PHONONIC

White Paper

Phononic Solid-State Cooling Technology

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Executive Summary

Phononic's sustainable thermoelectric technology is transforming applications that require refrigeration and freezing. Thermoelectric devices (also known as thermoelectric coolers, or TECs) offer inherent advantages over traditional vapor-compression refrigeration: they are smaller, quieter, more reliable, vibration-free, and can heat as well as cool. Phononic's unique technology and designs enable groundbreaking uses of TECs for applications that were previously only addressable with compressor-based systems, or in some cases were not possible at all. Phononic's approach combines development of high-performance thermoelectric devices and heat accept and reject systems, control systems design expertise, a deep understanding of market trends, and a focus on sustainability including clean refrigerants. This approach has fueled the development of breakthrough products in diverse industries including food and beverage, life sciences and healthcare, and optoelectronics. Companies can now "Design with Phononic" to bring those benefits to other industries and applications, enabling transformation of their existing products or introduction of innovative new ones.

"Phononic's unique technology and designs enable groundbreaking uses of TECs for applications that were previously only addressable with compressor-based systems."

Solid-state Cooling is Inevitable

Solid-state technology has transformed our lives and created completely new industries. Microprocessors have revolutionized the way we process information. Smartphones have transformed how we communicate. Solid-state LEDs are replacing inefficient, less-durable older lighting technologies. In the same way, the compelling advantages of solid-state technology will inevitably transform refrigeration – which currently relies on antiquated, noisy and bulky mechanical compressors.

What is Solid-state Cooling?

Solid-state cooling is based on thermoelectric coolers (TECs), which move heat using the Peltier effect: passing a current through the device causes it to transfer heat from one side to the other.

Within each TEC are many "legs" made of semiconductor materials (Figure 1). These legs move heat using carriers, which may be negatively charged electrons or positively charged holes. The legs are arranged in pairs, consisting of an n-type semiconductor leg (in which the carriers are electrons) and a p-type semiconductor leg (in which the carriers are holes). The legs are electrically connected in series in such a way that when current is applied to the TEC, the carriers all move in the same direction, transferring the heat from one side of the device to the other, as shown in Figure 1.

Figure 1. The Fundamentals of Thermoelectrics, University of Munich; https://www.nano.physik.uni-muenchen.de/nanophotonics/_assets/pdf/f1/K3_Thermoelectrics.pdf

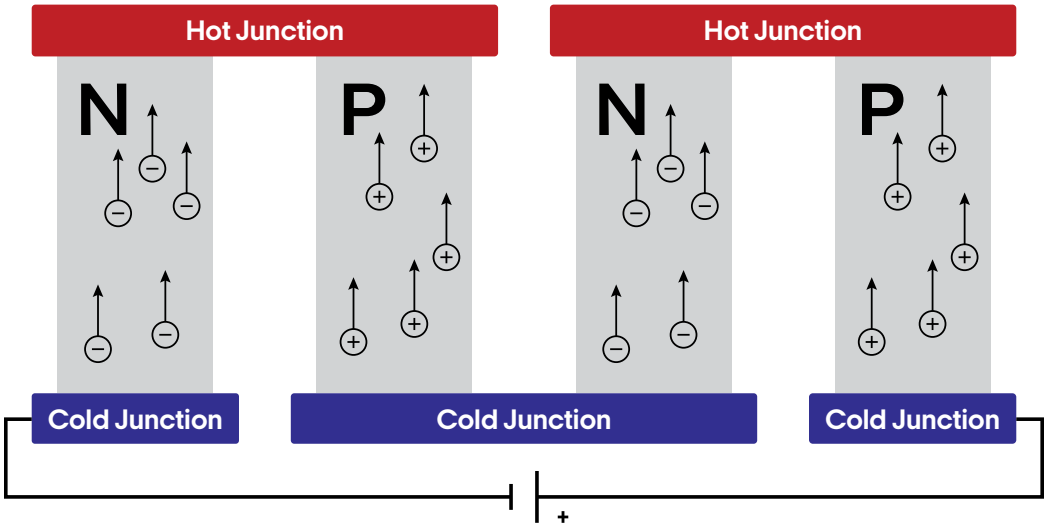


Figure 1. Semiconductor legs within each thermoelectric device transfer heat . The legs are sandwiched between thermally conductive ceramic plates, as shown in Figure 2. These plates absorb heat from a source (such as the interior of a refrigerator) and reject it to the outside world. The amount of heat that a device can transfer, and its energy efficiency, depend largely on the materials used in the legs and ceramic plates; with careful design and advanced semiconductor materials, it is possible to greatly increase performance and power efficiency.

Advantages of Solid-state Cooling

Solid-state cooling offers several advantages over the traditional vapor-compression method of refrigeration, which relies on mechanical compressors to drive a cycle of condensing and evaporating a refrigerant.

Solid-state cooling is extremely quiet and vibration-free, since thermoelectric devices have no moving parts; in contrast, compressors are noisy and cause vibration, which introduces operational limitations across many applications.

And because of the lack of moving parts to fatigue and wear out, high-quality solid-state devices last much longer and require less maintenance.

Solid-state cooling devices are tiny compared with bulky compressors. The small size provides several advantages. It frees up space, so solid-state refrigerators have larger capacity than similarly sized compressor-based units. Solid-state cooling makes it possible to build products that are highly compact, with smaller footprints. TECs can also be used in applications that simply don't have space for compressors, such as optoelectronics.

Finally, a unique property of thermoelectric devices is that they can be used either to heat or to cool; simply reversing the polarity causes heat to flow in the opposite direction. Therefore, unlike compressors, they can be used for applications that require both heating and cooling.

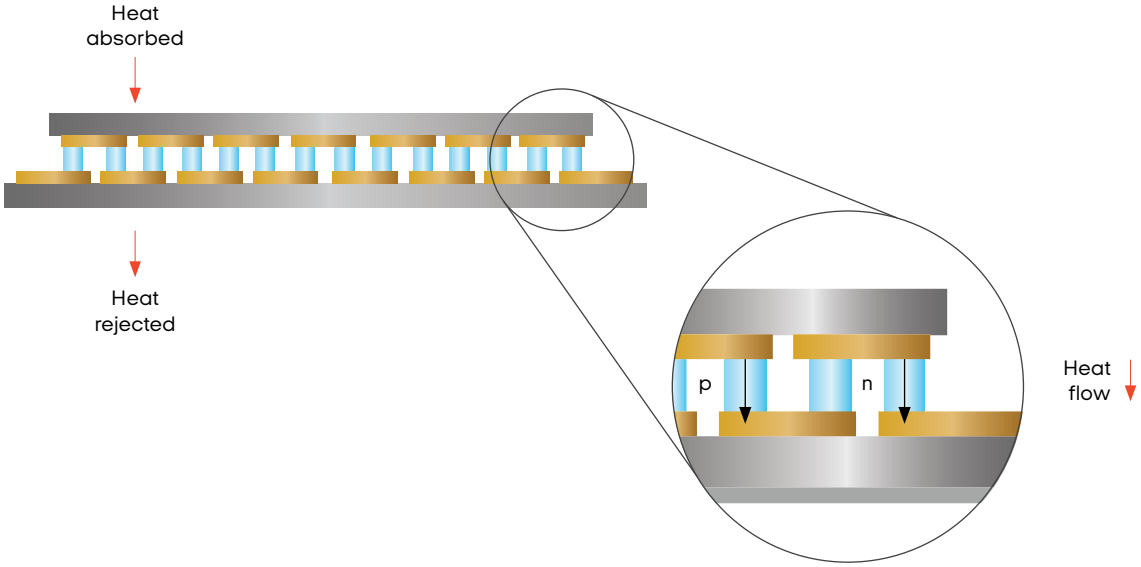


Figure 2. A thermoelectric device, showing legs and plates

Phononic Sustainable Technology Enables Groundbreaking Applications for Thermoelectric Cooling

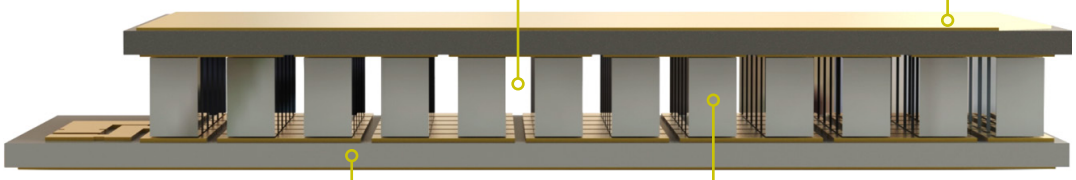
Despite the enormous potential value of thermoelectric technology, its applications in the past have been limited by the performance and efficiency of older products. Phononic's unique technology and system designs overcome those limitations, enabling groundbreaking uses of TECs to improve applications that were previously only addressable with compressor-based systems, or in some cases were not possible at all.

Phononic's approach combines several unique strengths:

- Phononic manufactures the highest-quality thermoelectric devices and combines them with advanced heat accept/reject systems.
- Deep design expertise enables Phononic to successfully apply thermoelectric technology to different applications with widely varying needs.
- Phononic continually analyzes and anticipates market trends in order to bring the right technology to market at the right time.
- A focus on sustainability, including clean refrigerants, supports growing demand for sustainable products from consumers and businesses.

Design and Manufacture of High-performance Thermoelectric Devices and Systems

Figure 3. Phononic's approach to TEC manufacturing enables designs, performance levels and annual part volumes not attainal by competitors



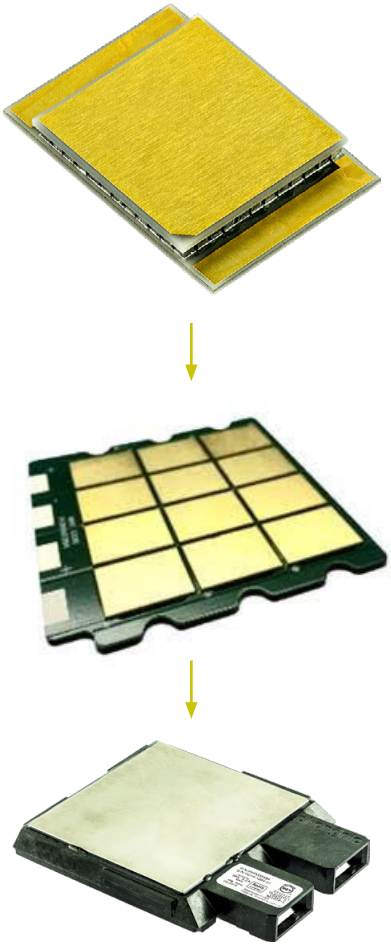
Phononic's vertically integrated design and manufacturing capabilities are key to the production of high-performance thermoelectric devices and systems. Phononic controls the manufacturing process at all levels, from raw materials and wafer processing through device manufacture and assembly. Manufacturing is conducted in ISO 9001-certified facilities within the U.S.

High-performance TECs. Manufacturing starts with the highest-performance raw materials. Each thermal and electrical interface of the device is then engineered to eliminate parasitics and deliver superior system-level performance. These innovations produce industry-leading heat transfer and efficiency, creating a significant competitive advantage and a barrier to market entry for other companies (Figure 3).

Phononic solid-state heat pump. To provide greater heat transfer for specific applications, Phononic combines multiple thermoelectric devices into a single, rugged package. Thermoelectric devices operate most efficiently at low current, so the most efficient way to scale cooling capacity is to combine multiple devices operating in parallel, with each device drawing a low current.

Phononic combines multiple devices into a cartridge, then adds packaging to create a Phononic solid-state heat pump (Figure 4). Solid-state heat pumps are rugged, reliable and easily serviced; in the unlikely event of failure, a maintenance technician can simply unplug the package and replace it.

Figure 4. Phononic combines TECs into a cartridge, then adds packaging to create a rugged, reliable and easily serviceable Phononic solid-state heat pump



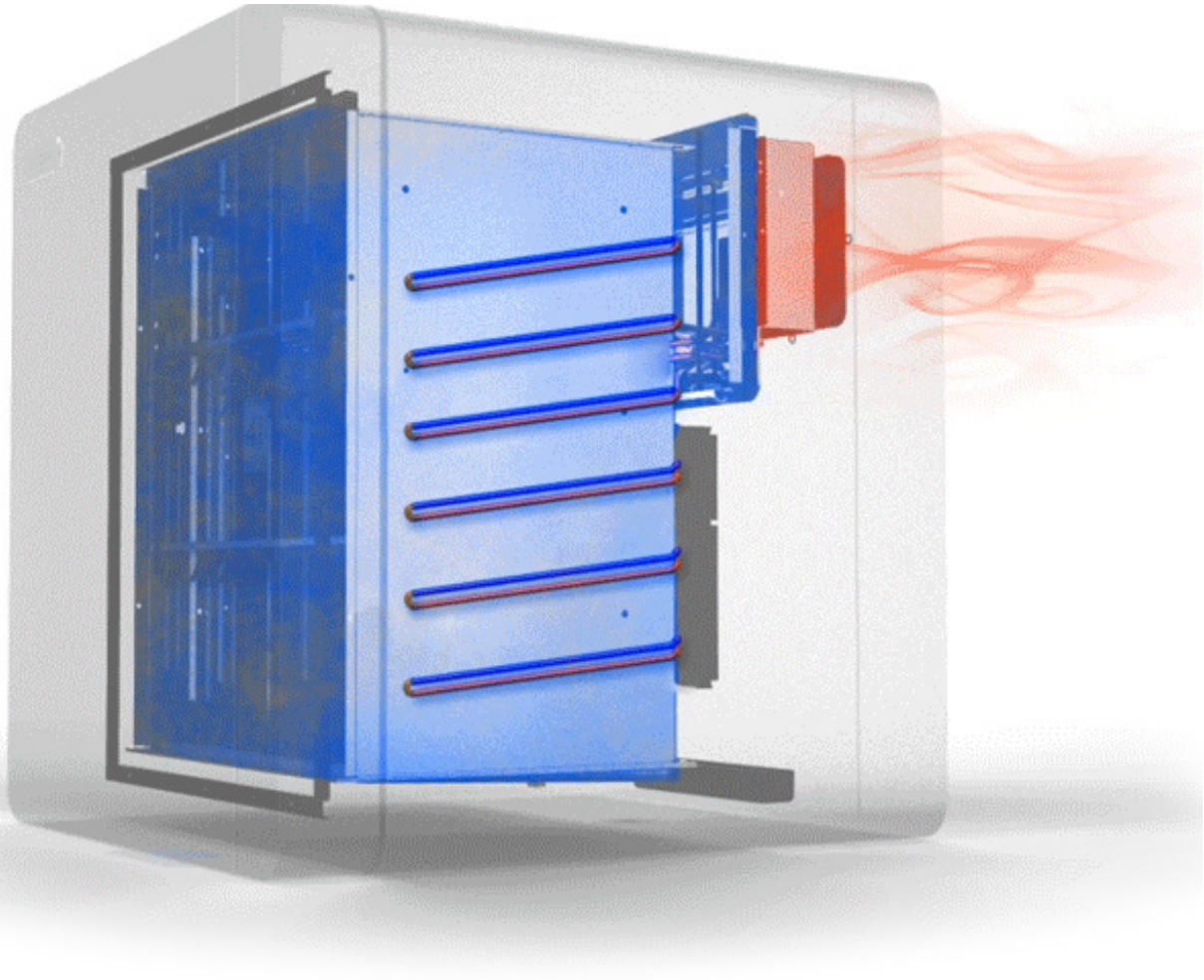


Figure 5. Phononic heat accept/ reject system: Thermosiphons and heat exchangers

Heat accept/reject systems

Phononic provides very uniform, stable cooling in refrigerators and freezers by combining thermoelectric devices with proprietary heat exchange systems that accept heat from the interior of the appliance and reject it to the outside world.

To accept heat, Phononic uses Thermosiphons, which are refrigerant-filled tubes embedded in the walls of the refrigerator (Figure 5). The refrigerant is typically CO2, maintained under moderate pressure during operation, which enables the substance to exist in a part-liquid, part-gas state. The Thermosiphons are angled downward from the thermoelectric devices so that cooled liquid refrigerant flows down the tubes due to gravity, cooling the interior of the appliance. The refrigerant evaporates as it absorbs heat from the appliance's interior. As the resulting gas fills the upper part of the Thermosiphon, it is cooled by the thermoelectric devices until it condenses and repeats the cooling cycle. The thermoelectric devices transfer the absorbed heat to a heat exchanger, which rejects it to the outside world. As long as the thermoelectric device is powered on, heat is pumped continually and automatically, without the need to recompress the refrigerant during the cooling cycle.

Appliances built with Phononic's technology produce a uniform, low level of heat. In contrast, the heat output from compressor-based systems tends to fluctuate widely, greatly increasing when the compressor is operating; this presents problems in many applications and limits where compressor-based refrigerators and freezers can be placed.

Control and monitoring technology

Phononic controls and monitors appliances through software and electronics, including sensors. This allows precise control, operational flexibility, and information-gathering that was previously impossible.

For example, a single appliance can be configured to operate either as a freezer or a refrigerator by simply reconfiguring its software. Appliances based on Phononic technology also can maintain very precise temperatures much more efficiently than compressors, by continuously varying the current supplied to the solid-state heat pump to maintain a target setpoint.

Phononic appliances can continuously gather data via sensors that not only monitor temperature but also when the door is opened. This creates a new paradigm that expands the value of a refrigerator or freezer; in addition to providing cooling, it becomes an information-gathering device, generating data that can be used for multiple business purposes.

Key Benefits of Phononic Technology

Phononic's combination of technologies and expertise deliver a range of economic and environmental benefits that are not achievable with other systems.

Versatility: from boiling to freezing. Phononic technology is extraordinarily versatile. As described above, a single appliance can operate either as a refrigerator or a freezer by simply reconfiguring its software and set point. Furthermore, the same solid-state heat pump can be used to warm as well as cool. Phononic also brings refrigeration, freezing and heating to smaller appliances, because thermoelectric technology is so much more compact than compressors. And with Phononic Solid-state heat pumps, products are rugged enough to be portable.

Reliability and serviceability. Phononic technology is exceptionally reliable and serviceable – qualities that translate into lower total cost of ownership (TCO). In internal testing, Phononic solid-state heat pumps have demonstrated time-to-failure cycle counts that are 100x higher than traditional TECs, which implies several years or even decades of reliable operation. Higher reliability means lower maintenance costs and longer product life. And if a Phononic solid-state heat pump does experience a problem, a technician can simply plug in a new one in a few minutes on site. When servicing a Phononic solid-state heat pump or control system, there's no need to recharge or replace the refrigerant. That's very different from the situation with compressor-based systems; repair is a highly skilled and often lengthy job, and because compressors are integrated tightly into the cooling system it's often more cost-effective and practical to replace the entire appliance or haul it away for off-site repair.

Freedom of placement: take the product category to the customer. Because Phononic appliances provide quiet, vibration-free operation and low heat output and have low power requirements, they can be located almost anywhere

— in contrast to compressor-based systems, which cannot be installed in locations where noise, vibration or heat present problems. That means companies can place refrigerated products where they are most convenient and accessible for the user. In retail environments, refrigerated and frozen products can be positioned at checkouts rather than requiring consumers to detour to the cold aisle; in hospitals, supplies can be stored at the point of care, increasing efficiency for staff and convenience for patients. Furthermore, with low and consistent DC power demands, appliances made with Phononic solid state heat pumps do not need a dedicated circuit, eliminating the need for a dedicated power drop for refrigerator and freezer placements. Products can even be used in mobile applications when powered by a battery.

Extremely stable and uniform cooling. Products based on Phononic technology provide exceptionally uniform, stable cooling, due to the combination of Phononic thermoelectric devices, proprietary heat accept/reject systems, and sophisticated control electronics and software. This is important for many applications. In life sciences applications, for example, maintaining drugs, vaccines and other products within a narrow temperature range is essential.

Supply chain simplification. Phononic's solid-state heat pumps can be deployed anywhere in the world, making it easier for manufacturers to build a single product and sell it globally; a universal power supply is all that is needed. With compressor-based systems, in contrast, manufacturers need to build different models for 50Hz and 60Hz mains frequencies. The versatility of Phononic's technology also helps to simplify the supply chain, since a single product can operate either as a freezer or a refrigerator. With Phononic, suppliers can build fewer different models and configure them as needed based on customer demand.

Insights into user behavior and product usage. Because Phononic appliances continuously gather data via temperature and door-opening sensors, businesses can gain new insights into user behavior and product usage, and use that information to increase revenue and profitability. For example, retail-sector companies can use the information to better understand consumer behavior, maximize sales, and monitor whether the product performs as intended.

Environmental Benefits and Sustainability: Clean Refrigerants and Power Efficiency

The environmental impact of refrigerants is a major concern for businesses and consumers.

When selecting the ideal refrigerant, there are three key environmental goals: the refrigerant should be non-toxic, non-flammable and have low global warming potential (GWP). Phononic has selected the only refrigerant that meets all three requirements: carbon dioxide (CO2), which is non-flammable, non-toxic, and has a low GWP value of 1. Other refrigerants, including those used in today's compressor-based systems, fail to meet at least one of these three requirements:

- Hydrofluorocarbons (HFCs) have very high GWP values; some are as high as 2,000-4,000. Manufacturers are transitioning from those products to other HFCs, but even these have relatively high GWP: R-32 (Difluoromethane), for example, has a GWP of 677.
- Hydrocarbons such as propane, isobutane, and propylene have lower GWP values than HFCs but are highly flammable, which is a concern in many applications.
- Ammonia's toxicity makes it unsuitable for many applications, such as indoor commercial or residential uses.

It should be noted that Phononic products, including food and beverage refrigerators and freezers, use extremely small amounts of CO2. It's also important not to confuse the Phononic solid-state cooling approach with compressor-based CO2 transcritical systems, which use CO2 stored at exceptionally high pressures — potentially increasing operating hazards — and involve inherent losses in efficiency.

Best-in-class power consumption

Phononic technology delivers energy consumption that is best-in-class among thermoelectric systems, and competitive with compressor systems. This made it possible to build the first Energy Star certified medical-grade refrigerator.

Life Sciences and Healthcare

Many applications in life sciences and healthcare require extremely stable and uniform temperature control, high efficiency, quiet operation and reliability. Because Phononic technology offers precisely those qualities, it is an extremely good match for these applications.

Phononic initially focused on the large and expanding market for laboratory and medical refrigerators and freezers, which is projected to grow at 4.6% annually to reach $3.75 billion by 2021. These products are used to store a wide variety of substances that must stay within a narrow temperature range at all times, including medicines, vaccines, breast milk.

The specifications are challenging: refrigerators must provide cooling that is accurate, stable and extremely uniform, to ensure that valuable and life-saving products such as vaccines and insulin are not destroyed by overheating or inadvertent freezing. The trend toward providing cooling at the point of care – to improve efficiency, patient satisfaction, and speed of response– requires products that are quiet and can be placed anywhere. There's increasing demand for sustainable solutions, and life sciences and healthcare companies also need products that support the ever-growing number of regulations.

We produced the world's first medical-grade solid-state refrigerators, which provide unmatched cooling performance while using 30% less energy than a conventional medical-grade refrigerator. Our products achieved the first-ever ENERGY STAR rating for a solid-state refrigerator. Key advantages include:

- **Unmatched stability**. Compressor-based refrigerators oscillate as much as 5°C, creating constant temperature fluctuations that can damage or destroy their contents. With constant monitoring and adjustment, Phononic's oscillating temperature range is only 0.5 °C, creating a safe and stable environment for the most challenging applications, such as the tight temperature ranges recommended by the CDC and FDA for breast milk storage
- **Temperature uniformity**. Phononic essentially eliminates warm and cold spots within the refrigerator. With as little as one degree of temperature variation, the entire space can be used for temperature-sensitive products. The stability and uniformity reduce the risk of inadvertent freezing, which is the biggest danger to vaccines and insulin.
- **Ultra-quiet operation**. By eliminating compressors, Phononic reduces operating noise to less than 35 dBA, which means refrigerators can be located close to patients and staff.
- **More space**. Elimination of bulky compressors means Phononic refrigerators offer up to 40% more space than conventional refrigerators.
- **Cleanroom ready**. Phononic's refrigerators are cleanroom ready without the need for special ventilation to achieve compliance with USP <797> and USP <800> regulations for handling hazardous drugs.
- **Efficient refrigeration**. Our innovations helped us achieve the first ENERGY STAR rating for a solid-state refrigerator.

Recognizing the significant market impact of Phononic's refrigerators, Thermo Fisher Scientific, a world leader in medical, life sciences and chemical industries, became the strategic distributor for the products, and now provides them to healthcare facilities, laboratories and other organizations worldwide.

New opportunities in life sciences and healthcare

Phononic's technology is well positioned to solve challenges in many other life sciences and healthcare applications that require precise temperature control – including those that require heating as well as cooling. **These include:**

- **Biotech manufacturing.** Single-use bioreactors, used in the production of pharmaceuticals and other products, require solutions that can both heat and cool, quickly and with precise temperature control. For example, some processes require that bioreactors are heated to a specific temperature to maximize cell growth, then rapidly cooled. Current thermal control products are typically bulky add-on systems that can double floor space requirements and have reliability issues. Phononic technology is smaller, highly reliable, and can be integrated directly into the bioreactor.
- **Incubators for platelets and cell/tissue growth.** Demand for incubators is growing rapidly, driven by applications including cancer and stem-cell research and tissue engineering. Phononic solid-state technology delivers the needed temperature precision with improved energy efficiency and space savings without the use of a compressor.
- **Molecular diagnostics.** As healthcare technology trends towards solutions that are smaller, faster and closer to the patient, Phononic's technology is a perfect foundation for portable molecular diagnostic solutions. Molecular diagnostic systems are used to detect dangerous infectious diseases, tumors and hereditary diseases, using rapid thermal cycling to amplify key segments of DNA that are used to identify the disease. Portable systems can be used in the field for early detection of dangerous disease outbreaks before they spread. Phononic's technology provides greater reliability, uses less power, and enables faster cycling -- so tests can be completed faster.

- **Pharmacy automation.** Automated drug dispensers are used by many pharmacies to improve efficiency and patient safety. Phononic technology enables a refrigerated drawer to be built directly into the dispenser, so technicians don't need to access a separate refrigerator for drugs and other products that require temperature control. A key advantage is that the same controls, security and workflow can be applied across all dispensed products, including refrigerated drugs.

Phononic's advantages of small size, portability, and ruggedness also open up new applications that are not possible with compressor-based products. For example, portable refrigerators could transport medicines to emergencies or to patients in their homes, replacing less-effective methods such as insulated containers or storing products on ice.

"Phononic solid-state technology delivers the needed temperature precision with improved energy efficiency and space savings without the use of a compressor."

Food and Beverage

In retail, Phononic technology is a game-changer. Phononic creates new revenue opportunities by enabling retailers and convenience stores to stock refrigerated and frozen items in high-traffic areas anywhere in the store, including the checkout counter.

Traditionally, refrigerated and frozen foods and beverages have often been restricted to cold aisles, deep ice chests and other out-of-the way locations, because of the heat, noise and vibration that compressor-based systems produce.

With Phononic technology, retailers and suppliers are freed from those restrictions. Phononic merchandising refrigerators and freezers are quiet, vibration-free, and produce a much lower and more uniform level of rejected heat. That means refrigerated and frozen items can be placed wherever they drive the most sales, without impacting nearby merchandise. For example, they can be placed at checkout, aisle endcaps, near deli and bakery sections or in any section of the store that has high traffic or impulse purchase opportunities. This enables a dramatic transformation of store layouts, which are currently designed around the constraints posed by compressor-based refrigerated systems for merchandise like ice cream and smoothies. Through freedom of placement, Phononic's solid-state technology creates new revenue opportunities, primarily due to enhanced in-store brand visibility.

Freedom of placement also plays into consumer trends as consumers today are busy, on the go and seek new foods, flavors and treats. They may not have the time or even the desire to see products in the back-of-the-store refrigerators and freezers. In Phononic's Store of the Future survey, 46% of consumers said grocery stores should have more frozen and refrigerated items at checkout. Placing items at checkout is also a great way to drive impulse purchases and get consumers to try new products.

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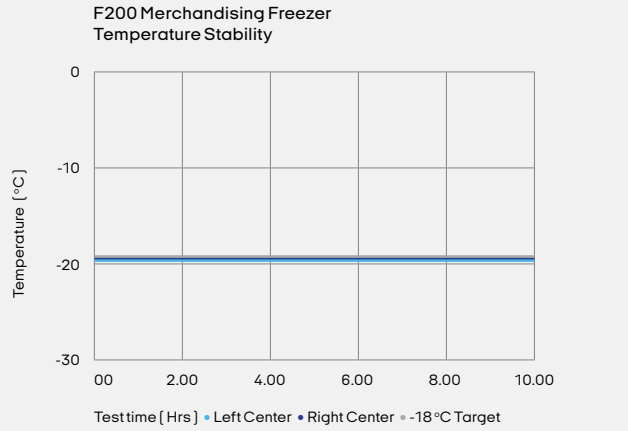

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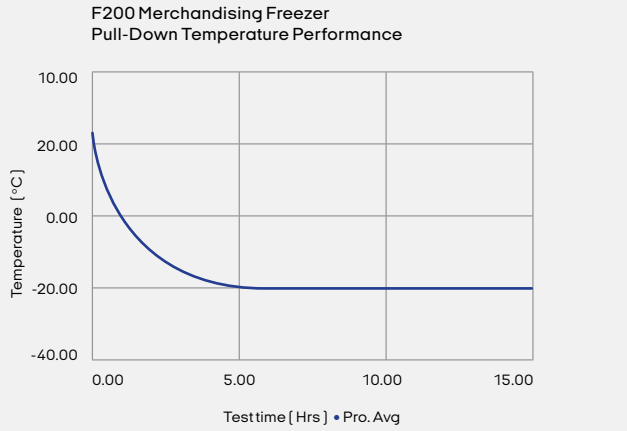


Figure 6. Phononic's Merchandising Refrigerator meets temperature pulldown requirements of major beverage manufacturer and can maintain extremely stable, uniform temperature at multiple firmware-controlled setpoints.

Phononic's refrigerators and freezers

Phononic offers food and beverage refrigerators and freezers designed to fit into a wide variety of retail environments.

Product architectures. At the core of Phononic's refrigerators and freezers is the solid-state heat pump, which operates within two different product architectures. Both architectures use CO2 as the primary medium to transfer heat from the cavity to the solid-state heat pump, which then rejects heat to the exterior via a heat exchanger.

The first product architecture is a hybrid cold wall system and forced air system, which is used in the Phononic C600 Merchandising Refrigerator. The cold wall heat accept system consists of copper tubes (Thermosiphons) inside both side walls. The tubes contain CO2 refrigerant that is used to extract heat from the cavity and move it to the solid-state heat pump, which pumps the heat to the exterior using the heat reject system. The forced air component of the system is a fan at the top of the unit, which provides air circulation to help drive industry best-in-class temperature stability and uniformity. The second product architecture uses a cold wall system without the fan. It is typically used for smaller cavities. The Phononic F200 Merchandising Freezer (Figure 7) is based on this architecture. Due to the smaller cavity and absence of compressor duty cycles, the F200 Merchandising freezer is able to attain a freezer set point of -18°C.

Another key distinction between solid-state cooling and compressor-based appliances is the ability to vary set point temperatures. This also makes it possible to reconfigure a single commercial appliance as either a refrigerator or a freezer. Traditional compressors are custom-designed to operate either in refrigerators or in freezers; a single compressor cannot do both. In contrast, with firmware-controlled temperature set points, the F200 Merchandizing Freezer can convert to a C200 Merchandising Refrigerator by changing the firmware.

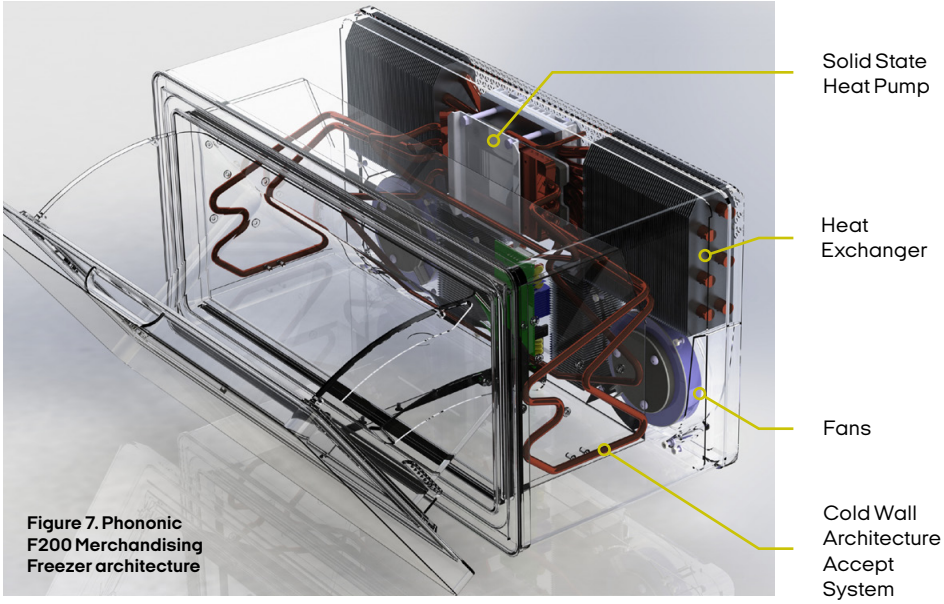


Figure 7. Phononic F200 Merchandising Freezer architecture

Lower TCO

Based on solid-state technology, Phononic technology is far more reliable than compressor-based systems, which means lower maintenance costs – and less risk of spoilage. Solid-state technology eliminates the moving compressor parts most prone to fail over time, reducing equipment maintenance costs by up to 70%. In field trials, the Phononic C600 Merchandising Refrigerator has required approximately one-fifth the number of service calls compared to compressor-based units.

If a Phononic solid-state heat pump does fail, the system can be quickly serviced on site by simply plugging in a new one, which means it is back in operation much faster, at lower cost. In contrast, fixing a compressor-based system often involves lengthy on-site or off-site repair by a specialized technician. If multiple service visits are required, it is often more cost-effective with compressor-based systems to simply replace the entire refrigerator or freezer. And while a unit is out of action, the business is losing sales.

More space

By eliminating the compressor, usable capacity increases by up to 30 %. This capacity increase translates into lower replenishment efforts and higher sales potential, presenting shoppers with a wider variety of products while reducing the chances of "out of stock" situations.

New insights

Retailers can take advantage of the data collected by door and temperature sensors to analyze user behavior, maximize asset utilization, and monitor product performance. For example, the refrigerator or freezer records downloadable data about exactly when and how often the door is opened. Retailers can use this data to gain insights into customer behavior that enable better decisions and drive revenue. Analyzing the data can answer key questions: When is the product most used — what day of the week and time of day? Does every door-opening turn into a sale? Are we re-stocking the shelves before high-traffic periods, in order to maximize sales? Do I need to change the product mix based on usage times?

Optoelectronics

Optical communications is a growing industry – but also a highly challenging one.

The rapidly increasing demand for mobile data and internet-based services are driving service providers and cloud content companies to increase their network capacity and provide faster network speeds. As a result, optical networking industry revenue is projected to grow at more than 10% annually to reach $10.7B by 2024. But at the same time, suppliers are under intense pressure to reduce costs in a highly competitive market.

These trends create new challenges in cooling the lasers that transmit data in optical communications. Many of the lasers used in optical communications require active cooling and temperature control to maintain their specified signal and data rate; if the temperature rises, fiber optic networks could experience problems that lead to signal loss, service interruptions and poor network performance.

Thermoelectric devices are used to cool these lasers, because they are the only technology that's sufficiently accurate and compact enough to supply active cooling and maintain temperature stability with less than 1°C variation inside tiny optoelectronics packages. These small packages mean thermoelectric devices must be able to pump more heat in a small area – up to 1W in a few square millimeters.

High-efficiency thermoelectric devices from Phononic support this increased heat density while reducing power consumption by up to 30%, providing a critical differentiator for suppliers manufacturing packages in industry-standard footprints.

Phononic works closely with our optoelectronics customers to customize our products to their requirements. This ensures that we deliver best-in-class performance and allows our customers to shorten their product development timelines. Unlike most thermoelectric devices, Phononic's products are manufactured using a tightly controlled process in a U.S.-based automated semiconductor production facility. This results in industry-leading product quality and the ability to scale quickly to meet mass production demands.

To help suppliers respond to demand for more cost-effective components, Phononic has introduced ReefTECTM, our line of non-hermetic compatible thermoelectric coolers. Non-hermetic laser packages can help significantly reduce costs compared with traditional hermetic packaging. Phononic helps suppliers develop products that withstand problems such as humidity, condensation and corrosion without the added cost of hermetic packaging.

"Unlike most thermoelectric devices, Phononic's products are manufactured using a tightly controlled process in a U.S.-based automated semiconductor production facility."

Design with Phononic

Design with Phononic is an initiative in which Phononic provides reference designs, technology and expertise to help other companies in multiple industries build leading products.

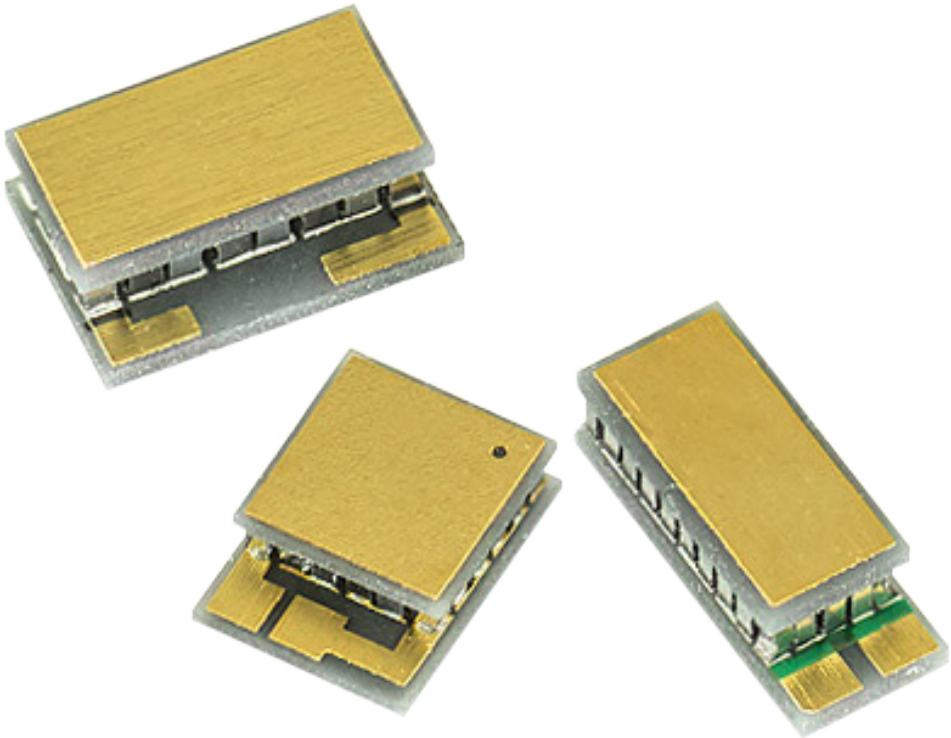
The program enables companies to:

- Develop breakthrough products that are not possible with other technologies
- Improve existing products to obtain a competitive edge
- Accelerate time to market

Phononic continuously develops new reference designs for a diverse and expanding range of applications. Novel product categories include a mattress or heating pad that can both cool and warm, to provide year-round comfort, and battery-powered refrigerators and freezers for last-mile delivery. Other reference designs enable manufacturers to develop better products in existing product categories, such as quieter, vibration-free water coolers, residential wine chillers that meet new U.S. Department of Energy (U.S. DOE) requirements, and residential draft beer dispensers. Phononic also provides reference designs to achieve specific heating or cooling targets: Cooling or heating a specified surface area or volume, for example, or achieving a desired increase in usable space by replacing the compressor. Phononic reference designs typically include the required solid-state heat pump, heat accept/reject system, and control software license, together with design expertise.

Conclusion

Phononic's groundbreaking sustainable technology is enabling the enormous potential of thermoelectric technology to be realized across multiple industries. Phononic's sustainable technology is already transforming refrigeration and freezing in industries such as food and beverage, life sciences and healthcare, and optoelectronics. Companies can now "Design with Phononic" to bring those benefits to other industries and applications, transforming existing products or developing entirely new product categories.



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Phononic is reimagining cooling and heating in ways never thought possible. Its breakthrough solid-state technology is transforming industries and creating new markets with innovative solutions that disrupt antiquated business models and incumbent technologies. Phononic is the critical element of innovation needed to radically change what it means to be efficient, effective and sustainable. The company has been named to the 2016, 2017 and 2019 CNBC Disruptor 50 lists, received the US EPA's 2017 Emerging Tech Award, R&D 100 Award and more.

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