Improving Temperature Uniformity at –86 °C in a Mechanically Refrigerated Ultralow Freezer:

Reducing Compressor Discharge Temperatures and Apportioning Energy Management Between Low- and High-Stage Cooling Circuits

by Joseph Laporte and Deepak Mistry

The development of an application-specific refrigeration compressor for use in a mechanically refrigerated cascade system results in lower compressor discharge temperatures, more balanced workload between high- and low-stage compressor systems, and more efficient location of evaporator systems around the interior chamber in the –86 °C ultralow temperature freezer. As a result, the freezer delivers better chamber temperature uniformity necessary for stability of stored product, better viability of frozen biological materials, and more accurate monitoring of operating anomalies that may warrant investigation by service personnel in advance of maintenance problems. This article examines new compressor technology developed specifically for use in the ultralow temperature freezer, and how this new technology will enable biorepositories and laboratories to comply with new recommended practices emerging from federal agencies such as those expressed in First Generation Guidelines for NCI Supported Biorepositories.[1]

Enhancing the viability of biochemical and biomedical products is essential in today's life science market. Depending on desired protocols, preservation of biological materials requires storage at temperatures ranging from –10 °C to –40 °C, –86 °C, and as low as –150 °C or colder. Because material stored in these freezers is of such a high value, or irreplaceable altogether, the potential for freezer failure is no longer considered an acceptable risk in the life science community.

Simple refrigeration principles

A mechanical refrigeration system is designed to remove heat (or move energy) from one location and transfer it to another. Key components in a refrigeration system include a compressor, a cabinet for the stored perishable product, evaporator, condenser, and refrigerant. The evaporator is wrapped around the top, sides, and back wall of the interior chamber within the cabinet insulation. The compressed refrigerant liquid passes through the evaporator, where it flash-expands into a vapor and absorbs heat. The compressor moves refrigerant through the system and compresses the vapor into a high-pressure liquid in the condenser. The condenser releases the heat to the ambient environment and the process continues on demand from the controller so that the interior chamber remains at the desired setpoint.

Basic ultralow temperature refrigeration system

Due to the significant temperature differences between ambient (room temperature) and the freezer (–86 °C), two systems are required for incorporating individual compressors and refrigerants with different boiling points for absorption and dissipation of heat. A single refrigerant does not have the physical properties to cover such a wide temperature range. Thus, ultralow temperature freezers employ a cascade refrigeration technique whereby two independent refrigeration circuits operate in a "high-stage" and "low-stage" configuration (see *Figures 1* and *2*).

In the cascade process, the low-stage system removes heat from the product located in the interior chamber. These products typically include vials, bags, canisters, or other commonly used storage containers or labware selected for archival use. Heat from this stored product is absorbed by refrigerant gas in the evaporator tubing wrapped around the interior chamber and concealed in the insulation. This heat is transferred to an interstage heat exchanger where it is passed off to the high-stage system and ultimately released to the ambient as room air is circulated through the condenser coils by a motor/blower/fan assembly. The interstage heat exchanger serves as the evaporator for the high-stage system.

Compressor

The most important component of any mechanical refrigeration system is a reliable compressor. Because ultralow freezers require two compressors working together, these compressors are particularly critical to the operation. Most ultralow freezer manufacturers acquire their compressors on the open market from commercial suppliers who also market their products to air conditioning, refrigeration, supermarket, food and beverage, consumer goods, and other commercial/industrial OEM customers. In terms of unit production, compressors sold for ultralow temperature applications comprise a very small fraction of overall compressor production worldwide. As a result, ultralow freezer manufacturers must make concessions to adapt open market compressors to highly refined ultralow systems.

Because relative demand and economies of scale dictate how compressor manufacturers serve their markets, manufacturers of ultralow freezers, classified as OEM customers, have little leverage in compressor design and/or adaptation to mass-produced product required to overcome heat and lubrication challenges presented in the ultralow environment. In some cases, compressor manufacturers will not warrant their products to the OEM customer if the compressors are used in high-stress ultralow applications. This in turn affects the scope and nature of the freezer manufacturers' warranty to the customer.

Cause and effect

The challenges of maintaining reliability in an ultralow refrigeration system relate to the system as a whole, and most specifically to the compressor, compressor motor, and wrist pins integral to the design.

- Commercial air-conditioning compressors are not designed for ultralow temperature (ULT) applications. In ultralow circuits, these compressors are subjected to higher-than-normal operating pressures required to achieve and sustain evaporator temperatures. Operating pressures generate heat. These pressures demand more compressor motor torque to accommodate startup and to maintain ultralow temperatures, thus adding stress and potentially more heat into the system.
- Some ULT freezer manufacturers increase the compressor motor horsepower in an attempt to overcome these issues. If the total refrigeration system is not properly balanced, however, excess motor capacity simply adds heat to the system.
- Refrigeration oil required to lubricate internal compressor components can break down chemically over time, resulting in poor component lubrication, additional heat, and a reverse cascade effect of heat generating more heat.
- Operating conditions in laboratories, hallways, mechanical rooms, and repositories are less than ideal. Most freezer installations are compromised by lack of air conditioning in laboratories or hallways, low voltage at the freezer connection, voltage fluctuations and power surges, high ambient temperatures and lack of adequate ventilation, dust and particulate buildup on condenser fins surrounding condenser tubing, frequent freezer door openings, and poor technique such as introduction of large amounts of warm or room temperature product without prefreezing.
- Despite advances in refrigerant chemistry, oils, and lubricating additives, today's environmentally friendly non-CFC refrigerants are not as efficient as earlier CFC-based ozone-depleting refrigerants of the past.

SANYO compressor development

Since mechanically refrigerated ultralow temperature freezers were adopted into the mainstream scientific community in the late 1940s, research investigators have learned that storing biological materials at colder temperatures enhances cell viability by reducing metabolic activity. Biological products can be sustained for longer storage periods at lower temperatures provided protocols for sample preparation and pulldown to storage temperature match scientific methods.

A proprietary refrigeration compressor was developed specifically for ultralow freezer applications. Bypassing the commercial air conditioning sourcing model, **SANYO** (Bensenville, IL) has successfully tested and refined its own compressor to meet the physical challenges of ultralow temperature operation using

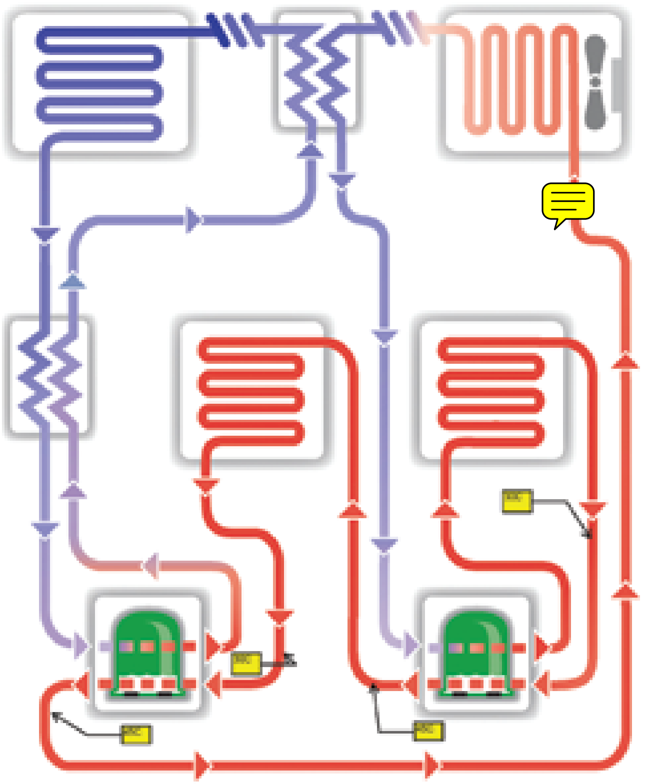

Figure 1 *The* **SANYO** *cascade refrigeration system employs two independent refrigeration circuits indirectly connected by an interstage heat exchanger. The company's proprietary integrated lubricating oil-cooling system (patent pending) automatically apportions the workload between compressors and permits both compressors to operate well within the expanded performance envelope. 1) Freezer cabinet with evaporator: The evaporator coil is strategically wrapped around the interior chamber and concealed within the composite wall of vacuum insulation panels and conventional foamed-in-place urethane insulation. 2) Low-stage heat exchanger: Energy is absorbed by the refrigerant gas and transferred to the low-stage heat exchanger to cool discharge gas. 3) Low-stage compressor: The compressor pumps refrigerant through the low-stage circuit. 4) Low-stage oil reservoir: High-stage refrigerant passes through the low-stage oil sump to cool lubricating oil, resulting in high-stage compressor energy being used to minimize the workload on the low-stage compressor. 5) Interstage heat exchanger: Energy is transferred to the high-stage circuit. 6) Low-stage capillary tube: Liquid refrigerant under pressure is passed through the capillary tube where it flash-evaporates in the low-stage evaporator to absorb energy (heat) from the product stored in the freezer. 7) High-stage compressor: The compressor pumps refrigerant through the high-stage circuit. 8) High-stage oil reservoir: High-stage refrigerant passes through the high-stage sump to cool lubricating oil en route to the low-stage compressor through the air-cooled precondenser. 9) Air-cooled precondenser: Removes energy (heat) from the high-stage refrigerant en route to the low-stage compressor. 10) Main condenser and motor/fan assembly: The motor/fan assembly blows ambient air across condenser coils to move energy (heat) from the high-stage refrigerant to the ambient environment. 11) High-stage capillary tube: Liquid refrigerant under pressure is passed through the capillary tube where it flash-evaporates in the interstage heat exchanger to absorb energy (heat) from the low-stage refrigerant circuit. 12) Air-cooled precondenser: Removes energy (heat) from the high-stage refrigerant en route to the high-stage oil reservoir. 13) High-stage refrigerant: Commonly available worldwide. A combination of R134a and R410a (Puron®) selected for optimum cooling performance in compliance with international environmental protection laws. 14) Low-stage refrigerant: Commonly available worldwide, R508. 15) Instrumentation (not shown): Temperature and pressure sensors throughout the high- and low-stage circuits transmit information to the Status 3 central controller for operation, monitoring, and interpretation.*

new, environmentally safe refrigerants. Collaborating with industry leaders in refrigeration chemistry, lubrication pathways, natural and synthetic oils, and cabinet insulation technologies, **SANYO** engineers have created a highly reliable ultralow temperature freezer based on the performance of compressors doing the work they were specifically designed to do.

Cabinet design prerequisites

Concurrent with refrigeration system research, **SANYO** pioneered the development of a composite cabinet wall based on a combination of conventional, high-density foamed-in-place insulation and new, state-of-the-art vacuum insulation panels (SANYO VIP®, U.S. patent no. 6,260,377) permitting a thinner wall profile and increased interior volume. This design optimizes use of available laboratory space by allowing more storage in the same footprint.

Since the original VIP design was introduced, company researchers developed proprietary improvements in the open cell panel technique, creating better matrices to support a sustainable vacuum, and giving manufacturing engineers more latitude in composite orientation with conventional foam. As a result, evaporator coils within the thin-wall cabinet are arranged for optimal interior uniformity and best heat removal (energy transfer), further reducing the burden on the cascade refrigeration system. A byproduct of the design permits a hot gas bypass to circulate around the peripheral edges of the cabinet door gasket, warming the gasket to mitigate the buildup of moisture to prevent ice formation or mold on external services (see *Table 1*).

Vertical component integration

The concept of vertical component integration is central to the company's entire product line. **SANYO** manufactures its own oil separators, circuit boards, and vacuum insulation panels, and designs its own compressors. This integrated supply chain ensures component quality from source to application, and permits the company to evaluate and improve its own components without third-party involvement.

Together with other refrigeration system components such as filter dryers, heat exchangers, condenser and evaporator tubing, metering devices, motor windings, and sophisticated microprocessor-based electronic controls, the company has created a holistic solution to biological preservation.

Key compressor components

Each component of the **SANYO** compressor has been electronically designed and modeled in stereolithographic beta form to exceed actual operating conditions. Pistons, connecting arms, valve plates, and wrist pins are designed to handle high load capacities. All testing is performed in a +35 °C ambient.*

Proper delivery and return of lubricants is a key factor in extending component life. Compressor motor sizing is predicated on refrigerant flow as well as energy required for initial pull-down, and then sustained ultralow temperature with reserve capacity. Motor windings are configured to accommodate fluctuating electrical supplies in many institutional settings. At the same time, **SANYO's** commitment to "green products" is expressed through more efficient motor operation with reduced energy consumption.

A better compressor yields better uniformity and improved reliability

Heat from multiple sources contributes to compressor wear. Heat is generated by compressors working to compress low-density refrigerants required in the low stage of the cascade loop. Additional heat is absorbed by room-temperature product placed into the freezer, as well as migration from the ambient environment.

In the **SANYO** research and development laboratory, prototype compressors were tested under harsh environmental conditions to exceed actual freezer use in typical laboratories. Because the company controls its own compressor design, all amendments and reengineering options were explored as needed, with new prototypes brought into test quickly. Life testing and tear-downs delivered critical data to **SANYO** engineers, permitting beta test results to be synthesized into the complete design program in support of the global ultralow freezer program.

Design mandate: reduce discharge temperature

The ultralow temperature compressor employs an orientation of conventional components to reduce discharge temperatures and compressor heat while using commercially available refrigerants and lubricants. Heat reduction results range from as low as 25 °C below previous **SANYO** compressors and more than 40 °C below leading-brand compressors used by numerous competitors.

At the heart of the solution is a compressor oil-cooling loop that reapportions the working heat byproduct between the low-stage compressor and the high-stage compressor. Due to low molecular weights in low-stage refrigerant formulations, low-stage compressors must work harder to achieve cooling targets. The **SANYO** technique uses existing lubricating oil to cool the low-stage compressor, passing the resulting heat load to the high-stage compressor, which, by design, is already doing less work.

By shifting a portion of the burden from the low stage to the high stage, the load on both compressors is balanced while reducing operating pressures and keeping heat loads and discharge temperatures well within tolerances required to prevent chemical breakdown of oils and refrigerants. As a result, refrigeration capacity is expanded and structural engineers have more latitude in strategic application of evaporator coils around the interior chamber, a key to temperature uniformity and, ultimately, to cell viability.

Applying the benefit

With lower compressor discharge temperatures and pressures, newer refrigerants can be more effective. Combined with VIP insulation, the migration of ambient

*Testing and evaluation: Consumer Advisory Performance testing and published data on **SANYO** ultralow temperature freezers is based on extensive testing in a +35 °C ambient to simulate worst-case conditions. When comparing performance of competitive ultralow freezers, it is important to establish and verify conditions under which tests are performed. Tests performed at temperatures below +35 °C may exhibit lower compressor discharge temperatures; these discharge temperatures are not typical of real-world conditions, however, and should be used with caution when evaluating new or replacement freezer selection. For summary information on test conditions contact **SANYO** (*Table 2*).

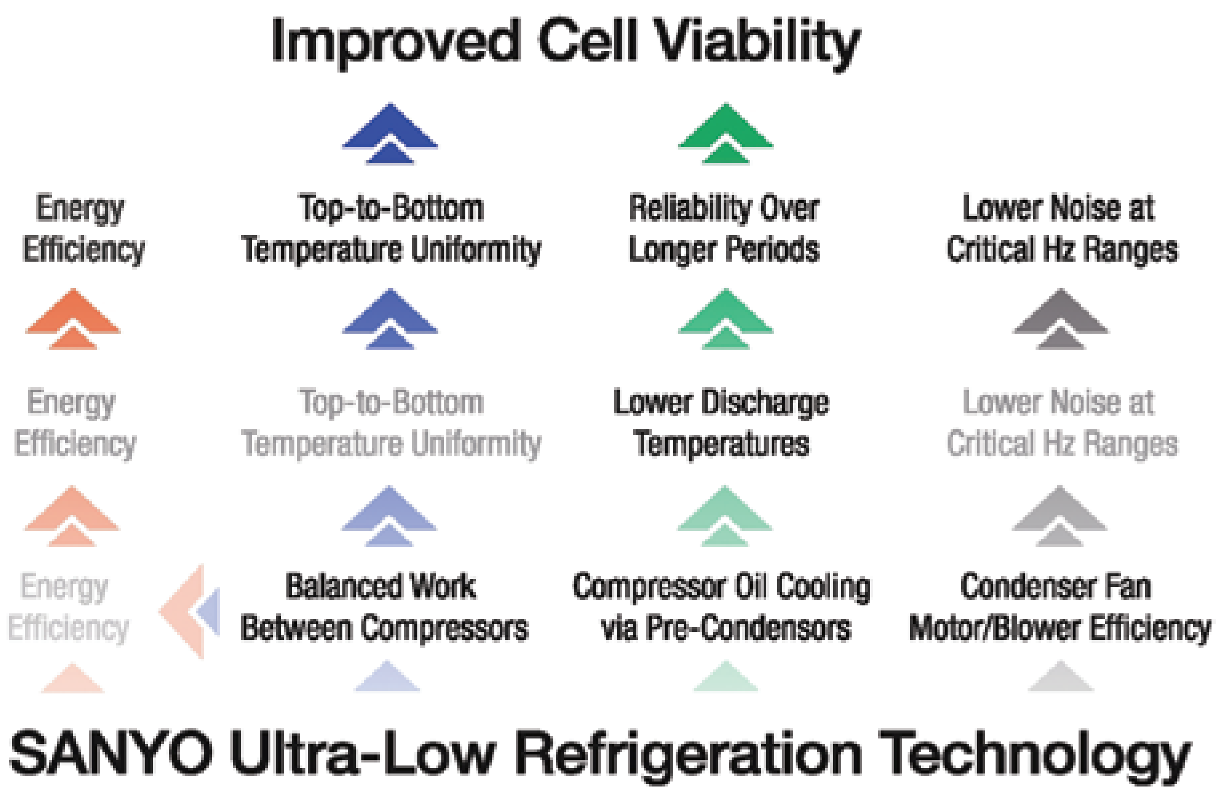

Figure 2 Ultralow refrigeration system benefits.

Table 1 Comparison chart: uniformity/noise

Performance	SANYO	Brand N	Brand R	Brand F
Temperature uniformity range (setpoint @ –80 °C)	4.2 °C	9.0 °C	12.5 °C	7.7 °C
Temperature, top of chamber (setpoint @ –86 °C)	–86.0 °C	–77.5 °C	–81.4 °C	–81.4 °C
Maximum warming point (10-sec door opening)	–75.0 °C	–34.3 °C	–57.7 °C	–76.8 °C
Noise level (1 meter from unit)	43.8 dB(A)	51.7 dB(A)	52.0 dB(A)	72.0 dB(A)
Storage volume efficiency (volume/sq. ft. floor space)	2.7 cu. ft./sq. ft.	2.67 cu. ft./sq. ft.	2.28 cu. ft./sq. ft.	2.19 cu. ft./sq. ft.

Table 2 SANYO ultralow temperature freezer testing protocol

Ambient temperature during test	+35 °C. Important: Performance testing and published data on **SANYO** ultralow temperature freezers are based on extensive testing in a +35 °C ambient to simulate worst-case conditions. When comparing performance of competitive ultralow freezers, it is important to establish and verify conditions under which tests are performed. Tests performed at temperatures below +35 °C may exhibit lower compressor discharge temperatures; these discharge temperatures are not typical of real-world conditions, however, and should be used with caution when evaluating new or replacement freezer selection. For summary information on test conditions contact **SANYO**.
Voltage range during test	Variable. For 220 V ac, 60-Hz models testing is conducted over voltage ranges starting as low as 202 V to simulate brown-out conditions typical of real-world installations.
Freezer load during test	Variable. Thermal mass of a fully loaded freezer at equilibrium under normal ultralow temperatures yields the best performance data. **SANYO** freezers are tested under empty, half-load, and full-load conditions.

heat from the laboratory to the interior is minimized. Evaporator wrapping concealed within the composite wall is wrapped around the interior chamber to achieve best energy transfer and leverage common physical properties of cold air density within the storage area.

Smart refrigeration monitoring system

While compressor improvements have led to more efficient refrigeration performance, **SANYO** engineers have tapped the company's extensive resources in electronics and controls to develop the Status 3 control, alarm, and security system. More than just a controller, the system collects internal data from waypoints deep within the cascade refrigeration system, and processes this information by comparing to normative values written to the onboard algorithm. This continuous, self-diagnostic protocol is automatic. If values range beyond those written to the factory-based performance permissions, the freezer will display an advisory signal on the main control panel.

If a condition self-corrects (as most do in highly fluctuating environments), the signal will switch off. If the condition persists, however, the signal will notify the user that a professional assessment of freezer performance is required. Often, this assessment can be initiated by a quick query of on-board data from the controller, conducted by in-house facilities maintenance personnel familiar with standard ultralow freezer operations.

Status 3 functions

1. *High ambient conditions*
    - The Status 3 system tracks high ambient (room or hallway) conditions that can occur periodically, but are not recommended for long-term operation. These usually constitute ambient temperatures at or above +35 °C. Repeated excessive ambient readings will activate the warning and the user must investigate the reason for the high ambient condition. The **SANYO** freezer will continue to function, but subjecting the freezer to extreme ambient conditions results in longer refrigeration run time and higher energy costs.
2. *Low voltage*
    - Low voltage is common in many laboratories due to increased power demand in clinical and research environments, drug discovery, storage, and processing. These conditions are most common in older institutions or those that have been retrofitted for laboratory use.
    - Often, freezer users mistakenly assume that proper power (120 V or 208/230 V) is readily available and sustainable at the wall electrical outlet. Often, however, supply voltage is erratic and usually lower than desired for proper freezer operation. The Status 3 detects low voltage and warns the user through the freezer control panel monitoring system. When this notification occurs, building maintenance or facilities engineering personnel should be contacted to investigate the issue.
    - To protect the valuable stored product, **SANYO** ultralow freezers with voltage enhancement systems will automatically correct the voltage through an internal transformer and boost the voltage to the proper level.

Run time data

High ambient temperatures, numerous or prolonged door openings, and introduction of warm or room-temperature product into the freezer storage compartment can cause prolonged refrigeration system run time. The Status 3 monitors compressor run time and performs diagnostics based on ambient temperatures, door openings, voltage, and other usage factors. If the low-stage compressor run time is inordinately high, the Status 3 will notify the user that the system and installation should be reviewed. These calculations are based on the following:

- Length of time from previous door opening
- Operating time below setpoint
- Ambient temperature.

In simple terms, the freezer senses when it is overloaded or operating under stress. The Status 3 warning system will alert the user of this condition in advance of any pending performance issues.

Compressor run time/power consumption

The **SANYO** ultralow system employs a high-stage and low-stage compressor controlled by the Status 3 microprocessor control system. By design, the high-stage compressor runs 100% of the time, permitting the low-stage compressor to cycle on demand for cooling from the interior chamber, reducing high head pressures on the low-stage system, permitting easier startup and reducing energy demand. Since conventional cascade refrigeration systems cycle both systems on and off, the high- and low-stage compressors must "step start" nearly simultaneously or with a slight delay. This requires a high power demand for two systems to start, and can trip a circuit breaker during periods of high electrical demand.

The phenomenon of high-temperature "in-rush currents" over time can weaken and degrade compressor windings, resulting in compressor failure. **SANYO** compressors feature oversized windings designed to anticipate and accommodate in-rush currents within the normal performance envelope to mitigate compressor degradation due to frequent startups.

Thinking green, thinking safe*

SANYO is conscious of the need to protect our environment and conserve energy. As a corporate pioneer in life science laboratory equipment and appliances, and as a global source of solutions ranging from energy management to solar power and alternative energies, the company remains committed to providing the best possible laboratory equipment for research and clinical needs. This commitment was demonstrated when it took the initiative to revamp and redesign newer refrigeration systems that would employ new, environmentally friendly refrigerants throughout the laboratory without compromising performance.

1. *CFC-free refrigerants*
   - **SANYO** was the first ultralow freezer manufacturer to employ non-HCFC R508 low-stage refrigerant, now recognized as today's industry standard and widely available. This nonproprietary refrigerant is available to refrigeration service professionals on the open market.
   - The high-stage refrigeration system is a mixture of R134a and R410a (Puron), available to refrigeration professionals on the open market as well.
2. *RoHS compliance*
   - In 2006, RoHS (Restriction of Hazardous Substances) legislation (EU Directive 2003/95/EU) became effective. RoHS relates to the restriction of hazardous substances and reductions in environmental pollution.
   - Through RoHS legislation, the EU and other participating countries are banning toxic substances in electrical equipment such as lead, cadmium, mercury, chromium 6+, polybrominated biphenyls (PBBs), and polybrominated diphenyl ethers (PBDEs).
   - While compliance with this legislation has posed a significant challenge for **SANYO**, all of its ultralow freezers and components are now 100% compliant to RoHS standards.
3. *Electrical standards*
   - All **SANYO** products, including ultralow temperature freezers, are tested and certified by Entela[2] NRTL (National Recognized Testing Laboratory) to ensure compliance with U.S. and international standards for electrical safety prescribed in 29 CFR 1910.7(c). **SANYO** has selected Entela for independent testing to accelerate testing on new products while maintaining the highest standards for quality, safety, and performance.
4. *Noise reduction*
   - Ultralow freezers are often located within research and hospital laboratories or production facilities. Users prefer close proximity for easy access to valuable stored products.
   - If operating noise from refrigeration compressors is excessive and/or compounded by installation of multiple freezers in adjacent locations, the working environment is severely compromised.
   - **SANYO** has included advanced noise abatement in all contemporary ultralow freezers and noise reduction levels are well below those of competitive freezers. (Data are available upon request.)
5. *Inventory management*
   - Those familiar with the technical design of the **SANYO** ultralow freezer can draw a quick connection between lower compressor discharge temperatures and better, more efficient inventory management.
   - Because benefits of the **SANYO** compressor design extend to evaporator tubing surrounding the interior chamber, and the interior chamber is part of the thin-wall composite based on the patented VIP cabinet, the company can offer more useable storage volume within the same square footage of floor space than competitive models.
   - The concept of high-density storage is enabled by advances in **SANYO** compressor design. The cost per cubic foot (or liter) of interior storage space is significantly lower in a **SANYO** ultralow freezer, generating immediate return on investment based on first costs, operating costs, and maintenance costs over time.
   - Additionally, the placement of evaporator surfaces within the cabinet walls achieves documented ultralow temperature uniformity, thereby permitting investigators more freedom in placing valuable cell lines and biologicals within the interior cabinet, and ensuring uniform cell viability when harvesting products from the ultralow archive.

Conclusion

By apportioning the oil-cooling function between specially designed **SANYO** compressors, and by employing cooler oil to minimize compressor operating temperatures, the **SANYO** ultralow temperature freezer refrigeration system is balanced to decrease component stress, increase system longevity and reliability, and improve temperature uniformity necessary for better cell viability regardless of where the specimen is stored within the chamber.

References

1. *Fed. Reg.* vol. 71, no. 82/Fri., Apr. 28, 2006/Notices Re: Department of Health and Human Services, National Institutes of Health, First-Generation Guidelines for NCI Supported Biorepositories. Agency: National Institutes of Health (NIH), National Cancer Institute (NCI).
2. *Fed. Reg.*, Entela, Inc., Expansion of Recognition. 64:11501-11502; publ. date: 03/09/1999; publ.: notice; *Fed. Reg.*: 64:11501–11502; standard number: 1910.7; 1919.7; title: Entela, Inc., Expansion of Recognition. U.S. Department of Labor, Occupational Safety and Health Administration, docket no. NRTL-2-93.

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***SANYO** has established a corporate-wide initiative, Think GAIA, to emphasize its commitment to energy conservation and environmental integration. GAIA, which stands for "the living earth," suggests that the earth is a green organism where mankind and all livings things exist in harmony. By treating the earth as a living organism, **SANYO** is creating products needed to promote harmony with the planet. In practice, GAIA is a threefold approach consisting of action on environmental, energy, and lifestyle fronts. In each of these areas, **SANYO** is redefining conventional ideas and taking advantage of unique technological resources to propose global solutions for the earth and all living things.