middle Shelf △	Top Shelf △
60 sec	0	0	+3.1 °C
30 sec	+0.5 °C	0	+2.8 °C
15 sec	+0.4 °C	+0.3 °C	+2.1 °C
Warmest Temp	-52.1 °C	-52.7 °C	-49.9 °C

Table 2: -60 °C ULT freezer temperature increases with different door opening times. Note that the warmest temperature reached on the cryologgers are also indicated as they varied from external door temperatures.

-70 °C Freezer	Bottom Shelf △	Middle Shelf △	Top Shelf △
60 sec	+0.5 °C	+0.1 °C	+3 °C
30 sec	+0.5 °C	0	+1.9 °C
15 sec	+0.5 °C	+0.1 °C	+1.2 °C
Warmest Temp	-66 °C	-62 °C	-65.3 °C

Table 3: -70°C ULT freezer temperature increases with different door opening times. Note that the warmest temperature reached on the cryologgers are also indicated as they varied from external door temperatures.

-80 °C Freezer	Bottom Shelf △	Middle Shelf △	Top Shelf △
60 sec	+3.1 °C	+3.3 °C	+8.1 °C
30 sec	+1.3C	+0.6 °C	+5.4 °C
15 sec	+1.6 °C	+1 °C	+5.2 °C
Warmest Temp	-77.3 °C	-73.9 °C	-71.5 °C

Table 4: -80 °C ULT freezer temperature increases with different door opening times. Note that the warmest temperature reached on the cryologgers are also indicated as they varied from external door temperatures.

Averages	Bottom Shelf △	Middle Shelf △	Top Shelf △
60 sec	+1.2 °C	+1.65 °C	+4.7 °C
30 sec	+0.77 °C	+0.3 °C	+3.4 °C
15 sec	+0.83 °C	+0.47 °C	+2.8 °C

Table 5: Average temperature variation of all three operating temperatures.

3. Warm-rate at Various Set Operating Temperatures Post-Power Cut.

Time to -50 °C	Bottom Shelf	Middle Shelf	Top Shelf
-60 °C	1 hr 25min	2hrs 15min	55min
-70 °C	3hrs 25min	5hrs 25min	4hrs 25min
-80 °C	4hrs 50min	5hrs 50min	5hrs

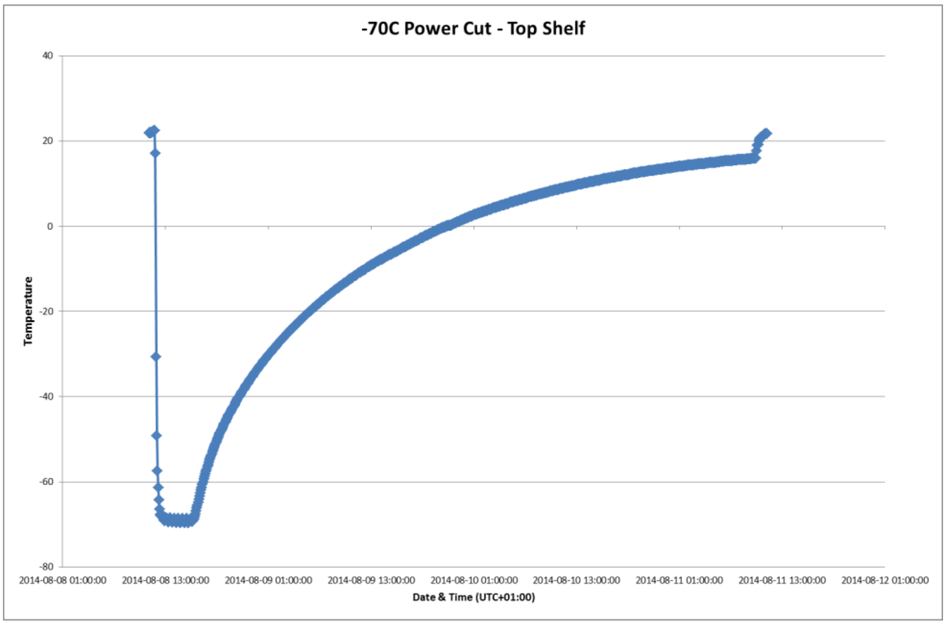
Table 6: Time for three freezers operating at various set temperatures to reach -50 °C. Times are for bottom, middle, and top shelves.

Time to -20 °C	Bottom Shelf	Middle Shelf	Top Shelf
-60 °C	9hrs 25min	9hrs 50min	8hrs 45min
-70 °C	14hrs 50min	19hrs 10min	18hrs 10min
-80 °C	16hrs 25min	19hrs 45min	18hrs 25min

Table 7: Time for three freezers operating at various set temperatures to reach -20 °C. Times are for bottom, middle, and top shelves.

Time to -0 °C	Bottom Shelf	Middle Shelf	Top Shelf
-60 °C	21hrs 30min	24hrs 55min	22hrs 45min
-70 °C	36hrs 55min	43hrs 50min	42hrs 15min
-80 °C	39hrs 40min	46hrs 50min	45hrs 25min

Table 8: Time for three freezers operating at various set temperatures to reach 0 °C. Times are for bottom, middle, and top shelves.



Graph 2: Typical temperature rise profile from power cut study. Note this is for a -70 °C freezer and the top shelf.

Discussion

1. ULT Energy Consumption at Various Set Operating Temperatures

The energy consumption as a function of an operating temperature confirms that operating a ULT freezer at -80 °C will consume significantly more energy than at -70 °C, 28% more. Considering that a typical ULT freezer will consume anywhere between 9-20 kWh/day, this can have notable consequences on energy bills. In the UK where this study was conducted, assuming a kWh costs 11 pence, a freezer consuming 13 kWh/day will cost £520 to operate per year in energy alone. This doesn't factor in additional costs such as for e.g. supplementary cooling to compensate for heat released by the freezers. A typical research institution will possess 100+ ULT freezers if not 300+. Assuming all are operating at 13 kWh/day, a 28% saving on 100 ULT freezers represents nearly £15,000 in annual energy savings. Again this does not factor in savings from reduced heat output from the freezers. The figures obtained in this study relate to brand new, well maintained freezers – older freezers with wear to component parts and seals may provide even greater savings if set operating temperatures are raised.

Of particular interest are the variations in energy consumption when the freezers were operating at -60 °C or -85 °C. Few if any studies have examined energy consumption associated with these operating temperatures, likely because they are not typical temperatures used for long-term storage. Freezer manufacturers will market ULTs[7] though as having a range of -50 °C to -86 °C, and it is not uncommon to find some freezers operating at -85 °C. Such freezers will consume 15% more energy, which if again applied to 100 ULTs operating at an average 13 kWh/day, represents £7,800 per year expenditure. A typical ULT freezer has an operational life of 10+ years, so we can see that the cumulative impact of operating temperature can have a large impact again on energy bills. Finally -60 °C as an operating temperature was assessed as well. ULT freezer banks will commonly have one designated freezer kept empty as a decant space in case of emergencies, often operating at -80 °C. In case of an actual emergency decant, the backup freezer would need to have its door open for long periods as it's refilled, quickly rising in temperature. It is likely that in the time required to refill the freezer, no matter what operating temperature, it would be at or near room temperature (door opening studies discussed in part 2 will attest to this). Our energy consumption data showed that a freezer operating at -60 °C will consume 42% less energy than operating at -80 °C. While this is not applicable to 100 ULTs, it still represents notable savings on decant freezers.

The data gathered suggests that if all operating temperatures between -20 °C and -86 °C were plotted against kWh/day, they would produce a logarithmic curve in which energy consumption jumps as temperature is lowered. This implies that freezer compressor efficiency is reduced exponentially with colder temperatures. It is likely that operating a freezer at a suitable warmer temperature could increase its operational lifespan while reducing operating costs and heat output.

2. Door Opening Times Effect on Internal Temperature

Tables 2-4 summarise the results from opening the ULT freezer doors for 60, 30, and 15 seconds while operating at -60 °C, -70 °C, and -80 °C. Temperatures were monitored on the centre of each shelf. Table 5 averages the results from the three tables. There are several trends which become evident from such monitoring: Door opening time has a strong effect of warm-up rate, colder operating temperatures result in higher initial temperature variation, and top-shelves experience the greatest temperature variation.

Prior to unpacking these trends though, some notes on methodology should be reviewed. When doors were opened, internal doors were opened as well – this process would require ~3-5 seconds alone and may be a slight source for variation between results. Furthermore each middle shelf possessed racking, which was limited in availability. The logic behind placing it on the middle shelf was to permit a comparison between top and bottom shelves in a single study while highlighting possible effects of racking. The racking did not contain boxes and thus probes were still exposed to warm air rushing in. Finally, when compiling the data it was noted that while the outside display would show the desired operating temperatures (-60 °C, -70 °C, and -80 °C), our cryologgers often showed starting temperatures notably warmer. 'Warmest temperature' was noted. This is likely due to ULT freezers possessing one single probe located at the back of the freezer where cold temperatures are more easily achieved. It was important to note this as it highlights how digital displays do not necessarily reflect accurate internal temperatures, and that the difference can be as high as 8-10 °C. To avoid such variances for future studies, it is recommended that the experiments don't necessarily commence immediately after the digital display reads the required temperature. Instead allow freezers a further 2-4 hours to ensure uniform internal temperature.

Opening doors for longer periods of time, as expected, permitted internal temperatures to rise more than for short door openings. This is well illustrated in table 5 where we observe that a 60 second opening will lead to an average 1.2-4.7 °C temperature rise, compared to only a 0.8-2.8 °C temperature rise in the 15 second opening. This data immediately suggests that opening a door for longer periods of time can expose samples to significant temperature changes – particularly if unprotected by boxes or racking. The next notable trend was that the shelf selected had impact on temperature variation. The top shelves showed far greater temperature variation (2.8-4.7 °C variation) than the bottom shelves (0.8-1.2 °C variation). We would expect this as warm air rises, and thus the top shelf will be exposed to the most variation as warm air enters and the cool air exits or falls to the lower shelves. Thus researchers may want to consider internal placement of their samples as a risk – samples located at the top and likely to the front of the shelf will be exposed to a greater increase in temperature during door openings.

While this study was not an ideal set-up to compare racking as not every shelf was tested with and without racking, some indication of the value of racking may still be inferred. After 15 and 30 second door openings, the average increase in temperature rise was actually lower in the middle shelf with racking than the bottom shelf without. Thus here we see that racking is countering the effect of the shelf being higher. Note that after 60 seconds the ability of the racking to reduce temperature increase disappears, thus further evidence illustrating the importance of ensuring that doors are opened for as little time as possible. Similar results from warm-up rates in section 3 of the discussion will further evidence the value of racking as it appeared to increase warm-up times.

The final observed trend was that operating temperature had an effect on warm-up rate. The ULT freezer operating at -80 °C showed increases in temperatures as high as 5-8 °C, whereas the freezer operating at -60 °C never showed an increase above 3.1 °C. Colder temperatures likely lead to stronger mixing with ambient air resulting in greater temperature changes. Curiously some of the -60 °C shelves showed 0 °C change during the 60 second door opening. Perhaps the initial warm starting temperature (~-53 °C) combined with the falling cool air from the top shelf protected the lower shelves from notable temperature variation, as other recordings excluding the top shelf were never greater than 0.5 °C variation. While these final results are a slight deviation from the expected, the overall trends still strongly suggest that the top shelf is exposed to the highest temperature variation. They also suggest that racking protects from such variation, cooler operating temperatures lead to greater temperature variation during door openings, and that opening a freezer door for longer will expose samples to greater increases in temperature.

3. Warm-up Rate at Varying Operating Temperatures Post-Power Cut.

One prevalent argument for storing materials at colder temperatures is that it provides more time to react during power failures. Few if any publicly available studies have quantified such warm-up times for ULT freezers, though many exist for food storage[8]. Tables 6-8 display the times taken for each freezer to have reached particular temperatures (-50 °C, -20 °C, and 0 °C) after they had their power cut off completely. Again the middle shelf of each freezer contained racking while the top and bottom shelves held polystyrene with water/ice.

Immediately two expected trends become evident; firstly that freezers operating at colder temperatures will take longer to warm up, and second that racking reduces the rate of warm-up. While it was expected that a freezer operating at -80 °C would take longer to warm than a freezer running at -60 °C, there were some interesting differences between the three operating temperatures used. Notably -60 °C appeared to warm much quicker than -70 °C or -80 °C. For example while it took the -60 °C freezer only 1-2 hours to warm to -50 °C, it took the -70 °C and -80 °C freezers 3-5 hours. Part of the explanation may be found in Graph 2 showing a typical freezers warm-up curve, which resembles a typical logarithmic-curve. This curve was consistently observed on all shelves and with all starting operating temperatures. Importantly this curve shows that there is a greater internal temperature increase initially. Thus -60°C is potentially warm enough that the initial period of more intensive temperature change allows the freezer to quickly reach -50 °C, whereas the colder freezers slow their temperature rise before reaching -50 °C. Importantly -70 °C appears to resemble -80 °C warm-up times more than -60 °C. This is illustrated in the times it takes to reach 0 °C, as the freezer operating at -60°C took an average of 23 hours whereas the -70 °C freezer took an average of 41 hours and the -80 °C freezer took an average of just under 44 hours. The differences are even smaller when looking at -20 °C as the -60 °C freezer took only ~9 hours to reach temperature, whereas the -70 °C and -80 °C freezers required 15-19 hours.

This experiment also appears to confirm the importance of racking, as the middle shelf consistently required the longest time to warm up. Racking provided an approximate 1-4 extra hours of reaction time. Note there did appear to be the same trend as in the door opening experiments in which the top shelf warmed quicker, though it wasn't as consistent as in the door openings study. This would be expected again as the warm air internally would rise. Thus for the middle shelf to consistently require the longest period of time to warm-up provides strong evidence that racking can significantly improve temperature stability in the event of a power cut.

In conclusion operating a ULT freezer at -70 °C instead of -80 °C will have an effect on warm-up time; such increases may be partially negated by appropriate racking. Operating at -70 °C instead of -80 °C will reduce warm-up times in the event of power failures, but only by a few hours over the course of several days. It is recommended that if warm-up time in the event of a power failure is a concern, racking, alarm systems and response methods should be assessed prior to storage temperatures. Systems should permit necessary responses to power failures in fewer than 24 hours let alone 12 hours.

Good Practice Summary

- Operating temperatures will have significant effects on ULT freezer energy consumption. Notably operating a ULT at -70 °C will save approximately 28% when compared to -80 °C. Consider operating ULT freezers at -70 °C, and backup freezers at -60 °C (saves 40% in energy consumption).

- Opening a ULT door will result in a rapid rise in interior temperature.

- Racking has significant effects in terms of reducing sample temperature variation, and should be employed where possible to improve sample integrity.

- Positioning within the ULT freezer counts – the top shelf will experience the greatest rise in temperature during the opening of a door, while the bottom shelf will be the most stable. Racking though can minimise this effect.

- Operating temperatures has an effect on possible warm up times during power failures for ULT freezers, but the variation between -80 °C and -70 °C was minimal. Users should consider ulterior methods to ensure safe storage such as alarming, response protocols, facility environment, and freezer insulation.

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