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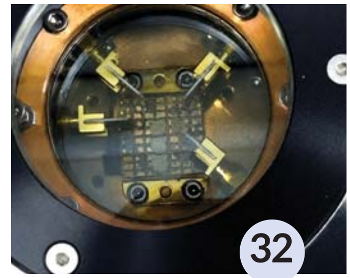

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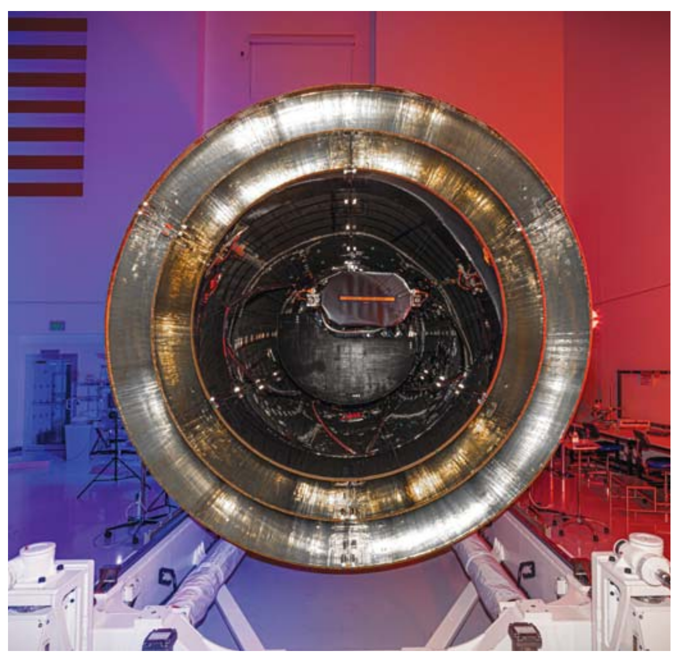

Looking into the cryogenic core of the SpectroPhotometer for the History of the universe, Epoch of Reionization and ices Explorer (SPHEREx).
Photo Credit NASA/BAE

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From the Executive Director

As summer winds down, there is a lot happening at CSA and plenty to look forward to in the months ahead.

September is shaping up to be a busy month for the cryogenic community. CSA will be attending the Applied Superconductivity Conference (ASC) in Pittsburgh, and I'm looking forward to seeing many of you there.

Conferences like ASC give us an important opportunity to connect with our members in person. They also allow us to meet others from across the cryogenics and superconductivity communities. We would love to hear what you're working on and what developments you're watching. Your feedback helps us understand how CSA can continue to serve the community.

While at ASC, CSA will also present the 2026 Roger W. Boom Award to Dr. Erica Salazar of Commonwealth Fusion Systems.

The award is named in honor of the late Dr. Roger W. Boom, emeritus professor at the University of Wisconsin. Over a career spanning more than 30 years, Dr. Boom inspired many young scientists and engineers to pursue careers in cryogenic engineering and applied superconductivity.

CSA established the award to recognize a young professional under the age of 40 who shows promise for making significant contributions to these fields. The spirit of the award is to recognize the pursuit of excellence, high professional standards, and clear communication.

We are proud to recognize Dr. Salazar as this year's recipient and look forward to presenting the award in Pittsburgh.

We're also beginning to look ahead to next year. Please save the date for the 32nd Space Cryogenics Workshop (SCW):

32nd Space Cryogenics Workshop

June 9–11, 2027
Crowne Plaza Resort Asheville
Asheville, North Carolina

SCW brings together professionals working in cryogenics and space applications. The workshop provides a focused setting for technical discussion and collaboration. More details about SCW will be announced in the coming months.

For now, we're looking forward to a great week at ASC. I hope to see many familiar faces and meet some new ones as well. If you see us in Pittsburgh, please stop by and say hello!

Megan L Galeher


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Why Axial Thermalization Is a Myth in Long Helium Transfer Lines—and What Engineers Do Instead

by Prabhat Kumar Gupta, SCRF Cavity Characterization and Cryogenics Section, Raja Ramanna Centre for Advanced Technology (RRCAT), Indore (MP), India and Homi Bhabha National Institute (HBNI), Mumbai, India

Helium transfer lines in accelerator, quantum, and cryogenic test-stand systems are cooled from ambient to cryogenic temperatures during commissioning. In this environment failures such as bellows cracking, weld leaks, and increased heat load are often blamed on "fast cooldown." A common assumption is that careful cooling allows the line to thermally equalize along its length. In reality, axial thermalization by solid conduction through stainless steel is far too slow to occur on commissioning timescales, even over meter-scale lengths. As a result, axial temperature differences persist during cooldown and drive thermal stress and long-term degradation. This article uses simple numerical examples to show why axial thermalization cannot be relied upon and explains how modern cryogenic systems instead manage cooldown through controlled ramp rates, segmentation, and mechanical compliance.

What Is Axial Thermalization?

Axial thermalization refers to the equalization of temperature along the length of a structure due solely to heat conduction within the solid material. This occurs without assistance from fluid convection, procedural holds, or mechanical motion.

The characteristic timescale for axial thermalization is given by the axial thermal diffusion time:

$$t_{axial} \sim \frac{L^2}{\alpha_{th}}$$

In this equation:

L is the axial length

a_{th} is the thermal diffusivity of the material

For austenitic stainless steels in the cryogenic temperature range, a representative order-of-magnitude value is:

$a_{th} \approx (3 \text{ to } 6) \times 10^{-6}\ m^2/s$

This expression highlights the strong quadratic dependence of axial thermalization time on length, which rapidly makes conduction-based equalization impractical for long transfer lines.

Numerical Reality: Axial Thermalization from 1 m to 50 m One-Meter Transfer Line Segment

A 1 m length represents the smallest meaningful axial segment between supports or bellows in many transfer lines.

$$t_{axial} \sim \frac{1^2}{4x10^{-6}} = 2.5x10^5 s \sim 3\ days$$

Interpretation

Even a 1 m stainless-steel section requires several days to equalize its temperature axially by solid conduction alone. Commissioning cooldowns typically occur over hours, not days. As a result, axial thermalization does not occur even at the meter scale during cooldown.

Longer Transfer Lines

The quadratic dependence of axial diffusion time on length rapidly makes conduction-based thermalization impractical for longer transfer lines.

Transfer line length	Axial diffusion time
1 m	~3 days
10 m	~290 days
50 m	~20 years

These values are not academic curiosities. Rather they demonstrate that axial thermalization by solid conduction is irrelevant over all practical commissioning timescales, from individual segments to full-length helium transfer lines.

What Actually Happens During Cooldown

During cooldown, a long helium transfer line cools non-uniformly along its length, with each axial segment responding primarily to local coolant conditions and forming a moving thermal front. Because axial heat conduction through stainless steel is extremely slow, it cannot redistribute heat on commissioning timescales, and axial temperature differences persist.

These differences drive differential thermal contraction between adjacent segments, which is accommodated by bellows and flexible supports. Therefore successful cooldown depends on mechanical strain accommodation and controlled cooldown procedures, rather than on axial thermal equalization by conduction.

Why This Causes Stress

Thermal stress is driven by internal temperature gradients, not by absolute temperature change. For constrained components:

Thermal stress $\sigma = E\alpha\Delta T_{axial}$

This is standard linear thermo-elasticity.

- E: Young's modulus
- α: coefficient of thermal expansion
- ΔT_{axial}: is the temperature difference that develops along the length of the structure (not the total cooldown from ambient to cryogenic temperature).

In this equation the internal axial gradient during cooldown scales are displayed as:

$$\Delta T_{axial} \sim \frac{dT}{dt}\frac{L^2}{\alpha_{th}}$$

Combining:

$$\sigma \sim E\alpha\frac{dT}{dt}\frac{L^2}{\alpha_{th}}$$

Key Implications

- Thermal stress scales with cooldown rate, not just with the total temperature change.
- Longer axial lengths amplify stress when axial diffusion cannot equilibrate temperatures.
- Because axial thermalization by conduction does not occur during commissioning, axial temperature differences inevitably develop unless cooldown is controlled.

In practice, these temperature differences are limited by boundary conditions and system dynamics, but axial conduction is too slow to mitigate them on commissioning timescales.

The Correct Engineering Solution

Because axial thermalization by solid conduction cannot be relied upon during commissioning, successful cooldown strategies are designed to control temperature gradients and mechanical strain directly, rather than to achieve axial thermal equilibrium. In practice, this is accomplished through:

Controlled cooldown rates. Ramp rates are limited (typically 10–20 K/hr for long transfer lines) to prevent large temperature differences between adjacent segments.

Segmentation with bellows. Bellows divide the line into shorter sections and provide axial compliance, allowing each segment to contract independently and absorb differential strain.

Uniform precooling. Low-flow helium gas precooling promotes gradual, distributed cooling and avoids sharp axial thermal fronts.

Intermediate temperature holds. Hold points (e.g., near 200 K and 80 K) allow lagging components to thermally and mechanically catch up before further cooldown.

Thermal shields and intercepts. Intermediate-temperature shields reduce the overall temperature span and the resulting contraction-driven stress.

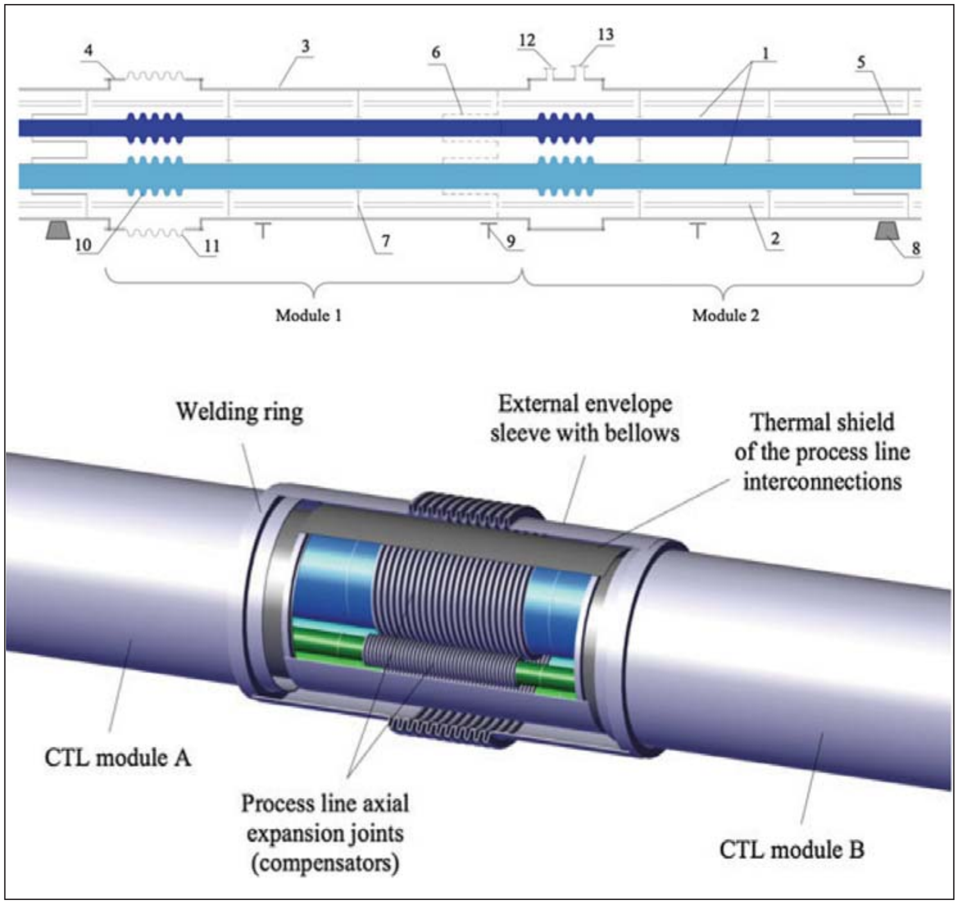


Figure 1:** **Schematic and three-dimensional views of a cryogenic helium transfer line illustrating axial segmentation, bellows, and supports. During cooldown, a thermal front propagates along the line while axial conduction remains negligible.
Credit: Chapter 9, Cryogenic Transfer Lines pages 244 and 249.
Source: https://s3.cern.ch/inspire-prod-files-b/b2c7312f54e8691014b3f7d5871f5a64

Practical Takeaway for Commissioning Engineers

The 1-meter example makes this key point unavoidable—axial thermalization by solid conduction through stainless steel is too slow to protect helium transfer lines (even at the local, meter scale) during commissioning.

Therefore, safe cooldown is achieved not by waiting for axial thermal equilibrium, but by deliberately:

- controlling the cooldown rate,
- providing mechanical flexibility, and
- intentionally managing axial thermal strain.

Conclusion

Axial thermalization by solid conduction in helium transfer lines cannot be relied upon on commissioning timescales, from meter-scale segments to full-length systems. Recognizing this reality transforms cooldown from a trial-and-error exercise into a controlled and predictable engineering process. Engineers who design and commission transfer lines with this understanding prevent hidden mechanical damage, avoid long-term heat-load degradation, and significantly improve overall system reliability.

Author's Note

This article is informed by commissioning and operational experience with long helium transfer lines and system-level thermomechanical analysis applicable to accelerator, quantum, and cryogenic test-stand infrastructures.

Bluefors Hosts 24th International Cryocooler Conference

by Nathan Kellar and Arifin Budihardjo

Syracuse, NY, welcomed the international cryogenic community to the 24th International Cryocooler Conference (ICC24), held June 15-18, 2026, and hosted by Bluefors at the Everson Museum of Art in downtown Syracuse. Bringing together 163 attendees, ICC24 attracted a diverse mix of representatives from leading cryogenic manufacturers, national laboratories, universities, and government research organizations.

The conference featured a strong international presence, with attendees traveling from North America, Europe, and Asia to present their latest work through technical presentations and poster sessions covering cryocoolers, cryogenic systems, superconductivity, and emerging quantum technologies.

As in previous years, the conference began with the CSA's Foundations of Cryocoolers Short Course on June 15, taught by Franklin Miller (University of Wisconsin–Madison), Mark Zagarola (Creare), Xihuan Hao (Bluefors), and Peter Bradley (NIST). It was followed by an evening welcome reception that reunited attendees from across academia, industry, and government. The technical program featured four days of presentations covering aerospace cryocoolers, Gifford-McMahon and pulse tube cryocoolers, Stirling and Brayton systems, JT and sorption cooling, regenerator and recuperator research, cryogenic technology, sub-Kelvin refrigeration, and cooler integration for a wide range of scientific and commercial applications. Two plenary presentations highlighted the growing role of cryogenic technologies in enabling next-generation radio astronomy (Paul Grimes of Center for Astrophysics | Harvard & Smithsonian) and superconducting quantum processors (Max Hays of MIT).

The June 17 program included parallel poster sessions, giving attendees the opportunity to discuss emerging research across multiple technical disciplines. Authors introduced their work during poster previews before engaging in one-on-one discussions throughout the afternoon, encouraging collaboration between researchers, manufacturers, and end users.

At ICC24, Logan Kossel of the University of Wisconsin–Madison (now with FormFactor) received the Best Student Paper Award for his presentation, "*Investigations of the Gravity Independence of Large-Scale Helium Pulsating Heat Pipes*." Carl Kirkconnell of West Coast Solutions was also honored with the ICC Exceptional Service Award in recognition of his longstanding dedication and contributions to the International Cryocooler Conference. There was a special memorial session for Ray Radebaugh, during which several attendees shared their good memories. Ray's sister Rada Radebaugh, son Keith Radebaugh, and daughter Carol James were in attendance.

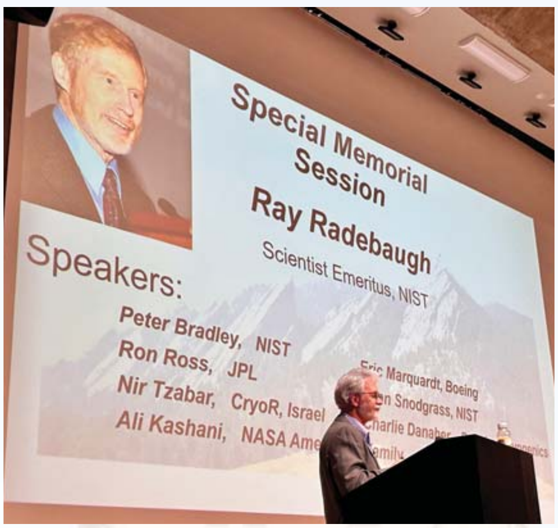
Beyond the technical sessions, ICC24 emphasized opportunities for networking and collaboration. Continental breakfasts and lunches each day encouraged informal discussions between attendees, while the final evening's conference banquet at the Milton J. Rubenstein Museum of Science & Technology (MOST) provided a memorable social event in downtown Syracuse.

Preparations for ICC24 were led by Conference Co-Chairs Arifin Budihardjo and Rich Dausman and Program Chairs Tim Hanrahan and Xihuan Hao, all with Bluefors. Together with the ICC Board, Session Chairs, organizing committee, and volunteers, their collective efforts ensured a well-organized and engaging conference that received many positive comments from attendees for both its technical program and hospitality. As ICC24 concludes, the International Cryocooler Conference now looks ahead to ICC25, which will be held in Huntington Beach, California, in 2028, and hosted by West Coast Solutions.

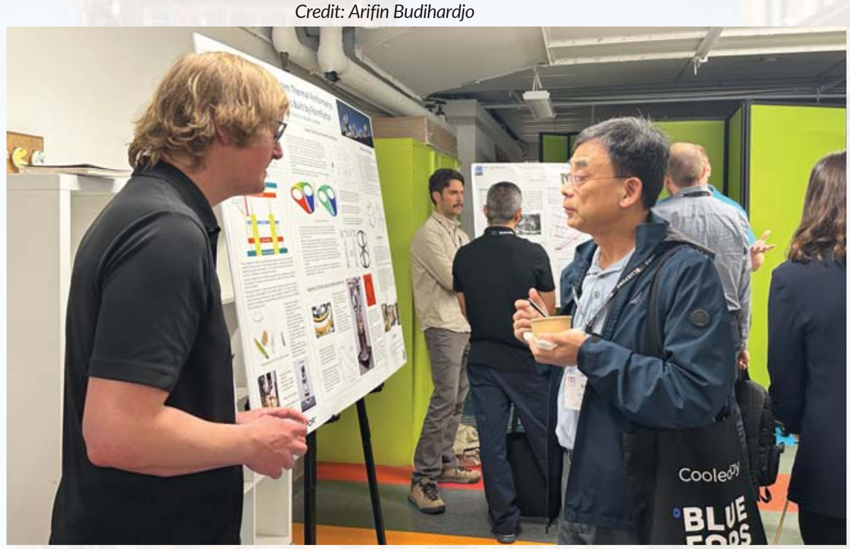
Attendees gather at the ICC24 meeting. *Credit: Jessica Johnson*

Arifin Budihardjo welcoming attendees to the ICC24 conference. *Credit: Nathan Kellar*

Gerd Jakob, European Southern Observatory, speaking at ICC24. *Credit: Arifin Budihardjo*



Peter Bradley speaking at a special ICC session honoring Ray Radebaugh. *Credit: Arifin Budihardjo*



Attendees at the ICC poster session meeting with Paul Owen of FormFactor. *Credit: Arifin Budihardjo*

Carl Kirkconnell (r) accepting the ICC Exceptional Service award. *Credit: Arifin Budihardjo*

Logan Kossel (l) accepting the ICC Best Student Paper award. *Credit: Arifin Budihardjo*

Vibration-Free Cryogenic Cooling for the Einstein Telescope: Part II

A Sorption-Based Joule-Thomson Approach

by Michiel van Limbeek, Cris Vermeer, and Marcel ter Brake, University of Twente. Romaine Kunst, Adrie Visser, Pieter Lerou, and Erik-Jan de Hoon, Demcon kryoz. Johannes Burger, Martijn Al, and Hassan Firouzbakht, Cooll.

The first part of this article appeared in Volume 42, Number 3 of ***Cold Facts*** and explained the architecture of the cryogenic cooling system. Part two of this article addresses the fundamental research and mitigation strategies implemented to achieve the most stringent requirement: extremely low-vibration levels.

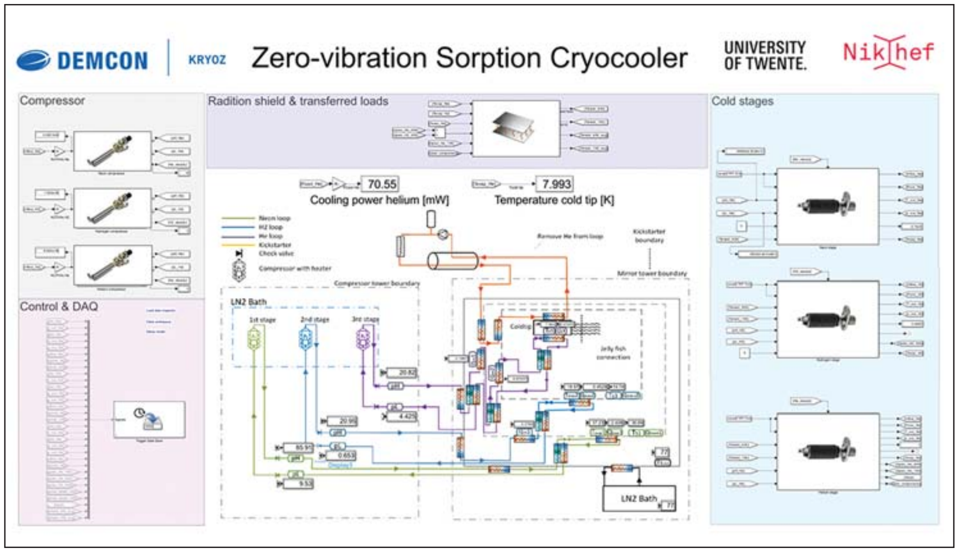


Figure 1. Top level of the Lumped-Element Model for the three-stage sorption based cryocooler in Matlab Simulink. *Credit: R. Kunst*

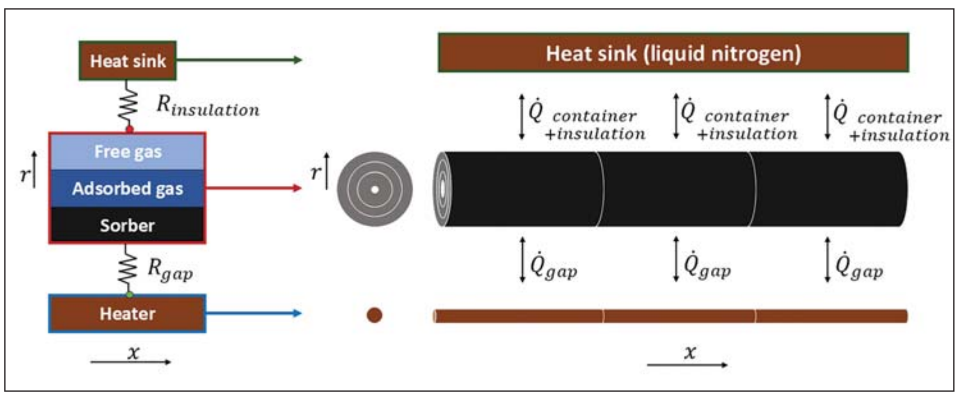


Figure 2. A schematic overview of the compressor LEM model. *Credit: R. Kunst*

The Role and Value of Systems Engineering and Lumped-Element Modeling

Large-scale scientific projects such as the Einstein Telescope are multidisciplinary and involve numerous stakeholders. In this project, systems engineering plays an essential role in managing complexity. It provides a structured approach for translating stakeholder needs into verifiable system requirements, while ensuring clear interface definitions and managing interdependencies across subsystems. At Demcon kryoz, we apply the industry proven Stage-Gate model to guide innovation from basic concept to qualified market introduction. This methodology introduces formal checkpoints to evaluate progress, ensure alignment, secure results and manage risks systematically in dynamic environments with evolving constraints.

Another typical challenge in large-scale scientific projects is the infeasibility and lack of cost-effectiveness of developing a full-scale prototype for validation. To mitigate this, a Lumped-Element Model (LEM) was developed. In this lumped system analysis, this complex thermal system is reduced to several discrete lumps. This model is used to dynamically simulate the entire cryocooler system, including all critical components: sorption cells, counter-flow heat exchangers, buffers, JT restrictions and connecting tubing (Figure 1). This model enables accurate prediction of system dynamic behavior under various operating conditions, providing essential insights before hardware is built.

With the requirement for cooling power and cooldown time in mind, the LEM approach allows the determination of working points (pressure, temperature, and mass flow) for each stage, while also defining the dimensions and thermal characteristics of all components. At its core, the model represents the sorption compressor as a two-dimensional block (radial and axial), incorporating three interacting phases: solid adsorbent, free gas, and adsorbed gas (Figure 2). These phases are assumed to be in thermal and fluidic equilibrium at any given time, ensuring realistic simulation of heat and mass transfer processes.

The model is designed to be very modular, supporting different design concepts such as external versus internal heating configurations. It also integrates Simulink-based sub models for counter-flow heat exchangers, JT-restrictions and cold plates, building on a modeling framework developed by Demcon kryoz over the last 20 years.[1] The heritage of both the University of Twente and Demcon kryoz, as shown in the technology roadmap in part one, provides a robust foundation for predicting the dynamic behavior of the entire three-stage system, optimizing design parameters, and verifying compliance with stringent requirements for cooling power, cooldown time, and vibration performance—long before (expensive) physical implementation. By enabling rapid iteration and validation, the LEM model significantly reduced technical risk in the project and accelerated progress toward the required (high) technology readiness level.

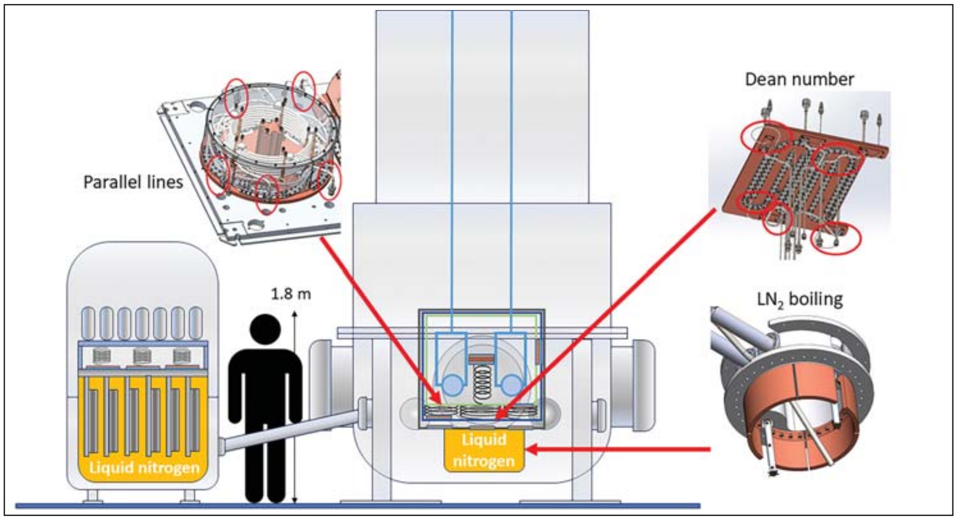


Figure 3. Schematic of the conceptual design showing the mirrors (the two blue circles) in the large vacuum tower in the middle and the compressor system on the left, in the smaller vacuum tower. In the top left corner, a CAD is shown of the counter-flow heat exchanger for the neon stage with five parallel lines, to ensure laminar flow. In the right upper corner, a drawing of a bottom plate demonstrates that the dean criterion on the ratio between radius of curvature and tube radius was applied throughout all bent tubes in the system. In the lower right corner, the liquid nitrogen vessel has an additional copper ring to increase the contact area and minimize potential vibrations. To put this scaled schematic into perspective, a person of 1.8 m is displayed. The compressor tower has a height of 2.5 m and the mirror tower has a height of 6.1 m. The outer shield (grey line), that contains mirrors, counter-flow heat exchangers, precoolers and evaporators has a width x length x height of 494 x 867 x 1040 mm. Credit: R. Kunst

Vibration Mitigation Strategies

For the Einstein Telescope, even the smallest vibration can compromise the detection of gravitational waves. To address this challenge, extensive fundamental studies were carried out to identify and mitigate potential vibration sources throughout the scaled ETpathfinder system. These analyses covered multiple domains, including fluid dynamics, structural interactions, thermal cycling effects, and component-level behavior. Each design choice was evaluated for its potential impact on vibration performance. This thorough and multidisciplinary approach resulted in the insights as detailed in the overview below.

Buffer Sizes

As shown in part one of this article, the sorption cell produces a fluctuating mass flow similar to a heartbeat. This creates pressure fluctuation in the system. In order to damp this pressure fluctuation, the system makes use of two buffers, a high- and low-pressure buffer. This ensures that within the cooler part of the system, a continuous mass flow is ensured. The ratios and total volumes were carefully chosen to establish a baseline in which the fluctuations in the high and low-pressure lines were minimized while ensuring sufficient cooling power.

Turbulent Flow

To minimize fluid-induced vibrations throughout the complete system, all the flows in all the components in the system are limited by the maximum Reynolds number for laminar flow. Establishing a baseline that ensures laminar flow involves a trade-off in enthalpy and mass flow to achieve the required cooling power and meet the flow requirement. In order to achieve a minimum mass flow while meeting the cooling power requirements, the enthalpy was optimized. This implied that for all three stages, the temperature and pressure operating points were carefully chosen. A balance was found between the cooling power, the Reynolds number and the number of cells required. Once a baseline of working points was established, the mass flow required for the neon stage was still in the turbulent regime. To ensure laminar flow, the decision was made to have five parallel lines of neon in the mirror tower (Figure 3).

The Joule-Thomson Restriction

The function of the JT restriction (expansion valve) is to cause a significant pressure drop in the flow. The change in pressure then provides cooling power by the Joule-Thomson effect. There are three concepts for the restriction: porous plug, capillary pipe, and orifice plate. The porous plug achieves a pressure drop by its viscous resistance to the flow. Gas is forced through small pores and undergoes isenthalpic expansion. In the capillary pipe, the pressure drop is achieved mainly by major pressure losses (frictional pressure losses) dependent on the length and (local) Reynolds number of the pipe. In contrast with the porous plug, where multiple parallel channels keep the Reynolds number low, the capillary pipe is a single channel and thus, for constant mass flow rate, the turbulence intensity increases for decreasing pipe diameter. The surface area interaction is raised, increasing the frictional forces and therefore causing the pressure drop. For the plate orifice, the pressure drop is achieved by the sudden change in cross section. Frictional pressure losses are minimal due to the small length of the orifice plate. A qualitative analysis was carried out with the focus on their potential for fluid-induced vibration. The simulations revealed that the porous plug exhibits the least potential for fluid induced vibrations, as it has a lower average vorticity in the flow compared to the other throttling devices. The porous plug is also the least prone to clogging, compared to the orifice plate and the capillary pipe, as the plug has many parallel flow channels. Therefore, the porous plug was selected for the JT restriction.

Violent Boiling at Liquid Nitrogen Interfaces

Liquid nitrogen is used as the backend cooling source in this system. There are two liquid nitrogen baths present in the system, one liquid nitrogen bath provides cooling power to the sorption-based compressor and the other to the 3-stage JT-cryocooler. At a low heat flux, heat can be transported

▶ *continues on page 14*

to the liquid nitrogen via individual vapor bubbles that can form and detach from the surface without interfering with each other. This flow regime is called the "isolated bubble regime." When increasing the heat flux, bubbles start to interact with each other and start to coalesce. This would increase the vibration level. To minimize bubble interaction and therefore vibrations, sufficient contact area is ensured in the liquid nitrogen baths.

Secondary Flow Instabilities

Next to the laminar flow requirement, secondary flow instabilities that occur in curved tubes were also investigated. Regarding flow phenomena that occur within curved tubes, the fluid is influenced by viscous shear forces and therefore the fluid exhibits velocity gradients. The centrifugal force causes fluid masses that have higher velocities close to the center move towards the outer wall. Then fluid masses close to the wall are compressed and flow towards the inner wall. This process causes secondary flows. After extensive literature research, a limit was imposed on the Dean number, the dimensionless number that quantifies the influence of curvature on flow as the product of the Reynolds number and the square root of the ratio between the tube radius to the radius of curvature. This was established to minimize the formation of secondary flow instabilities. This limit was used in the design of the curved fluidic components in the design to prevent the formation of secondary flow instabilities. (Figure 3).

Boiling in the Evaporators

Two-phase flow occurs only in the heat sinks (evaporators) of the neon and hydrogen stage. Two-phase flow can be chaotic and impose high-momentum fluctuations; therefore, a design should be proposed that limits the vibrations. Two-phase flow is affected by body forces such as gravity. The tube diameter of the evaporator is chosen to be sufficiently large so that gravity can be used to keep the liquid located on the bottom of the tube. Inside the evaporator is another, smaller tube that contains very small pores. The pore size is chosen so that liquid is kept in these pores with capillary forces. By adding this smaller porous tube, the contact area between heat and liquid increased. This increases the total surface area and lowers the local heat flux, which, as mentioned in the design of the liquid nitrogen bath, is advantageous in terms of minimizing potential vibrations.

Figure 4. Mirror tower in the ETpathfinder facility. The tower has a height of 6.1 m and a diameter of 2.8 m.
Credit: ETPF Project [2]

Conclusion

A sorption-compressor-driven Joule-Thomson cryocooler was developed with the goal to meet the ultralow vibration requirements of the Einstein Telescope. The system design is based on a three-stage architecture using neon, hydrogen and helium, and avoids active mechanically moving parts to eliminate vibration. While the system consists of multiple shields, heat exchangers, and cold plates, it contains commonly used stainless steel tubes and well-known materials, which do not impose design challenges and therefore highlight the simplicity of the system. Extensive modeling and design analyses were performed to ensure compliance with cooling power, cooldown time, and vibration specifications. Further, systems engineering played an essential role in managing the complexity of this large-scale scientific project. Construction of the system is currently underway at Demcon kryoz and Cooll Sustainable Energy Solutions. Validation of the cryocooler was performed at the University of Twente in the first quarter of 2026, with the first integration steps into the ETPathfinder setup expected by the end of 2026. These steps will bring sorption technology to the next TRL. Engineered for ultralow noise and cryogenic precision—we are ready for the Einstein Telescope.

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1. Lerou, P. P. P. M. (2007). Micromachined Joule-Thomson cryocooler. Ph.D. dissertation.

2. Gallery – ETpathfinder, visited on 10-13-2025

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Cryotreatment

by Jack Cahn, Chief Technologist, DCI, jack@deepcryogenics.com

The Physics of Cryogenic Treatment

Previous "Cryotreatment" columns for ***Cold Facts*** have explored material selection, cryo chamber design, and the science behind cryogenic treatment. But from a physics perspective: what are the thermal challenges of deep cryogenic treatment and how does payload size influence process success?

Temperature Change

Cryogenic treatment is a controlled thermal process used to improve the wear resistance, dimensional stability, and service life of metals and engineered components. Unlike conventional heat treatment, cryogenic treatment subjects materials to temperatures approaching -320°F using liquid nitrogen, promoting beneficial microstructural transformations. Although the objective appears to be simply cooling an item, removing heat from a large object in a controlled manner is considerably more difficult than adding it. This challenge is governed by thermodynamics, heat transfer, thermal inertia, and advanced process control.

Thermodynamics and Thermal Inertia

The first law of thermodynamics states that energy cannot be created or destroyed, only transferred or converted. During cryogenic treatment, thermal energy is removed from the workpiece until the target temperature is reached. The second law of thermodynamics explains why cooling is inherently more difficult than heating. Heat naturally flows from higher to lower temperatures, increasing entropy. Heating is relatively straightforward because energy is actively supplied through electrical resistance heaters or combustion. However, cooling depends on extracting heat and transporting it away — relying on temperature gradients, heat transfer, and the cooling medium's (LN_2) ability to absorb energy.

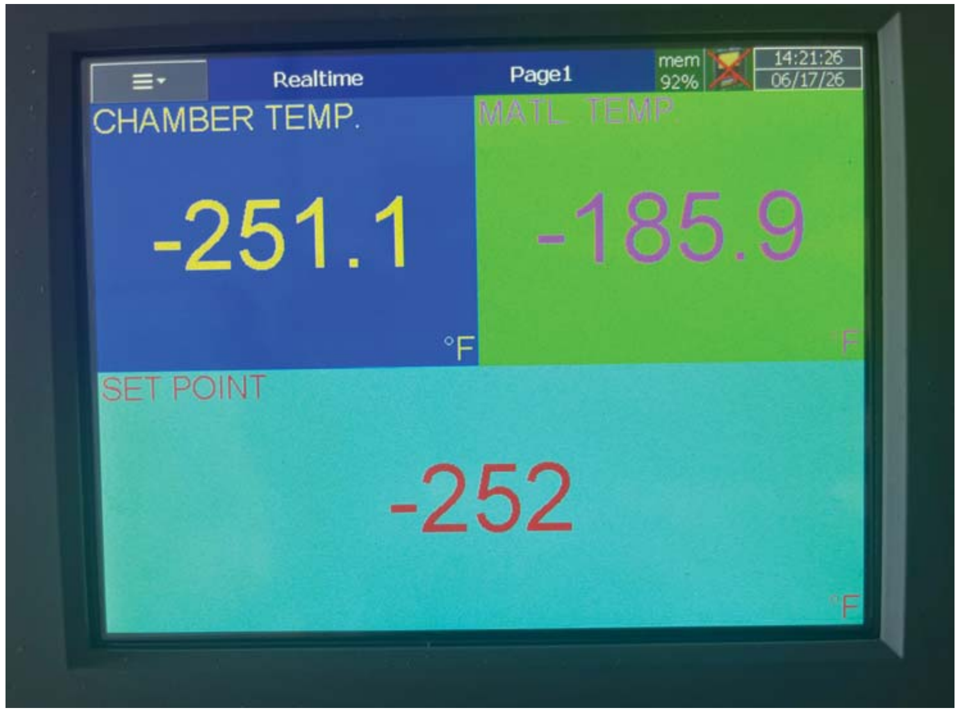


Figure 1. Chamber vs material temp - 10,000 lb payload on the way -294 °F. *Credit: J. Cahn*

A key factor is thermal inertia—an object's resistance to temperature change which depends on mass, density, and specific heat capacity. Large steel components retain substantial internal energy after their surfaces have cooled, creating temperature gradients between the cooler exterior and warmer core. (Figure 1) If cooling occurs too quickly, the surface contracts while the interior remains warmer, generating thermal stresses that can distort or crack the component.

Newton's law of cooling provides the mathematical framework for this behavior. The rate of heat transfer is proportional to the temperature difference between an object and its surroundings. When a warm component enters a cryogenic chamber, the large temperature difference allows rapid heat removal. As the component cools, this difference decreases and the cooling rate naturally slows. Therefore, maintaining a controlled, near-linear cooling profile requires continuous adjustment rather than simply exposing the load to a fixed cold environment.

Figure 2. Slow cooling a 14,000 crusher liner payload. *Credit: J. Cahn*

Chamber Design, Challenges, and Solutions

Modern cryogenic systems achieve this through precisely metered injections

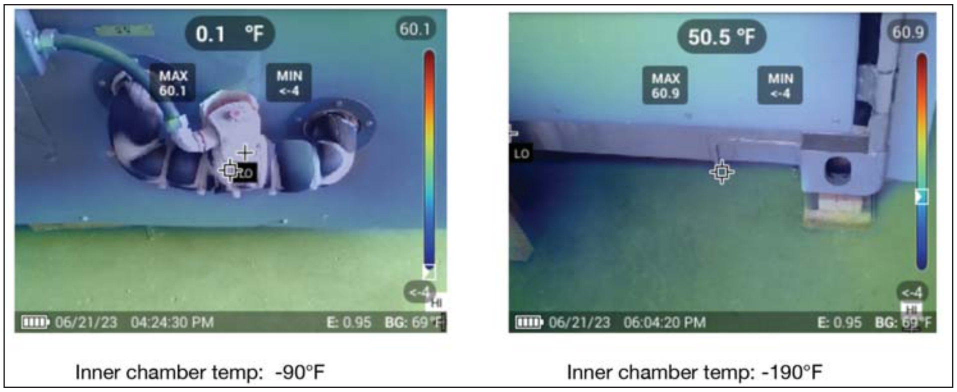


Figure 3. Infrared readings of thermal losses. *Credit: J. Cahn*

of liquid nitrogen into insulated chambers. Programmable logic controllers (PLCs) regulate nitrogen flow according to predetermined time-temperature profiles. Multiple sensors monitor chamber and product temperatures, while proportional-integral-derivative (PID) algorithms continuously adjust nitrogen flow to minimize deviations from the desired cooling curve.

The challenge increases significantly with large, dense industrial payloads. (Figure 2) Their high thermal inertia requires the removal of substantial quantities of heat before the target temperature is reached. Meanwhile, the chamber is surrounded by a warmer environment, creating a continuous inward heat flow. Although high performance insulation greatly reduces this transfer, heat still enters through structural supports, door seals, pipe penetrations, and geometric discontinuities such as corners and joints. These localized heat leaks create non-uniform temperature distributions that must be corrected by the control system. (Figure 3)

The chamber itself also becomes part of the thermal system. As its internal surfaces cool, they absorb heat conducted through the insulation from the surrounding environment, effectively acting as a thermal wick. This heat load varies with ambient temperature, humidity, insulation condition, and chamber geometry. Consequently, liquid nitrogen must remove heat from both the payload and chamber structure.

These unavoidable thermal losses interrupt the cooling process. Each injection of liquid nitrogen must first offset incoming environmental heat before further reducing the payload temperature. The resulting cooling curve reflects the combined effects of payload thermal inertia, chamber heat capacity, insulation performance, and external heat infiltration. Without active feedback control, temperature overshoot or undershoot would compromise process repeatability and the metallurgical transformations responsible for improved wear resistance.

Therefore, cryogenic treatment is far more than exposing components to extreme cold. It is a sophisticated application of thermodynamics requiring precise control of energy transfer, thermal gradients, and cooling rates. By combining the first and second laws of thermodynamics, Newton's law of cooling, advanced PLC-PID control, and carefully engineered chamber design, cryogenic processors achieve the thermal profiles needed to enhance wear resistance while avoiding thermal damage. The process demonstrates a fundamental engineering principle: removing heat with precision is often significantly more challenging than supplying it.

Success depends not simply on reaching ultralow temperatures, but on managing the complex movement of thermal energy throughout the treatment cycle. By applying sound engineering principles and precise process control, cryogenic treatment transforms extreme cold into measurable improvements in material performance, reliability, and longevity.

Who's New in the *Cold Facts* Buyer's Guide?

Renaissance Scientific

Renaissance Scientific manufactures cryogenic nanopositioners, scanners, and multi-axis motion systems optimized for millikelvin, UHV, and non-magnetic environments supporting quantum, photonic, and nanoscale research.

GIGAette Co., Ltd.

GIGAette, a Daejeon-based deep-tech company, specializes in cryogenic measurement for LH_2 and other cryogens. Its CryoIMS® monitoring system provides a revolutionary approach to cryogenic monitoring that eliminates complexity and maximizes safety.

Menlo Microsystems, Inc.

The MM4250, Menlo Microsystems' primary cryogenic product, is a high-performance RF switch designed for use in low-temperature environments and engineered to maintain exceptional electrical and mechanical performance at cryogenic temperatures down to 10 mK.

Peaco Support Automation

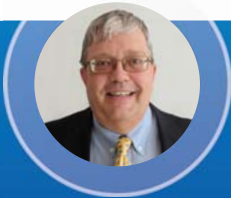
Distributor supporting a wide range of pneumatic and electronic automation components online for customers all over the world, such as motors, motor controls, power supplies, sensors, passive components, actuators, and other industrial automation products.

Magnetic Shields USA

Magnetic Shields USA supplies custom magnetic shielding for room-temperature and cryogenic applications. Capabilities include design, simulation, precision fabrication, and hydrogen annealing of high-permeability shielding components and assemblies.

SpotSee

LN_2 traceable sensors for -200°C applications: data loggers, wired and wireless monitoring systems for stationary, and logging during shipments. Remote asset monitoring and NIST traceable.



Cryo Bios

by Dr. John Weisend II, European Spallation Source ERIC, CSA Chairman, john.weisend@ess.eu

Ronald W. Fast *(1934 – 2024)* Engineer, Mentor, and Champion of Cryogenic Science

Ronald W. Fast (Ron) spent the majority of his career at Fermi National Accelerator Lab (Fermilab) where he made significant contributions to the use of liquid hydrogen and superconducting magnets in high energy physics experiments. He also made important contributions in scientific communication. He was sole editor of *Advances in Cryogenic Engineering* for many years and his efforts maintained that publication as a well-regarded archival source of cryogenic engineering information.

Early Life and Education

Ron was born in Toledo, Ohio, and he received a BS (magna cum laude) in physics from Washington and Lee University, in 1956. He earned his MS and PhD degrees in physics from the University of Virginia in 1958 and 1960. After graduation he had a brief stint in the U.S. Army and worked as a research scientist at the University of Wisconsin–Madison.

Building Fermilab's Cryogenic Infrastructure

In 1969, Dr. Fast joined Fermilab just two years after its founding. He started as an Applied Scientist in the Research Division, eventually becoming the head of the Research Division's Cryogenics Group. This group provided the cryogenic engineering expertise for the scientific experiments at Fermilab. Ron played a major role in the development, construction, and operation of liquid hydrogen and liquid deuterium systems used in fixed target experiments (Figure 1). Among his contributions were the creation of detailed design guides for these systems.

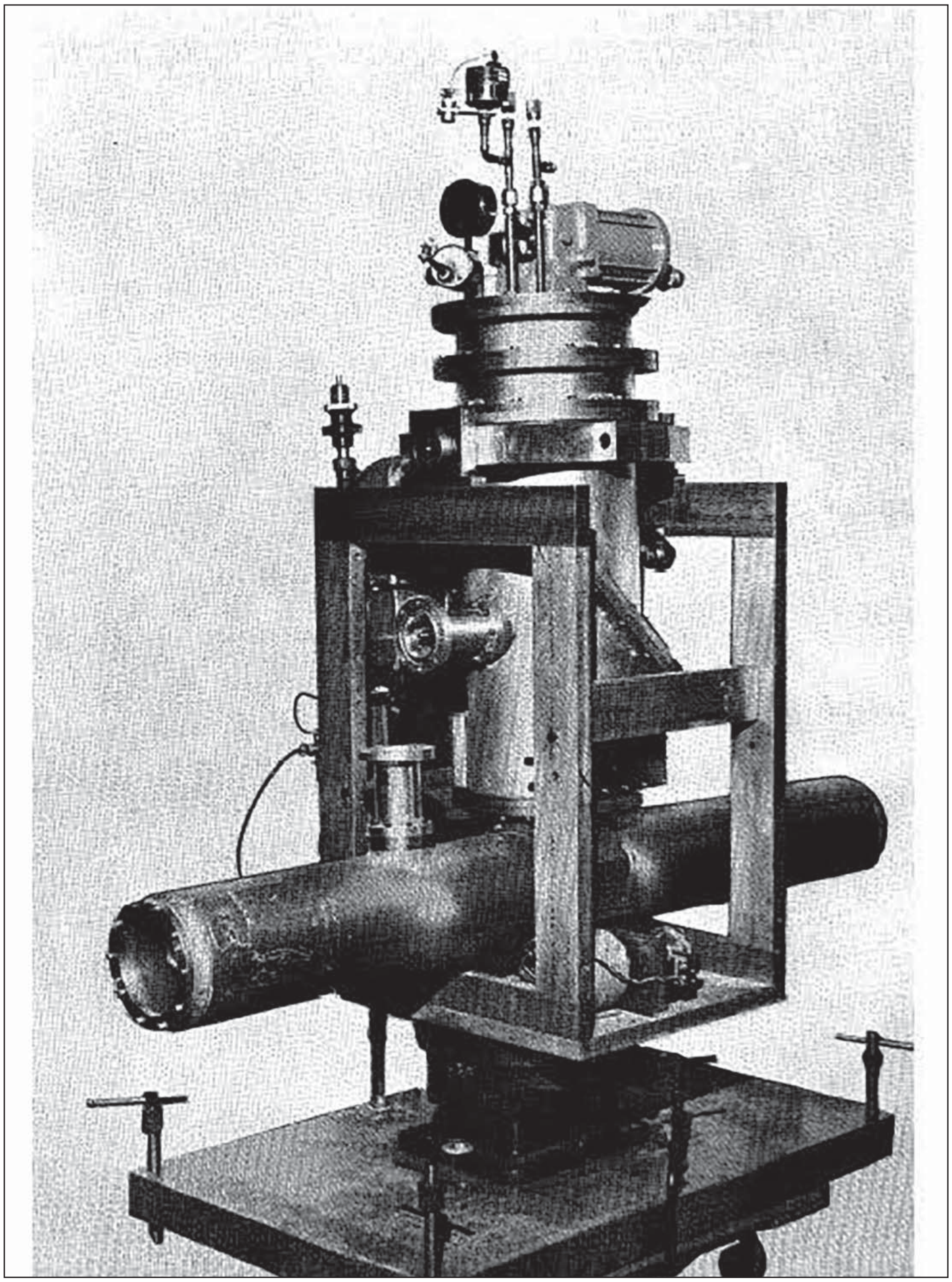


Figure 1. Typical Fermilab 2 Liter Liquid Hydrogen Target from "Design Guide for Liquid Hydrogen Targets up To 35 Liters."
Credit: R. W. Fast and M. A. Otavka, Fermilab TM-423 (1973)

Ron and his team also worked on the design of large superconducting solenoid magnets for use in particle detectors. This included the development of an innovative thin solenoid that was conduction cooled for the Fermilab Collider Detector Facility (CDF) and a 2 Tesla superconducting solenoid installed as an upgrade to the Fermilab D0 detector. In the late 1980s, Dr. Fast applied his expertise to the design of the superconducting solenoid for the Large Solenoid Detector to be built as part of the Superconducting Super Collider (SSC) project. Regrettably, the SSC was cancelled before construction could be completed.

Research and Innovation in Cryogenic Engineering

In addition to specific project tasks, Dr. Fast conducted research on cryogenic engineering topics. He established the Magnet Innovation Lab (MIL) at Fermilab. A good example of this work was an extensive series of experiments to better understand and optimize practical large-scale applications of multilayer insulation systems (MLI) (Figure 2).

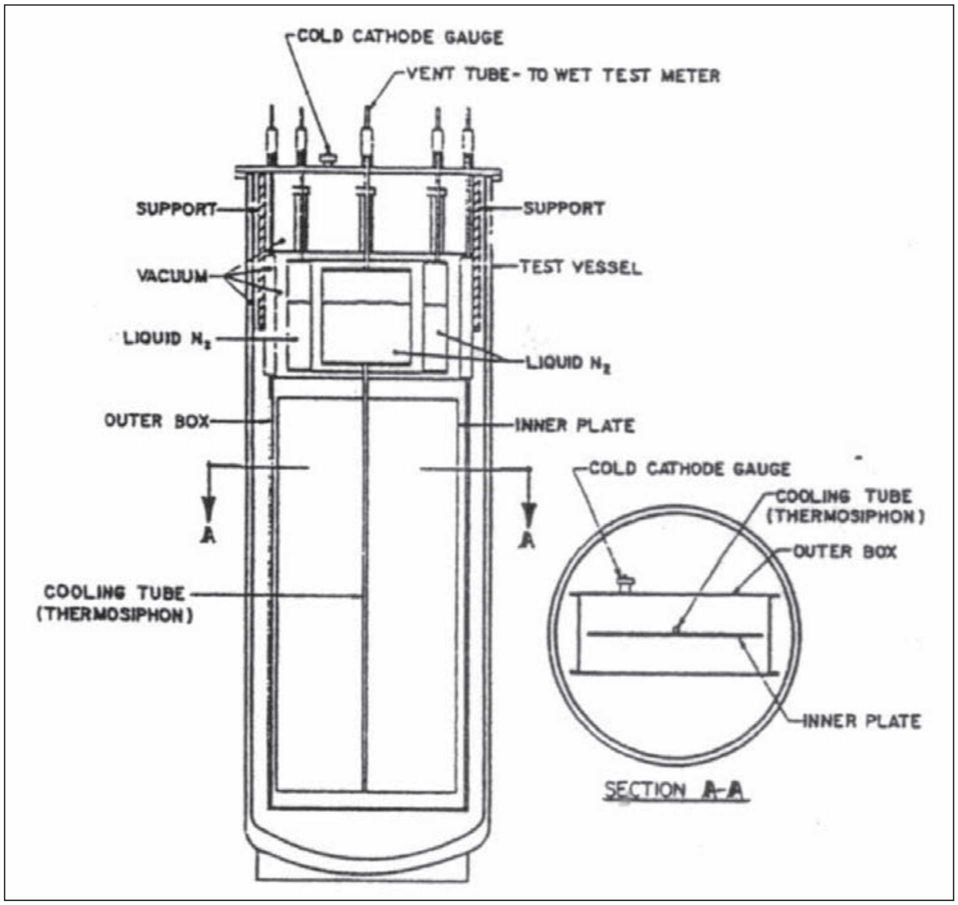


Figure 2. Cross section of the Fermilab MLI test cryostat from "An Experimental Study of Heat Transfer In Multilayer Insulation Systems from Room Temperature To 77 K". *Credit: Q.S. Shu, R.W. Fast, H.L. Hart, Adv. Cryo. Eng., Vol. 31, Plenum Press (1986)*

Throughout his career at Fermilab, Dr. Fast emphasized technical excellence and safety within his group. He was interested in developing his team and took time to mentor a number of scientists over the years. (See Q.S. Shu's remembrance starting on page 20 in this issue of ***Cold Facts***.)

Ron Fast believed strongly in scientific communication and collaboration. The MIL under Ron served as a link between Fermilab and international partners such as the Japanese High Energy Physics Lab (KEK) and Toshiba Corporation. Ron served on the Board of Directors of the Cryogenic Engineering Conference from 1973 to 1993. His greatest contribution in this area was probably his editorship of *Advances in Cryogenic Engineering*. This publication contains the technical papers presented at the biennial Cryogenic Engineering Conference. Typically, two to three hundred papers are given at each conference. As editor, Ron was responsible for seeking peer reviews of the papers, corresponding with authors about needed revisions, working with the authors as needed and deciding on the final acceptance of the papers. Dr. Fast served as editor from 1982 to 1992. From its inception, *Advances in Cryogenic Engineering* has been known as an archive of trusted information on cryogenic engineering. Dr. Fast's efforts during his tenure maintained that reputation. While Fermilab provided clerical assistance to Dr. Fast for this work, the bulk of the effort was Ron's. It's worth pointing out that today similar work on *Advances in Cryogenic Engineering* is carried out by a Chief Technical Editor assisted by five or six Technical Editors.

In recent years, *Advances in Cryogenic Engineering* has become an open-source publication with papers available for anyone to see. The most recent volume can be found here: **https://iopscience.iop.org/issue/1757-899X/1344/1**

Publications, Recognition, and Lasting Legacy

Dr. Fast produced numerous publications of his own including: "Design Guide for Liquid Hydrogen Targets Up To 35 Liters," R. W. Fast and M. A. Otavka, Fermilab TM-423 (1973); "Design of the 2 Tesla Superconducting Solenoid for the Fermilab D0 Detector Upgrade." B. Squires, J. Brzezniak, R. W. Fast, et al. *Adv. Cryo. Engr.*, Vol 39. Springer (1994); "Conceptual Design of a Superconducting Solenoid for a Magnetic SSC Detector," R.W. Fast, et al., *Proceedings 12th ICEC* (1988) and "An Experimental Study of Heat Transfer In Multilayer Insulation Systems from Room Temperature To 77 K," Q.S. Shu, R.W. Fast, H.L. Hart, *Adv. Cryo. Eng.*, Vol. 31, Plenum Press (1986).

In recognition of both his technical and community service work in cryogenics, Dr. Fast was presented with the Samuel Collins Award by the Cryogenic Engineering Conference.

Dr. Ronald W. Fast: His Enduring Legacy in Cryogenics and Lasting Influence on My Life

by Quan Sheng Shu

An Era-Defining Engineer and Mentor

My close friend and mentor, Dr. Ronald W. Fast, passed away on June 13, 2024. Born on April 2, 1934, Ron was widely recognized as one of the leading cryogenic and superconducting magnet engineers of his generation. As head of the Cryogenic Department in the Research Division at Fermilab, he played a pivotal role in the design and construction of the superconducting solenoid magnets for the Collider Detector at Fermilab (CDF and D0). These massive magnets provided the uniform magnetic fields needed to bend and track charged particles emerging from high energy proton–antiproton collisions—work that helped define an era of American particle physics. Figure 1 shows Ron working on the collider detector at Fermilab.

Beyond his technical achievements, Ron served the scientific community with immense dedication. He spent more than a decade on the Cryogenic Engineering Conference (CEC) Board of Directors and served as a longtime editor for *Advances in Cryogenic Engineering*. His profound contributions were ultimately recognized with the Samuel C. Collins Award, honoring his engineering accomplishments, his leadership, and his lasting influence on the fields of cryogenics and superconductivity.

A First Meeting and a Life-Changing Invitation

I first met Ron in 1983 at the CEC/ICMC conference at the Four Seasons Hotel in Colorado Springs. At the time, I was a visiting scholar at the National Bureau of Standards (NBS) in Boulder. Dr. Reed, the division director at NBS, introduced us. To ensure a strong first impression, Reed noted to Ron that I had translated *Cryogenic Engineering*—the seminal book by the deceased former director of NBS, R. Scott—into Chinese and published it in 1977.

Figure 1. Fast working on the collider detector superconducting magnet system at Fermilab (left). *Credit: Quan Sheng Shu*
Figure 2. Experimental studies of MLI blankets with penetrated cracks and slots (right). *Credit: Quan Sheng Shu*

Ron and I quickly found ourselves deep in conversation, and he passionately introduced me to new developments in cryostat designs for large superconducting magnets in the US. On the final day of the conference, he surprised me with an invitation to join him at Fermilab as a visiting scientist. I accepted with enthusiasm. Yet from the moment we met, he treated me as an equal partner in curiosity, engineering, and friendship. His passing leaves a profound, quiet space both in the cryogenic community and in my own life.

Pioneering Research: Bringing MLI to Megaprojects

I arrived at Fermilab in December 1984, and our research and experiments began in earnest. While we shared a broad interest in large cryostat design and magnet operations, my most influential work under his mentorship centered on multilayer insulation (MLI) for large, sophisticated superconducting magnets—including those envisioned for the Superconducting Super Collider (SSC).

Together, we explored how crinkled (embossed) layers, perforations for outgassing, and geometric imperfections (such as cracks and slots) fundamentally altered heat transfer behavior. Our studies helped shift MLI from a laboratory curiosity to a practical, robust engineering tool for megaprojects like the Tevatron, the SSC, and later, the Large Hadron Collider (LHC). Figure 2 shows our experimental studies on MLI blankets (cracks and slots). The four pillars of our collaborative work continue to guide accelerator, aerospace, and medical cryostat design today: real world deficiency diagnostics; substrate versus tape optimization; enhanced black hole theory and apparent thermal conductivity modeling; and a long citation lineage that remains foundational to the field.

A Deepening Fellowship Beyond the Lab

During those intense years of research, Ron's dedication often transcended normal working hours. One winter night in Chicago remains unforgettable. A 15 inch snowfall had completely blocked the parking lots around the test lab. Undeterred, Ron insisted we work together past 10 p.m. to check on our MLI tests and analyze the latest data. His commitment—both to science and to our partnership—was unwavering, even in the harshest conditions.

Figure 3. Fast (right) and Shu (left) bicycling along the Fox River in Batavia on a weekend (left). *Credit: Quan Sheng Shu*
Figure 4. Fast visiting my wife and daughter at Zhejiang University in Hangzhou (right) *Credit: Quan Sheng Shu*

Our professional partnership soon blossomed into a deep, lifelong friendship. On weekends, we rode bicycles along the Fox River in Batavia (Figure 3). At times, Ron would take me out on his 13 meter yacht, navigating the river waters out into Lake Michigan. Over those waters, we talked about family, childhood memories, and our hopes for the future. Even after my career took me to Cornell University and later to the SSC Laboratory, we stayed close. Ron traveled to China to visit my family, meeting my wife and daughter at Zhejiang University (Figure 4), and he continually offered me invaluable technical, professional, and personal guidance.

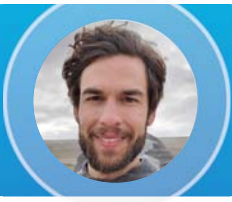
Shared Visions at the SSC and Editorial Leadership

In the early 1990s, I worked at the Superconducting Super Collider Laboratory as the cryogenic instrument section leader, and later as the technical head of the cryostat and interconnect group. During those years, our technical exchanges deepened as my responsibilities grew and Ron advanced the SSC detector design. We frequently compared design notes, insulation strategies, and integration challenges, sharpening each other's thinking and strengthening the engineering foundation of the project. As a core leader of the conceptual design team, Ron coauthored the blueprint for a truly monumental SSC detector solenoid—an 8 meter diameter, 16 meter long magnetic field volume. His visits to my family home in DeSoto, TX, during this period remain cherished memories.

When I was appointed Chief Editor of the Cryogenic Engineering Conference in 1997, Ron generously shared his decades of editorial experience with me. He offered practical advice, historical perspective, and warm encouragement—never in a superior tone, but always as a supportive colleague eager to see me succeed. His guidance during that transition shaped my editorial approach.

An Enduring Legacy

After we both retired, our connection remained strong. Ron encouraged me—sometimes gently, sometimes firmly—to write a book on cryogenic technology for superconducting applications, ensuring our shared knowledge would be preserved. Meanwhile, he devoted himself wholeheartedly to church and community service, living out the same quiet generosity in his personal life that he always showed in his professional career. Dr. Ron Fast was a gifted engineer, a generous mentor, and a fiercely loyal friend. His legacy lives on in the pioneering machines he helped build, the students he inspired, and the colleagues—like me—whose lives were permanently touched by his kindness and wisdom.



Space Cryogenics

by Bradley Moore, NASA - Jet Propulsion Laboratory, California Institute of Technology

SPHEREx: One Year of Passive 45 Kelvin Operation in Low Earth Orbit

The SpectroPhotometer for the History of the universe, Epoch of Reionization and ices Explorer (SPHEREx) is a passively cooled astrophysical observatory operating in a synchronous Low Earth Orbit (LEO). It is a planned 26-month mission that will map the entire sky four times in 102 color bands at near-infrared wavelengths. This all-sky mapping provides essential information on the large-scale structure of the universe and the distribution of interstellar ices (Bock, et al., 2026). The mission launched March 12, 2025, at 3:10 AM UTC and finished the first two all-sky surveys on May 14, 2026. The last image we have of SPHEREx itself is shown in Figure 1, drifting into the lonely black.

Figure 1. The last view of SPHEREx after separation from the Falcon 9 launch vehicle. *Credit: SpaceX livestream*

The Coldest Passive Observatory in Low Earth Orbit

The sensitive infrared detectors require low temperatures to sufficiently control dark current for these measurements, specifically 62 K (-211°C, -348°F) for the three short-wave (SWIR) detectors and telescope, and 45 K (-228.15°C, -378°F) for the three mid-wave (MWIR) detectors. Passive cooling is employed to reach these very low cryogenic temperatures, to avoid the cost and system complexity of an active cooler.

The concept of utilizing deep space for passive cooling is not novel: as early as 400 BCE, Persian engineers used night-sky radiative cooling to freeze water in desert climates using yakhchāls. In modern spaceflight, multiple missions in interplanetary orbits (such as Spitzer) or at the second Earth-Sun Lagrange point (such as JWST, Planck, and Herschel) have passively achieved temperatures at or below those of SPHEREx, often supplementing these stages with active coolers or stored cryogens.

Historically, LEO instruments relying solely on passive cooling have struggled to achieve temperatures below 80 K, typically requiring active cryocoolers or cryogens for colder operations. The Diffuse Infrared Background Experiment (DIRBE) instrument on the COBE mission is a notable point of comparison, as it is the only other mission to record temperatures near those of SPHEREx without cryogens or a cryocooler. It warmed to a passive equilibrium of 43 ± 5 K roughly 250 days after depleting its liquid helium (Volz & DiPirro, 1992). However, this temperature applied only to its infrared detectors. Unlike COBE, SPHEREx is designed to passively cool the entire instrument to a stable operating temperature. Building on decades of heritage from cryogenic missions, SPHEREx leverages state-of-the-art analytical techniques and system-level thermal design to establish the coldest passively cooled observatory in LEO.

Engineering a Passive Cryogenic System

SPHEREx achieves this cooling with multiple passive stages. Three layers of V-groove type radiators block spacecraft emission, and environmental loads from the Earth and sun, and allow the radiators a view of the cold of deep space to reject heat radiatively. This design achieves temperatures of ~250 K, ~150 K, and ~100 K on the three shields from the outside to the inside, respectively. The conical shield geometry gives the observatory a distinctive martini glass shape. Inside the glass, the "olive" is the telescope, which is painted black and cools with the SWIR radiator to 62 K, and the MWIR detector with a large discrete open cell honeycomb radiator cooling to 45 K. Composite and titanium structural supports and low conductivity wiring span the thermal zones. Other than a telescope cover,

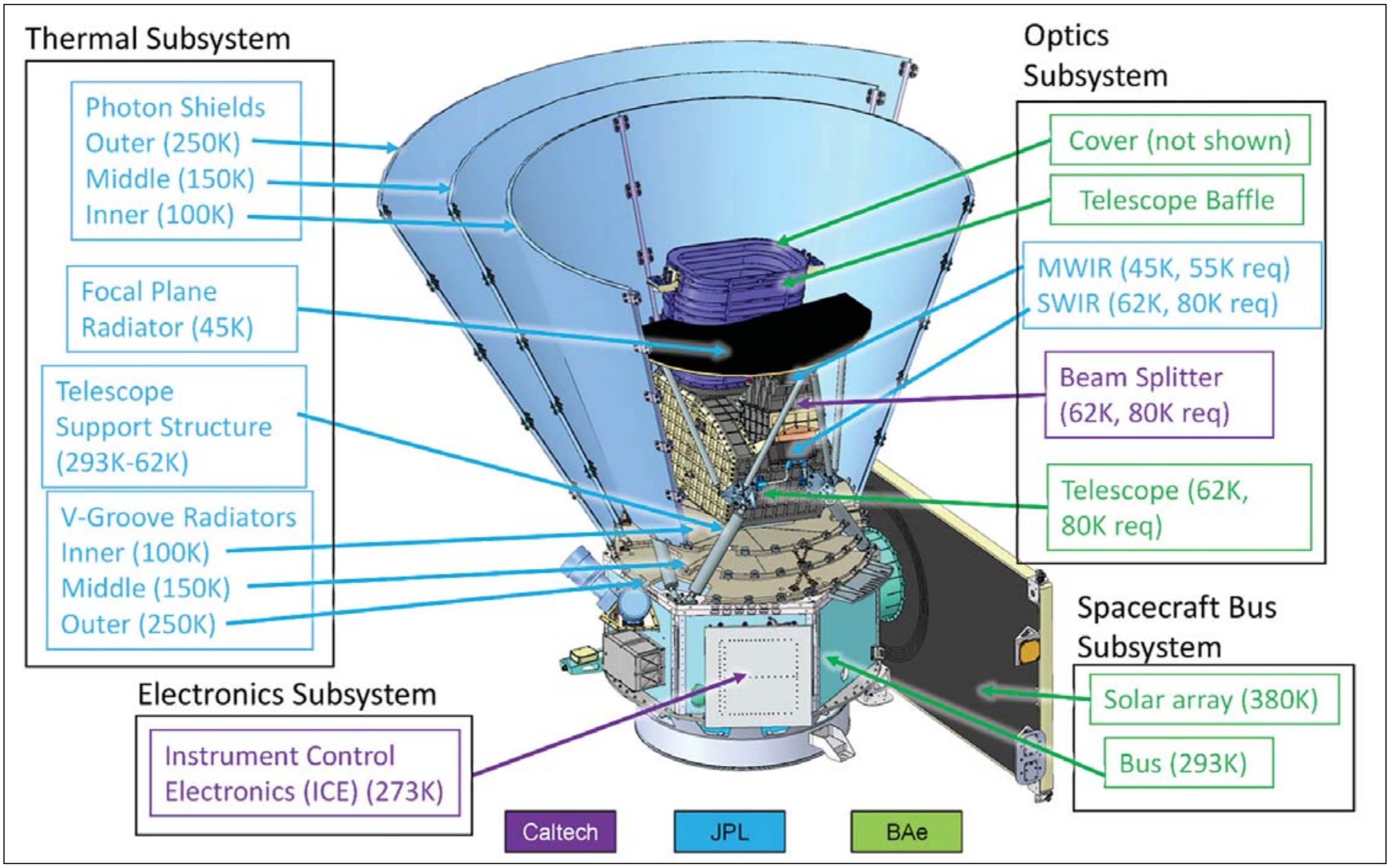


Figure 2. Primary components of the SPHEREx Mission, photon shields partially removed for clarity. *Credit: Bradley Moore*

which is deployed shortly after launch, there are no moving parts in the instrument and no propellant on the spacecraft. The repetitive slewing and pointing motions of the survey are achieved with reaction wheels recharged by magnetic torquer rods. An advanced survey algorithm (Bryan, et al., 2025) conducts the spectral mapping without the use of a steering mirror. The orbit and observatory were designed to safely deorbit passively after 25 years and burn up in Earth's atmosphere consistent with NASA orbital debris requirements intended to minimize the generation of "space junk."

JPL provided the system-level integration, thermal subsystem, and both MWIR and SWIR focal plane arrays. Instrument testing was conducted at Caltech along with the design and construction of the dichroic beam splitter. The instrument electronics were built in partnership between Caltech and UC Berkeley. BAE Space and Mission Systems provided the telescope and spacecraft bus. The deeply integrated, complex, and unique JPL system-level design, coupled with the agile environment of Caltech, and reliable heritage from BAE enabled the SPHEREx mission.

One Year of On-Orbit Thermal Performance

Even with such a strong team, fitting an integrated, passively cooled system into a cost-capped mission was a challenge. Performance predictions relied heavily on modeling with no direct verification of the passive system. Only one thermal vacuum test was conducted with the complete thermal system in a liquid nitrogen environment (~77 K, well above the operational temperature), though a subscale test was conducted at operating temperatures. Instead, subsystem and higher-temperature tests (coupled with model correlation and physics-based extrapolation) provided the required prediction accuracy to ensure on-orbit performance.

When the mission launched in March 2025, the initial on-orbit results were surprising. The spacecraft initialized in an inertial reference frame, essentially pointing "north" throughout its orbit. Thus, the cryogenic radiators received drastically varying thermal loads as the view changed from staring at a warm earth and reflected sunlight vs. deep space over each orbit. This orientation was expected and modeled. The surprise however, was that the model had predicted much lower temperatures at this phase. Given the heavy reliance on thermal modelling, this was a great concern to the team. However, some rapid turnaround modelling determined that the latitude varying albedo used in prelaunch predictions was from a 1981 paper (Stephens, Campbell, & Haar, 1981) and averaged over the year in coarse latitude bins. Once this was updated with a current and much finer latitude resolved derived albedo from the CERES mission measurements (Kato, et al., 2025), the predictions snapped to measurements perfectly. This was a sign that, even in astrophysics, we need to understand and

▶ ***continues on page 24***

appreciate the effects of the climate of our home planet.

After this initial excitement, the observatory pointed to deep space to cool down to the operating temperatures. A plot of the cooldown and performance to date with an ~1-year time break is shown in Figure 3. The shift in cooldown rate is driven by decontamination heaters, which keep the optics warmer than surrounding components. This thermal bias prevents volatile contaminants from migrating and condensing on the optical surfaces, critical for an instrument designed to measure cosmic ices. The cooldown behaved exactly as predicted, landing at temperature in 13 days vs. the predicted 13.7 days. There are no direct heat flow meters on the instrument, but the control heat required to hold the detector temperatures can be compared to the predicted values to determine model accuracy. Without any additional corrections in flight the model was accurate to within 3.9% for the SWIR detector and 5.5% for the MWIR detector of the estimated total heat load. The thermal design proved to be so robust and well understood that the pointing constraints could be relaxed to address higher-than-expected shuttle glow phenomena occurring on the leading edge of the observing range. Since the survey began, the active heating on the detectors has delivered exquisite temperature control, staying within 1 mK (millikelvin) on the MWIR detector and 5 mK on the SWIR detector, with the minimum heat applied of 36.4 mW (milliwatts) and 132.7 mW, respectively.

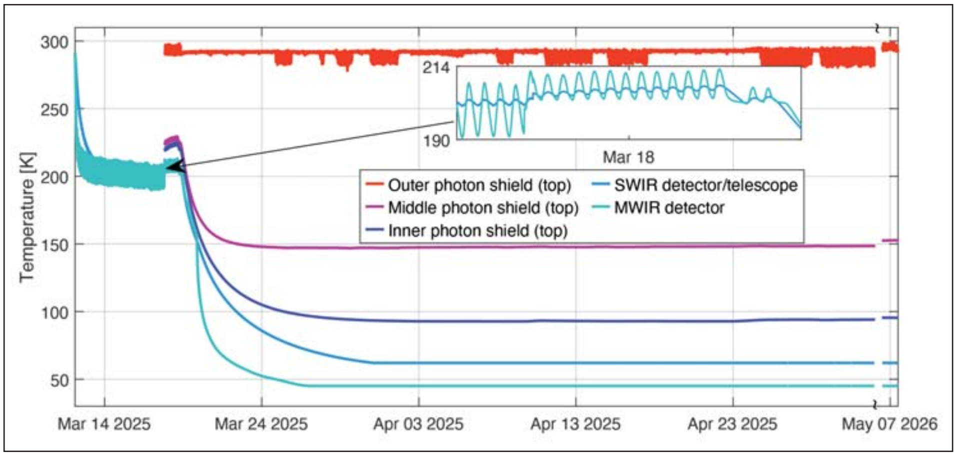


Figure 3. SPHEREx on-orbit cooldown and stability to date. *Credit: Bradley Moore*

What SPHEREx Means for Future Missions

We will now be able to deliver ultra-stable cryogenic cooling to low earth orbit at a much lower temperature than previous missions. As with any low temperature cryogenic system there is a constant push and pull with the structural and radiated thermal parasitic loads. The V-groove radiator performance is limited by fairing size, mass, and observing scenario. Structural loads are driven by launch dynamics and instrument mass. The asynchronous design inherent in a large system coupled with flight mission risk posture drove SPHEREx thermal parasitics slightly higher than the minimum achievable. The next mission will hopefully push this envelope even further.

Despite the constraints, due to robust system margins, the thermal system is outperforming the initial temperature requirements of 55 K for the MWIR detector and 80 K for the SWIR detector by a substantial amount, achieving 45 K and 62 K respectively, including the dissipation from active temperature control. The thermal system has been operating perfectly for over a year and promises to continue to do so for years to come. In the end, it is enabling groundbreaking astrophysics, and that is what cryogenic cooling is about: providing a platform to achieve unprecedented science, engineering, and industrial innovation.

Acknowledgments

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More information is available at: **www.jpl.nasa.gov/missions/spherex, https://spherex.caltech.edu**

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Zero Resistance Zone

by Quan-Sheng Shu, cryospc.com and Jonathan Demko, Le Tourneau University

Keeping it Below T*c*: Comparing Bath, Forced-Flow, and Thermosiphon Cooling

Superconductivity has enabled transformative applications in high-energy physics, medical imaging, X-ray free-electron lasers, fusion, quantum electronics, and power systems because of its defining property of zero electrical resistance. Maintaining superconducting equipment below its critical temperature (T_c) requires effective cryogenic cooling.[1–3] Engineers primarily rely on three approaches: cryogen bath cooling, forced-flow circulation, and thermosyphon cooling. Continued advances in these cooling methods are improving thermal performance, operational stability, and system efficiency, enabling the next generation of superconducting technologies.

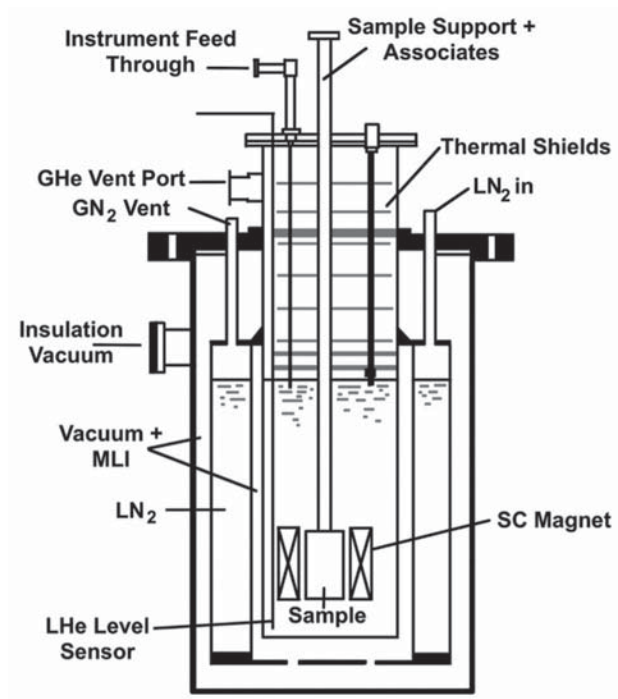

Figure 1. Conventional design of a bath-cooling cryostat for SC magnet applications. *[2] Credit: Shu and Demko*

Operation and Thermal Control in Pool-Boiling Systems

In pool-boiling bath cooling, the superconducting (SC) magnet is completely submerged in a liquid helium (LHe) vessel, ensuring direct thermal contact. Heat generated by the coil or sample is continuously absorbed via LHe vaporization, maintaining an exceptional operational temperature near 4.2 K. Though this represents a laboratory testing setup, the principles of its design, construction, and operation are broadly applicable across various large-scale cryogenic systems. As Figure 1 illustrates, thermal control and parasitic load reduction rely on a multistage insulation architecture.[2]

- **Vacuum + MLI Insulation.** The outer insulation vacuum with multilayer insulation (MLI) suppresses ambient thermal radiation.
- **LN_2 Shielding.** An outer liquid nitrogen (LN_2) reservoir (77 K) absorbs external heat influx, drastically minimizing LHe boiloff.
- **Level, Temperature, and Pressure Monitoring**. Instrumentation feedthroughs connect the temperature sensors and LHe level sensor for monitoring

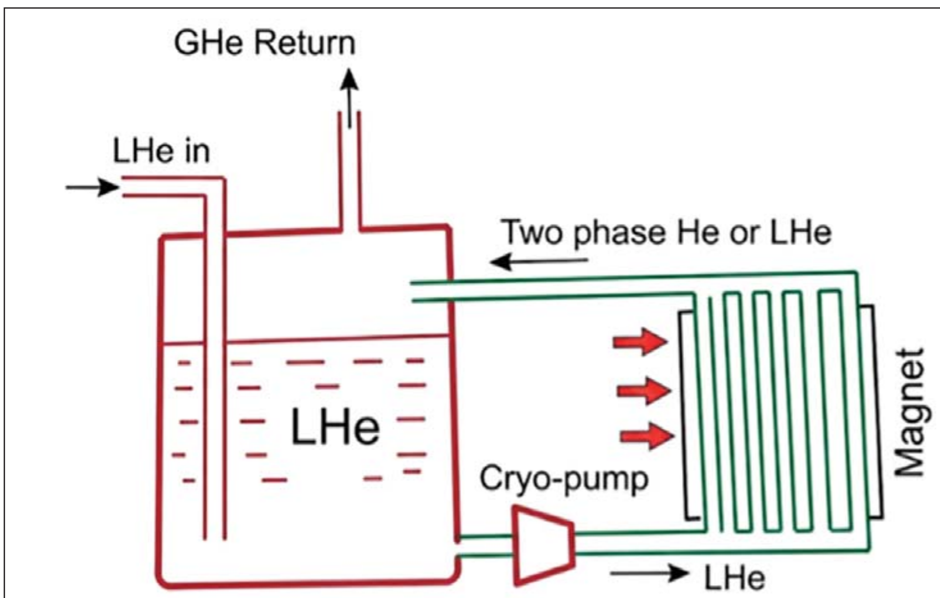

Figure 2. A simplified sketch of forced-flow cooling for SC magnet. *Credit: Shu and Demko*

inventory, while a dedicated GHe vent port manages boil-off gas and safe pressure relief.

This passive setup offers exceptional thermal stability and operational simplicity, making it the dominant choice for laboratory research magnets and clinical MRI systems. Early high-energy physics detectors, including the Big European Bubble Chamber (BEBC) and the OPAL endcap, also successfully utilized pool-boiling cooling before future designs shifted to forced-flow or thermosiphon schemes to reduce helium inventory.

Basic Principle of Forced Flow Cooling in SC Magnets

As large-scale superconducting devices expanded, the massive helium inventories and thick containment walls required by bath cooling became impractical. Forced-flow cooling overcomes these limitations by actively circulating cryogen through dedicated cooling channels or Cable-in-Conduit Conductors (CICC) attached to the magnet, as schematically illustrated in Figure 2.

The main advantage of this approach is a drastically reduced helium inventory alongside improved thermal performance in large, high-field coils. Active circulation ensures rapid heat removal and precise temperature control. However, forced-flow systems introduce operational complexity, including pressure drops along cooling lines, mechanical vibration risks, and potential flow instabilities during thermal transients or quenches. To drive fluid circulation across different operating environments, four primary mechanisms are employed (summarized in Table 1):

- **Cryogenic Pumps.** Utilize mechanical impellers or pistons to deliver massive flow capacities for stable single- or two-phase forced loops.
- **Cryogen Heating.** Capitalizes on localized thermal expansion, offering a vibration-free design with no moving parts.
- **J-T Expansion.** Uses an upstream gas compressor to force high pressure gas through a throttling valve, achieving extreme temperature drops.
- **Vacuum Pumping.** Employs downstream vacuum pumps to lower vapor pressure above the liquid interface, enabling sub-atmospheric operating regimes like 1.9 K superfluid helium.

Mechanism	Primary Force Source	Phase State	Key Advantage	Typical Use Case
Cryogenic Pumps	Mechanical Impeller/Piston	Single-phase or two-phase liquid	Massive flow capacity; stable forced loop	CERN ATLAS, ITER, LNG Transfer
Cryogen Heating	Localized Thermal Expansion	Liquid + Vapor expansion	No moving parts; vibration-free	Space cryogenics, micro-devices
J-T Expansion	Upstream Gas Compressor	High-P gas → Two phase	Extreme temperature drop via throttling	IR sensor cryocoolers, liquefiers
Vacuum Pumping	Downstream Gas Vacuum Pump	Liquid-Vapor interface	Reaches sub-atmospheric temperatures	1.9 K Superfluid Helium (LHC)

*Table 1. **Comparison of four primary mechanisms for forced-flow cooling.** Credit: Shu and Demko*

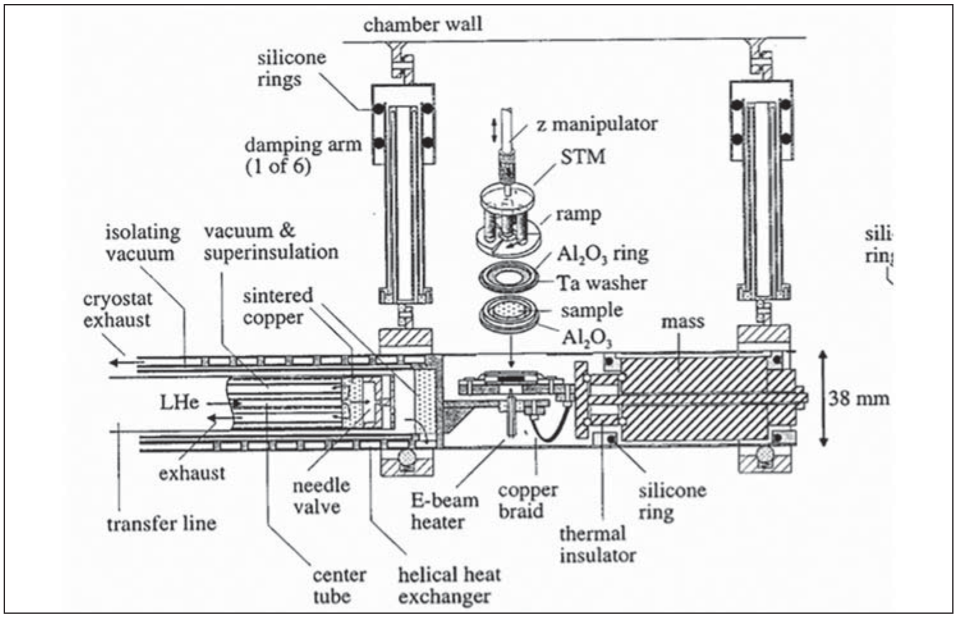

*Figure 3. **A cutaway side and front views of the continuous flow cryostat.** [4] Credit: Behler*

Practical Applications of Forced-Flow Cooling

At the sub-meter scale, Figure 3 illustrates a continuous-flow cryostat integrated with a Scanning Tunneling Microscope (STM).[4] Here, liquid helium is actively drawn through a needle valve and a helical heat exchanger, utilizing flexible copper braids to cool the sample stage without transmitting mechanical vibrations that could disrupt atomic-scale measurements.

Conversely, Figure 4 demonstrates forced-flow cooling on a giant scale within the CERN ATLAS detector's superconducting Toroid magnet system.[5] These massive, multimeter coils rely on forced circulation of two-phase helium through dedicated cooling circuits, such as at ETER, EAST, and LHD.[6-8] Active flow ensures uniform thermal management and minimal material density across vast dimensions, preventing high-energy particle scattering while maintaining the coils below critical temperature. Together, these systems highlight how forced-flow cooling adapts seamlessly across extreme physical scales.

▶ *continues on page 28*

Fundamentals of Thermosyphon Cooling

A thermosyphon cooling system relies on natural convection to circulate cryogen through a closed loop without mechanical pumps. As shown in Figure 5, liquid helium (LHe) flows downward from a central reservoir due to gravity. As it absorbs the external heat load from the superconducting device, the cryogen undergoes localized phase change, transforming into a lower-density, two-phase liquid-gas mixture. This density differential generates a buoyant force that drives the fluid upward, returning gaseous helium (GHe) and remaining liquid back to the vessel. The primary advantages of thermosyphon loops include high-operational reliability and vibration-free cooling, as the elimination of moving parts avoids mechanical wear. Furthermore, it significantly reduces total helium inventory compared to traditional bath cooling systems.

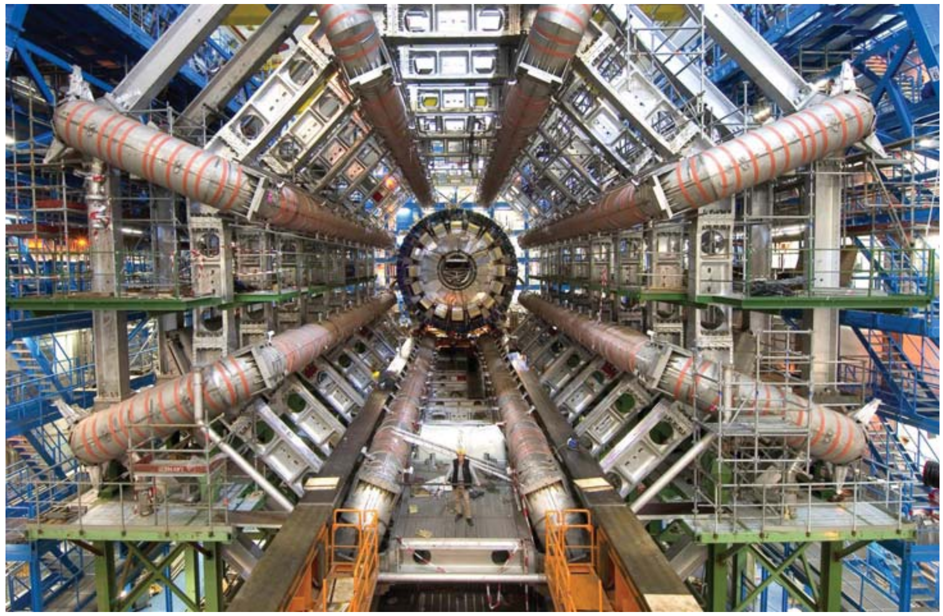

Figure 4. The ATLAS-Toroid magnet cooled by forced flow liquid He. [5] *Credit: Herman and CERN*

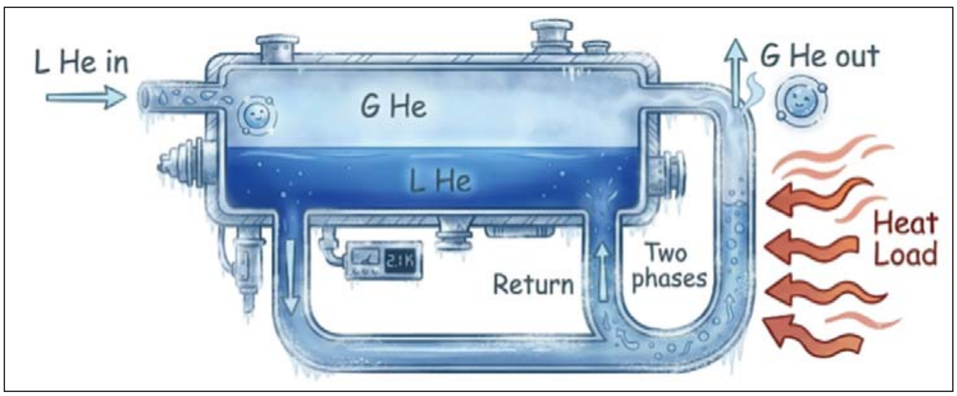

Figure 5. The fundamentals of thermosyphon cooling. *Credit: Shu and Demko*

Applications of Thermosyphon Cooling: The CERN CMS Solenoid

Thermosyphon cooling is widely adopted in large-scale superconducting magnets where high operational reliability, low vibration, and minimized liquid helium inventory are essential. As illustrated in Figure 5, the generic architecture employs an elevated helium phase separator vessel. Single-phase liquid helium (LHe) flows down a supply line to a lower manifold; feeding parallel cooling tubes (e.g., 14 mm inner diameter) attached to the coil's outer surface. Heat generated within the winding vaporizes a fraction of the cryogen, driving the resulting lower-density two-phase mixture upward back to the phase separator via a top return line.

The primary examples of this technology are the SC magnets such as for the CERN CMS (Compact Muon Solenoid) magnet, Fermilab CDF and D0 etc.,[9-11] depicted in Figure 6. Measuring 12.5 m in length and 6.3 m in diameter, this giant 4 T solenoid stores 2.7 GJ of energy. By utilizing indirect thermosyphon cooling, the CMS detector eliminates the need for mechanical pumps while maintaining uniform temperature control across its 225-tonne cold mass.

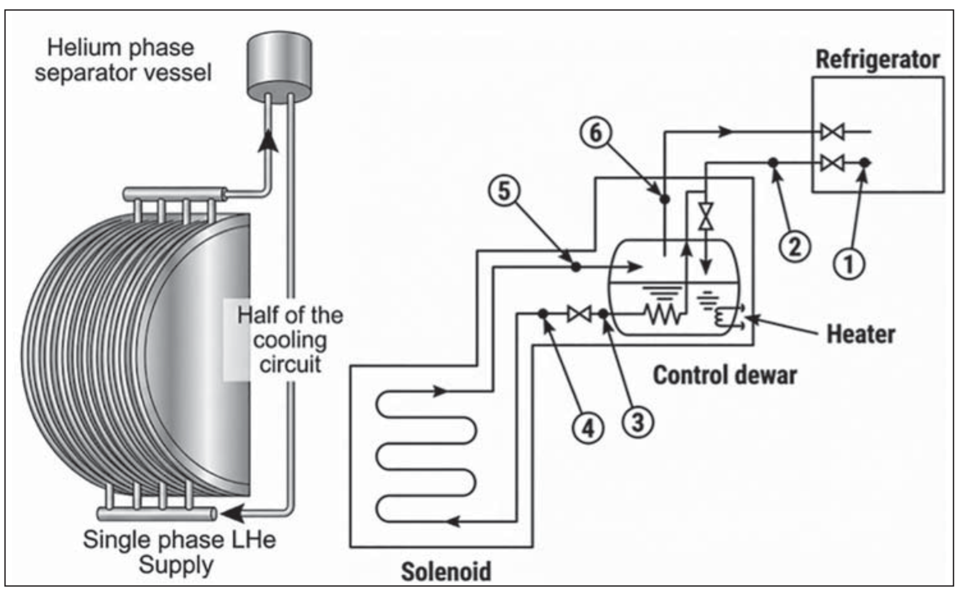

Figure 6. Left: Cooling circuit of the CMS solenoid in a thermosiphon mode [9]***. Right: The cryogenic flow diagram for thermosyphon cooling of the ATLAS ultralight central solenoid magnet.*** [11] *Credit: Lottin* [9] *and Yamamoto.* [11]

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Advancements in Cryogenic Cooling for Space Exploration

by Dr. Mark V. Zagarola, Principal Engineer and Partner, Creare LLC

Future space flight missions beyond low earth orbit will rely on large quantities of liquid oxygen and liquid methane propellant. Storing these fluids with zero boiloff is essential for mission feasibility, and maintaining zero boiloff requires efficient, high-capacity cryogenic cooling. The estimated heat loads for storing liquid oxygen and liquid methane are hundreds of watts at roughly 90 K and exceed the capacity of previously flown space cryocoolers by a significant margin.[1] To meet this need for high-capacity cryocoolers, Creare recently built and tested a turbo-Brayton cryocooler capable of delivering over 120 W of refrigeration at 90 K and more than 200 W at 118 K. This performance represents a significant advance in space-qualified cooling technology. The high-capacity cryocooler is now undergoing additional testing as part of NASA's CryoFILL (Cryogenic Fluid In-Situ Liquefaction for Landers) test program.

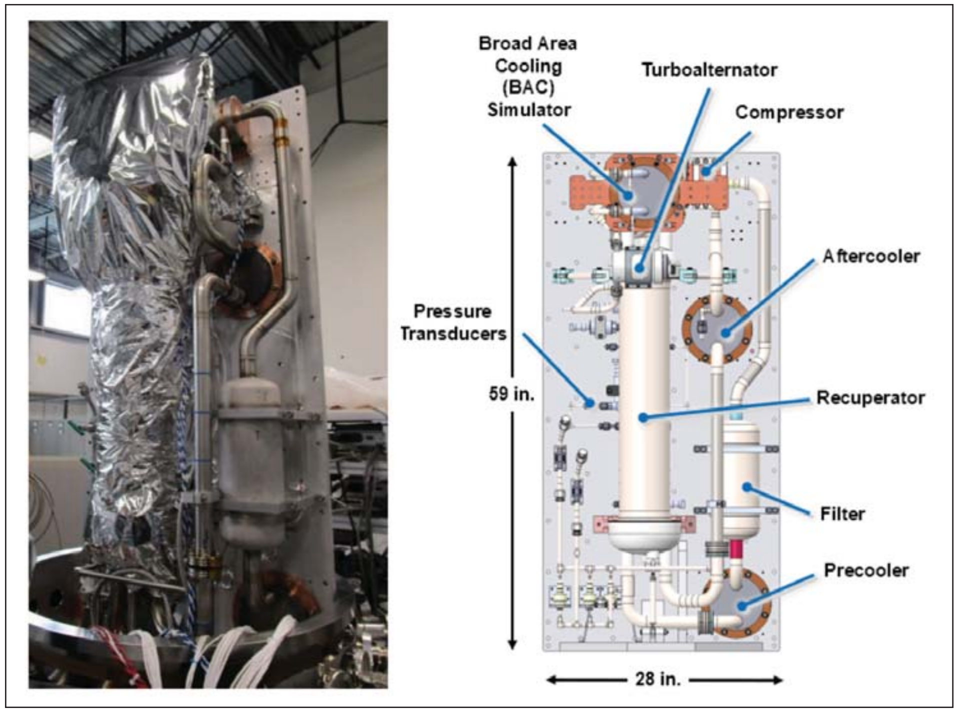

Figure 1. Integrated cryocooler installed in vacuum chamber for testing (left). Solid model of engineering model cryocooler (right). Credit: Creare

Cryogenic Cooling for the Next Generation of Space Missions

This cryocooler builds on Creare's earlier 15 W, 90 K turbo-Brayton cryocooler delivered to NASA in 2012. The earlier system enabled NASA's seminal demonstrations of reduced hydrogen boiloff and zero-boiloff oxygen storage.[2] Turbo-Brayton cryocoolers are ideal for cooling cryogen storage tanks because they scale favorably to high refrigeration capacities[3] and can interface directly with a broad area cooling (BAC) system, making them lighter and more efficient than alternative technology. Creare's new high-capacity 90 K cryocooler was configured as an Engineering Model (EM) with flight-like component mounting and automated system controls. The EM components are all representative of flight designs with the exception of a BAC simulator to replicate the heat load, pressure drop, and internal volume that would be present when integrated with a BAC network on a cryogen tank.

Figure 2. 90 K high-capacity cryocooler during vibration testing. Credit: Creare

Pre-vibration thermodynamic testing completed in early 2024 yielded promising results. The performance of the cryocooler was measured at three load temperatures and two heat-rejection temperatures over two test campaigns. The cryocooler provided a maximum of 112 W of refrigeration at 90 K and 172 W at 118 K. The performance of the compressor and turboalternator during thermodynamic testing matched component performance predictions very closely. Recuperator performance data indicated areas for improvement to increase performance and cooling capacity even higher.

Following this initial thermodynamic testing, the cryocooler underwent vibration testing at a qualified test vendor (Figure 2). The cryocooler was subjected to qualification-level random vibration per GSFC-STD-7000 (formerly known as GEVS) in each of the three principal axes. Vibration testing of the cooler was successful and identified improvement for flight future flight systems.

Designing for Higher Cooling Capacity

The cryocooler was then reinstalled in a test chamber at Creare for thermodynamic testing to verify proper system operation post-vibration testing. Thanks to slightly improved recuperator performance, cryocooler performance improved across all operating conditions following the vibration testing. The cryocooler demonstrated a refrigeration capacity of 128 W at 90 K and 203 W at 118 K. More details on specific test outcomes are available in reference 4. The cryocooler was then delivered to NASA for ongoing testing as part of their CryoFILL project.

The flight-like model met threshold levels for all NASA's performance metrics (see Table 1). The refrigeration capacity provided by this cryocooler at temperatures between 90–118 K is substantially greater than that of other available space cryocoolers at these temperatures. Figure 3 shows the superior cooling capacity of the described 90 K cryocooler as well as Creare's companion 20 K cryocooler that was previously developed for zero-boil-off storage of hydrogen.

Table 1. Comparison of As-Delivered Cryocooler Performance with Performance Targets

	Demonstrated Post-Vibe	Performance Target
BAC Return Temperature	90 K	90 K
Cooling Capacity	128 W	120 W (thresh.) 150 W (goal)
Flight Specific Power	12.3 W/W	15 W/W (thresh.) 8 W/W (goal)
Flight Specific Mass	0.66 kg/W*	0.8 kg/W (thresh.) 0.4 kg/W (goal)

*Predicted flight mass includes several items likely to be eliminated in flight system

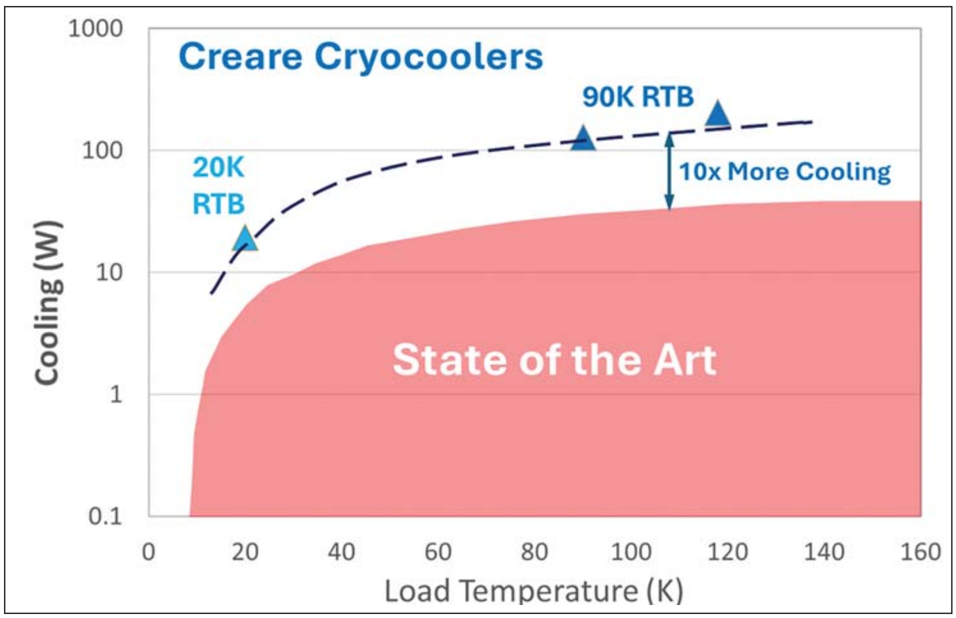

Figure 3. Creare's 20 K and 90 K cryocoolers compared with available space coolers. [5, 6, 7, 8, 9] *Credit: Creare*

Creare's new cryocooler was developed and qualified under NASA's Small Business Innovation Research Program and Cryogenic Fluid Management Portfolio Project. The cryocooler represents a new paradigm for space cryocoolers. A flight version of the cooler is predicted to demonstrate even better performance and will play a critical role in enabling manned exploration of the solar system. **www.creare.com**

To view the full list of references, visit **https://2csa.org/xu1**

Designing for the Cold: Cryogenic Characterization and SPICE Modeling for Space Imaging Electronics

by Akin Akturk, PhD, Co-founder, CoolCAD Electronics

High-sensitivity focal plane arrays deployed in low earth orbit (LEO) imaging satellites require readout integrated circuits that operate reliably at liquid nitrogen temperatures of approximately 77 K (minus 196 degrees Celsius). Silicon complementary metal-oxide-semiconductor (CMOS) devices exhibit measurable shifts in threshold voltage, carrier mobility, subthreshold slope, and leakage behavior. When cooled to these temperatures, standard room-temperature SPICE models do not capture these effects. Producing accurate, validated cryogenic SPICE models requires systematic physical characterization across the full operating temperature range and rigorous model extraction against measured data. CoolCAD Electronics has provided this service to aerospace programs, foundries, and government customers since 2005; delivering process design kit (PDK)-ready cryogenic models that give circuit designers a reliable, physics-based baseline for first-pass tape-out.

Extreme test setup examples for low and high temps. *Credit: CoolCAD Electronics*

Why the Readout Circuit Must Operate at 77 K

Most of the electronics on a LEO satellite operate in a thermally controlled warm box near room temperature. In the space environment, heat transfer occurs exclusively by electromagnetic radiation, with no conduction or convection pathway available. A well-insulated enclosure can maintain near-ambient temperatures even in LEO, and satellite bus electronics are routinely designed to that assumption.

The exception is the imaging payload. To achieve the photon noise-limited sensitivity that makes a focal plane array scientifically and operationally useful, the detector array and the readout integrated circuit bonded to it must be cooled to cryogenic temperatures. At 77 K, dark current drops dramatically, thermal noise in the readout circuitry falls, and the overall signal-to-noise ratio of the imaging system improves by orders of magnitude relative to room-temperature operation. Infrared imagers for Earth observation satellites, space-based astronomical imagers, and hyperspectral sensing payloads all depend on readout ICs that function reliably at liquid nitrogen temperature.

What Changes in Silicon at Cryogenic Temperatures

Silicon CMOS remains the dominant technology for readout circuit design at 77 K. Unlike wide-bandgap materials such as silicon carbide, silicon transistors operate well into the cryogenic regime. As temperature falls toward 77 K, threshold voltage increases, carrier mobility rises due to reduced phonon scattering, the subthreshold slope narrows toward its theoretical minimum of approximately 15 mV/decade at 77 K, and junction leakage current drops precipitously. These are largely favorable trends for analog precision, but they shift device operating points far enough from room temperature values that PDKs calibrated at 300 K cannot be used reliably for cryogenic design work.

The circuit designer using room temperature models for a 77 K design is working without a valid reference. Threshold voltage offsets in differential pairs, current levels across bias networks, analog bandwidth, and noise floor behavior all depend on accurately modeled cryogenic device parameters. Obtaining those parameters requires physical measurement at temperature.

What CoolCAD Measures, Delivers

CoolCAD characterizes silicon CMOS devices at temperatures from 4 K to room temperature using cryogenic probe stations with liquid helium and liquid nitrogen cooling. The measurement program covers DC current voltage and capacitance voltage characteristics across all relevant bias conditions, along with low-frequency transient measurements needed to resolve carrier trapping and interface-state dynamics at low temperature. The device matrix spans long-channel and short-channel structures, bulk CMOS, silicon-on-insulator and FinFET configurations, covering thin-oxide and thick-oxide variants across the voltage ranges appropriate to each process node.

From this characterization data, CoolCAD extracts validated SPICE models suitable for direct incorporation into the customer's PDK. The deliverable is a temperature-parameterized model set that the design team can deploy in their simulation environment, enabling realistic first-pass circuit simulation at 77 K before a wafer is committed to fabrication.

Methodology and Practical Considerations

CoolCAD operates cryogenic probe stations in-house and provides on-site characterization services at both customer and government laboratory facilities. In-house testing handles both die-level and packaged device characterization. For programs where devices cannot leave the customer site (or where specialized infrastructure is available at a national laboratory or foundry facility), CoolCAD engineers travel to the test location, execute the measurement program, and return with validated data for model extraction.

Cryogenic testing is resource-intensive and demands careful planning. Open-cycle liquid helium systems provide roughly 12-15 hours of usable run time per tank, requiring a fully optimized test sequence to capture the complete device matrix within each cooling cycle. Liquid nitrogen offers considerably more flexibility; a single tank supports multiple days of continuous measurement. Model extraction from a full characterization dataset typically requires two to four weeks. Programs with broad device families can extend to a month.

The investment is justified. A cryogenic model set that accurately reflects measured device behavior at 77 K eliminates the design iterations that follow a first tape-out built on room temperature assumptions, and it gives the program a reusable simulation asset for future design cycles on the same process node.

The Road Ahead

Demand for validated cryogenic silicon models is growing across two converging markets. The first is expanding LEO imaging constellation programs which continue to drive new readout IC development cycles. Each new process node requires fresh cryogenic characterization data. The second market, quantum computing control electronics, is a separate but closely related demand driver. It requires 4 K-calibrated models for the classical silicon circuitry that interfaces with qubit arrays. Both markets share the same fundamental requirement: physics-based SPICE models anchored to low temperature measured data rather than extrapolated from room temperature fits.

CoolCAD Electronics has operated at this intersection of cryogenic testing and silicon device modeling since the company's founding in 2008, carrying forward more than two decades of accumulated measurement methodology, model extraction expertise, and process knowledge across bulk, SOI, and FinFET silicon technologies. For engineering teams developing readout circuits, imaging sensor interfaces, or cryo-compatible analog front ends, that depth of experience is a direct path to first-pass simulation accuracy at the temperatures their designs will actually see in operation.

CoolCAD Electronics is an ISO 9001-certified company located in Greenbelt, MD, with strong ties to the University of Maryland and a portfolio of NASA, DARPA, and Department of Defense programs spanning more than two decades. For more information on cryogenic characterization and modeling services, visit **www.coolcadelectronics.com**.

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People & Companies in Cryogenics

In early August, **Bluefors** announced **Greg Parker** as President of its Cryocoolers business. Based in Syracuse, NY, Parker will lead the company's cryocooler operations and support growth across the global Bluefors organization. Bringing more than 20 years of leadership experience in technology, aerospace, and industrial markets, he succeeds Rich Dausman, who is retiring after a 50-year career. The appointment underscores Bluefors' commitment to expanding its cryogenic cooling technologies and strengthening its position in advanced cryogenic applications.

Greg Parker. *Credit: Bluefors*

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Atlas Technologies recently announced a new ebook exploring aluminum and titanium vacuum chambers and bonded dissimilar-metal solutions. The ebook highlights the benefits of these materials, along with common uses in quantum research, cryogenics, and other advanced applications. Download the ebook to learn more at **www.atlasuhv.com**

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Cyl-Tec recently launched a new e-commerce website, Cyl-Tec Parts, featuring several helpful tools for repairing and maintaining cryogenic tanks. The site makes it easy to locate the exact part you need using the smart search bar to browse by industry part numbers. Over 350 diagrams available at **https://parts.cyl-tec.com/diagrams/**. New users receive a 5% discount on their first order. Request your user account today.

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The delivery of the central magnet bundle for the **Princeton Plasma Physics Laboratory's** National Spherical Torus Experiment-Upgrade (NSTX-U) marks a major milestone in fusion research and highlights the critical role of cryogenic and magnet technologies in advancing future energy systems. Weighing 23,000 pounds and manufactured in Spain, the bundle combines toroidal field and ohmic-heating magnets that will generate and control the powerful magnetic fields needed to confine and heat fusion plasma. Once installed, the system will support experiments in one of the world's most advanced spherical tokamaks, helping scientists evaluate designs for commercial fusion power plants.

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West Coast Solutions Atlanta is now open for business. This new location will build on and accelerate our ongoing collaborations with Georgia Tech in cryocoolers, thermoradiative power conversion, lunar batteries, satellite power systems, and other leading-edge technologies. WCS is excited to see what arises through the accelerated maturation of these game-changing WCS-GT technologies by way of this new synergy. Learn more at **https://wecoso.com**.

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The **European Society for Applied Superconductivity** (ESAS) congratulates **Giampiero Pepe**, its secretary and former president, on receiving the 2026 IEEE Max Swerdlow Award for Sustained Service. The honor recognizes his leadership, mentorship of young scientists, and extensive service to national and international organizations. The award will be presented at the annual Applied Superconductivity Conference in September 2026.

Giampiero Pepe, winner of the 2026 IEEE Max Swerdlow Award for Sustained Service to the Applied Superconductivity Community. Credit: ESAS

Meetings & Events

2026 CryoUsers Conference
September 7-9, 2026
Manchester, UK
https://bcryo.org.uk/events/cryousers-conference-2026-university-manchester

European Cryogenic Days 2026 (ECD-2026)
October 13-16, 2026
Grenoble, France
https://www.ecd-2026.fr

Hydrogen Innovation and Technology Conference
October 14-15, 2026
Manchester, UK
https://www.icheme.org/training-events/hydrogen-2026

Hydrogen Technology World Expo
October 20-22, 2026
Hamburg Messe, Germany
https://www.hydrogen-worldexpo.com

5th International Workshop on Cooling Systems for HTS Applications
October 26-28, 2026
Twente, The Netherlands
https://hts2026.com

32nd Space Cryogenics Workshop
June 9-11, 2027
Asheville, NC
https://spacecryogenicsworkshop.org

Cryogenic Engineering Conference and International Cryogenic Materials Conference (CEC/ICMC)
June 13-17, 2027
Knoxville, TN
https://www.cec-icmc.org

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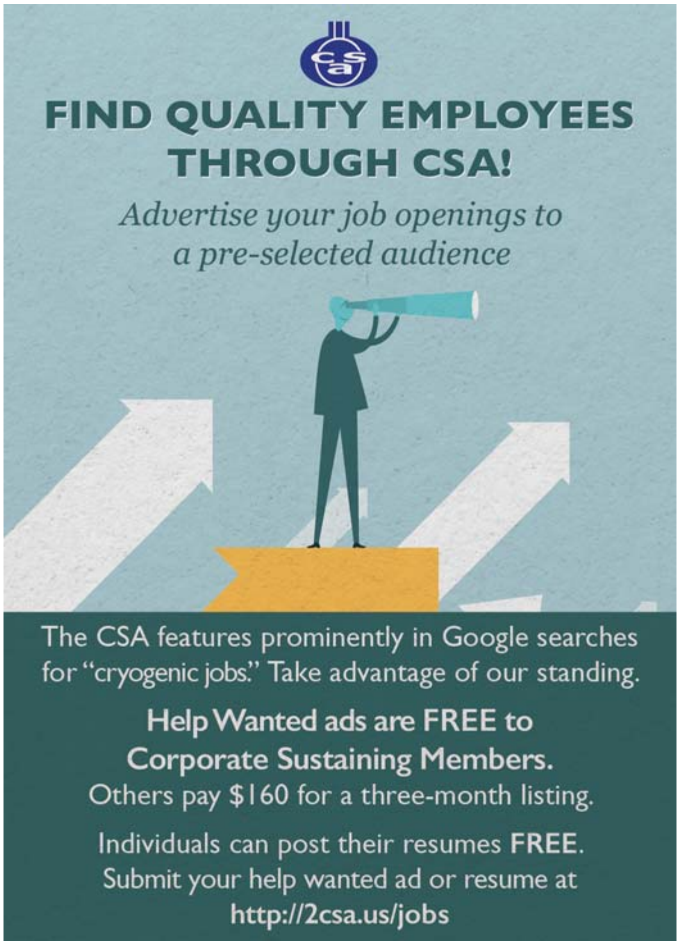
Ratermann Manufacturing has introduced Rex AI, a knowledge platform designed to bring decades of cryogenic and industrial gas expertise directly to customers, sales teams, and technicians. Built from more than 35 years of accumulated industry knowledge, Rex helps users quickly access information that has traditionally resided with a small group of highly experienced cryogenic professionals. Learn more at: **www.rmiorder.com.**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