Factors affecting the performance, energy consumption, and carbon footprint for ultra low temperature freezers: case study at the National Institutes of Health

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Abstract: The National Institutes of Health (NIH) recognises an opportunity to significantly reduce the energy consumption and its carbon footprint from plug load equipment can be realised by managing –86°C ultra low temperature (ULT) freezers. Energy meters were installed on ULT freezers operating in actual laboratory conditions to determine how their energy consumption is influenced by various factors. Ambient temperature, freezer condition, age, capacity, and set point temperature were the factors that were examined. Based on the study, ultra low temperature freezers operated efficiently when they are: well maintained, operating in ambient temperatures less than 25°C, less than ten years old, are operating at a set point higher than –80°C, and have an internal capacity greater than 23 ft^3. The results of the case study are presented and discussed. Freezer performance was assessed to determine how ambient temperature and the freezer condition influenced the freezer's ability to reach set point temperature. The results of the study indicate a freezer that is not maintained and operating in ambient temperatures above 32°C produce cabinet temperatures 12.5°C warmer than the desired set point temperature.

Keywords: ultra low temperature freezer; energy consumption; performance; carbon footprint; plug load.

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1 Background

A mechanical refrigeration system is designed to move heat from one location to another. The basic components for a refrigeration system involve a compressor, cabinet to store the perishable product, evaporator, condenser, and refrigerant. The refrigeration cycle begins when the compressed refrigerant liquid passes through the evaporator, where it flash-expands into a vapour and absorbs heat from the cabinet. The compressor moves refrigerant through the system and compresses the refrigerant to a high-pressure vapour, which then proceeds to the condenser. In the condenser, the high-pressure vapour dissipates its heat to the ambient environment and transforms to a compressed refrigerant liquid. The cycle continues until the desired set point temperature is achieved within the cabinet.

A ultra low temperature (ULT) freezer typically operates between –56°C and –86°C, but it must be able to operate within the range of –70°C and –80°C (CBEA, 2012). A single refrigerant does not have physical properties to cover the wide temperature range between the ambient room temperature and ULT range. In order to achieve these low temperatures, a ULT freezer requires two refrigeration circuits with each system requiring individual compressors and refrigerants with different boiling points for absorption and dissipation of heat. Both refrigeration circuits use a cascade technique, where the refrigeration circuits operate in high stage and low stage configuration. In the cascade process, the low stage compressor removes heat from products located in the cabinet. The heat from stored products is absorbed by the refrigerant gas in the evaporator tubing wrapped around the cabinet. The heat is transferred to an interstage heat exchanger where it is passed to high stage system and ultimately released to the ambient environment into the room air that is circulated through the condenser fins (Laporte and Mistry, 2007).

2 Introduction

The energy consumption attributed to equipment loads (plug load) can account for more than 50% of the energy use in a laboratory space [Enermodel Engineering, Inc. and NREL, (2003), p.15]. A lab grade freezer consumes approximately 20 kilowatt hours (kWh) per day of electricity, which is about as much energy as an average family household uses per day. There is a significant opportunity to reduce the energy consumption and carbon footprint from plug load equipment, which can be realised by efficiently managing ULT freezers. Questions have been raised regarding the influence of ambient temperature, maintenance, age, internal temperature, and set point on the wide plethora of ULT freezers operating under the various conditions. These concerns have prompted this case study to get a better understanding of these factors.

3 Methods

ULT freezer energy consumption was measured in National Institutes of Health (NIH) laboratory conditions using the electronic educational devices watts up? pro watt metre, power analyser, electricity metre (watts up? pro metre). The watts up? pro metre was set to measure the watts, volts, amps, watt hours, cost, duty cycle, power cycle, line frequency, and volt amps with a one-minute resolution over a 24 hour period. The duty cycle is the percentage of time the ULT freezer is 'on'. In order to accurately assess the duty cycle, the duty cycle threshold, which is the minimum level a ULT freezer is considered 'on', is set at 100 watts for a 115 volt freezer and 180 watts for a 208 to 230 volt freezer. The costs are based on the average fiscal year 2011 electricity consumption rate on the NIH main campus in Bethesda, MD at $0.11 per kWh.

EL USB W LCD+ ambient temperature RH/temperature data logger (ambient temperature probe) is used to measure the ambient temperature the ULT freezer is operating in with a ten-second resolution over a 24-hour period. The ambient temperature probe is positioned on the condenser air intake because the air blowing over the condenser is the air that moves the heat from high stage refrigerant to the ambient environment.

EL USB TC LCD thermocouple data logger with K type thermocouple (cabinet temperature probe) is used to measure the internal temperature of the ULT freezer. The K type thermocouple is positioned in the same position as the ULT freezer's thermocouple. Cabinet temperature was measured with a ten-second resolution over a 24-hour period.

The energy consumption for ULT freezers is highly dependent on the conditions a ULT freezer operates in. A qualitative assessment was used to assess the condition on the ULT freezer. Each freezer was rated qualitatively for three conditions, which are spacing; ice on the outer door gasket seals; and dust on the filter/condenser fins.

The ULT freezer age, capacity, and set point temperature were determined from manufacturing or acquisition date data, vendor brochures, and ULT freezer setting display, respectively.

The carbon footprint assessment from ULT freezer operation was computed in accordance to the methodology B.1.1 and C.2 outlined in the Federal Greenhouse Gas Accounting and Reporting Guidance Technical Support Document, and carbon emissions are assessed in units of metric tons (MT) of carbon dioxide equivalent (CO_2e) per year (White House Council of Environmental Quality, 2010). The NIH Main Campus is located in Bethesda, MD; therefore, the RFC East eGrid subregion output emission rate factors were used. The carbon emissions include emissions from the transportation and distribution of electricity.

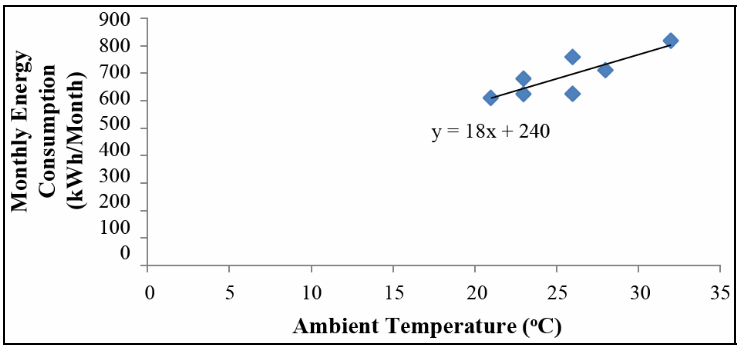
4 Results

Sixty-four ULT freezers were evaluated in the case study. ULT freezers operated efficiently when they are maintained; are operating in ambient temperatures less than 25°C; are less than ten years old; are operating at a set point higher than –80°C; and have an internal capacity greater than 23 ft^3. Maintained freezers are properly spaced; have little or no frost on the outer door gaskets; and have no dust on the filter and condenser fins.

4.1 Ambient temperature

According to freezer manufacturers, operating a ULT freezer in ambient temperatures higher than 32°C (Thermo Scientific, 2011) prevents the effective heat transfer from the high stage refrigerant to the ambient environment. Figure 1 depicts how energy consumption and carbon footprint for maintained 17.3 ft^3 ULT freezers are influenced by increasing ambient temperatures. A best fit curve indicates that the monthly energy consumption increases approximately 18 kWh and releases 9.27 kilograms (kg) of CO_2e for every 1°C rise in ambient temperature. Each 1°C drop in ambient temperatures from 32°C lowers the energy consumption for a ULT freezer by approximately 2%, which is in agreement with Thermo Scientific's analysis on the Thermo Scientific TS586e (Wisniewski, 2011).

Figure 1 Energy consumption versus ambient temperature for 17.3 ft^3 at a set point of –80°C maintained ULT freezers (see online version for colours)



4.2 Age

Technological improvements in cold storage have resulted in more efficient operation of ULT freezers. Advances in ULT freezer compressor design, insulation, and cabinet design have resulted in greater efficiencies to store samples. Nevertheless, the efficiency of ULT freezers decreases over time, due to the loosening seals, degraded refrigerants and lubricants, and fatigue of mechanical systems. Figure 2 illustrates the duty cycle over time for three different aged maintained ULT freezers at an –80°C set point operating in an ambient temperature from 25°C to 27°C. According to the graph, the duty cycle spikes due to the startup of the high and low stage compressors on the ULT freezer. After four to six hours, the high and low stage compressors stabilise, and there are only slight variations in the duty cycle. The duty cycle for a new, mid-age (five to seven years), and old (greater than ten years) ULT freezer is approximately 55%, 70%, 100%, respectively. As the freezer duty cycle increases there is greater risk of failure along with the increased energy use and the compressor motors continual operation.

Figure 2 The influence of age on duty cycle for maintained ULT freezers at a set point of –80°C operating in ambient temperatures of 25° to 27°C (see online version for colours)

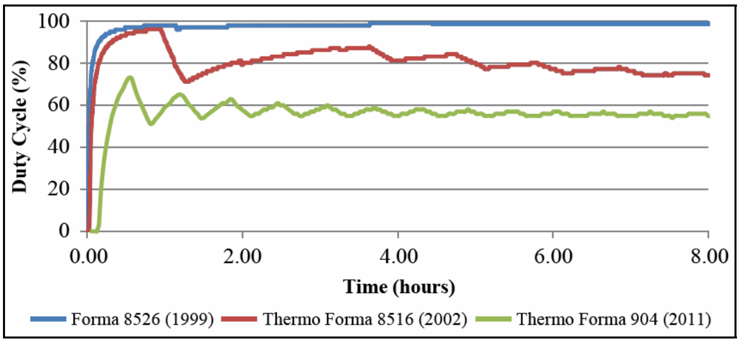
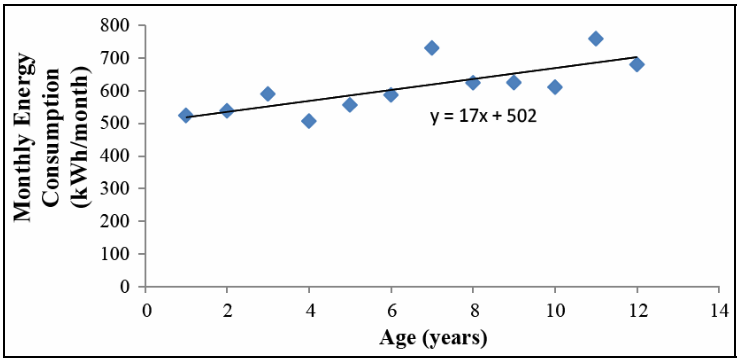


Figure 3 is a graphical representation of how age influences the energy consumption for maintained 17.3 ft^3 ULT freezers at a set point of –80°C operating in ambient temperature ranging from 23°C to 28°C. As seen in the figure, for each year a freezer ages, there is an increase of approximately 3% in energy consumption, and an additional monthly release of 8.75 kg of CO_2e.

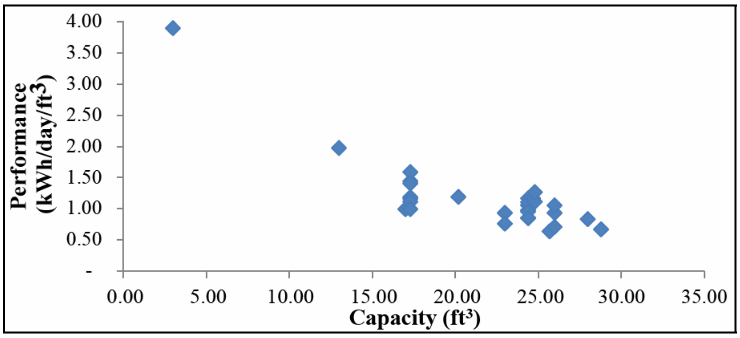
Figure 3 Energy consumption versus age for 17.3 ft^3 maintained ULT freezers at a set point of –80°C (see online version for colours)



4.3 Capacity

Smaller ULT freezers have a much higher energy consumption rate on a cubic foot basis when compared to larger ULT freezers, which is depicted in the figure below. Figure 4 is a graphical representation of a ULT freezer's performance in kWh/day/ft^3 versus its capacity in ft^3. All the freezers are at an –80°C set point and operating in ambient temperatures from 25°C to 28°C.

Figure 4 ULT freezer's performance in kWh/day/ft^3 versus capacity in ft^3 (see online version for colours)



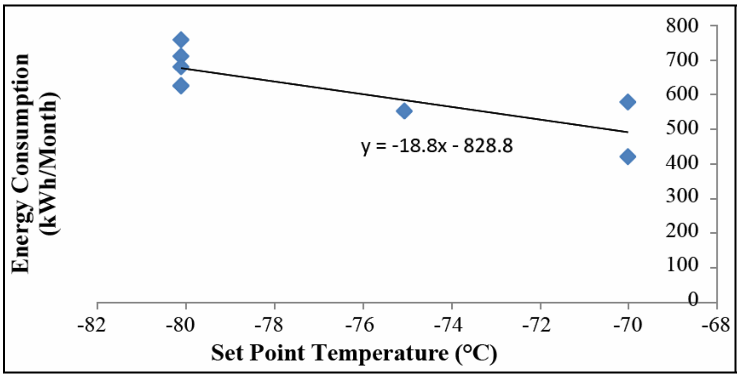
Note: The ULT freezers are operating at set point of –80°C and an ambient temperature of 25°C to 28°C.

A 3.0 ft^3 ULT freezer has the lowest energy consumption rate at 11.67 kWh/day among all the ULT freezers measured in the study; however, in a kWh/day/ft^3 basis, the 3.0 ft^3 freezer is six times less efficient than the best performing ULT freezer at 0.64 kWh/day/ft^3. ULT freezers greater than 23 ft^3 are the best performing units with a performance ranging from 0.65 to 0.80 kWh/day/ft^3.

4.4 *Set point temperature*

Increasing the ULT freezer's set point lowers the ULT freezer's duty cycle, which in turn lowers the ULT freezer's energy consumption. Lowering the ULT freezer's duty cycle also extends the life of the ULT freezer because it decreases the frequency that the compressor cycles on and off. Figure 5 depicts how the set point temperature influences the energy consumption for maintained 17.3 ft^3 ULT freezers in ambient temperatures ranging from 22°C to 26°C.

Figure 5 Energy consumption versus set point temperature for 17.3 ft^3 maintained ULT freezers (see online version for colours)



Based on the data, raising the set point temperature by 5°C for a ULT freezer reduces daily energy consumption by 3 kWh and avoids 1.54 kg CO_2e of emissions. Based on a University of California (UC) Davis study on set point temperature for various ULT freezer models observed a 2 to 4 kilovolt amp-hour per day (kVAh/d) (which is approximately 2–4 kWh per day reduction in energy consumption by raising the set point temperature from –80°C to –70°C) (Doyle et al., 2011). Differences in the results are attributed to how the analysis was performed between the case studies. In the NIH study, the monthly energy consumption rate for ULT freezers with varying ages, makes, and models are plotted against set point temperatures from –70°C to –80°C. In the UC Davis case study, the daily energy consumption for ULT freezers were measured at –80°C and –70°C, and the energy consumption rate data was compared to a specific ULT freezer model. Unlike the NIH study analysis, the UC Davis study analysis eliminates the variability with differences in age, make and model. Despite the differences in the results between both studies, the same conclusion can be drawn: that increasing the set point temperature for ULT freezers lowers the energy consumption.

4.5 Spacing

In order to provide proper ventilation around the ULT freezer, it is recommended to keep at least 8″ of clear space on the top (Thermo Scientific, 2011), and a minimum of 5″ of clear space in the rear and on both sides (Forma Scientific, Inc., 1999). Improper ventilation around the ULT freezer can prevent the condenser fins from effectively dissipating heat into the ambient environment from the high stage compressor, which increases the duty cycle of the ULT freezer and can negatively affect the performance of the ULT freezer in achieving the set point temperature.

The conditions of freezers are rated in accordance with the rating system outlined in Table 1. Table 2 depicts the conditions of the two freezers that were evaluated to determine the effects of spacing on the energy consumption.

Table 1 Freezer rating assessment to systematically rate the operating condition of a ULT freezer

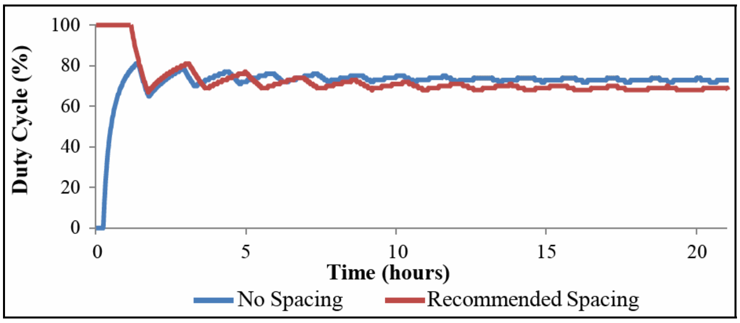
Spacing: 5 inches of spacing around freezer and 8″ of spacing on top of freezer	Spacing requirements met	Three out of four spacing requirements met	Two out four spacing requirements met	One out of four spacing requirements met
	0	1	2	3
Ice on door gasket seals	No ice	Light frost	Accumulated frost	Thick ice
	0	1	2	3
Dust on filter and/or condenser fins	No dust	Light dust	Medium dust	Thick dust
	0	1	2	3

Table 2 Selected ULT freezers to assess the impact of spacing on energy consumption

Manufacturer	*Model*	*Age (year)*	*Spacing*	*Ice*	*Dust*
Thermo Forma	8516	9	0	1	1
Thermo Forma	8516	10	3	1	0

Figure 6 depicts the influence of spacing on duty cycle for a ULT freezer that meets the recommended spacing requirements according to the manufacturer (red) and a ULT freezer that does not meet the recommended spacing requirements, and therefore has inadequate ventilation. According to the figure, improper ventilation results in a 4% increase in duty cycle, which translates to an additional 85 kWh of electricity consumed per month and the additional release 51 kg of CO_2e per month.

Figure 6 The influence of spacing on duty cycle for maintained ULT freezers at a set point of –80°C operating in ambient temperatures from 26° to 28°C (see online version for colours)



4.6 Dust

Dust on the filter blocks the normal air flow through the condenser, which reduces the ability of the ULT freezer to dissipate heat. Any air flow that bypasses the clogged filter will result in air carrying dirt to deposit on the condenser. Dirt on the condenser prevents the effective heat transfer from the high stage refrigerant to the ambient environment. Table 3 depicts the conditions of two freezers that were evaluated to determine the effects of dust buildup on the ULT freezer condenser fins and the filter.

Table 3 Selected freezer to assess the impact of dust buildup on the air filter and condenser fins

Manufacturer	*Model*	*Age (year)*	*Spacing*	*Ice*	*Dust*
Thermo Electron Corporation	8604	6	1	2	3
Thermo Forma	8604	8	1	3	0

Figure 7 depicts the amp draw over time for a significantly dusty Thermo Electron Corporation Model 8604, which is indicated in red and a dust-free Thermo Forma Model 8604, which is indicated in blue. Both freezer were operating at a set point of –80°C and operating in ambient temperatures from 23° to 25°C. The dusty Thermo Electron Corporation Model 8604 amperage cycles between 7.5 amps to 17.0 amps and has a duty cycle of 99%. The dust-free Thermo Forma Model 8604 amperage cycles between 0.10 amps to 13 amps and has a duty cycle of 70%. On a monthly basis, a significantly dusty ULT freezer consumes an additional 211 kWh of electricity and emits an additional 108 kg of CO_2e compared to a dust-free ULT freezer.

Figure 7 The influence of dust accumulation on ULT freezer filters and condenser fins on energy consumption for ULT freezers at a set point of –80°C operating in ambient temperatures from 23° to 25°C (see online version for colours)

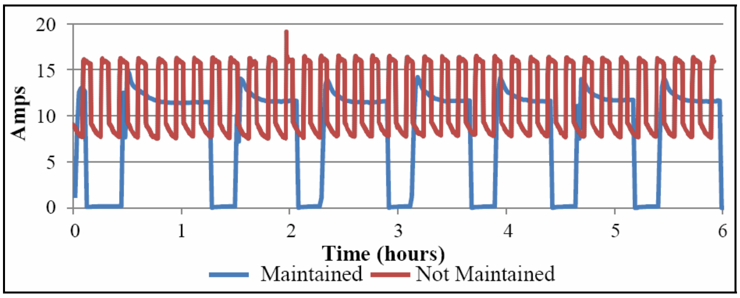


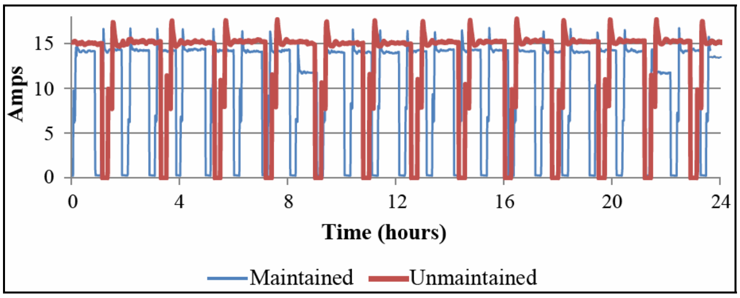
Table 4 depicts the conditions of two freezers that were evaluated to determine the effects of a thick dust on the filter and no dust on the condenser fins.

Table 4 Selected freezer to assess the impact of dust buildup on the air filter and condenser fins for Thermo Model 8604 ULT freezers

Manufacturer	*Model*	*Age (year)*	*Spacing*	*Ice*	*Dust*
Thermo Scientific	ULT2586-10HD-A41	0	0	1	0
Thermo Scientific	ULT2586-10HD-A40	2	0	2	3

Figure 8 depicts the amp draw over time for a Thermo Scientific Model ULT2586-10HD-A40 with heavy dust on the air filter only, which is indicated in red and a new Thermo Scientific ULT2586-10HD-A41, with no visible dust, which is indicated in blue. Both freezer were operating at a set point of –80°C and operating in ambient temperatures from 25° to 26°C. Based on the figure, the unmaintained Thermo Scientific Model ULT2586-10HD-A40 amperage cycles between 0.0 amps to 17.3 amps and has a duty cycle of 87%. The maintained Thermo Scientific ULT2586-10HD-A41 amperage cycles between 0.30 amps to 16.5 amps and has a duty cycle of 79%. On a monthly basis, a clogged filter on a ULT freezer consumes an additional 117 kWh of electricity and emits an additional 60 kg of CO_2e compared to a ULT freezer with a clean filter.

Figure 8 The influence of dust accumulation on ULT freezer filter and condenser on energy use for ULT freezers at a set point of –80°C operating in ambient temperatures from 25°C to 26°C (see online version for colours)



4.7 Ice

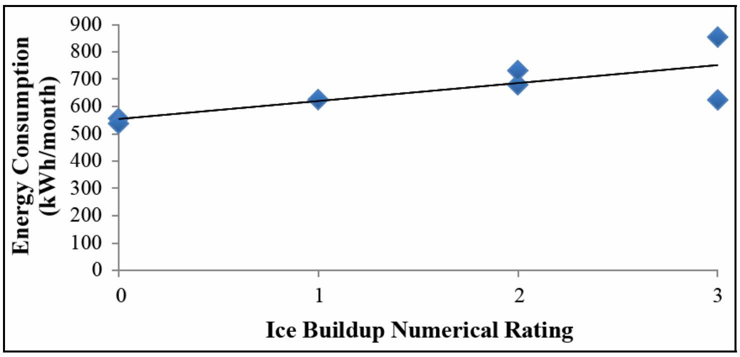
Frosting occurs on any surface with a temperature that is below the dew point of freezing air and below the freezing point of water. Frosting is observed generally on the evaporator coils and the outer gasket seals of ULT freezers. Frost build-up can accumulate on the door gasket seals, which can create gaps in the seals around the ULT freezer door. These gaps will allow cold air to be lost to ambient environment while also allowing warm air to enter into the cabinet freezer. Table 5 depicts the conditions of ULT freezers that were evaluated to determine the effects of ice on the outer gasket doors.

Table 5 Selected freezer to assess the impact of ice buildup on the outer gasket doors on ULT freezers

Manufacturer	*Model number*	*Age*	*Ambient temperature*	*Spacing*	*Ice*	*Dust*
Thermo Forma	8604	8	23	1	3	0
Thermo Electron Corporation	8604	7	23	1	3	0
Forma Scientific	8516	15	23	1	2	0
Thermo Electron Corporation	8604	6	23	1	2	0
Thermo Forma	8516	9	26	0	1	1
Thermo Scientific	904	2	23	0	0	0
Thermo Scientific	904	0	23	0	0	0

Figure 9 is a graphical depiction of the monthly energy consumption versus the ice buildup on the freezer's outer gasket seal. Based on the figure, there is a positive correlation that indicates as the ice builds up on the outer gasket seal, the energy consumption rate increases. However, on the figure, there is one point that does not fit the trend. This point shows a decrease in energy consumption rate with an ice buildup numerical rating of 3. In addition to the thick ice buildup on the outer gasket doors, this particular ULT freezer has thick ice buildup on the evaporator tubing.

Figure 9 The influence of ice buildup on the outer gasket on the ULT freezer on the energy consumption for ULT freezers at a set point of –80°C operating in ambient temperatures from 25° to 26°C (see online version for colours)



Generally, as frost builds up on the evaporator coils the heat transfer rate in the ULT freezer cabinet is decreased due to the insulating effects of ice, which results in an increase in energy consumption. However, in this atypical case, the opposite is observed, which can be attributed to the increase in the roughness of frost, which increases the total surface area. This phenomenon was also observed in a study for determining the effects of frost formation on domestic refrigerator-freezer evaporator coils (Ali and Crawford, 1992). From there an initial increase in heat transfer as frost increased was observed, but eventually the heat transfer decreased due to the insulating effects of the frost.

4.8 Performance

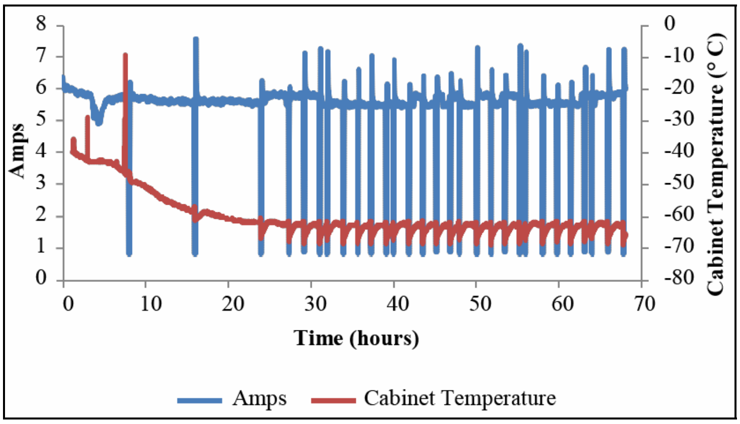
In addition to energy consumption, ambient temperature, freezer condition, and age are factors that can also influence a ULT freezer's performance in achieving its set point temperature. Table 6 depicts an 18 year old unmaintained ULT freezer operating with a –80°C set point in 32°C ambient environment.

Table 6 Selected freezer to assess the impact of age, ambient temperature, and freezer condition on the ULT freezer's ability to achieve set point temperature

Manufacturer	*Model*	*Age (year)*	*Spacing*	*Ice*	*Dust*
Revco	ULT2186-7-D12	18	0	3	3

Before the watts up? pro metre was installed on the Revco Model ULT2186-7-D12, the freezer was operating with a cabinet temperature of –40°C. The freezer had no filter in place, and there was a thick layer of dust on the condenser fins. The dust was first removed from the condenser fins using a broom, and then the watts up? meter, ambient temperature probe and cabinet temperature probes were installed on the ULT freezer. The ambient temperature probe indicated the Revco Model ULT2186-7-D12 was operating in 32°C ambient temperatures. Figure 10 depicts the amp draw and the internal cabinet temperature of the ULT freezer over a 68-hour period.

Figure 10 Amp draw and internal cabinet temperature for 18 year old Revco ULT2186-7-D12 operating with –80°C set point in 32°C ambient temperature with dust covered condenser fins and no air filter (see online version for colours)



Based on the figure, the Revco ULT2186-7-D12 operates continuously and only achieves a cabinet temperature of –40°C never reaching its set point. After removing the dust on the ULT freezer, the cabinet temperature does not reach –64°C until 24 hours later. When all three probes were removed, the ULT freezer indicated the cabinet temperature was –78°C; however, the internal temperature probe indicated the cabinet temperature was –65.5°C.

5 Conclusions

ULT freezers consume large amounts of energy, precious research dollars, and valuable space. The effective management of ULT freezers is imperative for ensuring freezers perform optimally in regards to maintaining the desired set point temperature on a consistent basis. The energy consumption for 64 ULT freezers manufactured from 1994 to 2012 was measured in 'real world' settings to determine the effects of ambient temperatures, freezer settings, and condition on a ULT freezer's performance. Based on the study, ultra-low temperature freezers operated efficiently when they are maintained, are operating in ambient temperatures less than 25°C, are less than ten years old, have an internal capacity greater than 23 ft^3, and are operating at a set point higher than –80°C.

Linear regression lines were established to correlate ambient room temperature, age, and set point temperature to monthly energy consumption. Based on regression lines, lowering the ambient temperature by 1°C lowers the energy consumption by 3%, raising the set point temperature 5°C lowers the energy consumption by 14%, and each year a freezer ages increases its energy consumption by 3%.

A 4% increase in the ULT freezer's duty cycle was observed for a freezer that did not meet the vendor recommended spacing requirements versus a ULT freezer that did meet the spacing recommendations. This translated to an improperly spaced ULT freezer consuming an additional 85 kWh per month over a properly spaced ULT freezer.

Dust accumulation on the filter results in approximately a 14% increase in energy consumption. However, if there is dust accumulation on the filter coupled with dust accumulation on the condenser fins, then energy consumption can increase by 25%.

In regards to frost buildup on the outer gasket seals, there is a positive correlation with increased energy consumption with thicker frost accumulation. However, freezers usually with thick frost on the outer gasket seals also have thick frost within the interior cabinet. Frost accumulation initially results in an increase in heat transfer in the ULT freezer cabinet, which is the result in an increase in heat transfer area from the roughness of the frost. The increase heat transfer area results in a decrease in energy consumption. Eventually, as the frost accumulates, the insulating effects of frost decrease the heat transfer area and energy consumption increases.

Carbon emissions were computed in accordance to methodology B.1.1 and C.2 outlined in the Federal Greenhouse Gas Accounting and Reporting Guidance Technical Support Document. Based on the accounting methodology, greenhouse gas emissions are directly proportional to the electricity that is consumed by the ULT freezer. Lowering the energy consumption through effective ULT freezer management will ultimately lower the carbon footprint attributed to consumption, transmission, and distribution of electricity.

In addition to lower energy consumption and carbon emissions, effective management of ULT freezers will assist the unit in maintaining the desired set point temperature on a consistent basis. Based on the study, an 18 year old, unmaintained ULT freezer operating in 32°C ambient temperatures cannot achieve the set point temperature, and instead only achieves cabinet temperatures 12.5°C warmer than the desired set point.

Management of ULT freezers must address all of the factors evaluated in this case study, including ambient air temperature, maintenance/dust accumulation, frost buildup, ventilation space around the freezer, age of the freezer, and set point temperature settings. Without proper management of ULT freezers, a facility is associated with an increased legacy cost through the ULT freezer's increased energy consumption and the sample integrity is compromised due to the ULT freezer's inability to maintain the desired set point temperature.

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