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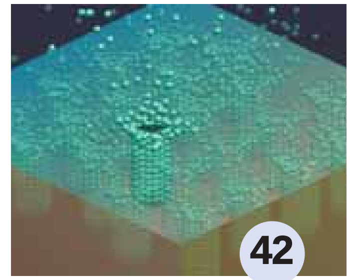

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Dr. Rasha Al-attar is advancing heart regeneration by developing nature-inspired cryopreservation techniques to improve stem cell-derived cardiomyocytes and organ preservation. Credit: Harvard Medical School and the Massachusetts General Hospital

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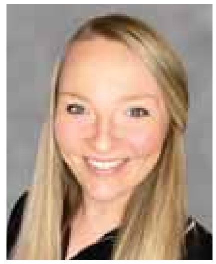
From the Executive Director



As summer transitions into fall and kids head back to school, many parents are taking a deep breath of relief, savoring the return to routine and the quieter days ahead. I know I am! In all seriousness, I hope you found some time to relax with family and friends this summer.

By the time you read this, the CSA team will likely have already returned from our trip to Salt Lake City for the 2024 Applied Superconductivity Conference (ASC24). We are looking forward to a jam-packed program of technical sessions and ample opportunities to network with members and other industry colleagues. At ASC24, CSA will present the Roger W. Boom Award, which is named in honor of the late emeritus professor from the University of Wisconsin. Dr. Boom's career spanned more than 30 years, during which he motivated a great number of young scientists and engineers to pursue careers in cryogenic engineering and applied superconductivity. This award was created by CSA to be given to a young professional (under 40 years of age) who "shows promise for making significant contributions to the fields of cryogenic engineering and applied superconductivity." The spirit of the Boom Award is to recognize young people for their pursuit of excellence, demonstration of high standards and clear communications. You can find more information about the Boom Award, including this year's recipient, on CSA's website at **www.2csa.org/award**.

CSA will also be hosting its annual in-person board meeting at the Applied Superconductivity Conference. During this meeting, the board will be reviewing and certifying the slate of nominees for the upcoming board election. If you are a member of CSA, expect to see an email ballot in the near future where you can place your vote for future leaders of CSA.

Later this fall, we are excited to open registration and abstract submissions for the 31st Space Cryogenics Workshop, which is taking place May 13-15, 2025, at the Hyatt Regency Lake Tahoe Resort, Spa and Casino. We are already accepting applications for event sponsors. A big thank you to our current sponsors: OPW and Spaceline Technologies. For full details and updates on the Space Cryogenics Workshop, visit **www.spacecryogenicsworkshop.org**.

Lastly, if you haven't had a chance to check out the CSA Job Center, I highly encourage you to. It is the go-to hub for employers and job seekers in the cryogenics industry. CSA members can post job openings for free, and job seekers can post their resume for free too. If you aren't a member of CSA, but would like to post a job, you can do so for a nominal fee. Visit **www.2csa.org/jobs** to see what the hype is about.

As always, I hope you enjoy this issue of *Cold Facts*!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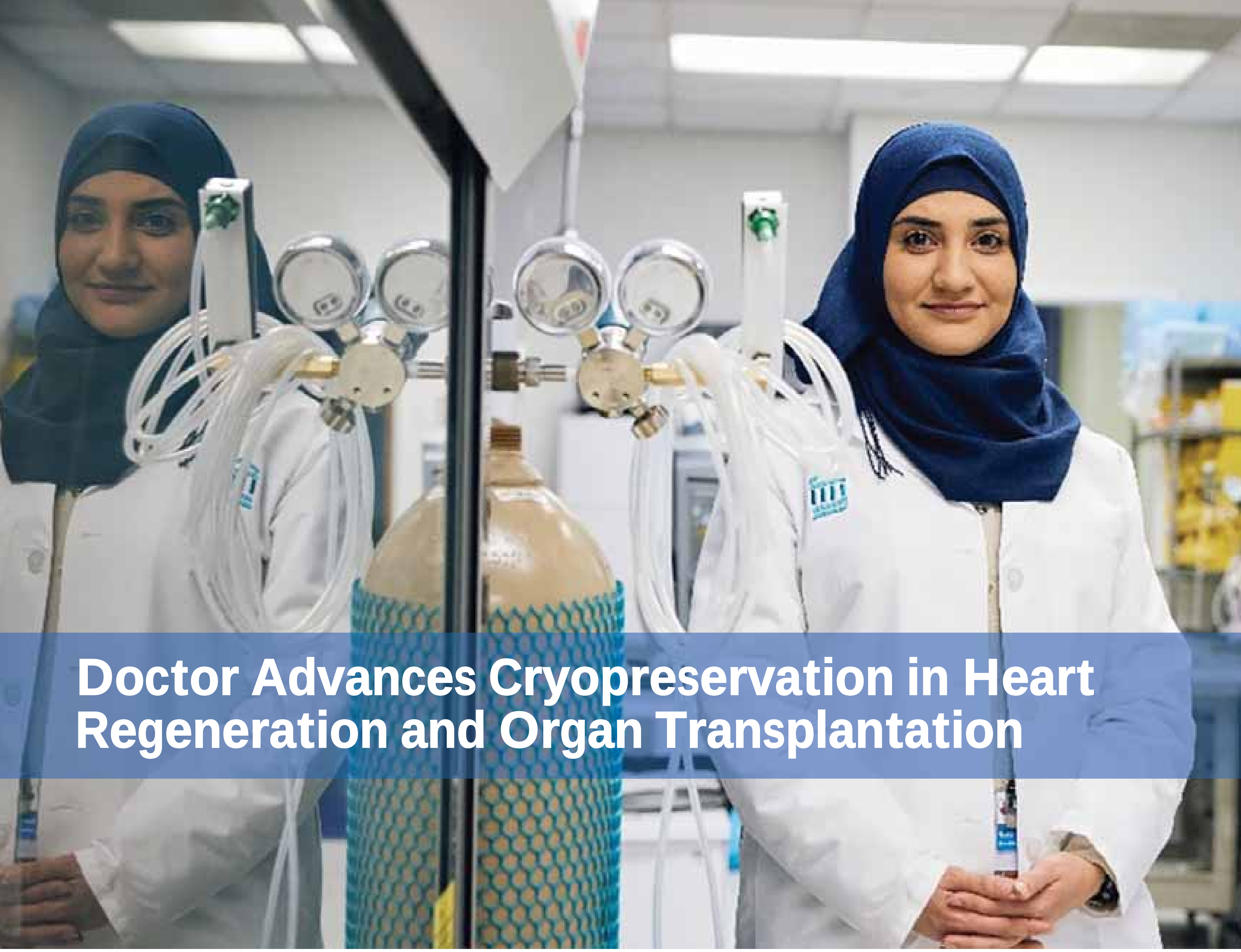

Doctor Advances Cryopreservation in Heart Regeneration and Organ Transplantation

Dr. Rasha Al-attar in the lab at the Center in Engineering in Medicine and Surgery, Harvard Medical School and the Massachusetts General Hospital.
Credit: Harvard Medical School and the Massachusetts General Hospital

Contributions attributed to Dr. Rahsha Al-attar

At Harvard Medical School and Massachusetts General Hospital, Dr. Rasha Al-attar's research is at the forefront of advancing heart regeneration and organ transplantation. Initially focusing on stem cell-derived cardiomyocyte (hPSC-CM) transplantation to repair infarcted heart tissue, Dr. Al-attar faced a significant challenge: while immature hPSC-CMs survive freezing, they often induce arrhythmias post-transplantation, limiting their clinical application. To address this, Dr. Al-attar transitioned to her postdoctoral work in Dr. Shannon N. Tessier's lab, where she applies nature-inspired techniques to advance cryopreservation methods. Inspired by freeze-tolerant frogs, her research includes developing techniques to preserve hearts at normothermic levels ex vivo, enabling real-time monitoring of arrhythmias and improving transplantation outcomes. Her work aims to overcome gaps in cryopreservation and organ preservation, enhancing the clinical feasibility of stem cell therapies and addressing key issues in heart regeneration.

Early Inspirations

Dr. Al-attar's interest in cryogenics began with the wood frog (Rana sylvatica), known for its ability to endure freezing temperatures and transition from suspended animation to full functionality. This curiosity led her to pursue a Master's degree in Dr. Ken Storey's lab at Carleton University, where she investigated the molecular mechanisms of cryobiology. Her research there fueled a broader interest in freeze-tolerant and hibernating species. Her passion grew during her Ph.D. studies, where she explored survival strategies of hibernating animals like bears, bats and squirrels.

"Towards the end of my Ph.D., I sought to apply my understanding of cryobiology to clinically relevant models, which led me to join Dr. Michael Laflamme's lab at the McEwen Stem Cell Institute," she explains. In Laflamme's lab, she worked on hPSC-CMs aimed at repairing damaged hearts. Despite advancements, arrhythmias remained a significant challenge. Dr. Al-attar noted, "These arrhythmias are partly attributed to the immature characteristics of hPSC-CMs, which differ from those of

Dr. Rasha Al-attar is advancing heart regeneration by developing nature-inspired cryopreservation techniques to improve stem cell-derived cardiomyocytes and organ preservation. Credit: Harvard Medical School and the Massachusetts General Hospital

mature adult cardiomyocytes." Efforts to mature the cells through electrical stimulation or metabolic supplementation compromised their freezing tolerance, highlighting the need for better cryopreservation techniques.

Challenges and Innovations in Cryopreservation

To address the issues associated with arrhythmias, Dr. Al-attar moved to Dr. Tessier's lab, where her research focuses on improving organ preservation and developing protocols for freezing complex organoids. "By learning from nature's strategies used by freeze-tolerant frogs and hibernating mammals," she details, "I aim to enhance organ preservation techniques." This work could improve the viability of transplantable organs, addressing the problem of discarded human organs due to short ex vivo viability periods.

Dr. Al-attar's early postdoctoral work significantly shaped her focus on cryopreservation and stem cell transplantation. During this time, she studied the electrophysiology of hPSC-CMs and their arrhythmias. Despite a 60-70% viability rate post-thaw using conventional methods, immature hPSC-CMs presented challenges, including arrhythmias. She recalls, "As we explored the literature, it became evident that metabolically mature hPSC-CMs offered superior functional properties compared to their immature counterparts for both in vitro testing and transplantation." However, mature cells had lower viability after thawing, prompting her to investigate cryopreservation techniques for these samples. "Recognizing the need for deeper insights into cryopreservation techniques for medically relevant samples," she notes, "I decided to join a lab dedicated to this specialty."

In Laflamme's lab, Dr. Al-attar learned that while progress had been made with hPSC-CMs, gaps remained in understanding cryopreservation's impact on these cells. "Most existing studies provide inconsistent results regarding their viability and functionality post-thaw," she explains. Moving to Dr. Tessier's lab allowed her to apply insights from her prior work to tailor solutions for organ preservation and stem cell research.

Dr. Al-attar's work on hPSC-CMs highlights critical challenges, such as mechanical displacement due to the heart's pulsatile nature, which impacts cell integration and functionality. "Injecting hPSC-CMs into a contracting heart presents notable difficulties due to the heart's pulsatile nature, which can lead to mechanical displacement of the cells from their targeted injection site," she notes. This issue, combined with acute ischemia causing a 90% cell loss within the first 24 hours, underscores the need for improved techniques.

Cryopreservation introduces additional complexities. Dr. Al-attar notes. "Immature hPSC-CMs generally exhibit better tolerance to ischemic conditions compared to their metabolically mature counterparts." While immature cells have higher post-thaw viability, Dr. Al-attar notes, they can cause arrhythmias, presenting a Catch-22 scenario where increased ischemia tolerance comes

▶ *continues on page 10*

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with a risk of arrhythmia." Mature hPSC-CMs, though more susceptible to ischemia, have heightened metabolic demands. The challenge is balancing ischemia tolerance with arrhythmia risk.

To address these issues, Dr. Al-attar emphasizes enhancing hPSC-CMs' maturation before transplantation. Techniques such as electrical stimulation, mechanical stretch, gene editing and pharmacological interventions are being explored. Cardiac patches and microtissues, though promising, currently cannot be cryopreserved, presenting practical challenges.

Dr. Tessier's lab utilizes nature-inspired methods, drawing from organisms like the wood frog. Dr. Al-attar elaborates, "Dr. Tessier's lab has developed a novel preservation protocol incorporating cryoprotectants such as glucose, inspired by the wood frog's ability to survive freezing." This approach has extended liver tissue viability, offering new possibilities for organ preservation.

Further, the lab's work on zebrafish larvae exemplifies these techniques. "By preserving zebrafish embryos or larvae, researchers can maintain the wealth of transgenic lines available, facilitating long-term storage and distribution for research," Dr. Al-attar explains. This method benefits genetic diversity and provides insights into preserving metabolically active cells like hPSC-CMs.

Preserving hearts at normothermic levels offers notable advantages. As Dr. Al-attar describes, "At normothermic temperatures, the heart remains in a state that closely mirrors physiological conditions, which is vital given the strong connection between metabolic fitness and arrhythmias." This allows for real-time monitoring of electrical propagation and precise arrhythmia management. "Real-time monitoring enables researchers to pinpoint specific areas of damage and identify the origins of arrhythmias," she notes, enhancing therapeutic interventions.

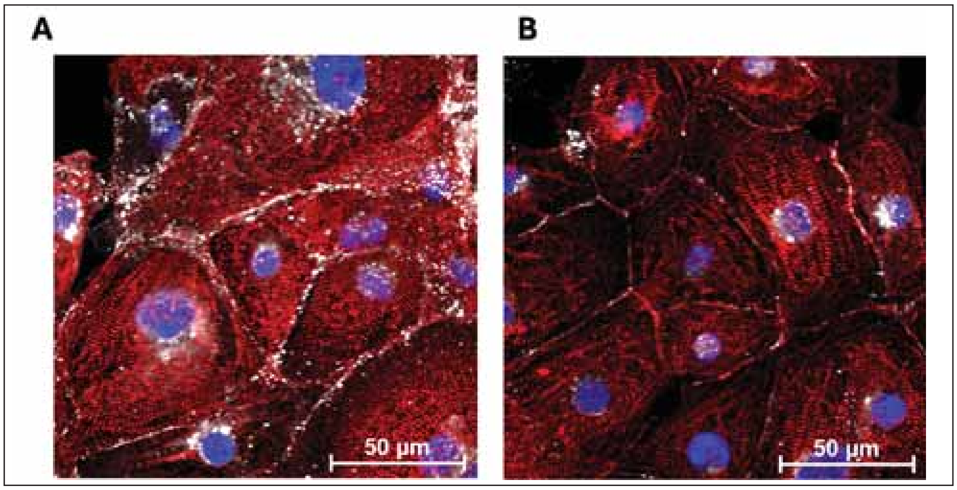


Figure 1. *Connexin 43 Gap Junctions in hPSC-CMs.* ***Wild-type hPSC-CM monolayers exposed to normoxic (A) or ischemic (B) conditions in vitro. (A) Displays connexin 43 gap junctions (white), α-actinin (red), and nuclei (blue) under normoxia. (B) Shows reduced connexin 43 gap junctions and altered α-actinin and nuclei under ischemic conditions. The reduction in connexin 43 in ischemic conditions is associated with an increased propensity for arrhythmias.*** *Credit: McEwen Stem Cell Institute, University Health Network, Laboratory of Dr. Michael Laflamme*

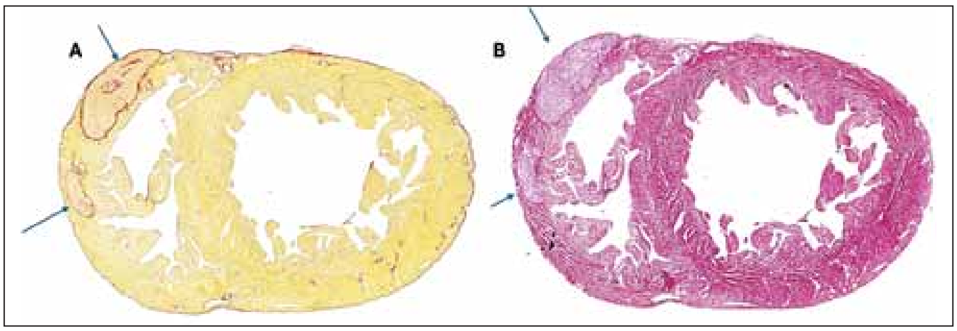


Figure 2. Picro-sirius red and hematoxylin and Eosin staining of guinea pig heart slices with hPSC-CM transplants. (A) Picro-Sirius Red : Highlights collagen fibers, with collagen appearing red under normal light and green or yellow under polarized light. This staining is used to assess collagen deposition and fibrosis in the heart tissue and to evaluate the integration and potential fibrosis surrounding the hPSC-CM grafts. (B) Hematoxylin and Eosin (H&E) : Shows general tissue morphology and the distribution of hPSC-CM transplants within the guinea pig heart slices. H&E staining provides a contrast between different tissue components, with nuclei appearing blue and cytoplasm and extracellular matrix appearing pink. This work is in collaboration with Dr. Christoph Haller. *Credit: McEwen Stem Cell Institute, University Health Network, Laboratory of Dr. Michael Laflamme*

Future Directions and Impact on Regenerative Medicine

Looking forward, Dr. Al-attar's research could revolutionize cryopreservation and transplantation. "By harnessing the power of hibernator biology, I aim to revolutionize the field of cryopreservation and organ transplantation," she states. Her future work includes developing stress-resistant hPSC-CMs and extending human organ preservation times, advancing regenerative medicine. Dr. Al-attar's interdisciplinary approach, integrating cryogenics, stem cell biology and organ preservation, is crucial in addressing complex issues. She highlights, "Combining perspectives from different scientific fields has been instrumental in addressing complex issues that might be overlooked when using a single approach." Collaborations with experts, including Dr. Rohil Jain's work on Raman spectroscopy and Dr. Michael Garton's expertise in genome engineering, exemplify the value of cross-disciplinary efforts.

Dr. Al-attar's work, blending fundamental research with practical applications, aims to overcome key challenges in cryopreservation and regenerative medicine. As she progresses toward securing a faculty position, she envisions using nature-inspired methods to enhance cryopreservation and transplantation. She advises aspiring scientists to "stay curious, adaptable and committed," emphasizing the importance of interdisciplinary collaboration and mentorship.

Dr. Al-Attar's long-term goals include improving cryopreservation techniques, developing ischemia-resistant hPSC-CMs and extending organ preservation times for both ex vivo testing and transplantation, all with the goal of revolutionizing regenerative medicine and transplantation. ***Cold Facts*** will continue to follow Dr. Al-attar's research. **hms.harvard.edu**

Beckman Institute Labs Bridge Advanced Imaging and Alzheimer's Research

Contributions attributed to Elizabeth Bello, Beckman Institute for Advanced Science and Technology at the University of Illinois Urbana-Champaign

The Beckman Institute for Advanced Science and Technology at the University of Illinois Urbana-Champaign has embarked on a life-changing research project to advance the early detection and diagnosis of Alzheimer's disease. With the support of a $3 million grant from the US National Institute on Aging of the National Institutes of Health, the institute is leveraging the capabilities of its Magnetic Resonance Imaging (MRI) Laboratory and the Molecular Imaging Laboratory to develop innovative imaging techniques. Central to this initiative is the use of Cu-64 for Positron Emission Tomography (PET) imaging and Mn^{2+} for enhanced MRI, offering new possibilities for studying Alzheimer's disease in living patients.

Alzheimer's disease, a progressive neurodegenerative disorder, is characterized by the accumulation of amyloid plaques in the brain. Accurate diagnosis currently requires post-mortem analysis, underscoring the need for advanced diagnostic tools that can detect the disease at an early stage. The collaboration at Beckman aims to address this gap by combining the strengths of PET and MRI imaging, providing detailed insights into the physiological and pathological processes associated with Alzheimer's.

The Beckman Institute's utilization of cryogenic technology to support advanced biomedical research, particularly in the early detection and diagnosis of Alzheimer's disease through sophisticated imaging methods, furthers the vital connection between cryogenics and biomedical imaging and highlights the wide-ranging applications and significance of cryogenic science in high-tech fields.

Wawrzyniec "Wawosz" Dobrucki (left) alongside Liviu M. Mirica (center) and colleague Dr. Daniel Llano. Credit: Elizabeth Bello, Beckman Institute for Advanced Science and Technology at the University of Illinois Urbana-Champaign

Cold Facts Invites You to Meet the Researchers

Two leading researchers at the Beckman Institute, Liviu M. Mirica and Wawrzyniec "Wawosz" Dobrucki, are at the forefront of pioneering research in Alzheimer's disease. Their interdisciplinary project focuses on developing and applying novel imaging agents to revolutionize the diagnosis and treatment of this condition. *Cold Facts* sat down with these innovators to get a closer look at how their contribution is changing the conversation about a disease affecting so many.

Liviu M. Mirica (LMM) is a synthetic chemist, the William H. and Janet G. Lycan Professor of Chemistry in the School of Chemical Sciences and a researcher at the Beckman Institute. Mirica's research group specializes in building and characterizing synthetic inorganic molecules in vitro, with a particular interest in developing novel radiopharmaceuticals for imaging and therapeutic purposes.

Wawrzyniec "Wawosz" Dobrucki (WLD) is a professor of bioengineering, the Neil and Carol Ruzic Scholar for Biomedical and Translational Sciences at the University of Illinois Urbana-Champaign and a researcher at the Beckman Institute. Dobrucki's research focuses on utilizing advanced imaging techniques to enhance our understanding of physiological and pathological processes.

Can you elaborate on the significance of using Cu-64 as the radioisotope for PET imaging in your newly acquired PET-CT scanner?

WLD: The energy of the positrons emitted by Cu-64 is suitable for high-resolution PET imaging. When used in conjunction with a high-performance PET-CT scanner like the U-PET7 from MILabs, Cu-64 can provide detailed images of physiological and pathological processes, improving diagnostic accuracy. In addition, Cu-64's properties make it suitable for quantitative imaging, which is crucial for accurately measuring biological parameters such as receptor density, blood flow and metabolic rates.

How does the use of Cu-64 enhance the capabilities of PET imaging compared to other radioisotopes commonly used in this modality?

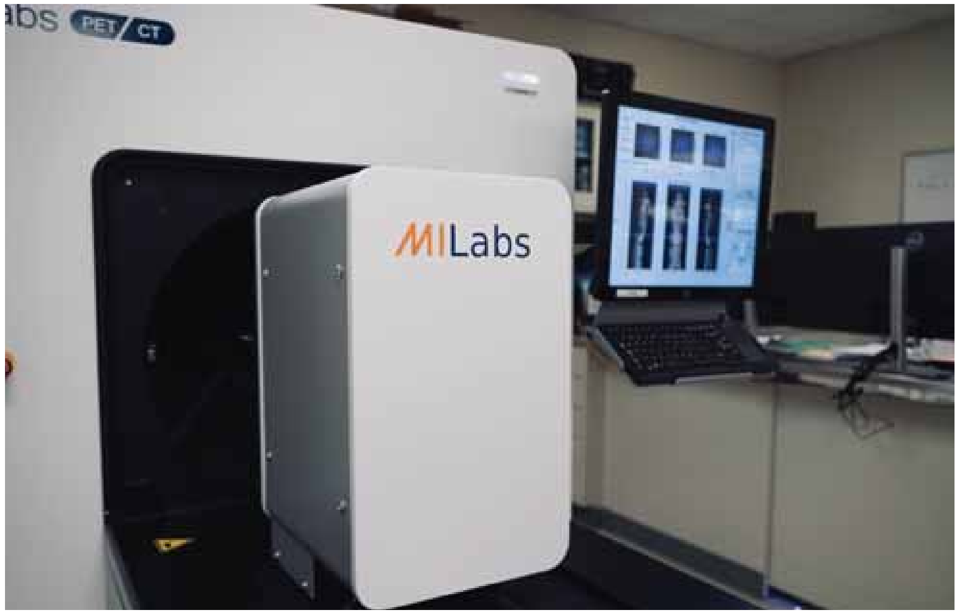
LMM: Most clinical applications of PET imaging employ agents containing the C-11 and F-18 radiotracers, yet these radiotracers are limited by their short physical half-lives (20.4 min and 109.8 min, respectively). Therefore, the development of radio imaging agents containing longer-lived radionuclides would be advantageous as it would allow the possibility of imaging at longer time points where better contrast may exist. In addition, such PET agents can be shipped over longer distances and used in remote areas. In this regard, Cu-64 (t1/2 = 12.7 h) has become a useful radionuclide in the development of a wide variety of radiopharmaceuticals for imaging and therapeutic purposes.

What specific biological processes or conditions do you anticipate studying with the aid of Cu-64 PET imaging?

LMM: We are developing better diagnostic tools and imaging agents for the early detection of Alzheimer's disease. A key marker of Alzheimer's disease is the presence of amyloid plaques, or aggregates, in the patient's brain. Currently, diagnosing Alzheimer's disease accurately can only be completed during post-mortem investigation. Thus, the development of new imaging agents as diagnostic tools that can rapidly assess the presence of early-stage amyloid aggregates in a living patient can have a large health-related impact.

Moving to MRI imaging, why have you chosen Mn^{2+} as the paramagnetic ion to provide improved contrast?

LMM: While PET imaging is by far the most used imaging modality in Alzheimer's disease, it can be invasive and expensive. Magnetic resonance imaging (MRI) has emerged as a potential complement to PET analysis, since it can also provide high-resolution images of the brain that would be beneficial for early diagnosis. In order to improve the quality of MR images, contrast agents based on paramagnetic ions such as gadolinium (Gd) are used to alter the magnetic properties of nearby water molecules; however, these Gd agents have drawbacks given their accumulation in the body and toxicity. Thus, the development of MRI contrast agents based on other less toxic paramagnetic ions such as Mn^{2+} would be extremely useful for early Alzheimer's diagnosis.



This PET machine located in Beckman's Molecular Imaging Laboratory will be operated by Dobrucki and used extensively during the team's research. Credit: Beckman Institute for Advanced Science and Technology at the the University of Illinois Urbana-Champaign

How do you foresee the combination of PET imaging with Cu-64 and MRI imaging with Mn^{2+} contributing to interdisciplinary research projects at your institution?

LMM: This joint research project is one of the first federally funded grants to bridge upcoming research between Beckman's Magnetic Resonance Imaging Laboratory and the Molecular Imaging Laboratory.

Are there any particular research areas or clinical applications where the synergistic use of these imaging modalities holds particular promise?

LMM: By developing multimodal imaging agents, we hope to employ the advantages of each imaging modality, while reducing their disadvantages. On one hand, PET imaging is highly sensitive but requires the use of a radiotracer that needs to be injected into a patient. On the other hand, MRI is an imaging technique that can produce high-resolution images but requires contrast agents to create the desired high contrast.

Could you discuss any challenges or considerations involved in integrating Cu-64 PET imaging and Mn^{2+}-enhanced MRI into your research protocols?

LMM: The main challenge we are trying to address is the unprecedented development of chelating agents that can target the amyloid aggregates found in the brains of Alzheimer's patients and can be labeled separately with Cu-64 and Mn^{2+} for PET and MRI diagnostic applications, respectively.

In terms of practical implementation, what steps are being taken to ensure the safe and effective utilization of Cu-64 and Mn^{2+} in imaging studies?

LMM: Since Cu-64 is a radiotracer, stringent safety protocols need to be put in place where PET imaging studies are being performed. Fortunately, at the Beckman Institute both the MRI lab and the Molecular Imaging Lab for PET imaging are close to each other in the basement of the institute.

Looking ahead, do you envision any future advancements or developments in the use of these imaging agents for even greater insights into biological processes or clinical diagnoses?

LMM: The development of multimodal PET and MRI diagnostic agents for Alzheimer's diseases could then be extended to other neurodegenerative disorders such as Parkinson's, Lewy Body dementia (LBD) and Frontotemporal degeneration (FTD), or for broad neuroimaging applications.

Tests Show High Temperature Superconducting Magnets Ready for Fusion

Contributions attributed to David L. Chandler, MIT News

In the early hours of September 5, 2021, engineers at MIT's Plasma Science and Fusion Center (PSFC) achieved a groundbreaking milestone by demonstrating a world-record magnetic field strength of 20 tesla with a new high-temperature superconducting magnet. This breakthrough is crucial for advancing fusion power technology, with the potential to usher in an era of virtually limitless energy.

The test of the new magnet was declared a resounding success as it met all the design criteria for the SPARC fusion device, which relies on these advanced magnets as a key component. The team's accomplishment was the result of extensive preparation, including rigorous testing and analysis. This involved not only reaching the record-breaking magnetic field but also subjecting the magnet to extreme conditions to uncover potential failure modes and ensure its reliability.

The results of these tests were comprehensively detailed in a special edition of IEEE Transactions on Applied Superconductivity published in March. This edition features six peer-reviewed papers that cover the magnet's design, fabrication, and diagnostic evaluation. These papers confirm that the new design is a solid foundation for the next generation of fusion power plants, highlighting the effectiveness of the high-temperature superconductors used and the overall system's performance.

Dennis Whyte, Hitachi America Professor of Engineering, emphasized the significance of this achievement, referring to it as "the most important development in the last 30 years of fusion research." Prior to this breakthrough, superconducting magnets were powerful enough to support fusion energy but were prohibitively large and costly. The new magnet's compact size and reduced cost have transformed the economics of fusion energy, significantly lowering the cost per watt of fusion reactors and making them more feasible.

In MIT's Plasma Science and Fusion Center, the new magnets achieved a world-record magnetic field strength of 20 tesla for a large-scale magnet. Credit: Gretchen Ertl

A team lowers the magnet into the cryostat container. Credit: Gretchen Ertl

Fusion, the process that powers the sun and stars, involves combining light atoms into heavier ones. Replicating this on Earth has been an immense challenge, requiring materials that can withstand extreme temperatures and pressures. Traditional superconducting magnets operate at temperatures around 4 kelvins, but the new material, REBCO (rare-earth barium copper oxide), operates effectively at 20 kelvins. Although this temperature is only 16 kelvins warmer, REBCO offers substantial

The test setup inside MIT's Plasma Science and Fusion Center. Credit: Gretchen Ertl

advantages in terms of its material properties and practical engineering.

The integration of REBCO into magnet designs necessitated a fundamental redesign of conventional principles. One major innovation was the elimination of insulation around the superconducting tape, a move initially met with skepticism. Engineers relied on REBCO's superior conductivity to maintain current flow without insulation, which simplified the fabrication process and addressed high-voltage issues.

The magnet assembly, a scaled-down model of those planned for the SPARC device, comprises 16 plates. Each plate features a spiral winding of superconducting tape and cooling channels for helium gas. The no-insulation design, while considered risky, proved successful during testing, demonstrating the stability and effectiveness of the new approach.

The test program included pushing the magnet to its limits, including creating quenching events where the magnet overheats. This approach was essential for gathering critical data to validate design models and understand the magnet's behavior under extreme conditions. Despite the risks, these tests provided valuable insights, confirming the magnet's performance and identifying areas for further improvement.

The final test revealed that most of the magnet survived with minimal damage, leading to design revisions expected to enhance durability in future devices. This success was attributed to the extensive expertise and infrastructure at PSFC, coupled with effective collaboration between MIT and Commonwealth Fusion Systems (CFS) (CSA, CSM).

The partnership between MIT and CFS combined academic and industrial strengths, with CFS playing a crucial role in scaling up the supply chain for the magnet's critical materials. This collaboration was key to achieving the project's ambitious goals and showcased the benefits of integrating academic research with industrial capabilities to drive technological innovation.

The successful demonstration of the 20-tesla magnet represents a significant advancement in fusion research. This achievement paves the way for the development of practical and economically viable fusion power plants.

The innovations introduced, particularly the use of high-temperature superconductors and the no-insulation design, mark a major leap forward in the field, with the potential to revolutionize energy production and bring us closer to a future where fusion power becomes a reality.

Chart Industries' IPSMR® Technology Achieves First LNG at NFE's "Fast LNG" Project

With contributions by Chart Industries Communication Team

The recent announcement from Chart Industries and New Fortress Energy marks a significant milestone in the liquefied natural gas (LNG) sector, showcasing advancements in cryogenic technology. The deployment of Chart's Integrated Pre-Cooled Single Mixed Refrigerant (IPSMR®) process technology has enabled the production of the first LNG at New Fortress Energy's Fast LNG project in Altamira, Mexico.

The Fast LNG project is revolutionary in its approach, leveraging offshore infrastructure like jack-up rigs to expedite the deployment schedule compared to traditional onshore liquefaction facilities. This method significantly reduces the time and cost associated with LNG production. The proprietary Fast LNG design by New Fortress Energy, coupled with Chart Industries' advanced cryogenic equipment, enables this innovative approach.

Cryogenics plays a crucial role in the LNG industry, particularly in the liquefaction process, which involves cooling natural gas to approximately -162° C to convert it into a liquid state. Chart's IPSMR® technology is pivotal in this process. It integrates pre-cooling and mixed refrigerant cycles, which enhances efficiency and reduces energy consumption during liquefaction. The use of brazed aluminum heat exchangers and cold boxes in the IPSMR system ensures optimal thermal management and heat exchange efficiency, critical factors in maintaining the low temperatures required for LNG production.

The success of this project is not only a testament to the technological prowess of Chart Industries but also highlights the potential of cryogenics to revolutionize LNG production. The modular design of the Fast LNG units allows for scalability and adaptability, making it possible to install these units in various offshore locations where stranded or flared gas is available.

Chart's Integrated Pre-Cooled Single Mixed Refrigerant (IPSMR®) technology enabled the first LNG production at New Fortress Energy's Fast LNG project in Altamira, Mexico. Credit: New Fortress Energy

This flexibility is a significant advantage, providing access to previously untapped gas reserves and reducing the environmental impact associated with gas flaring. Moreover, the environmental benefits of offshore LNG production are substantial. By utilizing stranded gas and reducing flaring, the Fast LNG project helps mitigate greenhouse gas emissions. The offshore nature of the project also minimizes the footprint compared to traditional land-based facilities, further reducing the environmental impact.

The strategic partnership between Chart Industries and New Fortress Energy exemplifies the industry's shift towards cleaner and more efficient energy solutions. This collaboration is part of a broader trend in the LNG sector, where companies are increasingly focusing on sustainability and cost-efficiency. Additionally, the use of a floating storage unit (FSU) in the Fast LNG project provides a flexible and cost-effective solution for storing LNG offshore, reducing the need for extensive land-based infrastructure. The cryogenic hose system used to transfer LNG from the FSU to tankers ensures safe and efficient loading, maintaining the low temperatures required for LNG.

The successful implementation of the Fast LNG project in Altamira, Mexico, sets a precedent for future offshore LNG developments. It demonstrates that with the right technological innovations, such as Chart's IPSMR process, it is possible to achieve faster, cheaper, and more environmentally friendly LNG production. This development is particularly significant as the global demand for LNG continues to grow, driven by the need for cleaner energy sources and the transition away from coal and oil.

"We appreciate our long-standing partnership with Chart Industries, which played a pivotal role in our offshore development in Altamira," said Wes Edens, chairman and CEO of New Fortress Energy. "First LNG represents a transformative moment for NFE and the industry as a whole and reaffirms our position as a fully integrated leader in the global LNG market." Jill Evanko, Chart's CEO and president, expressed the company's pride in supporting NFE and the industry as a whole with its modular liquefaction technology and all mission-critical equipment, including brazed aluminum heat exchangers, cold boxes and air coolers. "We congratulate NFE for this success of First LNG, and we look forward to further supporting the industry with our modular, adaptable, resilient and cost-effective technology and products."

As the LNG industry evolves, innovations in cryogenics will undoubtedly play a crucial role in shaping its future, making projects like Fast LNG a blueprint for the next generation of LNG production. **www.chartindustries.com**

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Bluefors Lab in Delft, Netherlands, offers cryogenic measurements as a service, providing startups and smaller institutions with cost-effective access to advanced cryogenic cooling systems and a full suite of measurement electronics necessary for quantum research, along with comprehensive support from experienced staff. Credit: Bluefors

Bluefors Lab Offers Cryo Measurements, a Low Risk Model for Experiments

by Arttu Huikuri, Technical Service Manager at Bluefors Lab, Delft

Quantum technology continues to develop at a rapid pace, and the need for access to cryogenic cooling systems for quantum research has never been greater. While established institutions have an increasing number of options to choose from, startups and smaller institutions still face considerable challenges, not least of which are the costs involved in investing in a dedicated cryogenic measurement system for their experiments.

One solution that offers enormous flexibility and cost savings is cryogenic measurements as a service, such as the service offered at Bluefors Lab in Delft, Netherlands. Recognizing the need for smaller companies to get their foot in the door with industry-leading technology, the Bluefors Lab offers proven benchmark products that the cryogenic industry relies upon, and makes them accessible and affordable.

A Full Suite of Cryogenic Tools

Bluefors has a deep understanding of the cryogenic equipment needs of customers around the world. A dilution refrigerator is of very little practical use without the supporting electronics needed for qubit control and measurement. The key advantages of the service-model access to cryogenic measurement systems at Bluefors Lab is the provision of a full suite of electronics for the LD system, and the integration of specialized wiring developed in-house that optimizes performance.

The Lab in Delft offers both LD400 and XLD1000sl dilution refrigerators complete with RF coaxial and DC twisted pair wiring, with both systems designed to be used with common superconducting qubit chips.

The LD system setup supports up to 5 qubits and is ideal for shorter measurement periods, delivering 15 µW cooling power at 20 mK on an 11.42-inch (294mm) experimental flange. The XLDsl is ideal for more demanding experiments, with a large 20-inch (500mm) flange, pre-installed Microwave Readout Module with travelling wave parametric amplifier, and the possibility for custom setups that utilize its side-loading technology.

The Lab's measurement electronics include everything needed for successful experiments. The LD service includes an OrangeQS rack, Qblox Cluster for RF control and readout, a Qblox SPI rack as a DC source, a spectrum analyzer, an oscilloscope and source measurement unit. There is also other commonly used equipment, such as a VNA, amplifiers, attenuators and test cables at the lab.

For many companies, this package not only offers a complete quantum computing setup, but it establishes baseline access to industry-standard tools. In this way, users are able to start off on the right foot and familiarize themselves with technology used worldwide.

Support That Drives Results

Another significant advantage to the cryogenic measurements as a service model is the support of the knowledgeable, experienced staff at the Lab. In Delft, the lab team is available on site to help customers through all phases, from operating and monitoring the cryostats, helping with sample installation, supporting the electronics setup and ensuring that users get the most value from their lab time.

Much of this supporting work comes down to extensive preparation and operational maintenance, so that when customers arrive everything is ready and in working order. Users do not need to visit the lab every day — the systems have been designed with remote operation in mind, so minor changes in measurement setup can be handled by the Bluefors team, and clients get to focus on what matters to them: results.

One of the Lab's current customers, QuantrolOx, recently used the Lab to test the integration of their Quantum EDGE software with the suite of included measurement electronics, and additional devices they added themselves. Vishal Chatrath, QuantrolOx's co-founder, is keen to promote the benefits of the service:

"Being able to test on a dedicated system and integrate leading control electronics from providers such as Qblox, Quantum Machines and Zurich Instruments, has been hugely beneficial. With the new XLD system, QuantrolOx has the ability to test its software with multiple electronics and multiple types of QPUs at the same time. It also gives us the ability to work with larger QPUs, allowing us to test new techniques and further improve the performance of our software."

Access to a dedicated testing environment in which an actual quantum computer can be operated is a fundamental requirement for many startups. Bluefors Lab provides companies a convenient, affordable, low-risk path to the tools, measurement infrastructure and expertise needed to carry out R&D on benchmark systems. At the same time, collaborating with an industry leader like Bluefors gives startups an opportunity to increase visibility and build deeper networks in the quantum ecosystem. **www.bluefors.com**

Thermionics Laboratory Empowers Precision Nanofabrication, Ultrahigh Vacuum Manipulator for Glancing Low Angle Deposition

by Karin Richey, Thermionics Laboratory

What does a leading optics manufacturer do when striving to develop cutting-edge lenses for high-resolution imaging systems? Their quest for flawless optical performance hinges on achieving nanostructured surfaces that minimize light scattering and maximize transmission efficiency.

In the intricate world of advanced materials and nanotechnology, achieving precise fabrication techniques is often the greatest challenge. Traditional methods struggle to meet these meticulous demands. This is where Thermionics Laboratory, Inc. steps in with their Ultrahigh Vacuum (UHV) Manipulator tailored for Glancing Low Angle Deposition (GLAD), revolutionizing how industries tackle the complexities of nanoscale fabrication.

Nude filament substrate heater. Credit: Thermionics Laboratory

Overcoming Precision Challenges in Nanotechnology

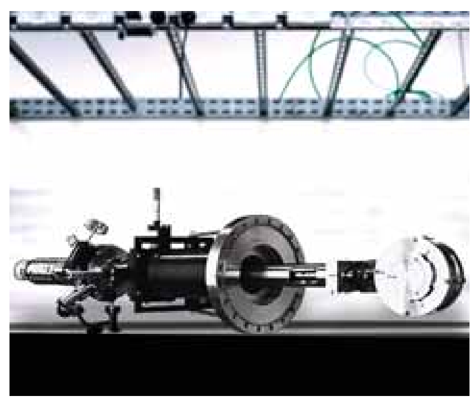
The optics industry is one of many industries with a pressing need for uniform and finely tuned optical coatings. Conventional deposition methods can result in inconsistent performance and wasted resources. The GLAD Manipulator by Thermionics directly addresses these challenges with several key features:

Precise Deposition Control: Featuring ±180° polar rotation and continuous azimuthal rotation capabilities, the manipulator ensures uniform coating thickness and deposition angles crucial for optimizing optical clarity and performance.

Temperature Management: Advanced heating options and liquid nitrogen cooling maintain substrate integrity during deposition, enabling precise material properties tailored to demanding optical applications. This careful control of temperature is vital for creating the high-quality coatings required for advanced optics.

By integrating Thermionics GLAD Manipulator into their production process, researchers have achieved notable advancements:

Enhanced Precision: The manipulator's XYZ movements facilitated exact substrate positioning, allowing for tailored nanostructure arrangements that significantly improved optical performance. This level of precision is essential for developing optics that meet the highest standards of resolution and clarity.



GLAD Manipulator. Credit: Thermionics Laboratory

Efficiency Gains: Automated control features streamline production workflows, reduce lead time and enhance overall yield while maintaining superior quality standards. The result is not only better performance but also more cost-effective manufacturing processes.

Future Prospects

As Thermionics Laboratory continues to innovate, their commitment to advancing nanotechnology remains unwavering. Their range of products, from thin-film deposition equipment to advanced manipulators, supports diverse applications in research and industry, from academic institutions to Fortune 500 companies. The Thermionics GLAD Manipulator exemplifies the pinnacle of precision engineering, empowering industries to push boundaries and unlock new possibilities in nanofabrication. **www.thermionics.com**

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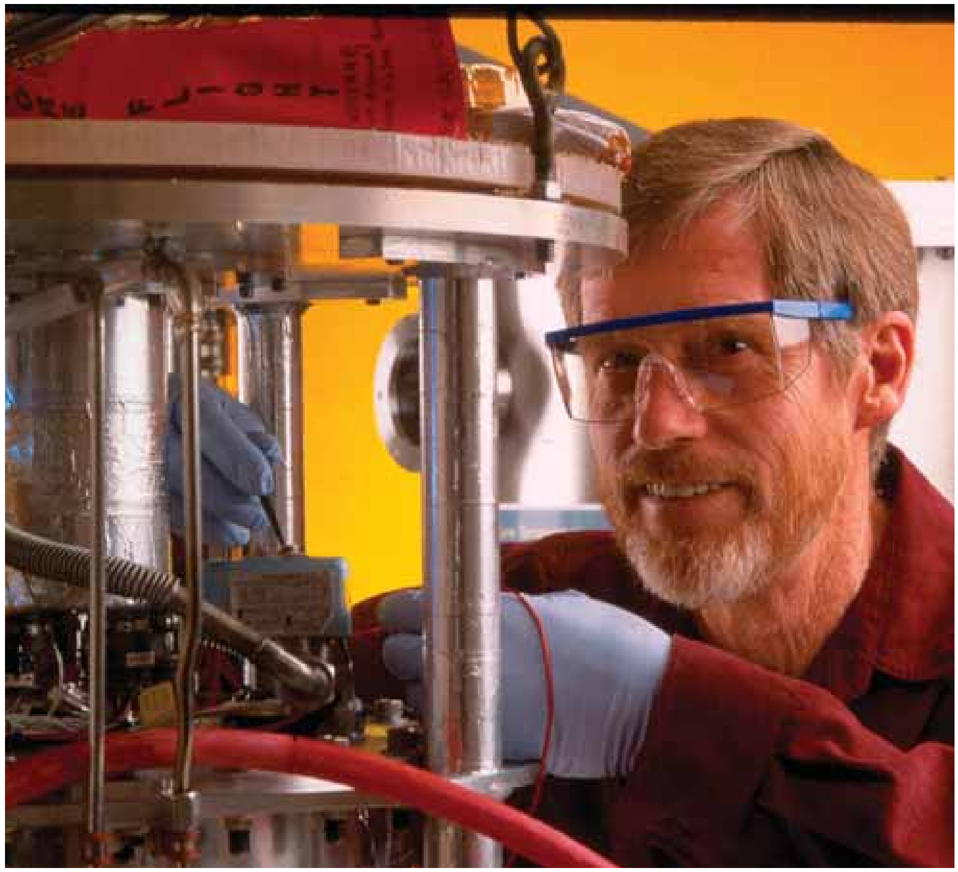
by Dr. John Weisend II, European Spallation Source ERIC, CSA Chairman, john.weisend@esss.se, with
Anne DiPaola, *Cold Facts* Editor

Ray Radebaugh



Ray Radebaugh assembling a miniature pulse tube cryocooler in an experiment for a space shuttle mission in collaboration with Lockheed Martin. Credit: Lockheed Martin/Denver

In our last Cryo Bios column, we announced the direction this longtanding column is moving toward. Beginning with this issue, we now focus on living prominent figures in the field of cryogenics who graciously sat for an interview with John Weisend II, European Spallation Source, and Anne DiPaola, Cold Facts Editor. Our first interview was with Ray Radebaugh, consultant emeritus at NIST Boulder and a well-regarded expert known as "Mr. Cryocooler."

Ray Radebaugh's journey into cryogenics began in his junior high years, where a unique blend of circumstances sparked his interest in the field. Growing up in the small town of Edwardsburg, Mich., his parents owned a forge and machine company in nearby Mishawaka, Indiana, which allowed him to learn the intricacies of various machinery. During the summers, he worked in the shop, mastering the use of lathes, milling machines, and other equipment. His curiosity led him to create model steam engines, eventually receiving a used 11-inch South Bend metal lathe from his parents at the age of 14. This gift further fueled his passion for making things, propelling him toward a future in experimental physics.

In high school, Ray's fascination with cryogenics took a concrete form. For a science fair project, he decided to build a compressor to produce liquid air. This project required extensive research, including studying the Joule-Thomson cycle and various liquefaction processes. Despite limited resources, he managed to construct a functioning air liquefier, winning first place at his school science fair and third place at the regional level.

This achievement caught the attention of Air Products, leading to a summer job where he worked on phase equilibria of nitrogen and carbon dioxide. His academic journey continued at the University of Michigan, where he operated a helium liquefier and and assisted in heat capacity measurements down to 4 K. Ray's early experiences laid the foundation for a distinguished career in cryogenics, spanning positions at National Bureau of Standards (NBS)/NIST, contributions to cryocooler programs and culminating in his role as a NIST Fellow Emeritus.

From its first purchase of an air liquefier in 1901 by its Electricity Division, the National Bureau of Standards, played a pivotal role in advancing cryogenic research during critical historical periods. Its subsequent achievements included pioneering the liquefaction of helium in the US in 1931 and the discovery of deuterium in 1932. The laboratory's relocation to Boulder, CO, in 1950 marked a strategic move in response to the Cold War, becoming a central hub for cryogenic engineering and supporting efforts such as the development of the hydrogen bomb. Under the leadership of Russell Scott, the newly established Cryogenic Engineering Laboratory (CEL) rapidly expanded, contributing significantly to national defense and scientific advancement. Ray's tenure at the CEL starting in 1966 provided firsthand experience of its growth and impact, setting the stage for ongoing research below 1 K and shaping the future of cryogenic technologies.

Ray Radebaugh's pioneering work in cryogenics spanned several pivotal areas, notably in the development of dilution refrigerators (DRs) and cryocoolers. His tenure at NBS/Boulder in the late 1960s marked a significant era in DR research, focusing on the thermodynamic properties of 3He-4He mixtures crucial for efficient DR design. His contributions, detailed in NBS Tech Note 362 in 1967, provided foundational data on specific heat, entropy and other key properties critical for subsequent DR designs. Ray's ongoing involvement in cryocooler development began with 4 K Stirling cryocoolers in collaboration with Jim Zimmerman, aiming to reduce magnetic noise for SQUID applications. This collaboration led to subsequent research on 4 K regenerators and to the development of efficient pulse tube cryocoolers, setting new standards in cryogenic cooling technology.

Throughout his career, Ray has witnessed transformative changes in cryogenics. He observed the evolution of cryogenic applications in space, medical imaging with superconducting magnets and the emergence of millikelvin cooling for quantum devices. Looking ahead, he anticipates two opposing trends: the miniaturization of cryocoolers to meet electronic device needs with reduced size and cost, and the expansion of cryocooler capabilities to support larger applications like space exploration and quantum computing, emphasizing the role of liquid hydrogen and fuel cells in future transportation innovations.

Following retirement, Ray continues to influence cryogenics through collaborative projects and consultancy. His work has included joint efforts with Professor Y.C. Lee of the University of Colorado on micro-cryocoolers and an ONR contract focusing on 4 K regenerators. These initiatives advanced modeling and experimental investigations, particularly in mixed refrigerant JT systems and regenerator refinement. Ray also expanded the cryogenic material properties database at NIST, enhancing data coverage across wider temperature ranges. Consulting roles with NIST's Quantum Sensor Division and engagements with various companies through Radebaugh Cryogenics have furthered cryocooling technologies for quantum sensors and diverse applications.

Ray's involvement in cryogenics extends beyond pioneering research and collaborations; it encompasses significant contributions to conference organization and educational initiatives. Notably, he played a pivotal role in the evolution of the International Cryocooler Conference (ICC) series, dating back to its inception at the National Bureau of Standards with the landmark ICC0 conference in 1977. In recent years, Ray has expanded on his membership and involvement with CSA by leading "Foundations of Cryocooolers" workshops, sponsored by CSA at various industry conferences since 1997. He also serves on the Editorial Boards for *Cold Facts* and the journal *Cryogenics*.

Ray's leadership extends to the Cryogenic Engineering Conference (CEC), where he served as a board member and chaired the 1987 conference at Pheasant Run, St. Charles, IL. His contributions to the CEC, including a tenure as awards chairman, reflect his ongoing impact in advancing cryogenic technologies and practices globally.

Ray Radebaugh in 1999 next to the flexure-bearing compressor built for a Mars pulse tube oxygen liquefier for NASA. Credit: Ray Radebaugh

ICC22 was preceded by the Cryogenic Society of America's Foundations of Cryocoolers Short Course, taught by Ray Radebaugh (at right) and Ralph Longsworth, SCAI-retired. Credit: CSA

Wesley Johnson, NASA Glenn Research Center, Cleveland, Ohio

What is the Temperature of Space?

One of the most common questions from students when presented with an introduction to in-space applications of cryogenics is "What temperature is space?" While the askers of this question are usually enthusiastically interested, thinking space to have tactile temperatures just like the playground outside the school, this is actually a bit of a trick question. Let's explore.

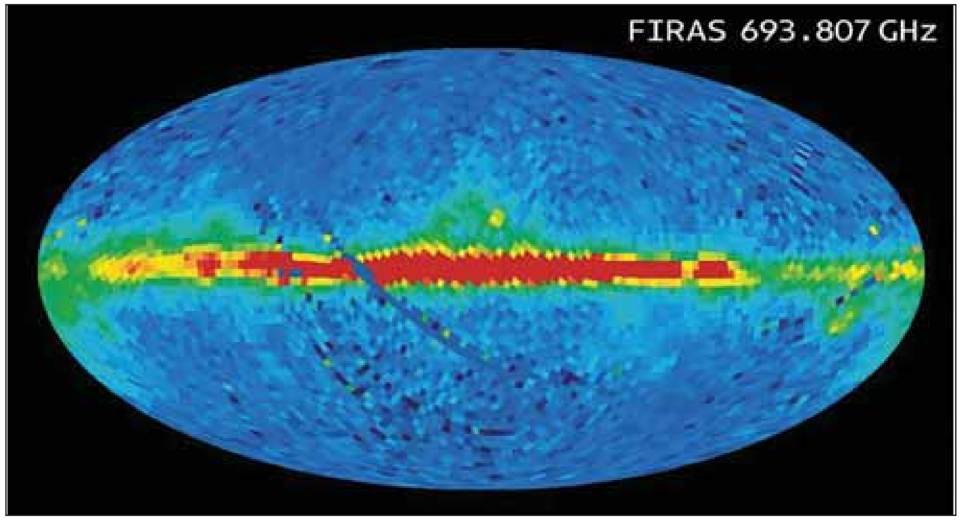
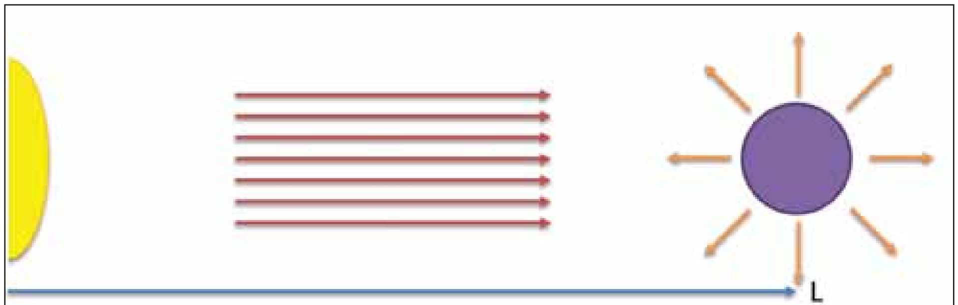


Figure 1: COBE/FIRAS image. Credit: NASA



Energy In:

$$\dot{Q}_{abs} = \alpha_{solar} \frac{\dot{Q}_{sun-earth}}{A_{sun-earth}} \left(\frac{r_{sun-earth}}{L}\right)^3 \pi r_{sphere}^2$$

Energy Out:

$$\dot{Q}_{emit} = \frac{4\pi}{3} r_{sphere}^3 \varepsilon_{IR} \sigma \left(T_{sphere}^4 - T_{space}^4\right)$$

Figure 2: Energy balance on a sphere in space. Credit: NASA

The first, most correct and most literal answer of the question is 2.725 +/- 0.002 K.[1] In 2006, Dr. John Mather of Goddard Space Center and Dr. George Smoot of UC Berkeley won the Nobel Prize in Physics for their work on measuring the cosmic microwave background residual from the Big Bang as measured by the Far Infrared Absolute Spectrophotometer (FIRAS) instrument on the Cosmic Background Explorer (COBE) satellite.[2] Their work showed that not only is the cosmic microwave background of the universe a perfect blackbody spectrum, but it also investigated disturbances in that background caused by galaxies and other celestial bodies.

However, this is not really the question that the student is asking. They are really asking what temperature are "things" in space. This requires a much more detailed answer that is usually somewhat shortened to avoid the technical details. Given that most of "space" is a vacuum or a bunch of "nothing," it can't have a temperature because to have a temperature, that "something" must contain atoms that are vibrating. Wavebands of energy, solar or infrared, don't produce thermal energy in a vacuum until they interact with a surface. Of course, this is a non-sequitur answer that just annoys the student so is usually not given.

The second, also mostly correct and somewhat literal, is that "it depends." Well, what does it depend on? It depends on where the object of interest is (relative to various celestial bodies), what sources of energy (generally radiation, but also local heaters on the spacecraft) are heating the spacecraft, how much energy (also in the form of radiation) is the spacecraft emitting and other similar parameters. In an orbit near to Earth (orbits less than 2,000 km from the surface of Earth are called Low Earth Orbit), the predominant heating source is the sun with secondary heating coming from Earth. The energy from the sun at the nominal distance from the Earth (approximately 150 million kilometers) averages 1361 W/m^2, ranging between 1317 W/m^2 and 1408 W/m^2.[4]

This energy from the sun is spread out across a spectrum of different wavelengths, including microwaves, infrared, ultraviolet and x-rays; of which only the visible portion of the spectrum can be detected by our eyes.[10] Outside of the protection of Earth's atmosphere, all of these different wavelengths provide energy which is converted by the outer surface of the spacecraft to heat.

The energy from the Earth is both in reflecting solar energy (albedo, approximately 30% of the energy from the sun on the Earth is reflected) or infrared radiation coming off of the Earth itself. The Earth emits energy from it as a blackbody of approximately 254 K.[3] The farther away from the Earth that the orbit gets, the less energy, both reflected and emitted, that the Earth imparts on that satellite.

The spacecraft also emits energy to deep space (the technical thermal engineering term for that 2.725 K microwave

▶ continues on page 26

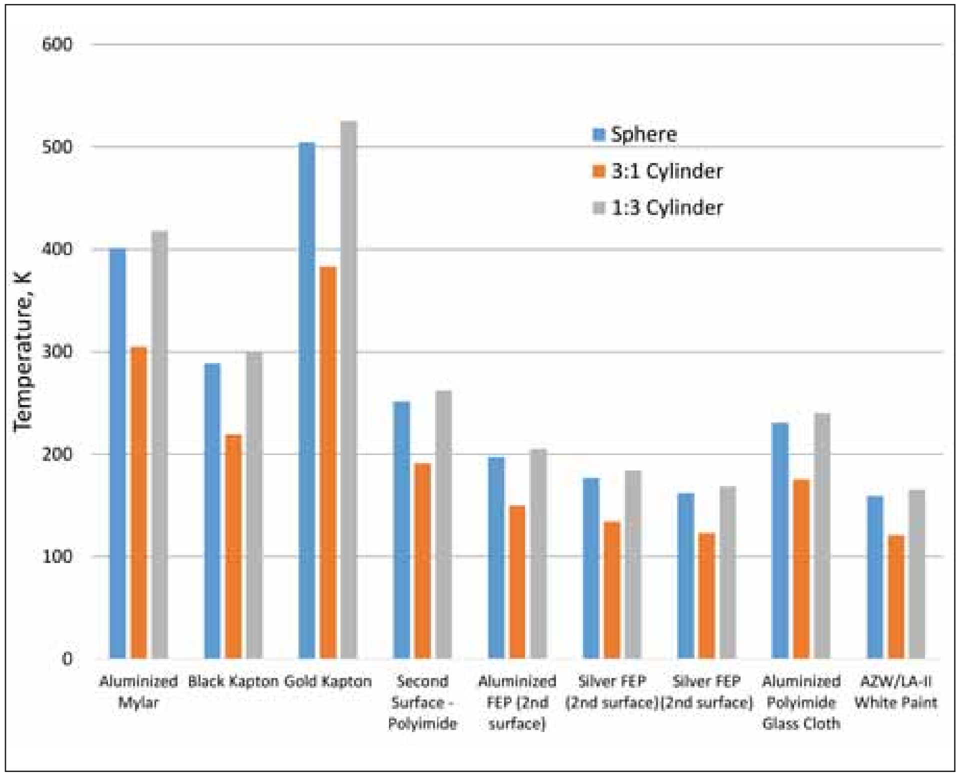


Figure 3: Temperature for sphere and cylinders with spherical end caps at 1 AU with different material properties. Credit: NASA

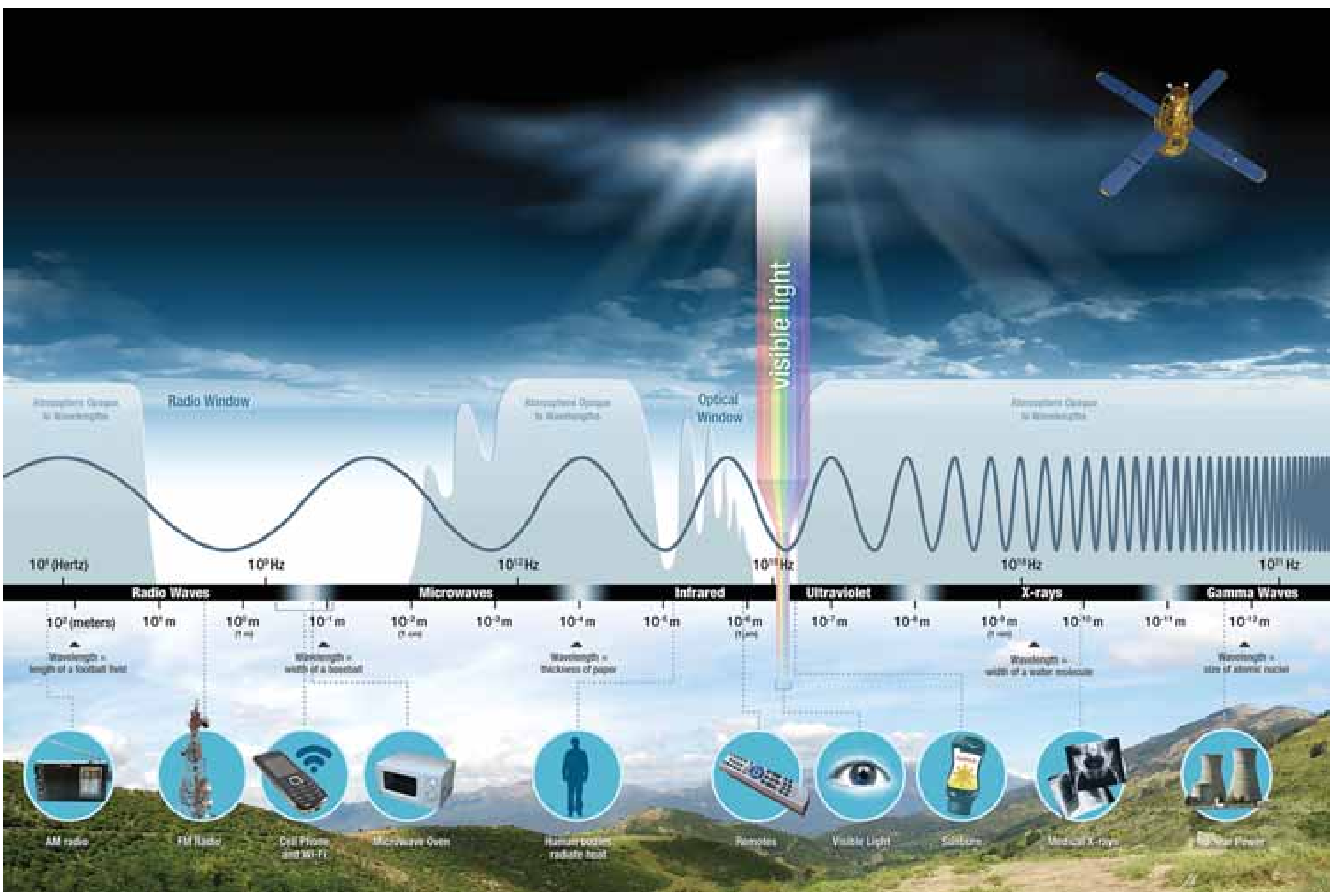


***Figure 4: Electromagnetic spectrum.**[10] Credit: NASA Mission Directorate*

background). As surfaces have different propensities to radiate energy (they can reflect, store, or emit energy), different materials can be selected during the design of the spacecraft to help to control the temperature. A spherical object at the same distance from the sun as the Earth, but without any energy from the Earth, with equal propensity to absorb and emit radiative energy (i.e. it's solar absorptivity and IR emissivity are the same) will be approximately 279 K (see Figure 2). Coating the sphere with different materials with different solar absorptivities and infrared emissivities (taken from the Sheldahl Redbook)[8] yields spheres of a range of temperature between 160 K and just over 500 K (see Figure 3). Recently, NASA has been developing coatings that absorb even less of the sun's energy and could produce temperatures much lower (less than 100 K) in the examples shown.[9] Additionally, the geometry of the satellite can be adjusted to be such as a 3:1 cylinder with spherical end caps, where the cross-section facing the sun is the same as the sphere but the length is extended three times the sphere's diameter, or a 1:3 cylinder with spherical end caps, where the same cylinder is turned broadside to the sun. Figure 3 shows that the 3:1 cylinder temperature drops as the shape yield significantly more area for the satellite to radiate energy from it with the same solar input whereas the 1:3 cylinder only slightly increases in temperature due to the change in relative heat transfer areas.

A real satellite has multiple different thermal environments it travels through, including periods of eclipse where the Earth blocks all of the sunlight from the satellite. This causes many temperature swings that the exterior surfaces of the satellite experience. As a result, most satellites are insulated with multilayer insulation and the interior of the satellite is maintained at approximately 300 K. This keeps the electronics on board the satellite working within their design temperatures. Some observatories and orbital telescopes use specially designed sunshields to insulate their optical elements from both solar and Earth-based radiation such that a cryocooler can keep them cold.

However, there are many interesting locations in the solar system that are at a wide variety of temperatures. In the craters of the Moon's south pole with rims that are angled such that sunlight never gets into them where NASA's Lunar Reconnaissance Orbiter measured temperatures as low as 33 K while nighttime temperatures get as cold as 110 K.[5] To further explore these cold regions where the possibilities for many unique elements and molecules to be trapped is one of the main scientific reasons for NASA's Artemis program.[6] The surface of Titan, one of the moons of Saturn, is known to contain lakes of methane-based liquids as evidenced by images from the Cassini spacecraft.[7] Average surface temperatures of Neptune and Pluto are also very cold due to their large distances from the sun.

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by Jonathan Demko, LeTourneau University and Quan-Sheng Shu, Retired Senior Scientist

Cryogenic Current Leads

Current leads are used to provide for a room temperature interface for bringing electric current to a low temperature device. Typical applications include large superconducting magnets for particle accelerators, magnetic imaging (MRI) magnets which are typically made using low temperature superconductors (LTS) and superconducting magnetic energy storage (SMES).[1-6] Heat loads to the cold space from the current leads can be one of the most significant thermal loads of a superconducting device. The heat load comes from two sources, including conduction due to the temperature difference along the lead and the electrical resistive heating.

Current leads are typically found in three basic configurations, as shown in Figure 1. The **conduction-cooled current lead**, the simplest version which carries current typically through a vacuum space to a low temperature device. One or more heat intercepts along the lead, as shown in Figure 1b, can be used to remove heat at different temperatures along the lead. Often this is the approach used between room temperature and 70 K with high temperature superconducting current leads to reduce the heat load to a cold space below 10 K. High temperature superconductors are generally considered to be those conductors which have a critical temperature that can be cooled using liquid nitrogen which typically falls in the range of 65 K to 90 K. Before the discovery of high temperature superconductivity, current leads were all made of conventional conductors such as copper, aluminum and brass. Figure 1c shows the **vapor cooled lead configuration** which is frequently used in helium cooled magnet systems. The helium can be forced flow for supercritical or produced from boil-off.

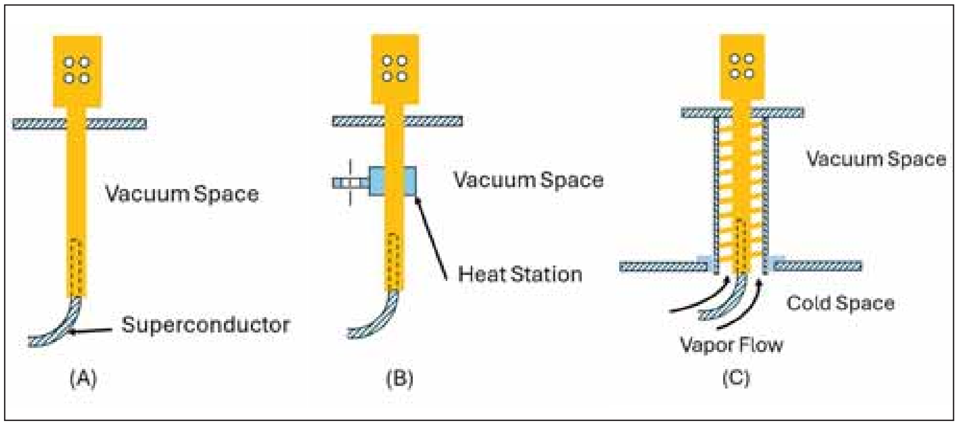

Figure 1. Three basic current lead configurations. (a) conduction-cooled, (b) conduction-cooled with heat stationing and (c) vapor cooled. Credit: Demko and Shu

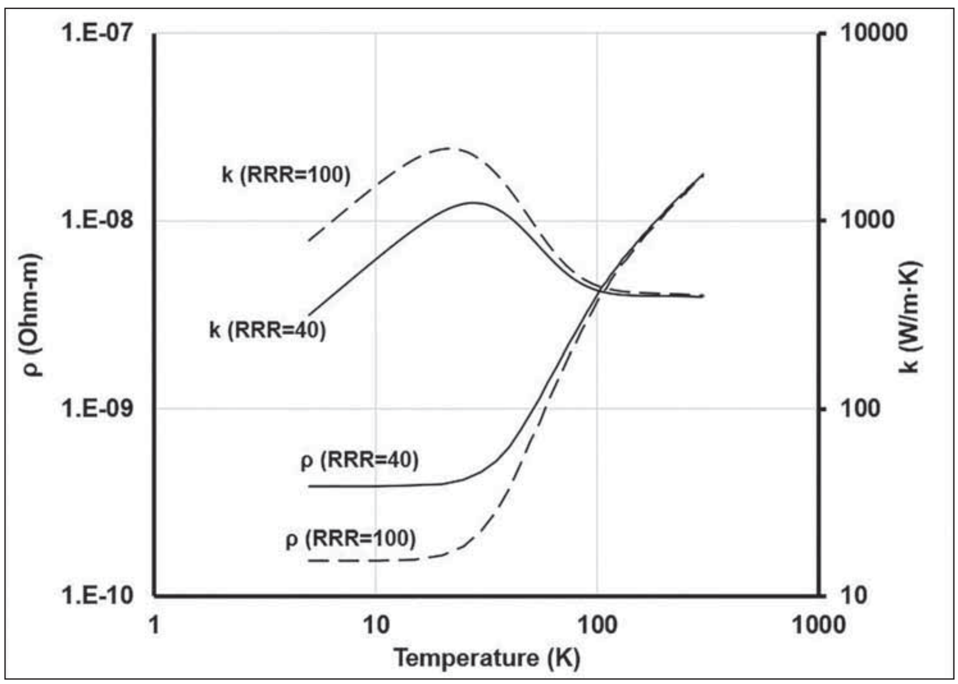

Figure 2. Temperature dependence of thermal conductivity, k and electrical resistivity, ρ, for copper.[7] Credit: N. J. Simon, E. S. Drexler and Peed, J. Demko

Conventional Lead Materials, Warm End

Since current leads are the interface with a room temperature environment, there must be a section of the lead that is made using a conductor such as copper or aluminum. This discussion is limited to the thermal conductivity and electrical resistivity behavior of copper cooled to low temperatures. Other materials such as brass alloys and aluminum have also been used. The thermal conductivity and electrical resistivity for copper are shown in Figure 2 as functions of temperature for two values of residual resistivity ratio (RRR). The RRR is defined by the ratio of the resistivity at 273 K to the residual resistivity at 4 K as given in the equation below.

$$RRR = \frac{\rho_{273K}}{\rho_{4K}} \qquad (1)$$

The residual resistivity is affected by several factors such as the purity of the copper, grain structure, annealing, etc. Frequently, the copper used in wire and electrical bus work falls in the range of 40 < RRR <100. If the bus has undergone machining operations, brazing, soldering, etc., the RRR may not be constant along its length. This will probably not be significant for applications between room temperature and 70 K. For temperatures below around 70 K the properties are sensitive to the RRR.

Conduction-Cooled Current Leads

Conduction-cooled leads are one of the simplest design concepts and are an important approach for cryogen free operating devices. The optimum configuration assumes that heat is removed from the lead at the cold end and that there is no heat exchange with the environment.

The temperature profiles along a conduction-cooled current lead between 290 K and 70 K are presented in Figure 4 for zero current, optimal current and higher than optimal operating current but still stable and not burning out. At the optimal operating current there is no heat transfer from the ambient surroundings as indicated by the zero-temperature gradient at the warm end. In actual practice, the temperature would be linked to the ambient temperature through a heat transfer coefficient. Very little discussion has been presented on the thermal connection of the warm end to the environment, but a value of 2.2 W/cm^2/K based on the lead cross-section has been suggested.[8]

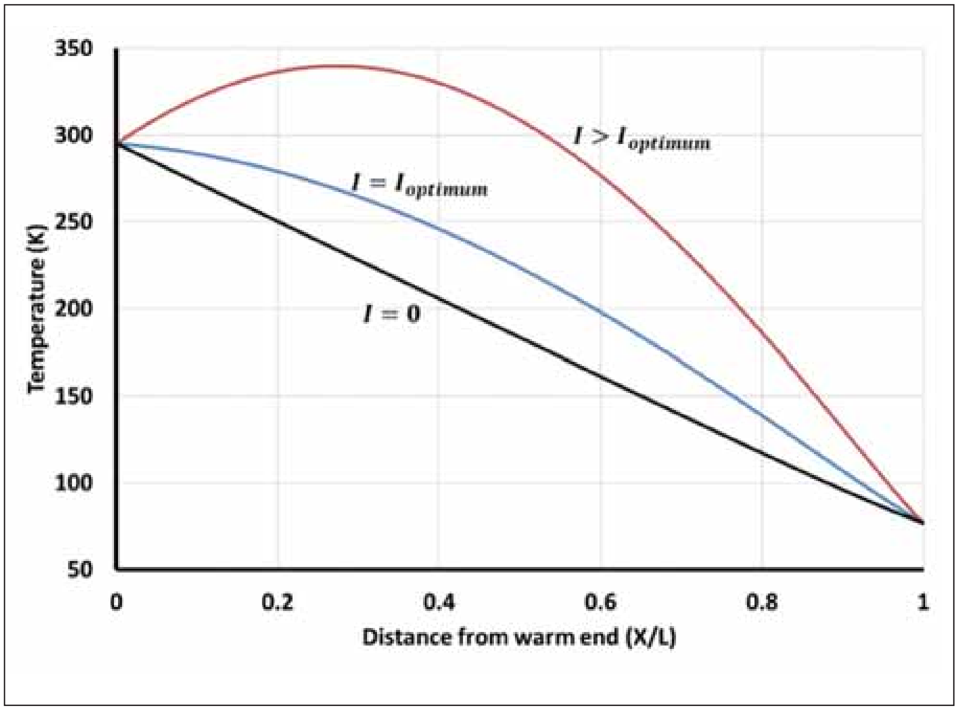

Figure 3. Temperature profiles for warm end temperature of 290 K and low-end temperature of 70 K at zero current, optimal current and overcurrent. Credit: Demko and Shu

Thermal optimization of conduction-cooled leads can be accomplished using the equations derived by McFee[9] for the optimum shape parameter which is the product of the operating current in amps and the length divided by the area or IL/A and minimum heat load to the low temperature end. The set of equations solved is based on the one-dimensional heat conduction equation with internal heat generation and temperature varying properties. After some mathematical manipulation as described in the paper, the following set of equations result:

$$[Q_L]_{\min} = I\left[(\rho k)_{avg}(T_H - T_L)\right]^{1/2}$$

$$\frac{IL}{A} = \frac{1}{I}\left[\frac{[Q_L]_{\min}}{\rho_L} - \int_{T_L}^{T_H} \frac{d\left(\frac{1}{\rho}\right)}{dT} Q(T)\,dT\right]$$

$$Q(T) = \left[2(\rho K)_{avg}(T_H - T)\right]^{1/2}$$

$$(\rho k)_{avg} = \frac{1}{T - T_L}\int_{T_L}^{T} \rho(T)k(T)\,dT$$

Equations (2 - 5) can be solved numerically using the temperature-dependent

▶ *continues on page 30*

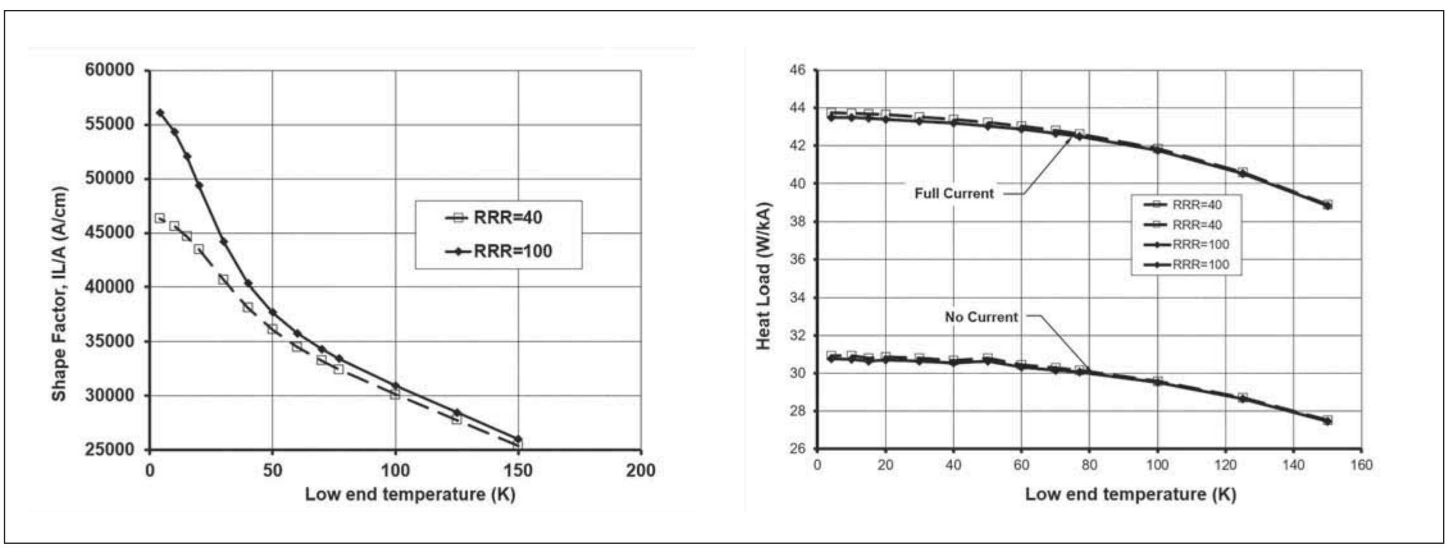

Figure 4. (a) optimum shape parameter for conduction-cooled copper leads as a function of low-end temperature and copper RRR and (b) optimum heat load as a function of low-end temperature. Credit: Demko and Shu

Figure 5. Sample heat exchanger designs for convection cooled current leads. (a) Spiral fin and (b) wire mesh. Demko and Shu

thermal conductivity, *k* and electrical resistivity, ρ, for the lead material to obtain the optimal shape factor, IL/A and minimum heat load $Q_{L,min}$ between any two temperatures. Figures 4a and 4b show how these parameters vary between T_H =300 K and 5 < T_L <150 K, for copper with RRR=40 and RRR=100.

Vapor or Forced Flow Cooled Current Leads

Analysis of vapor cooled current leads can be accomplished with a one-dimensional energy balance, as discussed in [10-11]. The energy balances for the conductor and the cooling flow are given in equations (6) and (7). In these equations, γ is the density, λ is the thermal conductivity, C is the specific heat, A is the cross-sectional area, *h* is the convective heat transfer coefficient, *P* is the heat transfer surface area per unit length, e_v is the vapor enthalpy, and ρ is the resistivity of the conductor. The subscripts *c* and *v* stand for the conductor and vapor, respectively. The set of coupled partial differential equations can readily be solved using numerical techniques [10-11].

$$\frac{\partial(\gamma_c A_c C_c T_c)}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda_c A_c \frac{\partial T_c}{\partial x}\right) + \frac{\rho I^2}{A_c} + hP(T_c - T_v) \qquad (6)$$

$$\frac{\partial(\gamma_v C_v T_v)}{\partial \tau} = \dot{m}_v \frac{\partial e_v}{\partial x} + hP(T_v - T_c) \qquad (7)$$

The design of current leads is in practice reduced to the selection and optimization of geometrical features. The current-carrying conductors of the current leads have been made in several configurations to allow for high heat transfer efficiency as well as compact current carrying capability. Current leads have been fabricated using bundles of small diameter wire and pipe as described in Efferson,[12] thin conducting foils, spiral fin, and zigzag heat exchangers are a few successful designs.[4,5,9] Examples of a spiral fin and copper mesh heat exchanger are shown in Figure 5 (a) and (b). The overall design for a 10-kA magnet lead is shown in Figure 6. Some of the design features are temperature measurements at the top and bottom for flow control and a low Tc superconductor tail at the cold end.

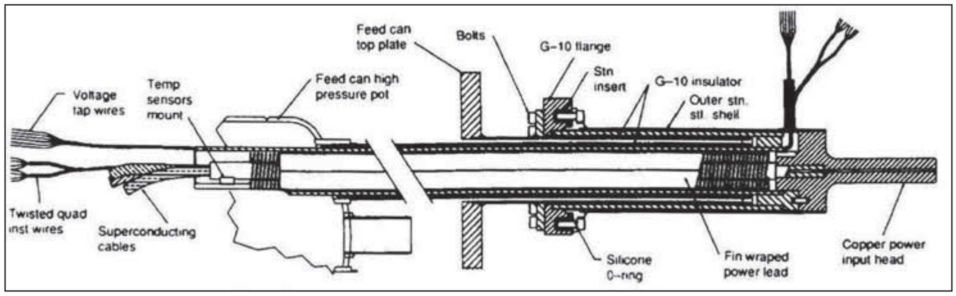

Figure 6. Assembly of a 10-kA vapor cooled power lead. Credit: Q-S. Shu & J. Demko

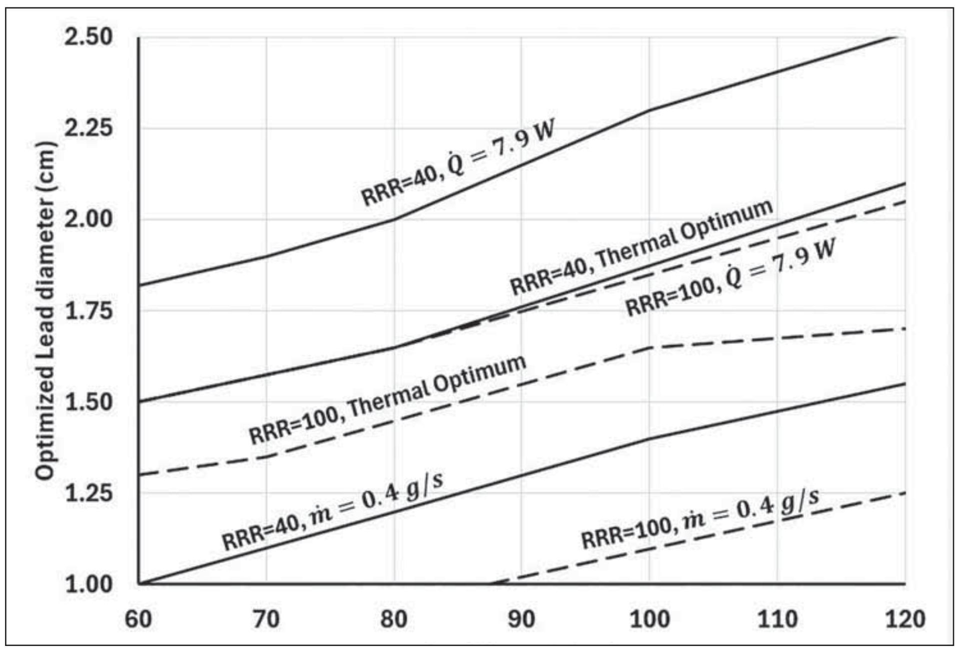

Figure 7. Optimized current lead dimensions for a 6.6 kA forced flow lead. Credit: J. Demko

Optimization can be based on minimizing the total Carnot power used to operate the leads [11]. This is the sum of the Carnot power to reliquefy the coolant stream and the Carnot refrigeration from the heat leak into the cold space. This can be expressed as:

$$P_{Carnot} = \dot{m}_{He}\Delta h_{liq} + \left(\frac{T_H - T_C}{T_C}\right)\dot{Q}_{Cond} \qquad (8)$$

The results for optimization of the length for a given diameter are shown for a 6.6 kA magnet lead in Figure 7. The thermal optimum falls between the limiting heat transfer of 7.9 W and the helium coolant mass flow of 0.4 g/s.[11]

HTS Current Leads

High temperature superconducting (HTS) leads can follow the conventional warm section. HTS leads are formed from stacks or bundles of HTS wire for the transition from around 77 K to the low temperature (4 K nominal) end. HTS leads are recommended for situations where high current connections are needed for LTS or devices at similar operating temperatures. HTS leads have been demonstrated to provide heat load reduction[13] and high reliability in systems such as the Large Hadron Collider (LHC).[3]

The current leads for ITER are a hybrid design that minimizes heat load to the cold end and helium flow.[14,15] A complete 68 kA hybrid lead for ITER is shown in figure 8a and b. The conventional or upper portion (300 – 65 K) of the lead is forced flow cooled using helium vapor supplied at 50 K and 0.4 MPa. The HTS material is a Bi-2223 superconductor tape with a gold-doped silver matrix.

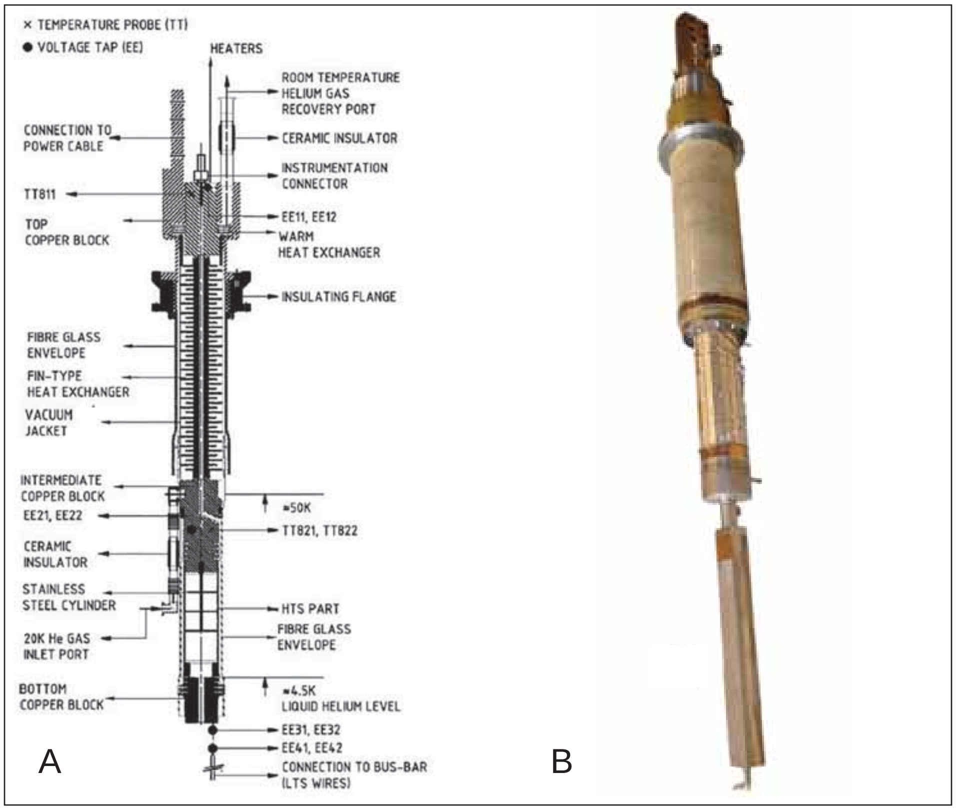

Figure 8. Hybrid HTS current leads: (a) Schematic of the LHC 13 kA current lead;[14] (b) Photo of ITER 68 kA current lead.[15] Credit: Ballarino. A., and Ding K, Bi Y, Feng H, et al.

Summary and Conclusions

The design of current leads for cryogenic applications depends on many factors which depend on the application. Small superconducting magnet systems may be able to use conduction-cooled leads. Large superconducting magnets, such as in fusion machines like ITER or particle accelerators, rely on vapor cooled leads because of the extremely high currents that must be supplied to the magnets and the availability of helium used to cool the magnet string.

The warm end of the current lead is always made using conventional conductors such as copper, aluminum or brass. If the low temperature end of the lead is at liquid helium temperatures, it is frequently advantageous to use high temperature superconducting wires below 75 K to reduce the heat load.

The analysis of high current leads is most often conducted with numerical models, and results obtained by those experienced in the field frequently match the final design. The designs being used are very efficient in minimizing the heat load to the cold component and the coolant flow needed. The optimal operating design depends on the refrigeration and liquefaction system operational requirements as well as stability to off design or fault conditions. As the number of applications for cryogenic equipment increases, so will the variety of designs of current leads that will be needed. But these will be based on the design principles discussed in this work.

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by James E. Fesmire, President, Energy Evolution LLC, james@321energy.us

Optimizing Advanced Thermal Insulation Systems for Low Temperature Applications—Part 1

Most systems that are designed to be operated at below-ambient temperatures require thermal insulation for both control and energy-efficiency concerns. For cryogenic systems the need is amplified, and the level of performance must be much higher to properly limit the heat transmission from the ambient environment. Relative to foam-type insulation materials in air, aerogels can reduce the heat flow by about half, and moderately evacuated ("soft vacuum") layered composites can reduce the heat by ten times. The latest evacuated bulk-fill systems (glass bubbles) can reduce the heat flow by almost 100 times and highly evacuated multilayer insulation (MLI) systems can reduce the heat transmission by more than 1,000 times compared to foams. With each higher level of thermal performance, the design approach, engineering, and manufacturing execution become progressively more challenging. A fitting combination of materials, testing, and engineering is key to meet the objectives of system control, safety, and performance. Most important, the thermal performance must justify the cost.

Simulation test platform Cryostat CS900 for LN2, LH2, or LHe testing. Credit: GenH2 (J. Fesmire)

The total heat leakage rate (Qtotal), or "heat leak," into any cryogenic system comprises three main parts in a cold triangle of integration: 1) heat leak through the insulation, 2) heat leak through the support structures, and 3) heat leak attributed to piping penetrations and feedthroughs. But real systems almost always have additional heat leak due to practical limitations of fabrication and installation, as well as the negative effects of supports and piping. This additional real-world heat leak for cryogenic systems is accounted for using the insulation quality factor (IQF). The "cold triangle" approach, with the use of the IQF, can be readily applied to piping systems, piping connections, cryostats, storage tanks, etc. to determine the best insulation system for a particular case. Presented below, the approach is applied to examples of three different cryogenic storage tanks and two different cryogenic piping elements.

Engineering analysis and thermal testing go hand-in-hand for determining the best insulation system for a given design situation. Conducting analysis and calculations according to standard methods is essential for fair comparison of different materials and accurate applications of results, as detailed by Fesmire (2015). Testing involves the measure of the total heat flow rate through an insulation system under relevant conditions. Relevant conditions typically include a large temperature difference (ΔT) and a controlled, steady-state test environment or vacuum level. The specific vacuum level is the key driver for thermal performance of any system.

Calculations for cryogenic insulation systems follow the guidance given in ASTM C1774 Standard Guide for Thermal Performance Testing of Cryogenic Insulation Systems. By measurement of the heat flow rate (Q) from boiloff calorimetry, the effective thermal conductivity (k_e) is calculated. This real-world heat flow rate (or heat leak) includes all modes of heat transmission (radiation, solid conduction, gaseous conduction, and convection). While solid conduction is usually fixed by the system design, the test environment determines the relative amounts of the other components of the total flow of heat. The test environment is defined by the cold vacuum pressure (CVP) (that is, the vacuum level under steady-state operating conditions of the system) and the composition of the residual gas. The k_e is defined as the heat transmission through the total thickness of the insulation test specimen (one material, homogeneous non-homogeneous, or a combination of materials) between specified boundary temperatures, and in a specified environment.

Standard laboratory cryostats currently in use include the following test platforms: cylindrical Cryostat CS100 (LN_2), flat-plate Cryostat CS500 (LN_2), and cylindrical Cryostat CS900 (LH_2 or LN_2). All are steady-state boiloff calorimeters designed for absolute thermal performance measurements. A solution for small-batch LH_2 supply is now provided by GenH_2 Corp. Example test conditions are a cold boundary temperature (CBT) of 20 K and a warm boundary temperature (WBT) of 293 K for a temperature difference (ΔT) of approximately 273 K. The test environment, cold vacuum pressure (CVP), is established using any necessary combination of starting gas composition, gas flow control, and vacuum pumping control system. Structural-thermal materials can be similarly characterized, under various compressive loads, using the Macroflash cryostat instrument.

Hydrogen liquefaction and controlled storage system LS20 for small-batch LH2 supply. Credit: GenH2 (J. Fesmire)

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CO2Meter Tackles Risks, Regulations and Safety Measures in Confined Spaces

by Morgan Morris, CO2Meter

While oxygen deficiency in humans is often the result of a medical condition, an oxygen-deficient atmosphere in a confined space is just as dangerous. Except for drowning or being lost in space, most people don't worry about a lack of oxygen. But if you are in a hospital, restaurant, bar, or any of a hundred businesses or factories where tanks or cylinders of compressed gas are stored nearby, then working or walking into an environment with a lack of suitable oxygen can occur. A leak in any of these tanks or cylinders in an enclosed area has the potential to lower the oxygen level, resulting in a hazardous oxygen-deficient atmosphere.

Compressed gas storage tanks must be equipped with safety valves and monitoring systems, ensuring regulated and secure containment. Credit: CO2Meter

What is Oxygen Deficiency?

OSHA defines an oxygen-deficient atmosphere as anything less than 19.5% oxygen by volume. At lower levels, different physical symptoms can occur.

Effects of Various Oxygen Levels

See the Occupational Safety and Health Administration's (OSHA) 29 CFR 1910.134 standard and ANSI/ASSE Z88.2-2015 (Z88.2) guidelines for more information. An employee who must enter a confined or potentially oxygen-deficient space may require a low oxygen alarm, a respirator, or personal protection equipment.

Oxygen Level Percent	Effects
20.8%	Normal - fresh air
19.5-21%	Acceptable low oxygen (OSHA)
10-19.5%	Increased breathing rate, accelerated heartbeat, impaired thinking and coordination
6-10%	Nausea, vomiting, lethargy, leading to unconsciousness
< 6%	Convulsions, cessation of breathing, cardiac arrest.

What is Considered an Oxygen-Deficient Atmosphere?

While normal atmosphere contains between 20.8% and 21% oxygen, OSHA defines an oxygen-deficient atmosphere as one that contains less than 19.5% oxygen and as oxygen-enriched, any atmosphere that contains more than 22%. The Occupational Safety and Health Administration regulation and many confined-space guidance documents indicate that an atmospheric oxygen concentration of 19.5% is the lowest level acceptable for entry into such spaces.

Oxygen Deficiency from Stored Gases

Stored gases used in businesses and industry include nitrogen, oxygen, carbon dioxide, argon, hydrogen, helium, acetylene and other specialty gases. With the exception of oxygen, all these other gases are asphyxiants. An asphyxiant gas is a nontoxic or minimally toxic gas which reduces or displaces the normal oxygen concentration in a confined space. Breathing oxygen-depleted air can lead to death by asphyxiation or suffocation.

Where are Stored Gases Used?

Have you ever noticed that big stainless steel tank at the side of a restaurant? That tank contains liquid carbon dioxide, used to carbonate your beer or soft drinks. CO_2 tanks are used in data centers for fire suppression systems. If you've ever taken a cruise, ships use them to fight fires too (you can't put out a fire on a ship with water). In addition to oxygen, your local hospital has tanks of CO_2 and medical liquid nitrogen installed on every floor.

Do you work in a factory? Welding is done using stored tanks of argon, CO_2, hydrogen, nitrogen and helium. Modern grocery stores are switching from ammonia (NH_3) to CO_2-based refrigerants to keep their meat, dairy and frozen food aisles cold. NH_3 is toxic and dangerous compared to CO_2, but in either case, gallons of it are stored as a liquid in the store for refrigeration.

Need to get an MRI? That machine relies on liquid nitrogen or liquid helium to cool the magnets to -270° C, just above absolute zero temperature. Your dermatologist and local cryo-spa use the same stored gases too. How much stored gas is around you? The market for CO_2 gas alone was 32,844 thousand tons of liquid CO_2 produced in 2019. The industrial gas market for all stored gases is expected to grow by over 5% annually. While you may not see them, when you go to work, to a store, or to a restaurant, a tank of stored gas is somewhere near you.

Stored Gas Tanks Are Safe

The problem isn't the tanks these gases are stored in. These are designed to strict government regulations and leaks are very unlikely. And small amounts of any pressurized gas are not harmful, especially when they can quickly mix with fresh air. However, a leak in a pressurized gas line indoors can easily become dangerous. For example, one liter of liquid nitrogen vaporizes to 696.5 liters of nitrogen gas at room temperature. For most common gases, the expansion ratio from liquid to gas is between 700 and 900 times its liquid size. This means that even a small leak can quickly lower the oxygen level in an enclosed room or area.

The challenge is that people can make mistakes. No matter how much training they receive, eventually someone will turn the wrong valve, not tighten a fixture, or cut a hose.

OSHA Oxygen-Deficient Atmosphere

According to the U.S. Chemical Safety Board, "breathing an oxygen-deficient atmosphere can have serious and immediate effects, including unconsciousness after only one or two breaths. The exposed person has no warning and cannot sense that the oxygen level is too low."

Oxygen Deficiency Alarms

With the growing use of stored gases, state and local governments are developing new procedures to audit their use. Building inspectors across the country now require oxygen deficiency alarms in rooms containing tanks of stored gases. CO2Meter offers a variety of oxygen deficiency monitors, including safety alarms for deficiency or enrichment.

Atmospheric O_2 Concentration (%)	Possible Results
20.9%	Normal
19.0%	Some unnoticeable adverse physiological effects
16.0%	Increased pulse and breathing rate, impaired thinking and attention, reduced coordination
14.0%	Abnormal fatigue upon exertion, emotional upset, faulty coordination, poor judgment
12.5%	Very poor judgment and coordination, impaired respiration that may cause permanent heart damage, nausea, and vomiting
<10	Inability to move, loss of consciousness, convulsions, death

Oxygen Deficiency Safety Alarm

This monitor can detect oxygen levels between 0-23% and is designed to be mounted near sources of inert gases like argon, helium, or nitrogen. It can also be used in walk-in freezers and refrigerators that are as cold as -50° C.

Oxygen Depletion Deficiency Alarm Monitor

This monitor activates an alarm when oxygen levels fall below 19.5%. It can include features like:

- Audible and visual alarms
- Remote displays
- Built-in relays that can be triggered
- Exhaust fan control
- The ability to send an alarm to a monitoring company or the fire department

For example, an oxygen depletion safety alarm monitors the oxygen level in a room in real time so that a leak will be noticed before it results in a dangerous situation. In addition, the alarm can control ventilation fans or be connected to a facility's HVAC and/or alarm system. In the case where CO_2 is stored, a CO_2 level safety alarm should be used.

The benefits of stored gases are numerous. From improved medical procedures to fire prevention to even the bubbles in the beer and soda we drink, we can all appreciate the benefits of stored gases. It's also important to know that with the benefits comes a small risk that should not be ignored. **www.co2meter.com**

The RAD-0002-ZR Oxygen Deficiency Monitor is advanced sensor technology for real-time monitoring and early detection of oxygen-depleted environments, ensuring safety in confined spaces. Credit: CO2Meter

GenH2's Cryo Solution to "Manage the Molecule" for Zero-Loss Hydrogen Transfer

by Greg Gosnell, CEO of GenH2

With the bipartisan infrastructure law supporting the build-out of hydrogen production and liquefaction facilities, the hydrogen economy promises to be a major component of the world's green energy future. It is important to understand that there are major differences between liquid hydrogen (LH_2) and gaseous hydrogen (GH_2), but the vast majority of people knowledgeable in the industry have come to the conclusion that LH_2 is superior. There are several benchmarks to achieve before the promise of hydrogen's contribution to net zero carbon emissions and clean air can be realized. The first is recognizing that LH_2 and not GH_2 is the key to build the hydrogen economy.

What Makes Liquid Hydrogen the Key

It's important to understand why industry experts believe so strongly in the advantages of liquid hydrogen versus gaseous hydrogen. Because liquid hydrogen is much denser than compressed gaseous hydrogen, significantly more liquid hydrogen can be transported in a single tanker truck. In addition, the footprint for storage of LH_2 is significantly less than that for gaseous hydrogen.

Without the liquefaction of hydrogen before transport, most use cases would not be economically viable. Procuring gaseous hydrogen is the first stage of producing liquid hydrogen and the number of sources is increasing. More methods will evolve for producing a gaseous hydrogen molecule at the site where the input (feedstock) to the process already exist. Examples of this include geologic formations such as expired hydrocarbon reservoirs and shale fields, other locations where natural gas is being flared. Additional locations will focus on where inexpensive or renewable energy can be used to power an electrolyzer that produces hydrogen.

Controlled storage utilizing active refrigeration provides a regulated internal environment within the bulk storage tank to eliminate the need for venting. Credit: GenH2

The greatest losses occur during LH_2 transfer to the bulk storage tank when GH2 must be vented. Credit: GenH2

Several barriers to the adoption of LH_2 still remain. First, a supply of hydrogen must be accessible and available, without being dependent on a supply chain. This requires a dependable supply of ultrapure liquid hydrogen. Second, we need to be able to deploy safe, low pressure storage of liquid hydrogen. Third, and perhaps most importantly, it will be essential to minimize losses during transfer, storage and dispensing.

The Cryogenic Challenge to Manage the Molecule

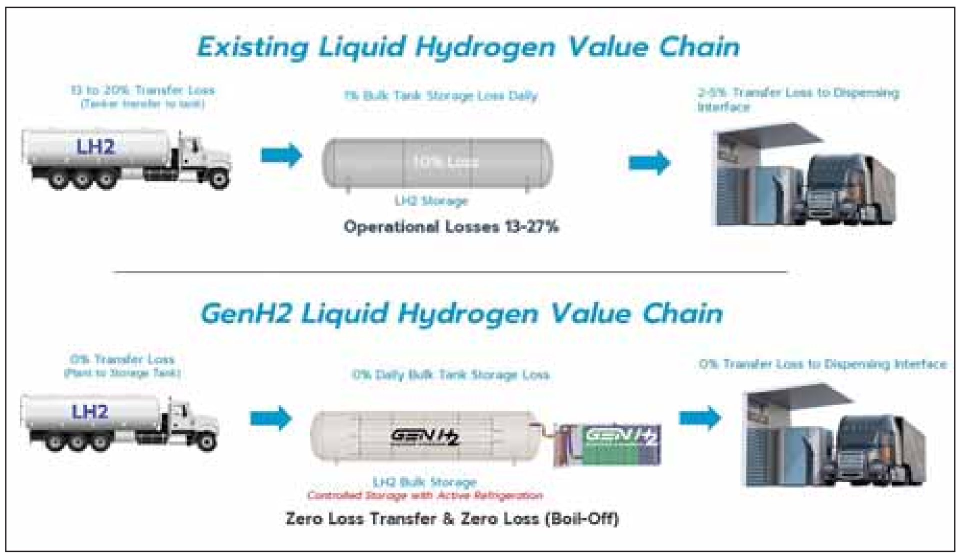
A major concern in liquid hydrogen storage is minimizing hydrogen losses from liquid boiloff. Because liquid hydrogen is stored as a cryogenic liquid, any heat transfer to the liquid will cause hydrogen evaporation and require venting once pressure builds. The source of this heat can be ortho-to-para conversion, mixing or pumping energy, radiant heating, convection heating, or conduction heating. Any evaporation will result in a net loss in system efficiency. However, there will be an even greater loss if the hydrogen is released into the atmosphere instead of recovered. Vented hydrogen also increases the effect of greenhouse gases, which in five to ten years may result in financial penalties due to government emissions' regulation.

The first step in avoiding boiloff losses is to perform an ortho- topara conversion of the hydrogen during the liquefaction step to prevent any conversion and subsequent evaporation from occurring during storage. Another important step in preventing boiloff is to use insulated cryogenic containers.

Much like comparing a refrigerator to a cardboard box, controlled storage systems and traditional hydrogen storage tanks differ vastly in their capabilities and efficiency. Controlled storage systems provide a regulated internal environment, which ensures stable pressure within the system and eliminates the need for venting. These systems achieve zero loss by enabling complete control over the stored liquid hydrogen, making them an absolute game-changer for global adoption.

Additionally, most people are unaware that the greatest losses tend to occur during the molecule transfer. To better control costs it is important to understand the potential losses that may occur during the value chain and that the ability to ensure zero-loss hydrogen transfer is key to unlocking liquid hydrogen's potential. The financial consequences associated with vented hydrogen are consequential, amounting to more than 20% loss per transfer, with some measurements reaching 40%. This loss number has earned the hydrogen molecule the "escape artist" label.

Typical bulk storage tank venting GH2 to relieve pressure. Hydrogen venting losses can exceed 20%, with actual 'real-world' losses at or near 40%. Credit: GenH2



The existing liquid hydrogen value chain as compared to Gen2's chain. Credit: GenH2

Meeting the Zero Loss Challenge

To optimize energy efficiency and output, it is imperative to minimize boiloff losses. When LH_2 is delivered to the bulk storage tank, the potential for significant loss during transfer must be addressed. With standard bulk storage transfer systems, the pressure increase requires venting and hydrogen loss. Controlled systems are very efficient as they can also significantly reduce the losses that occur during the hydrogen transfer process. These specialized systems offer the ability to subcool the liquid hydrogen before use to ensure it remains in a liquid state while moving between systems.

Recently, GenH2 debuted zero-loss hydrogen solutions that prevent evaporation and loss. The company's controlled storage, zero-loss transfer systems were developed based on proof of concepts from NASA. By utilizing a refrigerated storage system, it ensures that liquid hydrogen remains in a subcooled state, by constantly removing heat from the molecule. That process prevents evaporation (boiloff), therefore eliminating the need for venting. This innovative approach not only prevents transfer losses during bulk tank fills but also eliminates daily storage losses and losses that occur during dispensing operations.

With the capability to manage the molecule by producing and storing liquified hydrogen effectively, with zero loss transfer, the tipping point has been reached. The hydrogen economy is here. **www.DiscoverHydrogen.com**.

Cryospain Addresses Hydrogen Embrittlement, Mitigating Risks Across Industries

by Cryospain Communications Team

Hydrogen embrittlement is a significant concern with wide-ranging effects across multiple industries and sectors. Credit: Cryospain

Hydrogen embrittlement represents a critical issue with significant implications across multiple industries. The potential for sudden and catastrophic failures in essential components makes it a pressing concern for sectors such as aerospace, defense, energy and automotive. Addressing this problem is paramount, and understanding the phenomenon and the strategies to mitigate it is essential.

Hydrogen embrittlement occurs when hydrogen infiltrates and diffuses into certain metals, causing them to become brittle and prone to fracture. This issue is particularly detrimental to high-strength steels and alloys, significantly reducing their ductility and load-bearing capacity, ultimately making them susceptible to sudden failures. Identifying hydrogen embrittlement involves visual inspections that may reveal cracks and fractures in high-stress areas or changes in surface texture. Mechanical testing techniques, such as tensile and fatigue tests, can confirm its presence. Additional methods like microscopic analysis, non-destructive testing (ultrasonic or X-ray), and electrochemical techniques (hydrogen permeation testing) can also expose potential embrittlement issues.

Various factors contribute to hydrogen embrittlement, including specific types of corrosion. Corrosion, the gradual degradation of materials due to chemical reactions, can lead to hydrogen embrittlement by allowing hydrogen to enter the metal. Galvanic corrosion, caused by two dissimilar metals in electrical contact within a corrosive electrolyte, produces hydrogen gas absorbed by the metal. Pitting corrosion, a localized form resulting in small pits or holes, and crevice corrosion, occurring in confined spaces, also facilitate hydrogen absorption. These and other types of corrosion typically result in stress-corrosion cracking (SCC) or hydrogen-assisted stress corrosion cracking (HASCC). Additionally, electrochemical reactions like electroplating or cathodic protection, as well as high temperature processes such as welding or casting, can introduce hydrogen into metals, promoting embrittlement. Environmental factors like corrosive environments, moisture, or high temperatures further increase hydrogen generation and absorption.

The impact of hydrogen embrittlement on material structure is profound. It reduces ductility, causes structural degradation and increases susceptibility to fractures. Hydrogen embrittlement weakens atomic bonds (hydrogen-enhanced decohesion or HEDE), generates microstructural alterations and increases dislocation mobility, leading to plastic deformation (hydrogen-enhanced localized plasticity or HELP). The phenomenon can cause failure in critical components, posing severe risks in high-stress applications.

Preventing hydrogen embrittlement requires key mitigation strategies. Choosing materials less susceptible to embrittlement, such as austenitic stainless steels and specific nickel-based alloys, is crucial. Applying protective coatings like nickel, cadmium or zinc can act as surface barriers, limiting hydrogen exposure. Implementing hydrogen removal strategies, including baking and stress-relief annealing, also helps. Preventive technologies like cathodic protection and hydrogen barrier coatings have been successful in preventing corrosion and hydrogen generation. Non-destructive testing (NDT) facilitates the early detection of hydrogen embrittlement, reducing the risk of catastrophic failures. Preventive environmental control policies further reduce hydrogen production rates, minimizing embrittlement risk.

Design strategies play a significant role in mitigating hydrogen embrittlement. Minimizing residual and operational stresses by avoiding sharp corners and sudden cross-section changes is advisable, as these areas concentrate stress and facilitate crack initiation. Using thicker sections is preferable, as thinner sections are more susceptible to embrittlement. Adopting a preventive perspective, including redundancy in critical components, ensures that a single failure does not lead to catastrophic consequences. Design should also facilitate easy inspection and maintenance, enabling early detection of hydrogen cracking.

Materials processing should consider hydrogen embrittlement, from welding practices to thermal treatments, to minimize hydrogen introduction. Performing certain processes in a vacuum or under inert gas atmospheres can further prevent hydrogen exposure. The benefits of preventing hydrogen embrittlement are substantial. Components maintain their mechanical properties and performance for longer, preventing premature failure. Reducing the risk of structural faults, especially in high-stress applications, improves structural integrity and reduces the need for repairs and unplanned downtime. In industries like aerospace, automotive, nuclear, and oil and gas, preventing hydrogen cracking ensures safety and reliability, helping companies comply with stringent material performance and safety standards.

As a leading company in cryogenic engineering, Cryospain offers top expertise and services to help companies prevent hydrogen embrittlement. We manage hydrogen-related issues across various processes, from expert material selection and testing to successful thermal management. Our comprehensive solutions mitigate hydrogen-related problems, safeguarding processes and components against serious consequences. **https://cryospain.com**

Pressure Increase Method Marks Significant Advancement in Cryogenic Controls and Safety

by Séverine Grimberg, Leak Detection Tools

Ensuring the integrity of packaging in cryogenic environments is crucial for maintaining product quality and operational safety. Recent advancements in non-destructive leak testing technology underscore significant improvements in cryogenic controls and safety by emphasizing the need for precise and reliable testing methods. Effective leak detection is essential for preserving the performance of critical systems, and modern technologies, such as the Contura® series from INFICON GmbH, which illustrates how advanced leak detection systems can uphold these standards and enhance overall system reliability. Its advanced technology is particularly valuable in sectors where maintaining vacuum or low pressure environments is essential.

Packaging leak tests are carried out during production to prevent leaks and damage. Products like coffee are quickly affected by environmental influences: oxygen, moisture or light can cause damage extremely quickly which leads to loss of aroma and quality. Credit: INFICON GmbH

Precision in Leak Detection

Cryogenic systems often operate under extreme conditions that can exacerbate the risks associated with leaks. The Contura® series addresses this challenge through its pressure increase method. This method allows for the detection of both gross and micro leaks, which is critical for cryogenic applications where even minute leaks can lead to significant issues. In cryogenic environments, maintaining a controlled atmosphere is essential to prevent contamination and ensure the efficiency of the system. The technology used by INFICON measures leaks by creating a controlled pressure environment within a flexible test chamber. This approach provides a non-destructive means of evaluating the integrity of cryogenic components, thereby ensuring that the systems remain operational and safe.

Non-Destructive Testing for Enhanced Safety

One of the primary advantages of the new non-destructive leak testing technology is its ability to avoid damaging sensitive components. Traditional methods, such as bubble bath testing, can be problematic in cryogenic applications due to their reliance on high pressures that can compromise the integrity of the tested items. The advanced technology addresses this issue by using a pressure increase system that ensures the integrity of the components remains intact. This approach is particularly beneficial in cryogenic systems, where maintaining the original condition of components is crucial for operational reliability and safety.

The ability to detect leaks without compromising the integrity of the test samples is particularly valuable in cryogenic applications, where maintaining system integrity is critical. Traditional leak testing methods, such as bubble bath or CO_2 testing, create a pressure differential to identify leaks. However, these methods can be invasive and potentially damaging to the components being tested. In contrast, modern non-destructive technologies, such as those utilizing the pressure increase method, offer a more refined approach.

One prominent application can be found in something almost every person encounters every day: coffee—more specifically, coffee packaging. To ensure product quality, "it is important that we have established valid test tolerances in production," explains Arman Khazali, operations manager at Italian coffee manufacturer and INFICON customer Bialetti. These tolerances cover roasting quality, uniformity of grinding, and the efficiency of production machines. Bialetti's annual output includes 180 million coffee capsules and 2.9 million soft packs, all of which must withstand high water pressure during brewing. A leak would compromise coffee quality, making accurate and quantifiable testing crucial. Khazali highlights the benefits of non-destructive testing: "It offers added value compared to destructive methods, including reduced testing time and autonomy in personnel management, allowing for 24/7 production." This approach ensures reliability and efficiency in maintaining product quality, and the principles and benefits of the Contura series are applicable to other cryogenic systems where maintaining leak-free conditions is paramount.

Efficiency and Accuracy in Cryogenic Applications

Efficiency and accuracy are critical in cryogenic applications where precise conditions must be maintained. Advanced leak detection technology excels in providing rapid and reliable results, with a user-friendly interface that facilitates efficient monitoring and maintenance of cryogenic systems. By incorporating such technology, operators can ensure optimal system performance and promptly address potential issues. Cryogenic systems often operate continuously, making downtime due to leaks costly and disruptive. The advanced technology offers a solution for quickly identifying and quantifying leaks, which is essential for maintaining system efficiency and ensuring operations remain within required parameters.

The key advancement of the pressure increase method is its placing the test item in a flexible film chamber and creating a controlled environment where pressure changes are monitored. The chamber is evacuated to a low pressure, and any gas escaping from leaks causes a measurable increase in pressure within the chamber. The technology employs highly sensitive, self-developed pressure sensors that detect minute changes in pressure. This precision is crucial in cryogenic systems, where even small leaks can cause significant operational issues. The ability to quantify leaks accurately ensures early identification of potential issues, allowing for timely maintenance and reducing the risk of system failures.

Comprehensive Integration

The advanced leak detection systems are backed by extensive technical expertise, ensuring effective integration and operation, which is crucial for maintaining safety and performance in cryogenic applications. For cryogenic systems, where maintaining low temperatures is crucial, the non-destructive pressure increase method offers several benefits:

Preservation of System Integrity: This method avoids damaging components, unlike traditional methods that can alter test samples and lead to inaccurate results or compromised components. **Enhanced Accuracy:** The pressure increase method provides high precision in leak detection, crucial for cryogenic systems where minor leaks can impact performance. Its ability to quantify leaks accurately ensures timely identification and resolution of potential issues. **Reduced Testing Time:** The technology delivers results in less than 15 seconds, which is valuable in high-throughput environments for maintaining production schedules and ensuring reliability. **Improved Safety:** Early and accurate leak detection helps prevent hazardous situations from undetected leaks, enhancing the overall safety of cryogenic systems and operations.

Applications and Future Developments

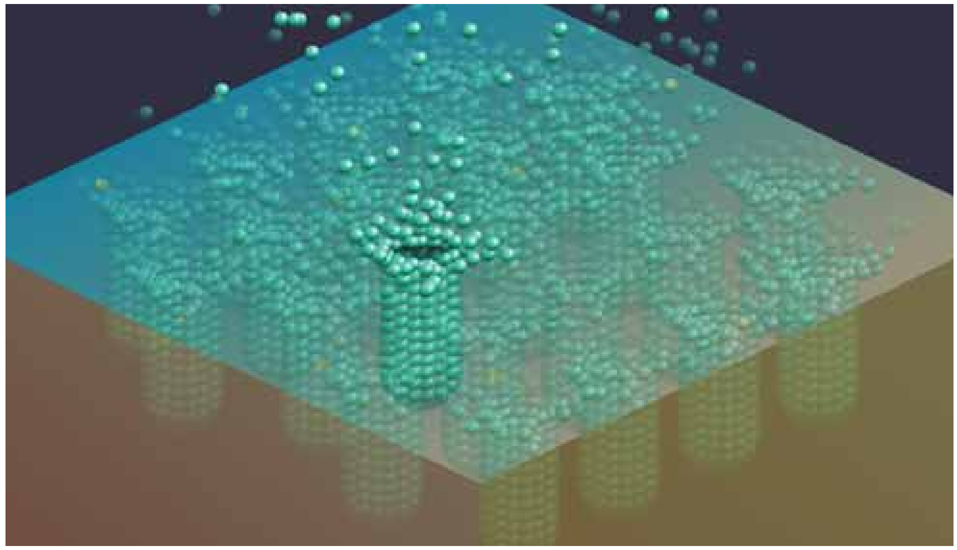
The pressure increase method is increasingly used in cryogenic applications, such as vacuum-sealed components and sensitive equipment. Its non-destructive testing aligns with the rigorous safety and performance requirements of modern cryogenic systems. Future advancements in sensor technology and data analysis are expected to further improve non-destructive leak testing methods. Continued development will enhance precision and reliability, supporting the progress of cryogenic technology.

As industries continue to emphasize high standards and effective operation, technologies like the Contura® series will be crucial in maintaining these standards. The pressure increase method marks a significant advancement in cryogenic controls and safety. By providing precise, reliable, and non-invasive testing, this technology is essential for maintaining the integrity and performance of cryogenic systems, ensuring their safe and efficient operation.

Cryogenic Lab Redefines 3D NAND Precision

by CSA Staff Writer

At a time when artificial intelligence (AI) is reshaping industries and driving unprecedented demands for data storage and processing, semiconductor technology faces a pivotal juncture. To meet these escalating demands, Lam Research, based in Fremont, Calif., has unveiled a groundbreaking advancement in cryogenic etching: Lam Cryo™ 3.0. This state-of-the-art technology promises to redefine the standards of 3D NAND flash memory manufacturing, delivering unparalleled precision, speed and sustainability.



Lam Cryo™ 3.0 allows for higher aspect ratio features with breakthrough precision and profile control. Credit: Lam Research

Precision and Speed

At the heart of Lam Cryo 3.0 is its remarkable precision. As semiconductor designs push the boundaries of what's possible, the ability to etch features with angstrom-level accuracy becomes critical. Lam Cryo 3.0 excels in this regard, achieving a profile deviation of just 0.1% — a feat that translates into superior electrical properties and yield. This precision is essential for creating the high aspect ratio (HAR) memory channels required for advanced 3D NAND, which are often less than 1/1000th the width of a human hair.

The technology's speed is another significant advantage. Lam Cryo 3.0 operates 2.5 times faster than traditional etching methods. This acceleration in processing not only enhances productivity but also helps meet the tight deadlines imposed by the rapid pace of technological advancements and market demands. The increased throughput ensures that manufacturers can keep up with the ever-growing need for high-performance memory solutions.

Sustainability at the Forefront

In addition to its technical prowess, Lam Cryo 3.0 is a testament to Lam Research's commitment to environmental responsibility. The technology incorporates several innovations aimed at reducing its ecological footprint. Notably, it achieves a 40% reduction in energy consumption per wafer and up to a 90% reduction in emissions compared to conventional etching processes. These improvements are made possible by harnessing temperatures well below -0 °C and utilizing high-power confined plasma reactors, which allow for the use of novel etch chemistries and process designs.

This focus on sustainability is increasingly important as the semiconductor industry grapples with its environmental impact. Lam Cryo 3.0's efficiency not only helps manufacturers lower their operational costs but also aligns with global efforts to minimize the carbon footprint of technological advancements.

The Challenges of the AI Era

The push towards 1,000-layer 3D NAND by the end of the decade presents several manufacturing challenges. The increasing complexity of these memory structures demands new solutions to ensure that the electrical properties of the memory cells remain stable and reliable. Lam Cryo 3.0 is specifically designed to address these challenges, providing the enhanced control needed to maintain high yield and performance.

Neil Shah of Counterpoint Research emphasizes the significance of this advancement: "Lam Cryo 3.0 represents a substantial leap forward, enabling the etching of memory channels that are over 50 times deeper than their width with near-perfect precision. This capability is crucial for achieving the high yields and performance required for the next generation of 3D NAND."

A Legacy of Innovation

Lam Cryo 3.0 continues the legacy of Lam Research as a leader in wafer fabrication technologies. Since the introduction of its first cryogenic etch technology in 2019, Lam has established itself as a pioneer in this field. The company has already produced five million wafers using its earlier cryogenic etch technologies, and Lam Cryo 3.0 represents the next step in this ongoing evolution.

This new technology is integrated into Lam's Vantex® dielectric system, which features scalable pulsed plasma technology and is compatible with the Flex® HAR dielectric etchers used by major memory manufacturers. This compatibility ensures that Lam Cryo 3.0 can be seamlessly incorporated into existing production lines, allowing manufacturers to leverage their current investments while benefiting from enhanced etching capabilities.

Looking Ahead

As the semiconductor industry continues to advance, the introduction of technologies like Lam Cryo 3.0 will play a crucial role in shaping the future of memory manufacturing. By combining cutting-edge precision, speed and sustainability, Lam Research is not only addressing the immediate needs of the industry but also setting the stage for future innovations. **www.lamresearch.com**

Product Showcase

This Product Showcase is open to all companies and related manufacturers offering new or improved products for cryogenic applications. We invite companies to send us short releases (150 words or fewer) and one high-resolution JPEG of the product using the form at **www.cryogenicsociety.org/submit-a-product-showcase**.

EDP 80-400 Vacuum Pumps

Edwards Vacuum

The EDP 80-400 series by Edwards Vacuum is designed for the chemical and pharmaceutical sectors. These oil-free pumps use non-contacting reverse claw technology for high efficiency, low costs and long service life. With pumping speeds of 80, 160, 250 and 400 m³/h, they minimize contamination risks and meet safety standards. Suitable for applications like drying, distillation, evaporation, polymerization and biofuel production, Edwards offers custom service solutions to ensure optimal performance and regulatory compliance. **www.edwardsvacuum.com**

CLAWVAC CP B

Leybold

Leybold's CLAWVAC CP B is a high-performance, energy-efficient dry claw vacuum pump suitable for cryogenic processes. It operates under harsh conditions with particles, vapors and contaminated gases. The pump features stainless steel claws that rotate without contact or wear, a corrosion-resistant chamber and a separate gearbox to prevent oil contamination. Its modular design simplifies maintenance and cleaning and accessories like flushing kits and liquid separators enhance performance. The CLAWVAC CP B is designed to meet stringent cryogenic requirements. **www.leybold.com**

SSA3218F Series Three-Inch Single Flange Internal Valve

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RegO®'s SSA3218F valve is ideal for LPG and NH_3 loading and unloading in cryogenic applications. This stainless steel valve is used in bobtails, transport trucks, nurse tanks and storage terminals. It offers manual, remote, or actuator operation and prevents liquid trapping between the valve outlet and downstream shutoff. With a nitrile seat disc and PTFE stem seals, it ensures durability. The valve features high-flow design to avoid pump cavitation and includes a built-in excess-flow valve and shear studs, meeting safety standards. It operates at up to 400 psig and temperatures from -40 ºF to 165 ºF. **www.regoproducts.com**

Industrial Stainless Steel O_2 Gas Detector

CO2Meter

The CM-902-S O_2 Gas Detector safeguards workers from hazardous gases like nitrogen, argon and helium in food grade and processing applications. Measuring oxygen levels from 0-23%, it alerts users to oxygen displacement incidents. The detector connects to building management systems, supports three configurable relays and withstands temperatures from -58° F to 122° F. It features an FDA-compliant industrial enclosure for harsh environments and wash-down applications. **www.co2meter.com**

People & Companies in Cryogenics

On May 25th, **Meyer Tool & Mfg.** (CSA CSM) celebrated a significant milestone as Vice President of Engineering **Ed Bonnema** marked 35 years of employment with the company. Ed holds Bachelor's and Master's Degrees in Mechanical Engineering from the Illinois Institute of Technology and an M.M. Degree in Business Administration from Northwestern University, Kellogg Graduate School. He is a Registered Professional Engineer in Illinois and a member of the American Society of Mechanical Engineers and the Society of Manufacturing Engineers. As VP, Ed has played a crucial role in de-

Ed Bonnema. *Credit: Meyer Tool & Mfg*

veloping Meyer Tool's capabilities and mentoring the third generation of its leadership. Drawing from his experience with prestigious projects such as Fermilab and Lawrence Berkeley National Laboratory's distribution boxes for the Large Hadron Collider at CERN, various UHV and precision motion stages for Argonne National Laboratory's Advanced Photon Source and Lawrence Livermore National Laboratory's National Ignition Facility, Ed has imparted invaluable design and fabrication techniques.

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Intelliconnect (Europe) Ltd. (CSA CSM), a UK-based manufacturer of RF, waterproof and cryogenic connectors and cable harness assemblies, has opened a new base in Witham, Essex. The 4,300-square-foot facility, set to be a hub for engineering, sales, administration and marketing, features an exhibition area and conference suite and will serve as a European base for other Trexon group companies. The grand opening event gathered employees, partners, customers and representatives from Trexon group companies to celebrate the milestone. Gareth Phillips, Managing Director

Intelliconnect (Europe) Ltd opened their new base for sales, marketing and engineering in Witham, Essex. *Credit: Intelliconect*

of Intelliconnect, highlighted the significance of the new office and the collective effort of the Intelliconnect team. The event included a keynote speech by Phillips, a celebratory barbecue and a ribbon-cutting ceremony by long-serving employees Maria Wright and Arden Lawson. Intelliconnect, founded in 2003, has grown to be a market leader in RF connectors and cable assemblies, known for their high-quality products and first-class service.

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New Zealand company **Fabrum** (CSA CSM) announced a collaboration with Toyota for its proprietary liquid hydrogen storage technology. This partnership marks Fabrum's first order from Toyota and signifies the start of their relationship as they work together on advancing hydrogen projects. Fabrum, renowned for its end-

Fabrum is set to supply Toyota with its proprietary liquid hydrogen storage technology. *Credit: Fabrum*

to-end hydrogen production and refuelling systems, is also involved in other global projects across aviation, heavy transport and industry. New Zealand Prime Minister Christopher Luxon praised the collaboration as a testament to New Zealand's decarbonization technologies and the significant role Japanese companies can play in the global economy. Fabrum is also engaged in its second Japan-New Zealand hydrogen project with Obayashi Corporation, focusing on dual-pressure hydrogen refuelling technology for Auckland.

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KLM Royal Dutch Airlines will conduct a groundbreaking flight demonstration of **ZeroAvia**'s ZA2000 hydrogen-electric engines in 2026. KLM CityHopper MD Maarten Koopmans announced at the Farnborough Airshow that the demonstration will involve a flight between two airports using liquid hydrogen fuel, underscoring KLM's commitment to leading in this field. The ZA2000, designed for large regional turbo-

ZeroAvia CEO Val Miftakhov (left) and Maarten Koopmans, KLM Cityhopper MD, at a signing ceremony during Farnborough Airshow. *Credit: Christine Boynton/Aviation Week Network*

props with up to 80 seats, will be tested on an ATR 72-sized aircraft. Key steps before the demo include selecting optimal airport pairs, securing regulatory permits, ensuring a liquid hydrogen supply and setting up fueling infrastructure. This collaboration aims to provide evidence for cleaner flight adoption across KLM's network and potentially accelerate hydrogen aircraft development in the EU. ZeroAvia has already conducted advanced ground tests on the ZA2000's cryogenic tanks, fuel cells and electric propulsion systems. The partnership builds on an existing MOU signed in October 2023 for technician training and component support.

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OPW has completed the acquisition of Demaco (CSA CSM), a company specializing in vacuum jacketed piping and cryogenic equipment for gas producers, research institutions, EPC contractors and users of liquefied gases. Founded in 1960 and based in Noord-Scharwoude, The Netherlands, Demaco will join OPW's Clean Energy Solutions business unit. With 150 employees,

Credit: OPW

Demaco designs, manufactures and installs cryogenic systems with a focus on hydrogen and other industrial gases. The integration is expected to drive growth and enhance benefits for both OPW and Demaco customers by complementing OPW CES's offerings and expanding its global product range.

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Credit: ASME

Christine Reilley has been appointed managing director of publishing for **The American Society of Mechanical Engineers** (ASME), reporting to Chief Operating Officer Jeff Patterson. ASME, one of the largest technical publishing operations in the world, offers thousands of titles, including prestigious peer-reviewed journals, conference proceedings and ASME Press e-books. Reilley, who began her tenure with ASME over 20 years ago, brings a deep background in strategy, innovation and publishing workflows, making her the ideal leader to enhance impact factors, improve submission and review processes and increase subscriber satisfaction. She holds a Master of Science degree in biomedical engineering from the New Jersey Institute of Technology and a Bachelor of Arts degree in journalism from Rutgers University. ASME, founded in 1880, is a not-for-profit professional organization that supports the global engineering community by enabling collaboration, knowledge sharing and skill development across all engineering disciplines. **www.asme.org**

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Credit: Beyond Gravity

Beyond Gravity Services has appointed **Iván González Vallejo** as its new Chief Transformation and Strategy Officer. As a member of the executive board, González Vallejo will oversee the transformation and strategy function, including IT, innovation and indirect procurement, and he will lead the EZYone transformation program aimed at enhancing operational efficiency. Previously, he was director of strategy and supply chain at Iberia Maintenance, and before that, he led business transformation projects at McKinsey and Company. With an aerospace engineering background and an MBA from IESE Business School, González Vallejo brings extensive experience in strategic planning and transformation.

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Brad Sutton, the technical director of the **Biomedical Imaging Center at the Beckman Institute for Advanced Science and Technology** and professor of bioengineering at the **University of Illinois Urbana-Champaign**, has been named a fellow of the International Society for Magnetic Resonance in Medicine. Recognized for his innovative algorithms that enhance the re-

Sutton was recognized at the ISMRM's annual meeting in Singapore on May 6, 2024. *Credit: Bruce Damon, Carle Foundation Hospital*

construction of brain images from MRI data, Sutton's work improves imaging efficiency and has broad applications beyond brain imaging. He has been with the Beckman Institute since 2003 and contributes to advancing MRI technology, including working with the state-of-the-art 7 Tesla MRI scanner. Sutton's recognition reflects his significant contributions to MRI research and technology.

Meetings & Events

2024 European Course of Cryogenics
August 19-September 6, 2024
Multiple Locations
https://2csa.org/d4i

2024 Applied Superconductivity Conference
September 1-6, 2024
Salt Lake City, Utah
www.appliedsuperconductivity.org/asc2024

The CERN Accelerator School – CAS Advanced Accelerator Physics
November 10-22, 2024
Spa, Belgium
https://indico.cern.ch/event/1380440/

31st Space Cryogenics Workshop
May 13-15, 2025
Incline Village, Nevada
https://spacecryogenicsworkshop.org

CEC/ICMC 2025
May 18-22, 2025
Reno
www.cec-icmc.org/2025

30th International Conference on Low Temperature Physics
August 7-13, 2025
Bilbao, Spain
www.lt30.es

European Conference on Applied Superconductivity (EUCAS)
September 21, 2025
Porto, Portugal
https://eucas2025.esas.org

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The US Particle Accelerator School (USPAS) has launched the Mel Month Scholarship for Women in Accelerator Science and Engineering (AS&E) to fully fund attendance and travel for women in AS&E. Named after USPAS founder Dr. Mel Month, the merit-based scholarship is available to actively enrolled graduate and undergraduate students. Two scholarships will be awarded each session, with the next session sponsored by Michigan State University in Knoxville, Tennessee, from January 27 to February 7, 2025. For more information and to apply, visit **https://uspas.fnal.gov**.

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