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Ultra-Low Temperature Freezers: By the Numbers

WHITE PAPER

How ENERGY STAR® Certification Brings Clarity to Performance Claims Critical to Investments in Ultra-Low Temperature Storage Technologies

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Abstract

The development of ultra-low temperature freezers spans decades of progress in component design. From refrigerants and compressors to controllers, cabinet insulation methods and inventory arrangements, manufacturers have attempted to present a best-case scenario for freezer performance based on internal testing, ambiguous publication of data and convoluted comparisons to competitive products. The industry-wide creation of ENERGY STAR criteria for managing independent testing against common performance values has prompted leading ultra-low temperature freezer manufacturers to invest in third-party evaluations of product functionality so that purchasing decisions can be based on reliable data, rather than sales or marketing claims. The benefits of performance profiles based on common criteria are valuable as long as customers understand the relative importance of test data in context with real-world conditions. This report summarizes key performance parameters of the ultra-low temperature freezer, why these are important and how to balance performance metrics to arrive at an informed purchase decision.

INTRODUCTION

Setting the Stage

Storage of biologicals for long-term preservation is crucial to scientific investigation. Reproducibility of research from one lab to another, from one location to another and from one generation to the next, forms a tapestry of scientific knowledge. While many factors impact cell viability and the cell culture equation,[1] the need for repeatability in the preservation of life forms within the cold chain remains a constant. Frozen cells are often a starting point from which research is regularly initiated or continued. Viability of frozen cells stored for long-term preservation is dependent on original cell preparation, type of media, rate of pull-down to desired storage temperature, temperature stability and uniformity in the frozen state, and thawing protocol.

Ultra-low temperature freezers have always presented a challenge to manufacturers who balance the laws of physics, refrigerant chemistry and the mechanical force required to create an ultra-low temperature sufficient to suspend or impede

MDF-DU702VH-PA
25.7 cu.ft. | 729 L

enzymatic activity within the cellular structure and, thus, maintain cells in suspended animation. While storage of critical research in mechanically refrigerated freezers has offered significant advantages and convenience over liquid nitrogen vapor or liquid phase nitrogen, severe temperature differentials from ambient laboratories as warm as 30°C to deep storage conditions of -70°C, -80°C or beyond has tested the boundaries of cabinet insulation, mechanical refrigerant circulation methods, refrigerant performance and internal data monitoring necessary for efficient control.

Throughout this evolution, PHC Corporation has asserted a proactive product development program focused on the need for performance, reliability and energy efficiency.

Performance. Performance is the first and foremost consideration in ultra-low temperature freezer design. Without performance, the freezer adds uncertainty into a scientific terrain already beset with reproducibility challenges. Poor performance places critical cell lines and isolated biologicals at risk and, in situations where stored product is lost, creates a setback to the scientific community that cannot be easily or quickly recovered. There are many examples of research disasters caused by ultra-low temperature freezer failures.

Reliability. Performance without reliability is unacceptable. While many manufacturers can build ultra-low temperature freezers that reach desired storage temperatures, freezer applications under real-world conditions are difficult to manage. Without highly specific engineering, normal stress on components, caused by frequent door openings, high ambient temperatures, voltage fluctuations, improper airflow and poor installation decisions, can result in total system failure, downtime, diminished credibility in grant application and collaboration, or catastrophic destruction of priceless work.[2] Thus, a history of brand performance over time can corroborate the likelihood of continued success when a new product is launched.

Energy Efficiency. Energy efficiency has moved front and center in contemporary marketing materials. This is largely due to exponential increases in biorepository volumes, environmental awareness, higher costs of power and shifting economies within public and private sector research institutions where actual life-cycle costs are emerging from obscurity. The true cost of conventional ultra-low temperature freezers is often concealed from those within the institution who perform the research, those who pay the bills and the shareholders who direct improvements in facility-wide sustainability. As a result, new developments in ultra-low temperature freezer platforms are now delivering energy efficiencies previously unmatched with conventional cascade platforms. Some, however, have a downside.

While other refrigeration technologies such as free-piston engines and thermoelectric panels may offer benefits in limited applications, new product roll-outs which are not based on proven systems can place research specimens at risk. Equally distressing, early introductions have placed customers in ill-positioned roles as research and development test subjects who appreciate the theoretical energy-saving benefits but bear the ultimate cost of stored product loss, downtime and overall uncertainty from one day to the next.

Engineering with Purpose

Against this scenario, PHC Corporation has continued a deliberate process focused on optimizing conventional cascade refrigeration platform technology while moving in the background to craft real solutions to assure performance and reliability, all the while trimming energy consumption one step at a time. During this period, some early adopters, especially large pharma firms focused on senior management mandates for energy reduction contributions, carbon footprint targets and sustainability directives, suffered from product introductions based on manufacturers' claims that simply do not materialize in the real-world.

PHC Corporation has remained steadfast in addressing the most valued deliverables – performance and reliability – while deliberately building a new refrigeration platform that has now earned ENERGY STAR Certification. Independent test results confirm the new VIP ECO upright ultra-low temperature freezer has the lowest total daily energy usage in its class in the industry.[3] The refrigeration platform, unique to PHC Corporation, is defined as a variable differential cascade system that uses variable speed inverter compressors, proprietary electronic controls and naturally occurring refrigerants.

Responsible manufacturers have always placed energy consumption high in the product development pyramid, but never at the expense of performance or reliability.

Navigating the Journey

In 2009, industry professionals started to work with the United States Environmental Protection Agency (EPA) to develop standards required to move scientific refrigeration products under an ENERGY STAR umbrella typically associated with consumer goods such as appliances and air conditioners. The PHC Corporation of North America product group director was present at the first meeting comprised of market leaders as an industry representative, and today remains the only original industry member of the ENERGY STAR standards development team.

Preliminary discussions set forth the premise that it was possible to build an ultra-low temperature freezer using smaller, more efficient compressors. These compressors, typically associated with domestic and commercial freezers, could reach and maintain storage temperatures as low as -80°C but with significantly reduced energy consumption. As the parameters for product development shaped up, a study of the market confirmed this premise.[4]

The problem confronting manufacturers, however, was a frequently severe trade-off between required performance and energy savings. While hyper-efficient freezers could reach target temperatures, they did not have the refrigeration power to recover temperature after door openings, to manage high ambient conditions, to tolerate broad voltage fluctuations and to achieve interior temperature uniformity at all shelf levels.

The industry was confronted with a reality check when the EPA set a precedent by publishing both steady state (no door openings) and daily (6x door openings) *temperature recovery* data, along with energy consumption tests for all freezers submitted to the ENERGY STAR program. Yet this examination did not go far enough. Recovery data can be obscured and because performance metrics only cover a snapshot in time, often immediately following a door opening, this data does not paint a broad picture of performance.

From the PHC Corporation point of view, scientific investigators do not buy freezers to save energy; they buy freezers to protect and preserve their work – no exceptions. Therefore, any energy-saving initiative that risks performance is unacceptable and conventional cascade or hybrid platforms remain the company's proven solution, regardless of energy consumption.

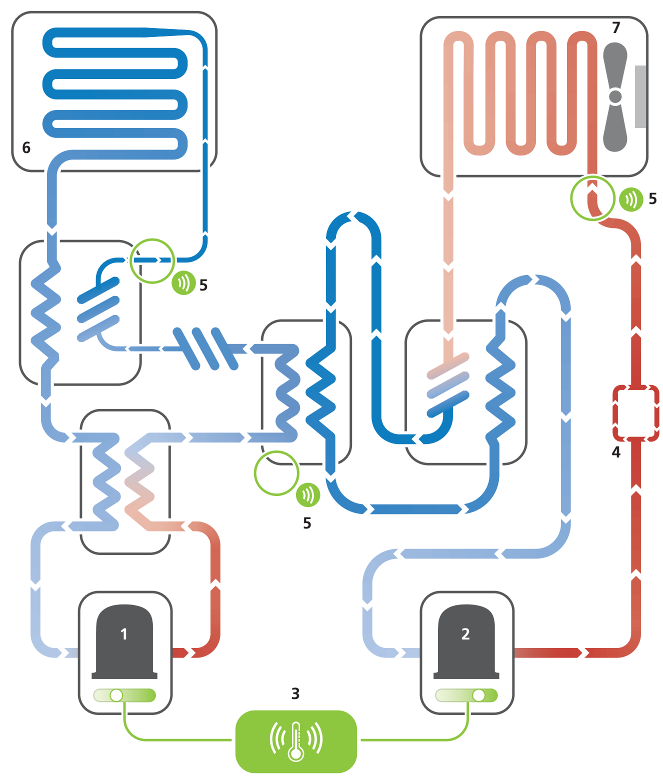
Other manufacturers, however, were quick to create systems that would satisfy the more superficial demand for low energy use. As a result, the scientific community suffered priceless stored product losses and hard lessons were learned.[5] Therefore, the PHCbi brand ultra-low temperature freezer line remained a mainstay in institutions around the world where risks assumed for energy-savings alone were simply not worth taking.

BRINGING FORTH A BETTER IDEA

The Variable Differential Cascade Platform

As new refrigeration technologies were introduced amid much fanfare, PHC Corporation focused its design efforts on achieving a balance without compromise. This effort was comprised of four primary areas where technology has improved. These include the widespread success of the variable speed inverter compressor, the increase in heat transfer efficiencies, the adoption of natural refrigerants and the integration of proprietary control algorithms that are unique to the industry.

The Variable Differential Cascade Platform uses the same energy twice by warming the outer door frame heater with warm bypass vapor, thereby controlling frost build-up on the replaceable door gasket without the need for added electrical power.



1. Low-stage inverter compressor
2. High-stage inverter compressor
3. Central controller with proprietary algorithm
4. High-stage bypass to outer door frame heater
5. Key data point
6. Low-stage evaporator
7. High-stage condenser

Variable Speed Inverter Compressor. The inverter compressor modulates cooling capacity by varying compressor motor speed or output. Unlike conventional, fixed-speed compressors that operate in an on/off cycle, the inverter compressor responds to cooling needs on demand by ramping up compressor speed to achieve desired refrigerant flow.

In this new cascade platform, two compressors drive the cooling process in a high-stage and low-stage configuration. The low-stage cools the cabinet, while the high-stage cools the interstage heat exchanger; this is where energy (heat) is moved from the freezer inside.

This platform is a variable differential cascade system whereby both compressors do not necessarily rotate at the same speed at the same time. Thus, demand for cooling within the system is met with a more flexible response which reduces electrical demand while apportioning refrigeration flow throughout the system more efficiently.

Benefits of this platform are reduced sound, reduced BTU output and quicker response to cooling demand after door openings.

Adoption of Natural Refrigerants. The use of natural refrigerants brings another dimension to the cooling power of this platform. Adopted in response to changes in the EPA stance on a widely used class of refrigerants, naturally occurring refrigerants pose no threat to the environment and contribute to achieving facility sustainability goals. Natural refrigerants have been used in commercial cooling systems for more than 100 years, but safety concerns prompted adoption of new, synthetic refrigerants in the 1930s. Most recently, however, new refrigeration methods, safety systems and more efficient compressors have won industry-wide approval as an effective method to achieve ultra-low temperatures.

Proprietary Control Algorithms. Orchestration of the variable differential cascade platform is centralized in the microprocessor control module. Long known throughout the world as a leading brand in innovative consumer and OEM electronics, PHC Corporation engineers developed a proprietary controller that manages system analytics *in situ*. Programmed with sophisticated algorithms, this controller directs high- or low-stage compressor speeds as required and compiles and reports internal data to a comprehensive control center where data can be displayed, logged and offloaded in batch or real-time streaming. This controller is among many proprietary sub-components that set the VIP ECO apart from competitors.

EARNING ENERGY STAR CERTIFICATION

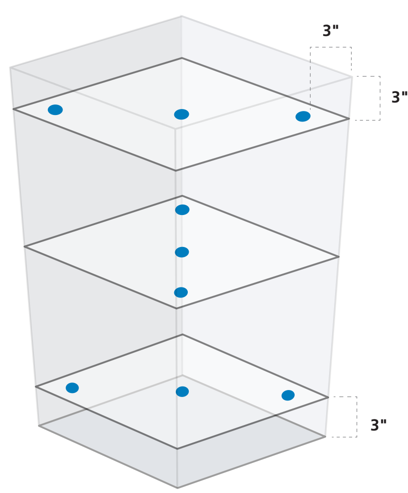
Going the Extra Mile

The PHCbi VIP ECO is ENERGY STAR Certified.[6] Certification is based on the results of independent testing to a set of specific and controlled performance criteria established by the EPA, as well as the United States Department of Energy (DOE), and agreed upon by leading ultra-low temperature freezer manufacturers and end user groups. All freezers under consideration for ENERGY STAR Certification must be independently tested; in-house or internal manufacturers' data is not accepted.

The primary benefit of ENERGY STAR Certification is accountability. Customers can now expect an expanding array of data to support manufacturers' claims related to key performance metrics that define the function of an ultra-low temperature freezer. These include uniformity and power consumption. If these data points are not independently evaluated and published, or if testing conditions are ambiguous or undisclosed, it is wise to request documentation beyond internal marketing information. While recovery is not mandated in the ENERGY STAR criteria, temperature recovery is collected by the certifying agency and provided to the manufacturer.

Key Performance Metrics

Uniformity. Uniformity is measured over time and space. Within a highly uniform interior, the placement of stored product must not affect the viability of the materials being stored. Temperature must be uniform at all shelf levels to minimize uncertainty and to improve the likelihood of reproducibility in the scientific investigation process. This information is provided to ENERGY STAR following the testing. Though manufacturers have access to this data, it is not currently published.



Measuring Uniformity
Over two periods, uniformity data is collected from nine different points in the freezer compartment 3 hours following door opening.

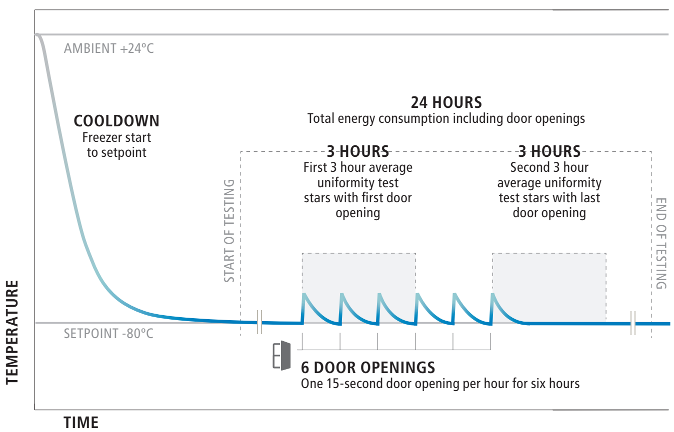
Logically, when a composite of data points is used, freezers that recover faster following door openings and following the final door opening will demonstrate a better uniformity profile in direct comparisons.

The most important data points establish the warmest and coldest points in the freezer chamber.

Power Consumption. Power consumption is central to the ENERGY STAR program. Given the inefficiencies of many conventional ultra-low temperature freezers, especially in facilities where hundreds or thousands of freezers are operating, any reduction in energy consumption quickly translates to the bottom line. Thus, industry efforts to reduce the energy use, BTU output and loads on facility HVAC systems are intense.

Measuring Power Consumption
Total energy is calculated over a 24-hour period. This is a composite of two commonly used setpoint temperatures of -70°C and -80°C.

During the 24-hour testing, which starts only when the freezer has stabilized, the outer and one inner door are opened for 15 seconds every 60 minutes for a period of six consecutive hours.



When comparing ENERGY STAR data from competing freezer manufacturers, it is important to determine that the freezers are operating on the same condenser types, specifically air-cooled vs. water-cooled.[7]

VIP ECO test data is based on the standard air-cooled Model MDF-DU702VH-PA, 25.7 cu.ft. (729 L) freezer.

Door opening test criteria was established by all ENERGY STAR participating manufacturers so performance data is acquired under identical conditions.

Comparative energy consumption profiles are easily acquired from the ENERGY STAR website at www.energystar.gov.

Temperature Recovery. Manufacturers who subject their products to ENERGY STAR testing have access to results for mandatory as well as optionally requested criteria. For example, temperature recovery following door openings is a critical deliverable. Under ENERGY STAR criteria, temperature recovery in an empty chamber must be measured under highly controlled conditions that account for ambient operating temperature, target setpoint, thermocouple location in air and incoming voltage stability. In addition, however, PHC requested supplemental testing with simulated product load in order to acquire a more comprehensive assessment of performance in real-world conditions.

ENERGY STAR Testing Requirements vs factory Internal testing

- ENERGY STAR target operating temperatures are -70°C and -80°C.
- ENERGY STAR requires testing under ambient conditions of 24°C, while factory tests under ambient conditions of 20°C, 24°C and 30°C. These additional tests at ambient conditions below and above stated ENERGY STAR requirements permit a broader range of comparisons with competitor data. Examples include temperature recovery under the stress of higher ambient temperature typical of warm labs or hallways where many freezers are located.
- All data is acquired in compliance with the ENERGY STAR standard since it most represents actual conditions as determined from more than 8 years of discussion through the ENERGY STAR standards development.
- Loads are empty or half full with simulated load of 50% water and 50% glycol. Probes are placed in air (and optional simulated load) where temperature is measured over time and space.

Temperature Recovery Testing Sequence[8]
The MDF-DU702VH-PA includes a single insulated outer door and two insulated inner doors. The temperature recovery testing sequence is comprised of timed outer and inner door openings with an opening dwell of 15 seconds and a total sequence of 23 seconds.

Test Sequence, Seconds	Outer Door	Inner Door
Open	2	2
Open Dwell	15	
Close	2	2
Total Elapsed	**23**	

Pull-Down. Pull-down is often noted as a key performance indicator in freezer operation. In reality, pull-down is ideally a one-time event, with the pull-down time on initial start-up of little consequence. Pull-down metrics, however, are a meaningful indicator of reserve refrigeration power. Although not required by ENERGY STAR testing, manufacturers are typically provided this data from their testing agency following the ENERGY STAR protocols.

The pull-down rate of an empty freezer depends on the desired operating setpoint, ambient temperature at start-up and internal load. A "no load" pull-down rate can also mislead with respect to reserve cooling power because many systems are designed to operate more efficiently at ultra-low temperatures than at ambient temperatures. The colder they get, the better they perform.

A Note on Peak Variance Peak variance, a term listed in the EPA criteria, is an observation, not a performance attribute and applies only to the impact of a door opening in an empty freezer. A properly designed and powered ultra-low temperature freezer should accommodate any peak variance deviation through the normal recovery functions immediately after the door is closed.

Additional ambiguities associated with a peak variance metric include ambient at time of opening, duration of door opening and configuration of inner doors. Because this criterion measures an air temperature increase that is quickly recovered, PHC Corporation of North America ascribes little to no value to the metric.

ENERGY STAR Total Energy Composite Rating

ENERGY STAR publishes a Total Energy Composite rating. This rating in kWh/day is calculated over a 24-hour period as a composite of two typical setpoint temperatures of -70°C and -80°C. Once the freezer has stabilized at the target setpoint, a 24-hour testing protocol is initiated.

ENERGY STAR Total Energy Composite Calculation

- **Blended setpoint ~ -75°C.**
  Daily, six door openings
  Steady state, zero door openings
- **Daily Energy Composite.** This is calculated as an average between the energy consumption at both setpoints. Reference "Measuring Power Consumption" for more details.
- **Steady State Energy Composite.** This is similar to the Daily Energy Composite, except that the doors are not opened. The Steady State Composite is simply calculated as an average between the energy consumption at two setpoints.

$$\textbf{Energy Consumption} = E1 + (-75 - T1) \times \frac{(E2 - E1)}{(T2 - T1)}$$

Ultra-Low Temperature Freezer Energy Consumption Calculation
The EPA formula for calculating Maximum Daily Energy Consumption, E1, is based on the formula whereby T = Overall average of all recorded interior temperature measurements over the course of the test, T1 at -70°C test condition, and T2 at -80°C test condition; E = Total Energy consumption during the test, E1 at -70°C test condition, and E2 at -80°C test condition.

ENERGY STAR TESTING DETAIL

Performance Summary: VIP ECO Models MDF-DU702VH-PA and MDF-DU502VH-PA

Performance 24°C Ambient, Empty	MDF-DU702VH-PA	MDF-DU502VH-PA
Daily Energy Consumption, kWh/day, 6x Door Openings*		
Setpoint -70°C	6.72	5.56
Setpoint -80°C	9.00	7.14
Composite -75°C	7.86	6.35
Steady State Energy Consumption, kWh/day, No Door Openings*		
Setpoint -70°C	6.19	5.20
Setpoint -80°C	8.40	6.75
Energy Efficiency by Volume: Minimum Daily Energy Consumption (MDEC), kWh/day		
Steady State	7.87 kWh/day ÷ 25.74 cu.ft. = 0.305 kWh/cu.ft.	6.49 kWh/day ÷ 18.6 cu.ft. = 0.348 kWh/cu.ft.
Composite Energy Consumption (MDEC), kWh/day		
Daily	7.86 kWh/cu.ft.	6.35 kWh/cu.ft.
Steady State	7.29 kWh/cu.ft.	6.00 kWh/cu.ft.
Temperature Uniformity		
Setpoint -70°C	1.95°C	2.51°C
Setpoint -80°C	2.67°C	1.38°C
Temperature Recovery, Minutes		
Setpoint -70°C	8	7
Setpoint -80°C	8	12
BTU Output		
Setpoint -70°C	810	725
Setpoint -80°C	1109	967

* Daily energy consumption and steady state energy consumption are calculated following the same criteria as the ENERGY STAR Daily Energy Composite and Steady State Energy Composite respectively. However, data collected at each setpoint temperature is expressed individually, rather than as an average.

***BTU Output Explained.** Air conditioning and ventilation systems (HVAC) consume most of the energy in laboratory buildings. Reducing electrical outlet loads creates more energy savings, both directly and indirectly through reduced demand on building HVAC systems.[9]

Determining the energy reduction impact on HVAC systems depends upon the efficiency of the HVAC system to remove heat energy from the lab space. This efficiency is dependent upon variables such as expected heat load, external ambient conditions, geographic latitude of the facility location, monthly cooling degree day values and summer design temperature.

Reducing the amount of heat output has a positive effect on reducing energy consumption in the HVAC system itself. The VIP ECO Model MDF-DU702VH-PA set at -80°C rejects 1109 BTU/Hr of heat energy at a 23°C ambient into the surrounding environment. This represents >66% savings in energy required to remove the heat from the freezer installation area. This is why additional savings can be realized when older, less efficient freezers are replaced with the VIP ECO.

While most manufacturers calculate the BTU/Hr heat reject based on energy consumed by the freezer, PHC Corporation performs direct measurements over a range of ambient temperature conditions.

Heat Reject in BTU/Hr in 23°C Ambient,
VIP ECO Model MDF-DU702VH-PA[10]

-70°C | 810 BTU/Hr
-80°C | 1109 BTU/Hr

In California alone, for example, ultra-low temperature freezers are estimated to consume upwards of 648 GWh/yr.[11] Even if one quarter of the currently installed base of ultra-low temperature freezers were replaced with units that are only 35% more efficient, more than 37 GWh/yr. would be saved. This is the equivalent of replacing 31 million old household refrigerators from 1996 with ENERGY STAR models. The new VIP ECO is 50% more efficient than previous models marketed as "energy efficient."

CONCLUSION

Most Important Numbers

Acquisition of an ultra-low temperature freezer (or dozens of them) is no longer a joint decision by a scientific investigator and the purchasing department. Due in large part to industry leaders who have invested in more efficient ultra-low temperature freezers, an effort to educate facility managers about the true costs of operating ultra-low temperature freezers is beginning to pay off. Today, total life cycle costs of acquiring, operating and maintaining an ultra-low temperature freezer over time may be more accurately predicted and factored into purchasing decisions.

While energy savings are important to facility managers, the fundamental purpose of an ultra-low temperature freezer is to preserve research. This is why performance and reliability, and the design attributes that assure both, take precedence over initial purchase price. As purchasers appreciate long term benefits of investing in high-performance freezers, and as ENERGY STAR Certification based on independent testing becomes a prerequisite in advance of a purchase decision, a set of common performance values has emerged to offer consumers the information they need to make informed decisions. Additionally, rebates from power companies that support energy efficiency initiatives may also factor into the equation.

[1] The cell culture equation refers to the direct and supplemental systems, products and components required for reproducibility in scientific investigation. These include accurate refrigeration and freezing of media and enzymes, proper handling and methodology in work surface integrity in the biological safety cabinet, accurate *in vitro* replication of the *in vivo* environment created in the cell culture incubator and safe storage of cell lines and cell products in ultra-low temperature or cryogenic storage freezers.

[2] Examples of media coverage of freezer failure and/or loss of stored product: https://opexshare.doe.gov/lesson.cfm/2015/2/5/4747/Ultra-Low-Temperature-Freezer-Failure-Resulted-in-Loss-of-SUNY-SB-Research-Samples; http://www.nj.com/news/index.ssf/2014/10/michael_j_foxs_foundation_sues_nj_medical_institute_for_destroying_samples_collected_for_parkinsons.html

[3] Based on independent, third-party testing at time of publication. ENERGY STAR test results for submitted products can be compared for performance across the competitive market. Results are published on the ENERGY STAR website at www.energystar.gov. See certification Number 4787624501, Model MDF-DU702VH-PA, 25.7 cu.ft. (729 L) upright ultra-low temperature freezer, air-cooled condenser, standard features.

[4] "Ultra-Low Temperature Freezers: Opening the Door to Energy Savings in Laboratories." ETCC Partners, California Public Utilities Commission, January 31, 2017. http://etcc-ca.com/reports/ultra-low-temperature-freezers-opening-door-energy-savings-laboratories.

[5] ibid.

[6] ENERGY STAR Certification Number 4787624501

[7] Heat is removed from the freezer via a condenser. The condenser is cooled by air or water. Air-cooled condensers move heat into the room. Water-cooled condensers require special utility connections to a water supply; water circulation absorbs energy and moves it to the outside or, in large installations, to a regeneration system within the facility where energy is partially recovered and used for heating. Performance data herein is based on independent testing at time of publication.

[8] Temperature recovery is based on a sequence of outer and inner door openings and closings as follows: time to open outer door, 2 seconds; time to open inner doors, 2 seconds; dwell time with inner and outer doors opened, 15 seconds; time to close inner doors, 2 seconds; time to close outer door, 2 seconds. Total elapsed time of test sequence, 23 seconds. This is repeated once per hour for 6 hours to determine average temperature recovery time.

[9] Paradise, Allison. Market Assessment of Energy Efficiency Opportunities in Laboratories. Report no. ET14PGE7591, ET15SCE1070, ET14SDG1111. Emerging Technologies Coordinating Council. Sacramento, CA: ETCC Partners, California Public Utilities Commission, 2015. 160.

[10] BTU output of the VIP ECO is factory tested by PHC Corporation of North America.

[11] One GWh is equal to one million kWh.

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