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The Future Titans of Cryogenics | 8

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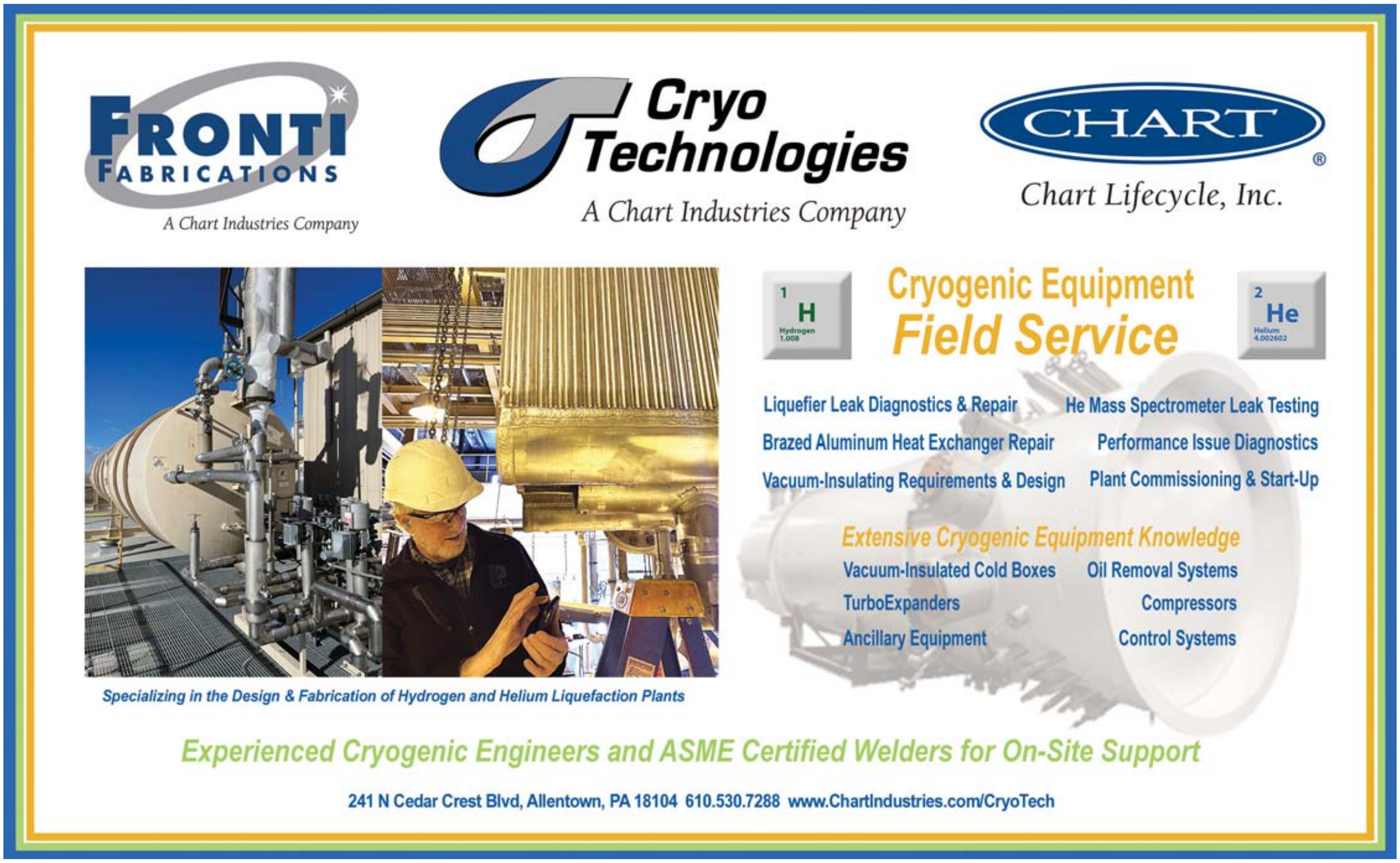
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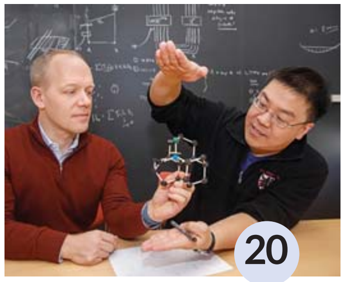

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ON OUR COVER

Young professional Mika Peter Wolfgang Kuschnitzky testing RS&H's lunar liquid oxygen quick disconnect with liquid nitrogen. *Credit: RS&H*

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From the Editor

We're absolutely thrilled to present this year's exceptional finalists for our "Young Professionals in Cryogenics and Superconductivity" feature. These talented individuals represent a wide spectrum of expertise, from groundbreaking cryobiology breakthroughs to cutting-edge innovations in liquid hydrogen, quantum technologies, zero resistance applications and more. Their work exemplifies the dynamic and impactful contributions emerging across the field.

As we applaud their achievements, let's also gear up for an exciting array of upcoming industry events. Our Foundations of Cryocoolers Short Course will be offered Monday, June 3, 2024, at the University of Wisconsin in Madison in conjunction with ICC23. Led by renowned experts Dr. Ray Radebaugh, known as "Mr. Cryocooler," and Dr. Alphons De Waele, the course dives into cryogenic applications and thermodynamic principles, focusing on gas-cycle cryocoolers from 2 K to 150 K. Topics include recuperative and regenerative cycles, modeling, design, fabrication, measurement techniques and a special emphasis on dilution refrigeration for millikelvin temperatures, particularly dry dilution refrigerators. It's an invaluable opportunity to enhance an understanding of cryocooling technology. Those interested can register at **www.cryogenicsociety.org/foundations-of-cryocoolers-short-course-2024**.

Shifting focus to another exciting event, the schedule for the Applied Superconductivity Conference (ASC), September 1-6, 2024, held in Salt Lake City, Utah, is now available on the conference website. Since 1966, the ASC has been the main hub for scientists and engineers working in applied superconductivity to present and discuss their latest findings. Several important dates are coming up for conference attendees. Nominations for the Applied Superconductivity Educational Foundation board are due May 1; registration and hotel reservations open May 15, with the early fee registration deadline set for June 27, and the exhibit and sponsorship registration deadline is July 1. For all ASC 2024 information, visit **www.appliedsuperconductivity.org/asc2024**.

At ASC 2024, CSA will be announcing the recipient of the Roger W. Boom Award, named in honor of the emeritus professor from the University of Wisconsin, Dr. Roger W. Boom, who inspired numerous young scientists and engineers in cryogenic engineering and applied superconductivity throughout his thirty-year career. Created to recognize young professionals under 40 years of age making significant contributions to cryogenic engineering and applied superconductivity, this award aims to honor excellence, high standards and effective communication. Nominate a deserving individual by July 1, 2024, at **www.cryogenicsociety.org/boom_criteria_and_nomination_procedure**.

Once again, we congratulate this year's Young Professionals and hope you enjoy this jam-packed issue of ***Cold Facts***, filled with the latest updates and findings in our ever-growing industry.

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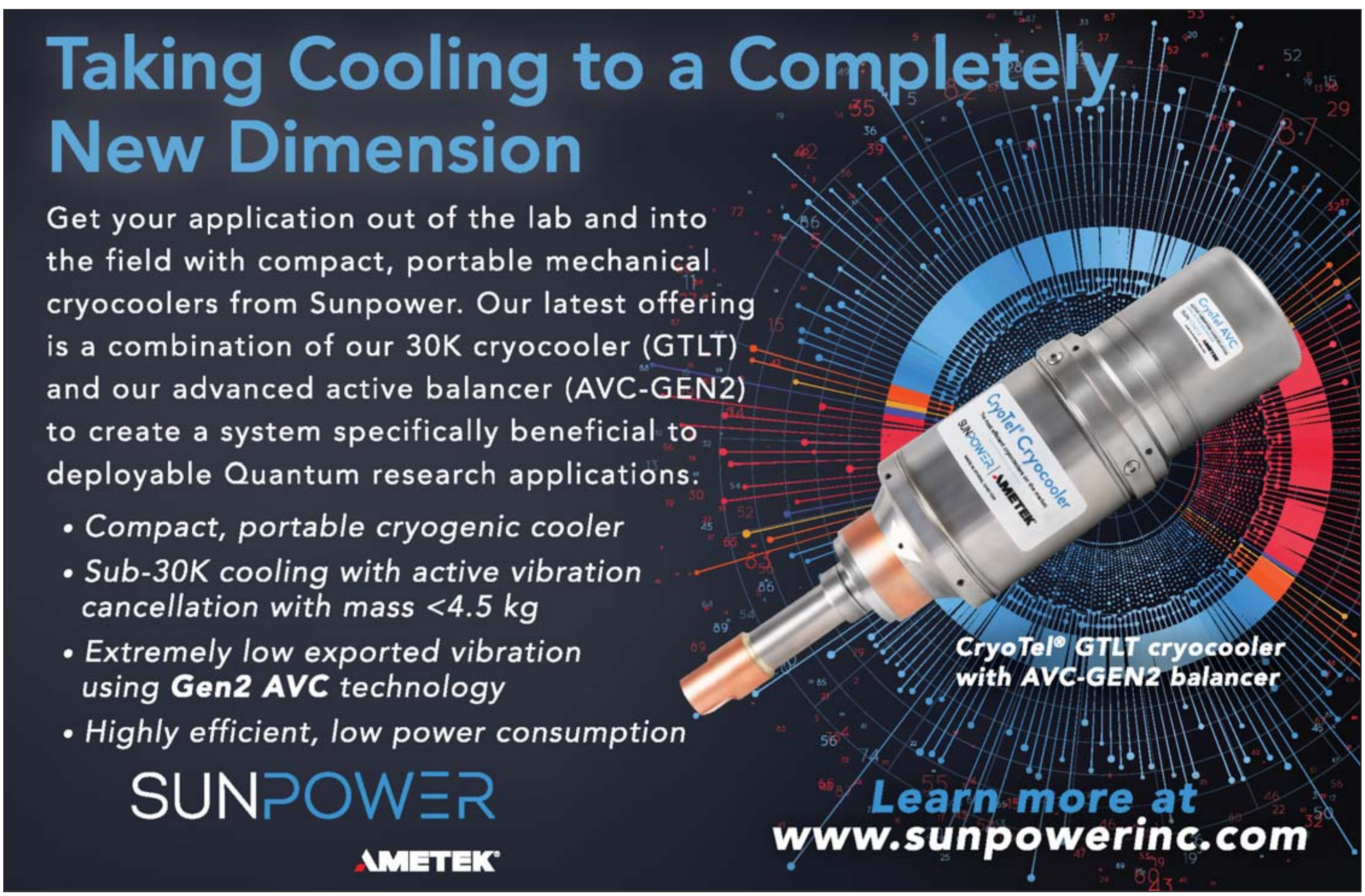
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YOUNG PROFESSIONALS 2024

The Next Generation in Cryogenics and Superconductivity

This feature introduces outstanding young professionals (under 40 years of age) who are doing interesting things in cryogenics and superconductivity and who show promise of making a difference in their fields. Debuted in the 2006 issue, the feature has presented many young persons whom we are proud to see have indeed lived up to that promise.

Rasha Al-attar, 32

What is your present company/position? I am a postdoctoral fellow at Harvard Medical School and Massachusetts General Hospital.

What is your educational and professional background? I hold a master's in biology and a Ph.D. in biochemistry and molecular biology, with postdoctoral training in stem cell therapy and organ biobanking.

How did you get into cryogenics? During my graduate studies, I had the privilege of working under the supervision of Dr. Ken Storey, a distinguished researcher known for his groundbreaking work on animal models thriving in harsh environments lethal to humans. Dr. Storey's investigations, which encompassed freeze-tolerant frogs, hibernating squirrels and hypoxia-tolerant naked mole rats, to name a few, shed light on the extraordinary resilience of these species. My research centered primarily on freeze-tolerant wood frogs, a subject that deeply fascinated me. These frogs exhibit a remarkable ability to freeze to a solid state, ceasing all heartbeat, brain activity and movement, only to fully regain function within hours of thawing, completely unharmed. Exploring the intricate biological and physiological responses of these creatures to ice was a profoundly inspiring experience. Inspired by the similar approach used in Dr. Shannon N. Tessier's lab, where rat livers were successfully partially frozen and fully recovered for multiple days by mimicking wood frog responses, I endeavored to apply these principles to my own research. My overarching objectives are to refine cryopreservation methods for stem cell products for cell-based therapies, prolong the viability of transplantable hearts ex vivo and develop tailored freezing protocols for zebrafish embryos and larvae. These efforts are aimed at preserving and archiving numerous unique lines and transgenic zebrafish species for future research and transportation.

Do you or did you have a mentor? I've been fortunate to have had several mentors throughout my academic journey. Dr. Ken B. Storey, my Ph.D. supervisor, provided me with a solid foundation in cryogenics and encouraged innovative, nature-inspired approaches to address challenges in organ biobanking. Under Dr. Michael A. Laflamme, I developed my techniques in stem cell research and synthetic biology, pushing me closer to my academic aspirations. Currently, under the guidance of Dr. Shannon N. Tessier, I've gained invaluable insights into organ perfusion and biobanking. I am deeply grateful to all three mentors for their guidance and mentorship.

What awards/honors have you received? Most recently, I received two postdoctoral awards from the Ted Rogers Center for Heart Research (Canada) and the Canadian Institute of Health Research award that I am currently funded by.

What are some of your contributions to the cryogenic field? My primary contribution to the cryogenic field involves elucidating the molecular mechanisms of suspended animation/freeze tolerance in wood frogs across various organs. This research underscored the necessity of a synchronized approach integrating biology, biochemistry and physiology for successful cryogenic survival. By exploring molecular pathways, I expanded my perspective to examine similar pathways in non-stress-tolerant models. I utilized innovative approaches to replicate pro-survival responses observed in wood frogs within nonresistant models. Presently, I am employing pharmacological interventions to emulate suspended animation in zebrafish embryos, larvae and transplantable hearts.

What do you believe are the most important developments in cryogenics? In my view, the pivotal development in cryogenics is comprehending the cell-specific responses during freezing, thawing and exposure to cryoprotective solutions which are vital for post-thaw survival. My approach involves employing molecular biology and biochemistry to decipher these reactions. Furthermore, I utilize genome engineering and synthetic biology to customize cell-specific responses, fostering survival in cryogenic conditions.

What advances do you hope to see in the future? Looking ahead, I envision a future where researchers adopt an integrated approach, combining biomolecular and physiological understandings to tackle the complexities of cryogenics. Collaboration across disciplines, involving biologists, medical professionals and engineers, holds the key to unlocking remarkable advancements in this field. With dedication and synergy, I am optimistic that significant strides can be made within the next few years!

Where can readers find out more about your projects? www.researchgate.net/profile/Rasha-Al-Attar and www.linkedin.com/in/rasha-alattar

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Kyle Appel, 24

What is your present company/position? As the graduate student lead at the HYPER Center, I liaise with fellow graduate students, industry partners and elected officials representing the potential of hydrogen.

What is your educational and professional background? As a farmer, who enjoys days in the field long past when most sane people have gone to bed, I dream of bringing real change back to my small family farm. My hydrogen journey began at Washington State University completing my B.S. in mechanical engineering and gaining experience with systems design, safety and technology development.

How did you get into cryogenics? The small family farm is slowly becoming extinct. Many farmers must work side hustles to keep the farm afloat as large corporate enterprises buy up land and equipment, driving prices to the moon. Integrating hydrogen to produce fuel and fertilizer onsite allows the small family farm to compete on the platforms of emissions, sustainability, efficiency and profit.

Do you or did you have a mentor? In Dr. Jacob Leachman's combustion engines course, the class analyzed a report that detailed the specifications for a single cylinder diesel engine that was capable of operating on 90% hydrogen and 10% diesel. On the farm, tractors and combines are powered by a big block diesel engine. By operating these engines on hydrogen in addition to diesel, I imagine a way to transform my family farm. I got in contact with Dr. Leachman about the Hydrogen Properties for Energy Research (HYPER) Center, and we found a fit for me there, rebuilding the Cryo-Catalysis Hydrogen Experimental Facility (CHEF) to gain critical hydrogen systems experience.

What are some of your contributions to the cryogenic field? To inform future design and operation of cryogenic storage tanks, I am developing a reduced-order model for liquid hydrogen storage vessels that utilize mass and energy equations to predict self-pressurization and cyclic venting. In addition, my work has experimentally recreated the statistical thermodynamics curve for ortho-parahydrogen equilibrium composition, a necessary step for unlocking zero boiloff storage.

What do you believe are the most important developments in cryogenics? Hydrogen fuel cells are implemented in 4% of all the forklifts utilized in industry. Standardization of liquid hydrogen as a fuel will lead us from small-scale applications to large-scale adoption.

What advances do you hope to see in the future? I hope to see the hydrogen-powered family farm revolution.

Where can readers find out more about your projects? www.linkedin.com/in/kyle-appel-7795241ba/ and www.hydrogen.wsu.edu/

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Akanksha Apte, Age: 33

What is your present company/position? Currently, I work as a cryogenic process engineer in the cryogenics division at SLAC National Accelerator Laboratory.

What is your educational and professional background? I completed my bachelor's in chemical engineering in India and earned a master's degree in chemical engineering at the University of Pittsburgh. I started my career as a process engineer in the oil and gas industry in India, and later worked at Bechtel OGC in Houston, Texas, after finishing my master's degree and joining the Linac Coherent Light Source II (LCLS-II) project at SLAC.

How did you get into cryogenics? While working in the oil and gas sector, I participated in the design of an LNG plant where I was briefly introduced to cryogenics. However, I had the opportunity to work with helium refrigeration when I joined the LCLS-II project at SLAC. At SLAC, I contributed to the team responsible for the startup and commissioning of the LCLS-II cryoplant. I was involved in performance tests of two cryoplants, each comprised of high pressure warm compressors, 4.5 K cold boxes and 2 K cold compressors. This experience allowed me to gain insights into the field of cryogenics. Currently, I support cryoplant operations and the development of future SLAC cryogenics infrastructure, such as LCLS-II HE and the cryomodule test facility.

Do you or did you have a mentor? With my career spanning two continents, I have encountered many influential coworkers who greatly influenced my journey as a process engineer. In the oil and gas sector, my supervisors guided me in enhancing my technical expertise in process design and applying theoretical knowledge of chemical engineering practically. At SLAC, I am particularly thankful to my supervisors, Viswanath Ravindranath and Eric Fauve, for recognizing my strengths as a process engineer and supporting me in advancing my skills in cryogenics operations, process control and process design. I am also grateful for having strong female engineer role models in both fields.

What awards/honors have you received? I was part of the team receiving the Director's Award, the highest honor at the lab, for successfully achieving 2 K in the LINAC, SLAC's first superconducting LINAC. I was also

▶ *continues on page 10*

included in the 2022 Women in Cryogenics feature in ***Cold Facts***.

What are some of your contributions to the cryogenic field? I authored a paper for CEC2023 that presents the performance results of the LCLS-II helium refrigeration system and outlines the challenges encountered during the commissioning phase. Our team at SLAC will continue to publish similar papers to share our commissioning and operational experiences with the cryogenics community.

What do you believe the most important developments in cryogenics are? Efficiency in the refrigeration system is consistently a focal point for those involved in cryogenics. The commissioning of the LCLS-II cryoplant was completed in 2023, and our team has been able to achieve results exceeding the project requirements. Additionally, our team has automated various complex tasks through rigorous testing of the machine during commissioning. Currently, we are focused on optimizing the operational performance of the cryoplant by identifying various excess heat loads on the system and developing operating strategies to mitigate the effects of these heat leaks. We are also optimizing the design of upcoming projects based on learnings from LCLS-II.

What advances do you hope to see in the future? I hope to see quantum computing operating at a temperature where it can utilize the refrigeration capacity of commercially sustainable liquefiers to scale up their usage. Many entities are advancing with this idea of scale up, which is very interesting.

Where can readers find out more about your projects? www6.slac.stanford.edu/news/lcls-iiv and www.linkedin.com/in/akanksha-apte/

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Christopher Edwards, 29

What is your present company/position? I am currently an engineering project manager within the Illinois Accelerator Research Center group at Fermilab. Our team works to take technology developed at Fermilab for science and tailor it to industrial applications that benefit the nation's health, wealth and security.

What is your educational and professional background? I hold a bachelor's degree in electrical engineering from Northern Illinois University. I have worked at Fermilab as an intern and engineer working on controls systems, instrumentation, field-programmable gate array development, application-specific integrated circuit testing and now superconducting radio frequency (SRF) accelerators.

How did you get into cryogenics? Cryogenics is an important part of the work we do at the US Department of Energy's Fermi National Accelerator Laboratory. I've used cryogenics for testing custom electronics, and now I am working on our conduction-cooled SRF accelerator, which uses pulse tube cryocoolers to reach superconducting temperatures.

Do you or did you have a mentor? I have had two mentors in my career, one in my previous engineering role and one in my current role. Mentorship is something that, I believe, is extremely important in the early stages of a career in engineering as that experience is invaluable when you're transitioning from school to the workforce. The mentorship I've received has helped me understand how to apply theories and principles I learned in school to help solve real-world problems. In addition to improving my real-world engineering skills, mentorship helped me understand career paths and professional development opportunities which have helped me further my career. Now that I'm further into my career, I have started mentoring young engineers as well via internship programs and internal mentorship programs at Fermilab.

What are some of your contributions to the cryogenic field? Our team at Fermilab is working on demonstrating the first conduction-cooled SRF accelerator. This demonstration will change the thought process of how to cool SRF accelerators to superconducting temperatures in the future by showing that if you manage the heat loads properly, you can run accelerators without liquid cryogenics.

What do you believe the most important developments in cryogenics are? The most important developments in my field are the recent advancements in cryocooler performance. The advancements in these devices allow us to design higher-power accelerators that increases the number of applications for our projects.

What advances do you hope to see in the future? I'd love to see continual improvement in the cryocooler's capacity as well as increases in the power consumption of these devices. I'm not sure how long these advances will take, but I know the companies in this space are working hard on this and have a great team to make this happen.

Where can readers find out more about your projects? www.fnal.gov (Fermilab's main landing page) and www.iarc.fnal.gov (IARC's landing page). The team also travels to various conferences to present our most recent publications and findings. We are at a very exciting time and will have several publications coming out in the near future detailing our accelerator design and testing.

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Graham Harrington, 27

What is your present company/position? I currently work at Bluefors Cryocooler Technologies Inc. (formerly known as Cryomech Inc.) as a mechanical engineer.

What is your educational and professional background? I have my bachelor's degree in mechanical engineering from Syracuse University. I started working at Cryomech Inc. in 2018 during my senior year of college and started full time after graduation in 2019. Since starting at Cryomech (now Bluefors), I have worked with liquid helium recovery products more than anything else. My main duties include product development and design customization and optimization to meet the ever-increasing demand for helium recovery products.

How did you get into cryogenics? I was always most interested in thermodynamics and heat transfer courses throughout my engineering education, and working in cryogenics has been a great way to continue to be exposed to those fields while getting the opportunity to make products that support research.

Do you or did you have a mentor? I would consider Abner Oviedo to be my mentor. He was the first person with whom I interacted when I started working as an intern, and he has taught me most of what I know about cryogenics and liquid helium recovery. He always challenged me to improve and displayed a level of trust that gave me confidence to take chances in my career. Observing his passion for cryogenics and his willingness to do anything needed to get things done continues to inspire me to do my best.

What are some of your contributions to the cryogenic field? My contributions to the field include the advancements that I have helped make toward the product line at Bluefors. The largest project that I have been part of is the low vibration helium reliquefier, which is a closed-loop, point-of-use recovery system, optimized for low vibration, low-boiloff applications. Another project is the development of a compact helium recovery system. This is a helium recovery system that uses a variable-speed compressor rather than a helium bag to reduce contamination and helium losses associated with helium bags.

What do you believe the most important developments in cryogenics are? I think that liquid helium recovery is a very important advancement in cryogenics. Helium is a valuable resource that is often lost after use. Capturing and reusing this gas reduces the load on helium gas production, transportation and storage and helps researchers become more self-reliant while reducing their environmental impact. While impactful, liquid helium recovery is a challenging task that has required significant user involvement and understanding of processes. My work has focused on making this process less time intensive to allow our customers to focus on research rather than keeping up with a helium recovery system.

What advances do you hope to see in the future? I hope to see quantum computing continue to grow. This is a powerful tool that will accelerate progress across industries. I am excited to see the infrastructure that grows around this industry as it becomes more accessible.

Where can readers find out more about your projects? www.bluefors.com.

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Justin Jessop, 24

What is your present company/position? In addition to my role as a graduate student, I am a lab safety lead. I conduct failure hazard and operability studies (HAZOP), mode and effects analyses, and procedural HAZOPs during the design process, incorporating safety into every step.

▶ *continues on page 12*

What is your educational and professional background? As a first-generation college student, I obtained my bachelor's in mechanical engineering at Washington State University (WSU) in 2022. During my time as an undergraduate at WSU, I worked as a research assistant at the Hydrogen Properties for Energy Research (HYPER) Center for two years, gaining experience with cryogenic hydrogen systems. After graduation, I spent seven months working an internship at Daimler Truck North America, where I utilized my knowledge gained at HYPER to assist their advanced engineering team with the development of a hydrogen fuel cell semitruck. Currently, I am in the first year of my master's in mechanical engineering.

How did you get into cryogenics? I have always had a passion for renewable energy, which gives me a strong desire to address climate change, but finding an impactful field to pursue was challenging. During my junior year at WSU, I took thermodynamics with Dr. Jacob Leachman where I learned of hydrogen's potential to play a key role in decarbonizing multiple industries while enabling a renewable grid and how liquid hydrogen would be essential in facilitating hydrogen's adoption. By the end of the semester, I was assisting one of his Ph.D. students with the Cryo-Catalysis Experimental Facility (CHEF), studying ortho-para hydrogen conversion and measurement, an essential yet widely misunderstood phenomenon of hydrogen liquefaction.

Do you or did you have a mentor? Dr. Leachman's knowledge of the field of cryogenic hydrogen is only surpassed by his passion for developing young professionals to make an impact in the field. His dedication to the teaching process, such that the solution to one problem provides the skills needed to solve many, sets his mentoring style apart. His patience to ensure understanding makes learning and applying these processes an incredibly rewarding experience.

What are some of your contributions to the cryogenic field? During my time as an undergraduate, I collaborated with a graduate student to design a 1 tesla modular magnet array to study the effects that an applied magnetic field has on catalyst performance during ortho-para hydrogen conversion. As a graduate student, I have shifted to testing the thermal conductivity of common cryogenic insulation's transient effective conductivities during a rapid loss of vacuum event. This testing will be paired with a model that simulates liquid and two-phase transfers to understand in-pipe behavior. In turn, allowing for loss of vacuum scenarios should be understood and adequate safety precautions implemented.

What are the most important developments in cryogenics? Zero-boiloff storage, either from active or passive cooling, will fundamentally change the economic viability of liquid hydrogen storage and infrastructure. Two-phase flow is inherently present in any cryogenic transfer, a process that will be essential for infrastructure. The ability to accurately model and understand two-phase hydrogen flows will improve the efficiency and viability of clean fuel, putting us closer to a renewable future.

What advances do you hope to see in the future? I see a future where the steady humming of a hydrogen production plant adjacent to the dam has enabled constant flow, reduced cyclic stresses and increased the life of the turbines. Overlaid wind turbine blades put on a show as they harvest electricity, turning excess power into hydrogen and eliminating curtailment. Solar farms channel their excess electricity into producing hydrogen reserves that will keep their regions powered at night. On the bustling highways, hydrogen tanker trucks once carrying petroleum are filled with liquid hydrogen, distributing hydrogen across the country. A robust renewable grid rests easy, knowing it can remain self-sustaining. A breath of fresh air is had by all in the carbon-free society we have achieved. Our future is green. I will see you there.

Where can readers find out more about your projects? www.linkedin.com/in/justin-jessop-388b501b8/ and ww.hydrogen.wsu.edu/

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Mika Peter Wolfgang Kuschnitzky, 25

What is your present company/position? My current position is as a mechanical engineering associate within RS&H's Aerospace Solutions division.

What is your educational and professional background? I am a FAMU-FSU College of Engineering graduate with a bachelor's and master's in mechanical engineering.

How did you get into cryogenics? My undergraduate senior design project with NASA Marshall Space Flight Center was how I was introduced to cryogenics. We were tasked with a design-build project to develop an ergonomic LOX quick disconnect apparatus that future astronauts could utilize on the lunar surface. I've been fascinated by the field ever since.

Do you or did you have a mentor? My mentor in school was Dr. Mark Vanderlaan who shepherded our senior design team in designing our cryogenic system for NASA. As the lead cryogenic engineer at the National Magnet Laboratory, Dr. Vanderlaan's expertise in the field was instrumental in our team succeeding and igniting our passion for the field itself.

What awards/honors have you received? I received a spot award (given to an employee for exceptional performance or achievement) from RS&H for my engineering support on a proprietary contract.

What are some of your contributions to the cryogenic field? A few of the contributions to the cryogenic field I have made this early in my career include the development of a cryogenic quick disconnect for the lunar surface, and now I am directly involved at Kennedy Space Center's Launch Complex 39B as RS&H is supporting NASA on modifying the mobile launcher in preparation for Artemis II.

What do you believe the most important developments in cryogenics are? I believe that as the world ramps up its cadence in traveling out of our atmosphere, safe, reliable and cost-effective cryogenic fueling solutions must be developed for launch infrastructure to sustain the growing demand for traveling to space.

What advances do you hope to see in the future? I hope to see the development of the lunar launch infrastructure come to fruition and contribute to the design of lunar cryogenic systems which would support future generations in traveling among the stars. I believe that the lunar launch infrastructure necessary could be developed within the next 30 years.

Where can readers find out more about your projects? www.linkedin /in/mikakuschnitzky. and www.rsandh.com/solutions/aerospace/

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Mercedes Corrales Rodríguez, 27

What is your present company/position? I am a project engineer at Cryospain.

What is your educational and professional background? I received my degree in chemical engineering at the University of Castilla-La Mancha, and later, my official master's degree in chemical engineering. I started working in March 2021 in the field of renewable energy, carrying out green hydrogen production projects from photovoltaic and wind energy. Later I developed an expertise in the world of electric vehicles, participating in the installation of charging points at service stations.

How did you get into cryogenics? My first jobs were related to engineering, but it was very different from what I had always wanted to do. I wanted to develop my professional career focused on my studies, and that is how I got into cryogenics.

Do you or did you have a mentor? Jaime Gutierrez, Cryospain's technical director, is my mentor, a very constant and organized person who is always willing to help and who trusted me from the beginning, for which I am very grateful.

What are some of your contributions to the cryogenic field? I am currently carrying out a project that consists of two skids for the distribution of LH_2 to the other elements of the plant. The difficulty is that since it is such a new technology, and there are not many developments yet, we have to face new in-house solutions and proposals adapted to each client and project.

What do you believe the most important developments in cryogenics are? The most important advances in cryogenics are being shown in the development of LH_2 projects, which in the long run is surely an essential component given the enormous benefits it has (a good fuel, it does not pollute, it can be created through technologies renewably, etc.). Given the scarcity of reference information, I have steered my work away from conventional standards, exploring new avenues in my process.

What advances do you hope to see in the future? The advancements I hope to see in the future include a greater use of H_2 as a fuel for vehicles of all types. From my point of view, with the great importance that is being given to it, in five years we will surely begin to see greater use of this element.

Where can readers find out more about your projects? www.linkedin.com/company/cryospain/ and www.linkedin.com/in/mercedes-corrales-rodriguez/

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Ian Wells, 23

What is your present company/position? As a graduate research assistant at the HYPER Center, my additional role includes being chief revisualist, designing and building systems to enable visualization for other researchers and showing cryogenic and extraterrestrial phenomena to the center in the way it is meant to be seen.

What is your educational and professional background? As a researcher with Washington State University's (WSU) Hydrogen Properties for Energy Research (HYPER) Center, I focus on optical systems to explore cryogenic boiling phenomena. My passions for photography and aerospace have led to projects to develop technology for both extraterrestrial and terrestrial application for NASA, Janicki Industries and the Institute for Materials Research. My current work continues this trend and, in the process, enables future human presence on the moon and Mars.

How did you get into cryogenics? Developing a Schlieren imaging system, I harnessed the optical refractive index to detect leaks from cryogenic test systems. In creating and testing that system, I became fascinated with cryogenic flows and boiling; I want to visualize film boiling and how it changes based on flow conditions, introducing to the literature active, optical identification of boiling regime in two-phase hydrogen.

Do you or did you have a mentor? Through the HYPER Center, Dr. Jacob Leachman has given me a place to turn theory into reality and to rapidly learn not just engineering but project management and process. Where else could a scholar hang their cryo-gloves?

What awards/honors have you received? I received the Russell B. Scott Memorial Award for Best Application Paper 2023 at the Cryogenic Engineering Conference; the S. Town Stephenson Award for the WSU Honors College 2023; the President's Award for Leadership at WSU 2022; the Artemis Award-NASA BIG Idea Challenge 2021; and the Best Technical Paper-NASA BIG Idea Challenge 2021.

What are some of your contributions to the cryogenic field? A liquid nitrogen based carwash for spacesuits on the moon, funded by NASA, provided a technique for the removal of abrasive silica dusts from fabrics with higher efficacy than other removal techniques. It also poses natural synergies with airlock pressurization due to the high expansion ratio of nitrogen upon evaporation. This technique received the Artemis Award from NASA, acknowledging its likelihood for implementation on the upcoming lunar missions.

Currently, I am developing a flow cell to quantitatively image two-phase hydrogen,

▶ *continues on page 14*

identifying the conditions for different boiling phenomena; this system will also determine the optical properties of two-phase hydrogen. This data can then inform the evaluation and development of heat transfer correlations and can also inform the design of optical systems for imaging cryogens.

What are the most important developments in cryogenics? The recent transfer and reignition of cryogenic fuel in space opens the door for further use of cryogens in spacecraft. It also enables lunar refueling from electrolyzed ice, potentially cooled in permanently shadowed craters. This refueling necessitates understanding of two-phase flow due to radiative heat flux into transfer lines.

What advances do you hope to see in the future? I'd like to see boots on the moon by 2030, facilitated by better understanding of cryogenic fuels, that will enable extraterrestrial refueling stations, ultrahigh vacuum, large-scale manufacturing techniques, and analysis of gravitational and radiative effects on biology. Electromagnetic characterization of cryogenic fluids enables the two-phase propellant transfer and mass gauging technologies necessary for this future.

Where can readers find out more about your projects? www.linkedin.com/in/ianwellss/ and www.hydrogen.wsu.edu/

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Michael Wood, 30

What is your present company/position? I am a graduate research assistant at the HYPER Center.

What is your educational and professional background? I achieved my bachelor's in mechanical engineering in 2017 with Magna Cum Laude from Washington State University (WSU). From 2018 to 2022, I worked as a control valve project specialist managing the review and repair of any valve, including cryogenic valves. I anticipate receiving my master's in mechanical engineering this coming fall.

How did you get into cryogenics? In the spring of 2016, I took a system design class taught by Dr. Jacob Leachman where we were tasked to make a hydrogen liquefaction station that could fit into a shipping container–not just theory, changing the world by designing, purchasing and building (with my own two hands) accessibility to hydrogen.

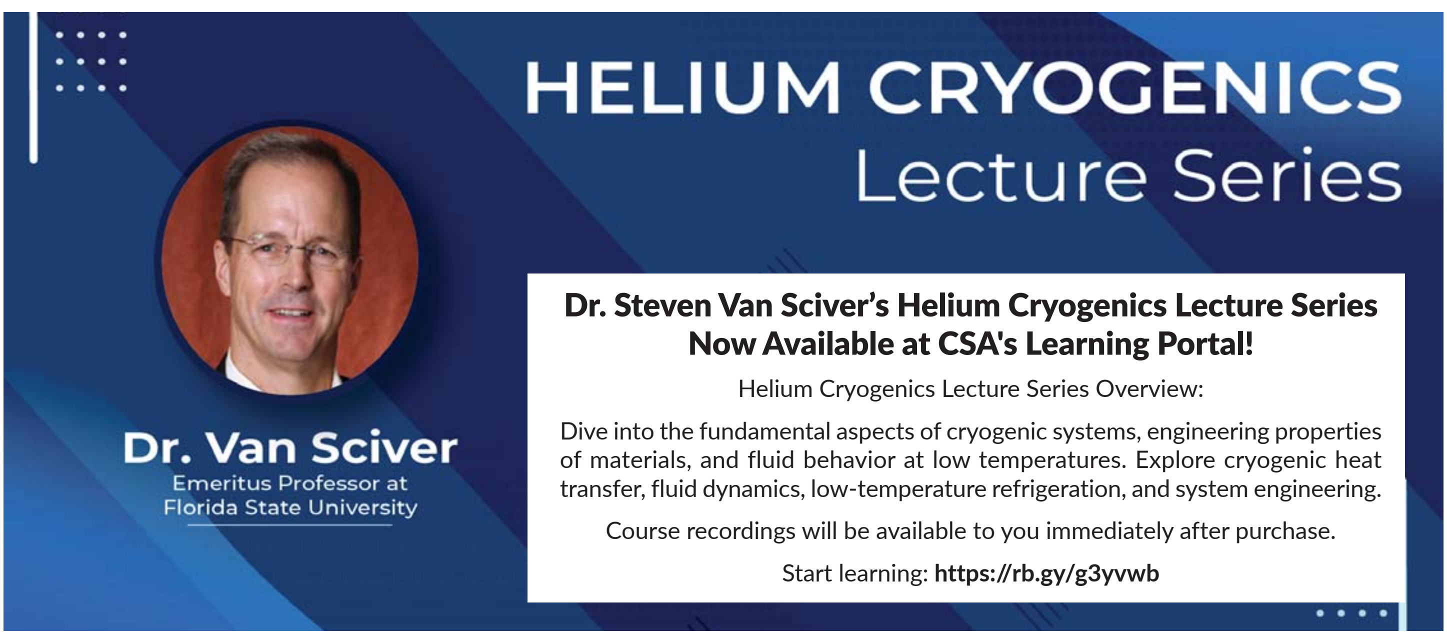
Do you or did you have a mentor? After working in the industry for a number of years, I had an idea to contribute to the world of cryogenic valves. Then I reached out to my mentor Dr. Leachman and we noticed a shared "understanding" of cryogenic valves. As Dr. Leachman developed the equation of state for hydrogen, as well as a countable number of cryogenic technologies, I knew the WSU HYPER Center was the only place to make my technology come to life.

What are some of your contributions to the cryogenic field? While my research is in the prototype phase, leading experts at the Cryogenic Engineering Conference believe the technology I am developing is advanced.

What do you believe the most important developments in cryogenics are? Foreign object debris (FOD) like dirt, frozen impurities, etc., is the leading cause of valve failure in cryogenics. Standard practice in 2024 is to simply say that FOD is the end user's fault, but good luck! While, yes, it is important to keep these systems clean, isn't there anything to be done on the side of the valve manufacturer? My research is designing a cryogenic valve that will prevent leakage from FOD as well as develop valve packing that does not require a thermal standoff to operate.

What advances do you hope to see in the future? When a valve fails, operation must be suspended until the valve is fixed. This price of entry is too high for many and delays the rapid development of the field of cryogenic hydrogen. This advancement will be the hydrogen atom to drive the fusion reaction.

Where can readers find out more about your projects? www.hydrogen.wsu.edu



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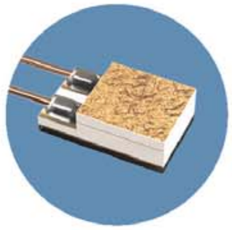

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How CRYOCO Is Empowering the Next Generation

CRYOCO is at the forefront of cryogenic education, training and consulting, boasting a 45-year legacy of providing unparalleled expertise. With a focus on fostering technical prowess across various sectors, from aerospace to medical industries, the company has been instrumental in shaping the landscape of cryogenic applications. Led by David-John Roth, a seasoned cryogenic engineer and subject-matter expert at Kennedy Space Center, CRYOCO offers an array of in-person classroom-style courses tailored to meet the diverse needs of industries worldwide. As ***Cold Facts*** celebrates up-and-coming scientists and engineers in our "Young Professionals in Cryogenics and Superconductivity" feature, we sit down with David-John Roth to explore the professional development opportunities CRYOCO offers and discuss the opportunities young professionals bring to the industry.

CRYOCO and David-John Roth have a rich history of involvement in space applications, including support for NASA's Space Shuttle and Space Launch System. *Credit: CRYOCO LLC*

Could you walk us through the history of CRYOCO from its inception to its current position? What inspired its founder, Dr. Thomas M. Flynn, to establish the company, and how has it evolved?

Dr. Flynn, as with most engineers, wanted to operate a consultancy along with his normal duties at NIST because cryogenics is a specialty engineering discipline. He founded CRYOCO, Inc., in 1955 as a consulting firm. In 1985, when I was in college, he brought me on as an intern and, working together, we wrote a class for AIChe and taught it for two years when we realized there was a greater need for cryogenics training in general that no one in the world was offering. Even today, only a couple of people offer any real, in-depth cryogenics training. We worked together for 28 years, training all over the US and internationally. Dr. Flynn became unable to teach as of 2008, so I took over the duties until I left the company to work at Kennedy Space Center in 2009. Later when Dr. Flynn became unable to work, I was given full ownership and reincorporated it in 2009 as CRYOCO LLC. Today, I offer classes as the sole offeror of standard and/or custom-written cryogenic training courses.

With a focus on in-person classroom-style training (though online options are on the horizon), what advantages does CRYOCO see in this approach?

In-person classes give an instructor direct, one-on-one contact with a participant and the opportunity to know a person in depth. You cannot properly gauge the audience with remote learning. Also, fielding questions in remote venues is troublesome, and most people are more apt to not ask questions during class times. Often in these in-person classes, I stay afterward, and we do our best work at those times, including walkdowns to the customer facility.

In-person course participants often get the opportunity to do walkdowns to customer facilities. *Credit: CRYOCO LLC*

CRYOCO has a rich history of involvement in space applications. How has this experience shaped the training courses you offer?

50 percent of CRYOCO's customers are the cutting-edge launch and space application companies of NASA. We have served the space community, in particular NASA, since the very first day of the course offerings. I have taught at eight of the twelve NASA centers in my career. My day job is working on Artemis at Kennedy Space Center, so my experience on large launch systems translates very well to those in the launch business today. I previously worked with orbital and flight hardware, so the ability to write and deliver custom classes for those customers has been very well received to date and expanded my capability in the course offerings with each new course written.

Could you elaborate on the customization options available for on-site courses and how CRYOCO tailors its training to meet the specific needs of different industries?

I have taught 205 total courses to date. Approximately half of those were custom orbital, hydrogen, aerospace, research grade and facility, as well as general cryogenics courses. With each custom rewrite, I increase my capability to offer expanded and new courses. I have an unlimited and unrivaled library of course materials, photographs and films that I have collected over 45 years that can back up any new course.

Safety is paramount in cryogenic applications. How do you ensure that your training programs effectively address safety concerns and compliance with relevant standards?

All CRYOCO courses include cryogenics safety sections. In fact, safety runs through the classes in almost every aspect: fluids, materials, construction and components. I also include extensive references and explain how the national standards and codes apply to construction and use of components and systems.

CRYOCO offers courses covering a wide range of cryogenic substances. How do these courses differ in terms of content and target audience?

The customer usually advises me of the audience. It can be a mix of degreed engineers, technical operations or design staff. Typically, a customer will have resources concentrated in one area like a single type of system. For example, liquid nitrogen only is typical. Aerospace or national labs may use a wider variety of cryogenic fluids, so those classes are more intensive and may address mechanical refrigeration as well, plus deep cryogenics at the lowest temperatures. Commercial aerospace companies will be interested in almost all cryogenic fluids, systems and, most especially, propulsion and test type systems.

What are some of the emerging trends or developments in cryogenics that young professionals should be aware of?

Because I teach for almost every commercial space entity, most national labs, medical and US government entities (US Air Force, Navy, NASA, DoD, and even nuclear), I get to see the newest technological applications, the standard state-of-the-art research, even in computer applications, in the normal performance of my courses with customers. Of course, most of my knowledge in those areas is proprietary. I would say to young professionals to choose an area that allows development and piques your interest. Then stay long enough to develop a marketable skillset. Many employers are starving for cryogenic engineering staff with any experience and will hire a two-year engineer, but most are seeking a more experienced professional with five years prior experience.

David-John Roth is making a significant contribution to the cryogenic industry every year by being a consistently reliable resource for government and commercial entities to get quality cryogenic training after hiring. *Credit: CRYOCO LLC*

What advice would you give to young professionals aspiring to build a career in cryogenics?

My advice to younger engineers is to get some formal training and do fieldwork—design for thermal and mechanical stress (CAESAR II, SINDA and Fluint), the formal analysis tools for cryogenic pipe stress and other systems. With those tools, any young engineer will find ample opportunities for high-end employment almost anywhere these days. My other advice is if their company cannot afford to have an on-site course, or does not have enough employees to justify the expense, CRYOCO offers an annual summer five-day cryogenic engineering and safety course that one or any number of employees can enroll in. It is held once per year in August only. It gives a solid foundation of the entire cryogenic toolset to work in numerous fields from aerospace to national labs.

As the owner of CRYOCO, what are your primary goals and aspirations for the company's future?

I am the sole instructor still to this day. So, the viability of CRYOCO depends on emerging into online courses in the long run. I have an understudy at present, but I also have a partner forthcoming to capture the online future expansion, mostly out of necessity of my wanting to retire in the next four years.

How does CRYOCO envision drawing more interest in cryogenics from the younger generation, considering the impending need for succession within the industry and the need for more young professionals entering the field?

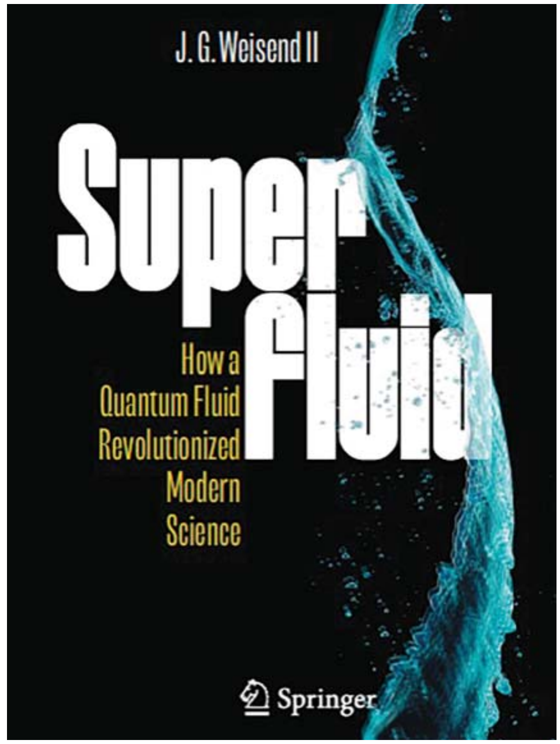
I mentor and encourage young engineers every day at Kennedy Space Center. The commercial aerospace industry is doing a good job of bringing them in by the dozens as well. Both of those are newsworthy cryogenic engineering opportunities and well-known.

So I think opportunities are there, and we all need to advertise the need and openings so that young engineers can see that a career in cryogenics is available and that there is a need for that specialty. It is true that we need to encourage STEM, and each current cryogenic engineer has many opportunities to encourage young grade school and high school students to be aware of the engineering world as an option for careers. It really does start at the youngest levels, and students who have that interest should be encouraged early. **www.cryocourses.com**

Review of John Weisend II's *Superfluid: How a Quantum Fluid Revolutionized Modern Science*

by John Pfotenhauer

Over the recent holidays, we hosted some new friends in our home. The young couple are both technically savvy but have never previously encountered the world of cryogenics, low temperatures, or superfluid helium. I had a copy of John Weisend II's new book, *Superfluid: How a Quantum Fluid Revolutionized Modern Science*, sitting around, and one of the two picked it up out of curiosity. The cover design is cool, and it grabs your attention. Our young friend was captivated by the contents and commented on how great it was that he could understand it all. I will now be ordering a copy for him. (I had yet to read my own copy and would not let him take it with him when he left.) This is a great book. It relates a technically fascinating story in a manner accessible to the general public. You should order a copy for yourself!



For those of us who have studied superfluid helium at some point in our academic pursuits, we will confirm that it can be a very complex and confusing topic. It is easy to get lost in the details. However, John gives us a happily readable journey through the many interesting features of superfluid helium. Rather than being confused when you read John's account, you will enjoy the same fascination that captivated the attention of those who first investigated such features as the fountain effect, quantized vortices and film flow seemingly defying gravity.

Of course, there have been numerous people involved in the exploration of this intriguing fluid, and the story John presents is even more captivating because of the human element that he includes. Within the story of superfluid helium, we encounter Nobel Prize winners such as Einstein and Feynman, as well as many amazing scientists like Kamerlingh Onnes, Willem Keesom, Peter Kapitza, Lev Landau, D.V. Osborne, Joe Vinen and others. Through the account of their discoveries and interactions within the background of major world events during the 20th century, John brings the story of superfluid helium to life.

John Weisend II was an eager graduate student struggling with measurements of counterflow and bulk fluid flow in superfluid helium when I first met him in the mid-1980s. Following his graduation, we continued to bump into each other at various cryogenic conferences and associated committees. Each time we met, it seemed he was living in a new location. In fact, John has been involved in multiple large-scale science projects utilizing superfluid helium around the nation and the world, and it is from his firsthand encounter with these endeavors that we learn of the many impressive scientific advances that have been enabled by the unique properties of superfluid helium. From super-large particle accelerators in underground tunnels to tanks of superfluid helium cooling telescopes in outer space, superfluid helium has played and continues to play a crucial enabling role in advancing our understanding of the universe. John relays this story also in a very enjoyably readable form, taking us from one location to another while summarizing the amazing features of such facilities as Tora Supra in Cadarache, France the Superfluid On-Orbit Transfer (SHOOT) spacecraft at NASA-Goddard, the Large Hadron Collider (LHC) at Geneva, the TESLA facility in Hamburg, the European Spallation Source (ESS) in Lund, NASA's Spitzer Infrared Space Telescope and the National High Magnetic Field Lab (NHMFL) in Tallahassee.

It may take you more than one sitting to flow through the pages of *Superfluid*, but not much more than that. The story is enjoyable and easy to read. So, grab a cup of coffee or tea, find a comfortable chair and treat yourself to a pleasant encounter with the story of superfluid helium.

Soft Cover: $37.99 USD
Ebook: $29.99 USD

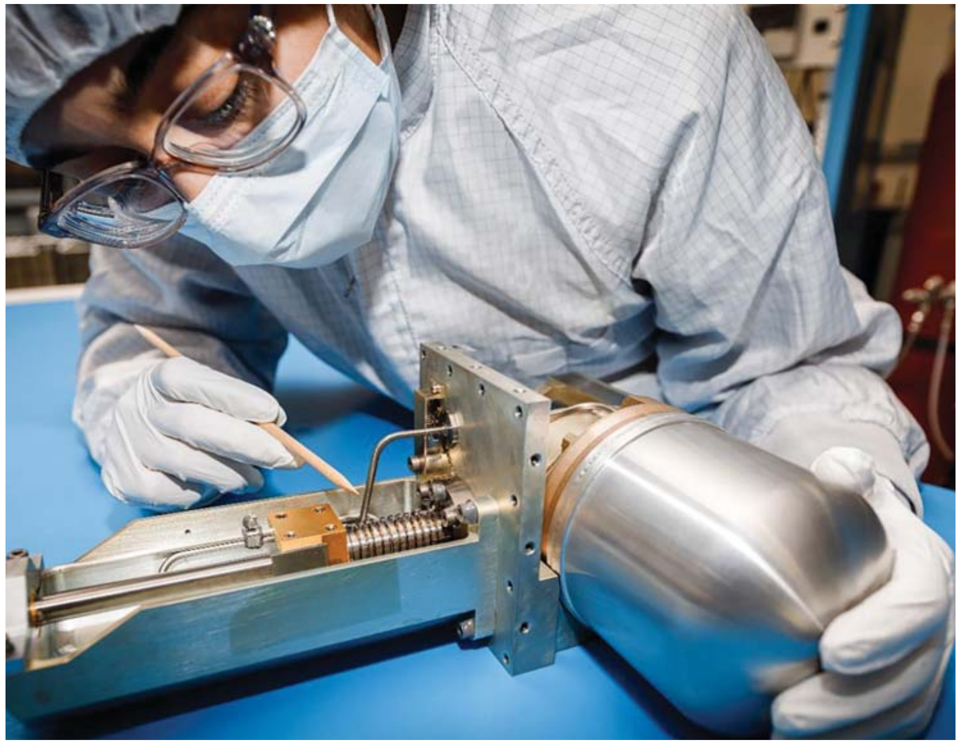
https://rb.gy/fyl0z6

CLARREO Pathfinder's Cool Breakthrough, from Space to Quantum

by Carri Karuhn, Northrop Grumman

For decades, Northrop Grumman has been making highly dependable cooling systems, cryocoolers, for spacecraft. In spacecraft, a cryocooler is most often essentially a specialized refrigerator deployed on satellites and space telescopes to maintain extremely low temperatures for onboard sensors. This is crucial for capturing high-resolution images of Earth or outer space, like the ones captured by the James Webb Space Telescope. Reliability is key because cryocoolers are part of a symbiotic relationship. If the cryocooler malfunctions, then sensors won't function. They need each other.

"Our cryocoolers are incredibly reliable – they're performing the same at the end of their 20-year mission as they did on day one. We've observed absolutely no degradation in performance over their mission life," said Owen Cupp, general manager of the cryocooler operating unit at Northrop Grumman.



Northrop Grumman is developing a more cost-effective, reliable class of cryocoolers based on proven designs used in critical national defense, climate, weather, quantum computing and astronomy missions. *Credit: Northrop Grumman*

While consistent performance over such a long period of time is noteworthy, not every mission requires a cryocooler to last for 20 years. However, no matter the length of the mission or budget, this technology needs to be reliable because in space, fixing isn't an option.

Northrop Grumman is developing a more cost-effective, reliable class of cryocoolers based on proven designs used in critical national defense, climate, weather and astronomy missions. These new cryocoolers have a simpler design, can be produced more quickly and in larger quantities and are suitable for less demanding missions.

The Climate of Opportunity

Engineers at the University of Colorado at Boulder (CU Boulder) were building a special sensor for the Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder Mission, which is slated to launch at the end of this decade. Like most space-based missions, the sensor requires a highly reliable cryocooler. However, the mission is only for two years, and the university has a tight budget.

"We knew Northrop Grumman had a strong heritage with cryocoolers, and with their new class of cryocoolers, we can have the capability and assurance we need within our price point," said Greg Ucker, project manager for the Laboratory for Atmospheric and Space Physics at CU Boulder.

Once launched, the CLARREO Pathfinder (CPF) will help scientists better understand how our planet's climate is changing by precisely measuring sunlight that bounces off the Earth. These measurements will be five to ten times more precise than what current sensors can achieve. CPF will also be able to transfer its high-accuracy data to other Earth-viewing sensors. With Northrop Grumman's cryocooler technology maintaining optimal temperatures for the CLARREO Pathfinder, advances in climate sensing can be unlocked.

Unlocking More Potential

Northrop Grumman's engineers are exploring other potential applications for this new class of cryocoolers, including its use in quantum computing.

"Customers are going to have a greater idea of how to use the technology in a broader sense, and we may be surprised at what we see," said Dale Durand, a Northrop Grumman cryocooler engineer. "This new line of cryocoolers opens possibilities for different missions, applications and customers."

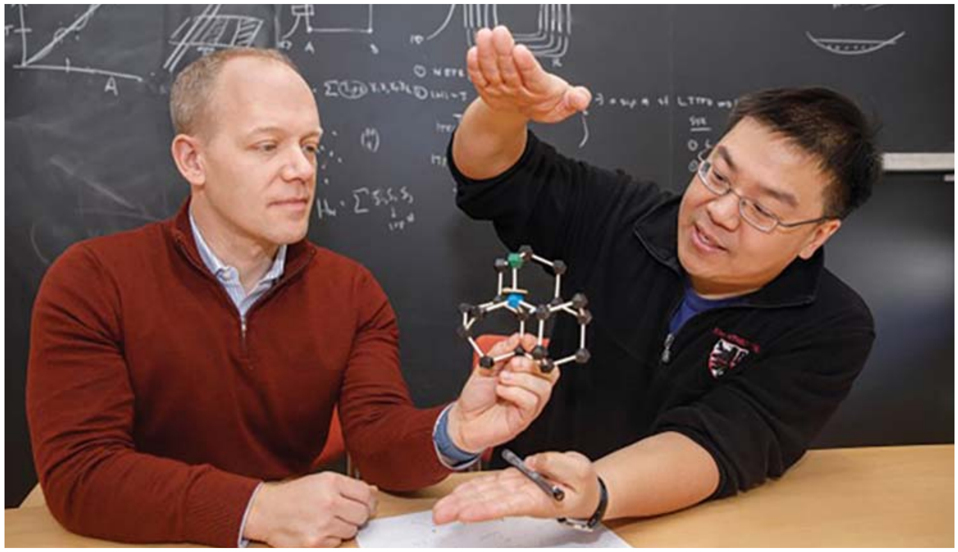
Northrop Grumman's leadership in the cryocooler industry serves as a benchmark in the field. To date, the company has delivered more than 50 space flight cryocoolers and has accumulated more than 300 years of failure-free, combined on-orbit operations.

With a new, affordable line of cryocoolers, the company will continue to push new limits, regardless of climate or budget. **www.northropgrumman.com/space/cryocoolers**

Under Pressure: Harvard Scientists Break Through Precise Measurement with New Tool

by Anne J. Manning, The Harvard Gazette

Hydrogen (like many of us) acts weird under pressure. Theory predicts that when crushed by the weight of more than a million times Earth's atmosphere, this light, abundant, normally gaseous element first becomes a metal and then, even more strangely, a superconductor – a material that conducts electricity with no resistance. Scientists have been eager to understand and eventually harness superconducting hydrogen-rich compounds, called hydrides, for practical applications ranging from levitating trains to electric grids that transmit power with perfect efficiency to new types of electronics and memory devices. But studying the behavior of these and other materials under enormous, sustained pressure is anything but practical, and accurately measuring those behaviors ranges somewhere between a nightmare and impossible.



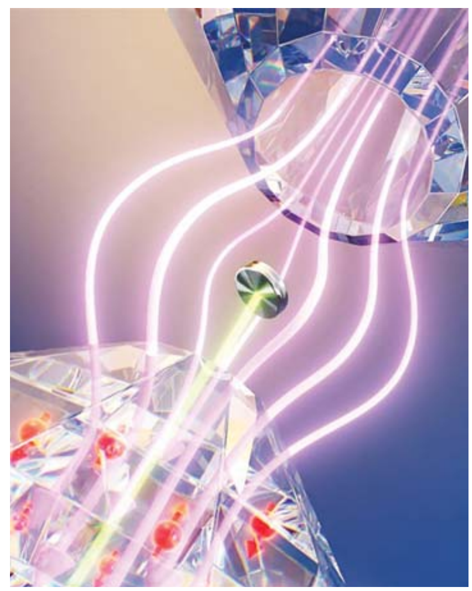
Chris Laumann (left) and Norman Yao explain high pressure hydride superconductor research. *Credit: Kris Snibbe/Harvard Staff Photographer*

Harvard researchers now believe they have a foundational tool for the thorny problem of how to measure and image the behavior of hydride superconductors at high pressure. Published in *Nature*, they report creatively integrating quantum sensors into a standard pressure-inducing device, enabling direct readouts of the pressurized material's electrical and magnetic properties. The innovation came from a longstanding collaboration between Harvard's Professor of Physics Norman Yao and Boston University professor and former Harvard postdoctoral fellow Christopher Laumann, who broke from their theorist backgrounds into the practical considerations of high pressure measurement several years ago.

The standard way to study hydrides under extreme pressures is with an instrument called a diamond anvil cell, which squeezes a small amount of material between two brilliant cut diamond interfaces. To detect when a sample has been squashed enough to go superconducting, physicists typically look for a dual signature: a drop in electrical resistance to zero, as well as the repulsion of any nearby magnetic field, a.k.a. the Meissner effect. (This is why a ceramic superconductor, when cooled with liquid nitrogen, will hover over a magnet.) The problem lies in capturing those details. In order to apply the requisite pressure, the sample must be held in place by a gasket that evenly distributes the squishing, then enclosed in a chamber. This makes it hard to "see" what's happening inside, so physicists have had to use workarounds that involve multiple samples to separately measure different effects.

"The problem is that you can't just stick a sensor or a probe inside because everything's closed off and at very high pressures. That makes accessing local pieces of information from inside the chamber extremely difficult. As a result, nobody has really observed the dual signatures of superconductivity in a single sample," Yao said.

To solve the issue, the researchers designed and tested a clever retrofit: they integrated a thin layer of sensors, made from naturally occurring defects in the diamond's atomic crystal lattice, directly onto the surface of the diamond anvil. They then used these effective quantum sensors, called nitrogen vacancy centers, to image regions inside the chamber as the sample is pressurized and crosses into superconducting territory. To prove their concept, they worked with cerium hydride, a material known to become a superconductor at about a million atmospheres of pressure, or what physicists call the megabar regime. The new tool could help the field not only by enabling the discovery of new superconducting hydrides, but also by allowing easier access to those coveted characteristics in existing materials, for continued study.



An artist's rendering of nitrogen vacancy centers in a diamond anvil cell, which can detect the expulsion of magnetic fields by a high pressure superconductor. *Credit: Ella Marushchenko*

The US Department of Energy supported this research.

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Quantum Corner

by Ioana Craiciu, NASA Jet Propulsion Lab

Tiny Circuits, Big Fridges: Advancing Quantum

In this column, I'll talk about scaling up millikelvin cryocoolers for superconducting quantum computers.

As the transistor is the fundamental unit of the classical computer, so the qubit is the fundamental unit of the quantum computer. Physical qubits, which can take the form of single atoms, quantum dots, superconducting current loops, etc., are typically very high maintenance. They are prone to decoherence and bit-flip errors through interactions with their environment. For superconducting qubits, operating at millikelvin temperatures goes a long way toward decreasing these errors, but it is not enough. Quantum error correction can be used to make quantum computers that are tolerant of these errors but at a high cost. One logical qubit must be composed of hundreds to thousands of physical qubits, and solving useful problems will require hundreds to thousands of logical qubits. The result is that useful quantum computers will need many physical qubits, likely in the millions.

The Colossus dilution refrigerator at SQMS. The team working on the refrigerator, Christopher James, Matthew Hollister, and Grzegorz Tatkowski (clockwise from the left) are shown for scale. *Credit: Ryan Postel, Fermilab*

Most quantum computing efforts now have a good handle on how to build and control a single physical qubit and are working on the next challenge: to assemble many qubits in one place and control them all. Focusing on the world of superconducting qubits, IBM currently holds the record, with slightly more than 1,000 physical qubits on a chip. Each of these qubits must be individually initialized, controlled and read out. According to IBM's website, readout and control of this number of qubits requires over a mile of cryogenic wiring inside a dilution fridge. The chip itself is small. It is the wiring that determines the requirements of the cryogenics that house it – both in terms of size and cooling power, since cables conduct heat from the environment.

Superconducting quantum computers will soon exceed the capabilities of the dilution fridges currently on the market. For this reason, quantum computing research groups as well as cryogenics companies have started to focus on increasing the size and cooling capacity of dilution refrigerators. For example, IBM designed and built their own Goldeneye cryostat, with 1.7 cubic meters of experimental volume, and Bluefors has released its new Kide system with a 1.6-square-meter flange at 25 mK. Another large dilution fridge for the books is the aptly named *Colossus*, which is currently being built by the Superconducting Quantum Materials and Systems (SQMS) National Quantum Center at the Fermi National Accelerator Laboratory.

I recently spoke to cryogenics expert Matt Hollister, who has been involved with Colossus since its conception. What follows is an edited account of our conversation.

What is Colossus?

Colossus is a large millikelvin cryostat being built as part of the SQMS Center for quantum computing and dark photon physics. It has an experimental volume of 2 meters in diameter that is cooled to below 20 mK using dilution refrigerators. What is unique about Colossus, besides its size and cooling power, is that the cooling above 1 K is provided by an on-site helium cryogenic plant.

Why use a helium plant to cool down to 4 K?

Dilution refrigerators require a baseline 4 K environment. This is usually achieved using a closed-cycle or "dry" cryocooler such as a pulse tube refrigerator. These cryocoolers are quite inefficient, usually providing a few watts of cooling power at 4 K with a power budget of over 10 kilowatts. Initial efforts to build large millikelvin cryostats with more cooling power at 4 K have so far relied on several pulse tubes in parallel.

Helium cryogenic plants can be an order of magnitude more efficient than pulse tubes at scale. In a helium cryogenic plant, the initial removal of heat from the high pressure helium and much of the heat of compression created in the refrigeration cycle are dissipated using liquid nitrogen. This is more efficient than the chiller water loops used to cool pulse tube compressors. Additionally, there is a thermodynamic advantage to having a higher flow rate of helium, as provided by the helium plant. Of course, building a helium plant is not going to be economically or even energetically favorable for a small lab-scale millikelvin refrigerator; the breakeven point seems to be around a few tens of pulse tube cryocoolers.

Can we make cooling down to tens of millikelvin more efficient too?

Unfortunately, it's difficult to scale up dilution refrigerators. Another way to say this is that dilution refrigerators are about as efficient as they can be at their current size. The best we may be able to do is a parallel approach where multiple dilution units are used to achieve the required cooling power. In Colossus, up to 12 dilution units may be used.

Fortunately, in quantum computing applications, much of the cooling power required is at the 4 K stage, with lower heat dissipation expected at millikelvin stages. Superconducting wire, which has very low thermal conduction, can be used to send signals between 4 K and the millikelvin stages, so that the heat load on the millikelvin stages can be quite small. For signals traveling between 4 K and higher stages, superconducting cable is not currently an option due to the critical temperature of available superconducting cables. Additionally, there is a trend toward placing more control electronics in the cryogenic environment. While this reduces the requirements of the cabling and room-temperature electronics, it does increase heat dissipation at the cold stages.

What do you hope to demonstrate with the Colossus system?

In addition to demonstrating the largest millikelvin cryocooler to date, Colossus will enable quantum computing and dark photon physics at SQMS. We also hope that this effort will spur additional commercial development in this space.

The views expressed are the author's and interviewee's own and do not necessarily reflect those of NASA or JPL.

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

Frederick Alexander Lindemann

Frederick Lindemann is best known for his role as Winston Churchill's confidant and science advisor during World War II, but he also did important research in cryogenics and other fields and was responsible for establishing the very productive cryogenic research program in Oxford.

Born in Germany to an American mother and a German father who had previously become a naturalized British subject, Lindemann initially attended school in Scotland. He completed his secondary education in Darmstadt, Germany, and then went to the University of Berlin where he completed his Ph.D. under Walter Nernst (***Cold Facts,*** Vol. 37 #3). Nernst and his team were investigating specific heats at cryogenic temperatures, and this was Lindemann's first exposure to cryogenics. Lindemann's Ph.D. topic was on the applicability of the Dulong-Petit law to the specific heat of solids at cryogenic temperatures. He also made important contributions to the relationship between atomic oscillations and the melting point of solids. Lindemann's intellectual interests were broad, and over his life he made contributions to many areas including physics, atmospheric science, geomagnetism, astronomy and chemistry. It was this breadth of interest that, in part, made him so valuable as a science advisor to Churchill. Throughout his adult life, Lindemann was known to many as "the Prof."

In 1915, during the First World War, Lindemann took a position at the Royal Aircraft Factory in Farnborough. There, he developed a mathematical theory of aircraft spins and developed a technique by which pilots could safely recover an aircraft in a spin. He learned to fly and tested out these techniques, with some great hazards to himself, in aircraft he flew. This was an important advance in aeronautics and made flying safer.

Lindemann was appointed professor of experiment philosophy and director of the Clarendon Lab at the University of Oxford in 1919. The Clarendon Lab was Oxford University's physics research lab, but at the time was not really carrying out much work. Lindemann made it his mission to increase both the capabilities and the research program of this lab. One of the first areas he started with was research in cryogenics. He purchased a hydrogen liquefier from Francis Simon (***Cold Facts,*** Vol. 37 #2) and in December 1932, he purchased a helium liquefier as well. Kurt Mendelsshon (***Cold Facts,*** Vol. 31 #1), a colleague of Simon, came to Oxford to set up the liquefier and in January 1933 produced the first liquid helium in the United Kingdom. This just beat out the Mond Laboratory of Cambridge University, led by Peter Maritza (***Cold Facts,*** Vol. 34 #5), which was close to accomplishing the same thing. One-upping Oxford's traditional rival no doubt gave Lindemann some joy.

With the rise of Hitler, many German scientists, including Mendelssohn, were under threat. Lindemann realized that he could help these people and at the same time benefit Oxford and the Clarendon Lab by bringing them to the UK. Among the people brought over to the Clarendon Lab in the 1930s were Simon, Mendelssohn, Nicholas Kurti (***Cold Facts,*** Vol. 38 #1), Heinz London (***Cold Facts*** Vol. 38 #4) and Fritz London (***Cold Facts,*** Vol. 38 #3). These people provided the nucleus of an extremely productive cryogenics group at Oxford. The Oxford cryogenics group made important discoveries in cryogenics, superconductivity and superfluidity. The Clarendon Lab became a world leader in cryogenics and superconducting research.

Professor Lindemann had been a friend of Winston Churchill for a number of years because they moved in the same social circles. When World War II started, Lindemann joined Churchill's cabinet as paymaster general. More importantly, Lindemann acted as a scientific advisor to Churchill. In this role, he wrote near-daily reports to Churchill summarizing complicated topics, both scientific and nonscientific. Topics included the bombing campaign in Germany, submarine detection, the availability of doctors, economics and farm policies. Lindemann's ability to clearly describe and give advice on complex subjects was invaluable to Churchill, who was being inundated by long reports from all parts of the government. During the war, Clarendon Lab completely switched to defense work, with Simon and Kurti making important contributions to the problem of uranium enrichment and Mendelssohn working in medical physics where he helped develop an ether vaporizer that could be used by medics in field hospitals. Other Clarendon staff worked on Radio Detection and Ranging (RADAR) and other defense topics.

Lindemann returned to Oxford and the Clarendon Lab after the war. Among other activities, he unsuccessfully pushed for the creation of a technical university in the UK similar to MIT. When Churchill became prime minister again from 1951 to 1955, Lindemann rejoined the government as paymaster general and personal advisor to Churchill. Lindemann was accorded many honors including being raised to the nobility as Baron Cherwell in 1941 and promoted to Viscount Cherwell in 1956. He was a fellow of the Royal Society and was awarded the society's Hughes Medal in 1956.

Additional details on Lindemann can be found in his Royal Society biography by G. P. Thomson (1958). Lindemann and Churchill's activities during the London Blitz are described in *The Splendid and the Vile* by Eric Larsen (2020). Details on cryogenic research in the Clarendon Lab can be found in *History and Origins of Cryogenics*, R. Scurlock, ed. (Oxford, 1992) and in *Going for Cold: A Biography of a Great Physicist*, Kurt Mendelssohn, J. G. Weisend II and T. Meaden, Springer (2021).

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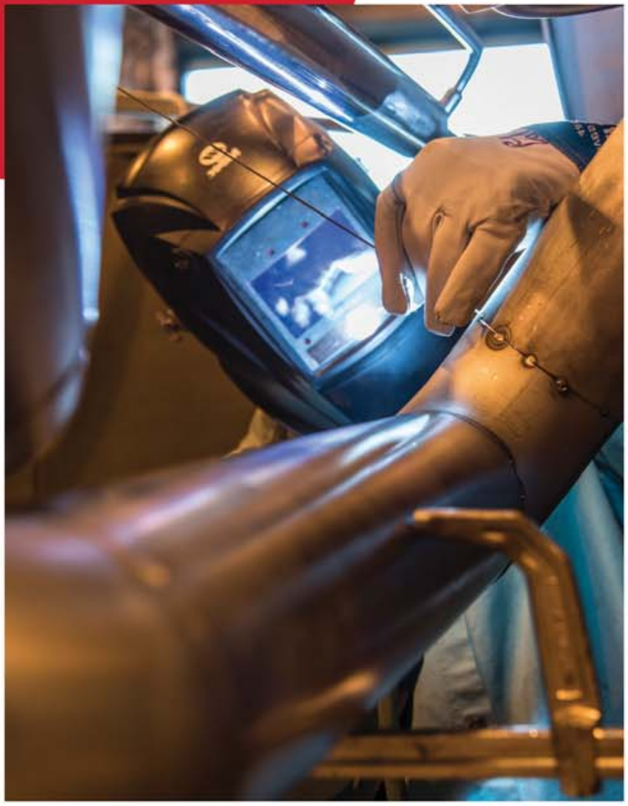

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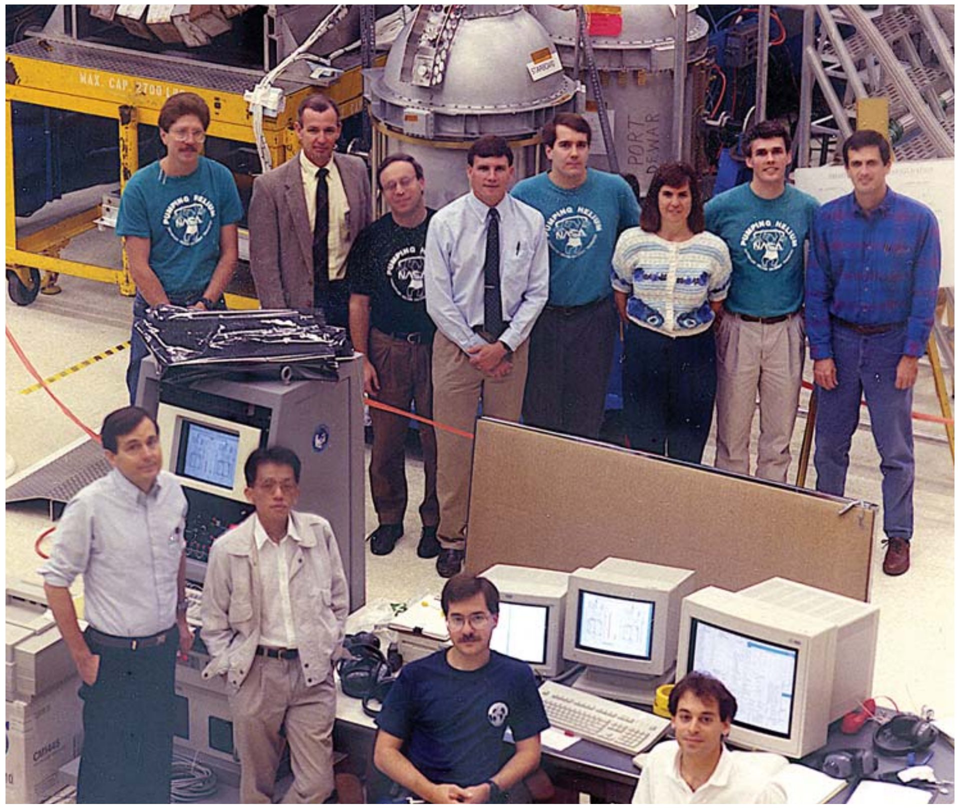
Space Cryogenics

by Mark O. Kimball, Ph.D., Cryogenics and Fluids Branch, NASA Goddard Space Flight Center

Goddard Goings: When NASA Went SHOOTING Into Orbit

The '80s have been thrust back into our collective conscious! Hits such as Tracy Chapman's "Fast Car" and "Running up that Hill" by Kate Bush have been introduced to a new generation by an incredibly popular cover of the first song and the repetitious use of the second in a recent hit TV series. So, I thought it was appropriate to bring back something spaceflight-related from that decade. The Superfluid Helium on Orbit Transfer flight demonstration, SHOOT, was conceived in 1982 and executed by NASA Goddard Space Flight Center over the remainder of the 1980s.

This was the era of the Great Observatories program at NASA. Of the four telescopes that defined the program: the Hubble Space Telescope, the Compton Gamma Ray Observatory, the Advanced X-ray Astrophysics Facility (AXAF, renamed to Chandra shortly before launch), and the Space Infrared Telescope Facility (SIRTF, renamed to Spitzer post-launch); two of them, AXAF and SIRTF, were anticipated to require superfluid liquid helium to operate their detector technology. As you likely know, informed reader, liquid helium enters a quantum-mechanical state at temperatures below 2.17 K. In this state, helium is called a superfluid due to some amazing properties. Well, a few clever low temperature physicists who wear engineering hats at Goddard asked the following question: “Can we extend these missions if a technology is developed to resupply liquid helium to observatories while on orbit?” Then they asked, “Why stop there? Could a technology be developed to supply liquid helium in its superfluid state directly to these observatories?” This eliminates the loss of liquid since there is no need to first transfer 4.2 K helium and then reduce the temperature by pumping away vapor. Hence, SHOOT was born.



In this image are people well-known to the cryogenics community: Mike DiPirro, Peter Shirron, and Jim Tuttle. If you know them, you should be able to pick them out. (Hint: look at the second row.) Also included are the astronaut mission specialists Janice E. Voss and Peter J. Wisoff, who were tasked with taking care of SHOOT while on orbit. They are third and first from the right in the second row. The two dewars are seen in the background. *Credit: NASA Goddard Space Flight Center*

Both a demonstration and experiment, SHOOT was a pair of 210-liter liquid helium dewars with cryostat inserts. These two dewars were linked via a vacuum-insulated helium transfer line and could pump helium in either direction using the thermomechanical effect (aka the fountain effect) in superfluid helium. Since the transfer was designed to happen in a low-G environment, other issues needed to be solved—the lack of a well-defined fluid location on orbit being one of them. So, each cryostat contained a liquid acquisition device (LAD) that collects the liquid helium and directs it toward the thermomechanical pumps. (Actually, there was a different LAD in each dewar to experimentally verify which version was more effective.) Of course, there was the typical assortment of valves, pressure gauges and relief devices typically found in helium cryostats. Also, each dewar had a special device known as a porous plug phase separator. Its job was to prevent liquid in the superfluid state from rapidly creeping along the vent line and draining helium from a dewar quickly. This rascal plays a major role later in this column.

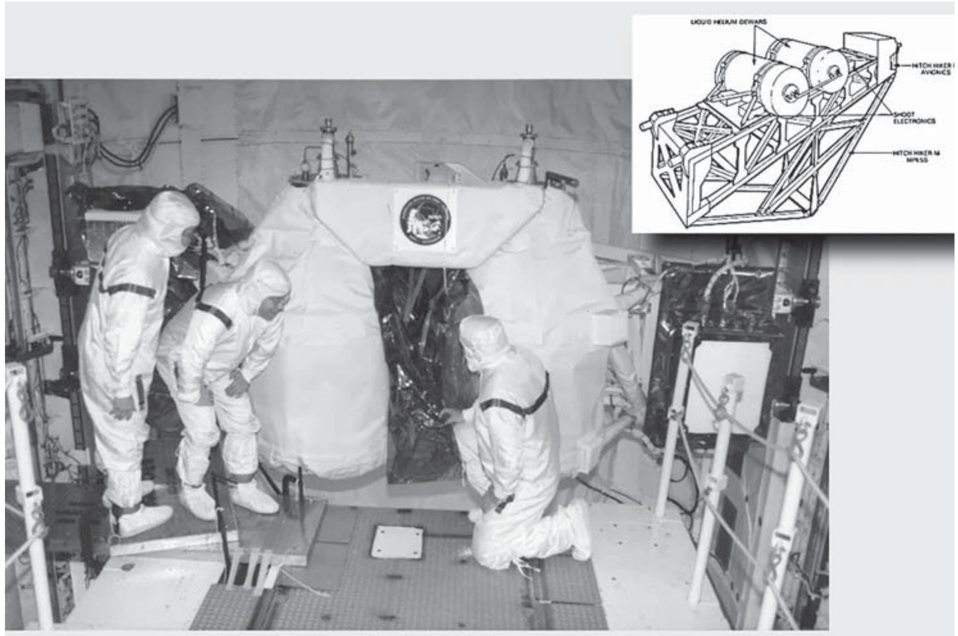
The dewars and cryostats were designed, built and tested on the ground. This work was performed at Goddard in the same building that houses the cryogenics and fluids branch. (The first image shows the SHOOT team during a test campaign with the two dewars seen in the background.)

Ground testing went well, so the focus shifted to the ultimate goal of demonstrating this in low Earth orbit. The International Space Station was not developed yet, so the bay of the space shuttle was the target. The inset in the image at right shows the initial concept of how the demonstration would be mounted in the Shuttle bay, and the larger image is SHOOT in the bay of Shuttle Endeavor. This photo was taken in May 1993. On June 21 at 09:07:22, STS-57 left the ground with SHOOT along for the ride.

On orbit, SHOOT successfully completed eight transfers of superfluid helium from one dewar to the other, meeting all objectives and delivering a considerable amount of useful data. Some of the larger accomplishments include the demonstration that one can transfer helium between dewars on orbit without disrupting the superfluid state; the testing of not one, but two different types of cryogenic liquid acquisition devices in a low-G environment; and the precise mass gauging of liquid helium in low-G. All this may be found in the literature. However, there were a few things that you won't get from anything published. I'll let Jim Tuttle, now retired from NASA, explain one of them:

"As part of the final launch preparations, we needed to lock-wire several bolt heads. When cutting off the excess wires, one piece unfortunately flew away and landed on top of our hardware. For a long time, nobody found it, but the Kennedy Space Center (KSC) people insisted that we keep looking. They claimed that even the smallest bit of FOD could cause damage during the launch. They never allowed any known debris to remain. Finally, Tom Hait's sharp eyes spied the wire, and he carefully removed it with tweezers. (Tom was an uber technician within the cryo branch for decades.) During all of this 'overtime' period, we feared that angry KSC facility folks would come in and 'help' us with our problems. Instead, I looked around and saw the pad technicians discreetly and quietly enter the facility and begin their preparations as far from us as possible. Nobody interacted with us at all; they left us undisturbed to work through our difficulties! It was impressive, and undoubtedly resulted from many previous experiences like ours."

It's my understanding that the SHOOT team was watching a replay of the astronauts entering the shuttle bay after the bay doors had opened. What was captured on that video was a storm of debris exiting the bay when the hatch opened. The SHOOT team gave each other sideways glances since they were told that no debris can remain in the bay. The mission control personnel caught onto this and laughed out loud proclaiming something like, "Oh that? Well, it happens every time!" SHOOT initiated a more serious on-orbit event, where the porous plug mentioned earlier takes center stage. I'll let Mike DiPirro, the principal investigator of SHOOT, tell the story:



SHOOT in the bay of the shuttle Endeavor in May 1993. Inset shows the initial concept of how the demonstration would be mounted. *Credit: NASA Goddard Space Flight Center*

"In the first 24 hours of the mission, with the astronauts sleeping, the final part of the pump-down of the SHOOT dewars was occurring. The dewars had pumped from about 3.7 K down to about 2.2 K. It was time to open the high-flow separator valves and provide more direct pumping to space. Unfortunately, shortly after opening the valves, we received an alert that the shuttle was swinging more than six degrees off vertical, and the astronauts were awakened. The shuttle is placed in the gravity gradient attitude with the nose pointed toward Earth to minimize the disturbing noises caused by attitude control thrusters. It turns out that unexpectedly high vent rates of helium caused the shuttle's attitude to be perturbed, even though we had diffusers at the helium vents to minimize this effect. The onboard thruster easily overcame this extra venting momentum. At the time, we thought that our high-flow phase separators had failed mechanically.

We later discovered that late changes in the wall thickness of the phase separator inlet had increased the thermal impedance, which limited the effectiveness of the fountain effect. In turn, this allowed liquid helium to escape the helium tanks and flow into space. We lost 100 to 150 liters of helium over 10 to 30 minutes due to this. As this helium escaped the diffusers, some portion struck the inside of the shuttle bay (with no large heat capacity, so no effect on the shuttle equipment) and reflected off the concave shape, imparting momentum to the spacecraft. SHOOT was able to continue with its demonstrations with a reduced complement of about 150 liters of superfluid."

I don't think many people can say they jolted astronauts awake by swinging the entire shuttle! However, as I've heard said, "The worse the time, the better the story!" I think this qualifies as one of those examples. Anyhow, the data from SHOOT was analyzed, presentations created and papers written. The earliest results were presented at both the Cryogenic Engineering Conference and the Space Cryogenics Workshop in 1993. It's possible you were in the audience for one of those presentations. It's also possible you've never heard of SHOOT before this. In either case, I hope you enjoyed this brief insight into the NASA flight demonstration known as SHOOT.

Cheers,
Mark.

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

SQUID: From Nobel Prize to Most Sensitive Quantum Instruments

The Nobel Prize in Physics in 1973 was awarded to Josephson, Esaki and Giaever for their theoretical predictions (made in 1962) and experimental discoveries of the supercurrent through a thin tunnel barrier between two superconductors, known as the Josephson effects. **Superconducting Quantum Interference Devices (SQUID)** based on Josephson tunneling effects are the most sensitive measuring devices for detecting magnetic flux. They allow for the generation, mixing, detection and amplification in signal processing. SQUIDs surpass other instruments in detecting low-frequency electric or magnetic signals, converting them into magnetic flux signals with superior sensitivity, as illustrated in Figure 1. SQUIDs have been successfully utilized in geophysics, non-destructive testing, quantum computers, astrophysics, magneto-encephalography, enhancement of MRI and material science.[1-3]

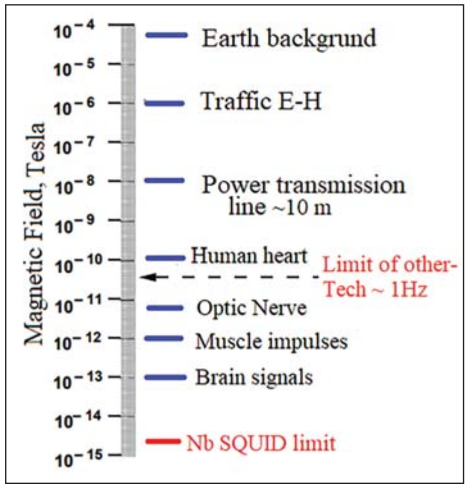


Figure 1: Magnetic signal levels vs both other-Tech & SQUID. *Edited by: Shu and Demko*

Amazing Josephson Effects

Figure 2 depicts a Josephson junction, comprising two superconductors separated by a thin insulation barrier (about tens of Å). When the junction is biased with a DC current, the voltage across it stays at zero until reaching a critical current (I_0) because of Cooper pair tunneling through the insulation barrier (DC Josephson effect). More uniquely, applying a constant voltage across the barrier results in a microwave-frequency tunnel current. The junction transitions to a resistive state when the bias current exceeds I_0. The fundamental equations of the Josephson effect are:

$$I = I_0 \sin\phi \text{ and}$$

$$\frac{\partial\phi}{\partial t} = \frac{2e}{h} V$$

where I_0 - critical current, ϕ - phase difference between of the Cooper pairs to the two superconductors, and V is the voltage across the junction. If the voltage is constant, the phase difference is a linear function of the time,

$$\phi = (2e/h)V \cdot t + \phi_0$$

gives an oscillating current,

$$I = I_0 \sin(2\pi f t + \phi_0)$$

so-called AC Josephson effects. Broadly speaking, Josephson effects occur when two superconductors (either bulk or film) are connected through a "weak link," such as a bridge that allows the passage of electrons (supercurrent). Practically, there are four types of tunneling junctions: 1., Tunnel oxide (SIS) junction with an insulation layer of 10 – 20 Å; 2., Proximity (SNS) Junction; 3., Constriction (microbridge) junction; and 4., Point contact Junction.

SQUID Sensor

Superconducting Quantum Interference Devices have various designs, with each system tailored for specific applications. The SQUID sensor is a central component in all systems. Typically, the SQUID sensor comprises two parallel Josephson junctions forming a superconducting ring, as illustrated in Figure 3A, with flux quantization. The remarkable sensitivity of SQUID devices is attributed to their ability to measure changes in the magnetic field corresponding to a single flux quantum.

$$\Phi_0 = h/2e = 2,068 \cdot 10^{-15} \ (T \cdot m^2)$$

If a constant biasing current is maintained in a SQUID, the measured voltage oscillates with changes in the magnetic flux. Counting the oscillations allows for the evaluation of the flux change. Generally, voltage varies as the magnetic flux steadily

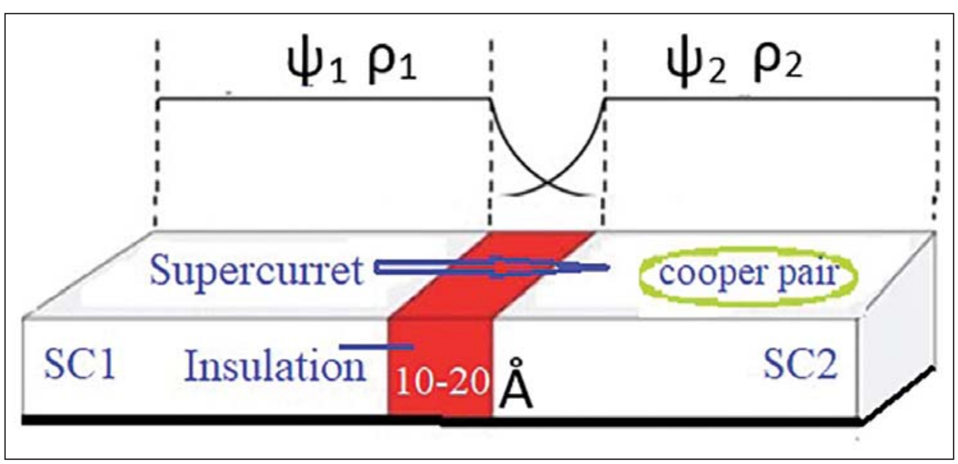


Figure 2: A Josephson junction: Cooper pairs are tunneling through insulation barrier. *Credit: Shu and Demko*

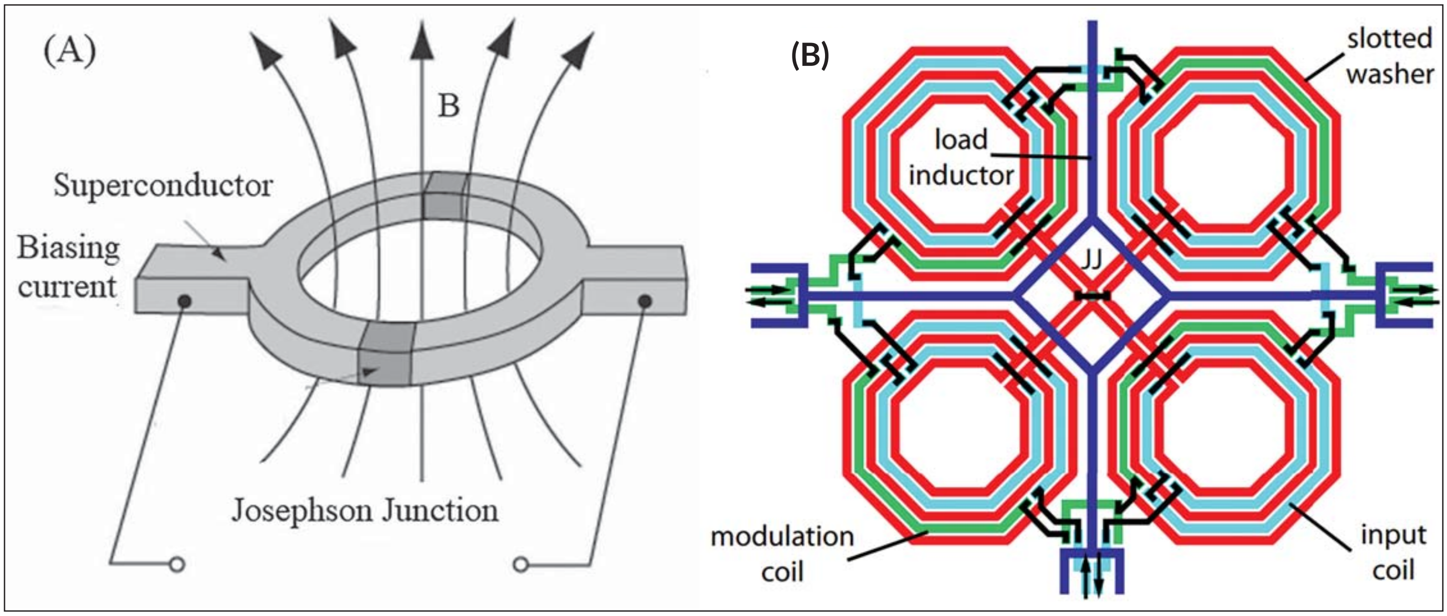


Figure 3A: Sensor of a SQUID. B: a RF-SQUID for the RF-SQUID multiplexer.[3] *Credit: (A) Shu, (B) Demko.*

increases, and one period of voltage variation corresponds to an increase of one flux quantum. Figure 3B shows RF-SQUID for the RF-SQUID multiplexer and the Josephson Junction (JJ) is in the middle of a SQUID.[3]

Initially, the Josephson junction is made of low temperature superconductors (LTS), such as niobium (Nb) or lead (Pb) alloys. These devices work only at low T with LHe or 4.2K cryocooler. With development of high temperature superconductor (HTS), the SQUID made of HTS, like YBCO or other HTSs, which work with LN_2 or 77 K cryocoolers.[1]

Design Methodology of SQUID System

In general, a complete SQUID system comprises three main sections: the signal detection/pickup section, the SQUID sensor with an input coil and the control electronics/data acquisition system. The SQUID sensor and signal pickup system operate in a cryogenic environment, while the electronics and data system are located at room temperature. Figure 4 (lower) presents a sketch of the noise thermometer evaluation system with SQUIDs, pickup coils, dilution refrigerator, etc.[4] Depending on the nature of the tasks assigned to the SQUID, the channels for pickup and sensors can be single, multiple, or numerous. HTS SQUIDs are convenient for the use of LN_2, but their sensitivities are normally several times lower than those of LTS SQUIDs (in NDE case, normally sensitivity <10 fT/√Hz for LTS and <100 fT/√Hz for HTS).

Both LHe and LN_2 dewars are constructed from specially selected materials (such as FRPs) to minimize their magnetic interactions with the SQUID sensors and detection coils. Dewars capable of 90° and even 180° operation are available.[1] The tailed dewars can have the spacing between the outside surface of the tail and the detection system (tail gap) as small as ~3 mm in some cases. There is a wide range of detection coil configurations used for DC, AC and pulse measurements as shown in Figure 4 upper.[1]

Key to any measurement is ensuring that the detection circuitry (coils) is optimized for the measurement being performed. Axial gradiometer coils offer excellent resolution and reasonable noise rejection for nearby sources: they can be shaped as symmetric, second-order gradiometers and asymmetric gradiometers as shown in Figure 4 (upper).[1] Planar gradiometer coils can be constructed as radial gradiometers and 'double-D' planar gradiometers, which offer excellent spatial resolution. Synthetic gradiometers can be extended to more sophisticated schemes for improvement in LTS and HTS systems. As a design tradeoff, if spatial resolution is most important, the area of the SQUID loop can be optimized for the desired spatial resolution. Figure 5 shows a Magneto-Encephalography (MEG) system which serves as an exceptional example to illustrate the complete cryogenic temperature zone of a SQUID system.[5] This system comprises a cryogenic system (dewar/cryocoolers), 64 channels of SQUID sensors & pickup coil arrays and its entirety.

SQUID Applications

SQUIDs exhibit remarkable sensitivity to magnetic fields, detecting signals at the femto-tesla level (1 fT = $1x10^{-15}$ T). This sensitivity makes them ideal for the detection and measurement of weak magnetic fields across various applications.[3-9] These are crucial for applications such as detecting weak magnetic signals in the brain (magnetoencephalography), studying magnetic properties of materials at the quantum level, or with quantum-enhanced imaging and sensing in precision metrology.

Quantum computer

The Josephson junctions are a key component in the construction of superconducting qubits, which are the building blocks of SC quantum computers with the potential for solving complex problems more efficiently than classical computers. The different quantum states of the supercurrent in the loop represent the logical states of the qubit (|0⟩ and |1⟩). Operations on qubits, known as quantum gates, are implemented using microwave pulses applied to the SC qubits. Josephson junctions are also

▶ ***continues on page 30***

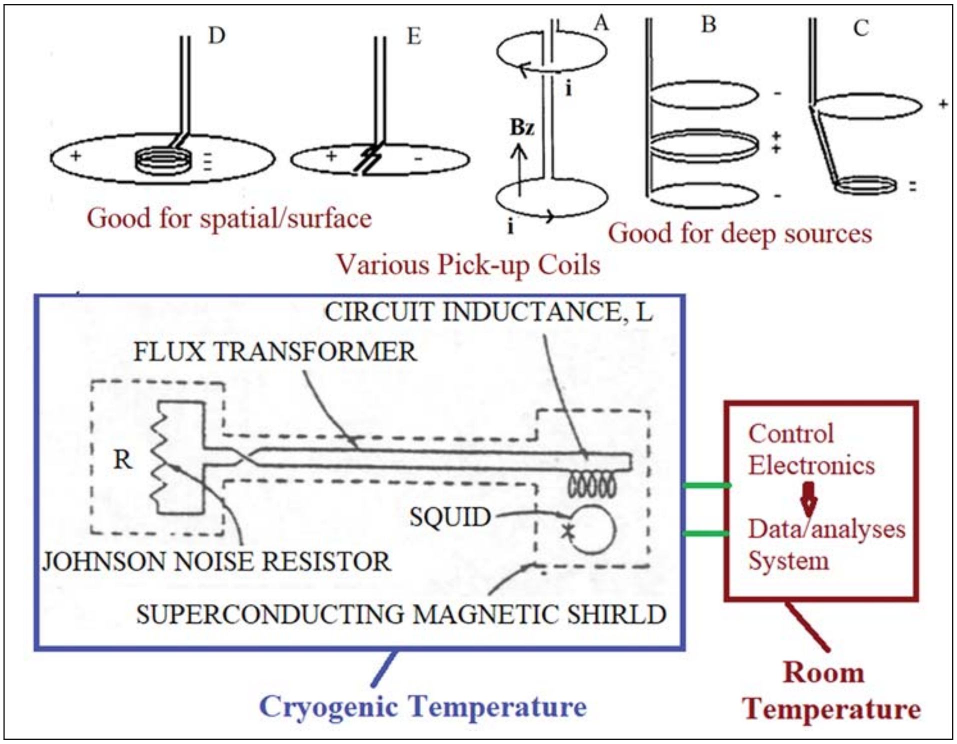


Figure 4: Block diagram of a SQUID system studying noise thermometer.[4] Credit Q-S. Shu, J. Harrison et al. and various configurations of pickup coils[1] and Fagaly

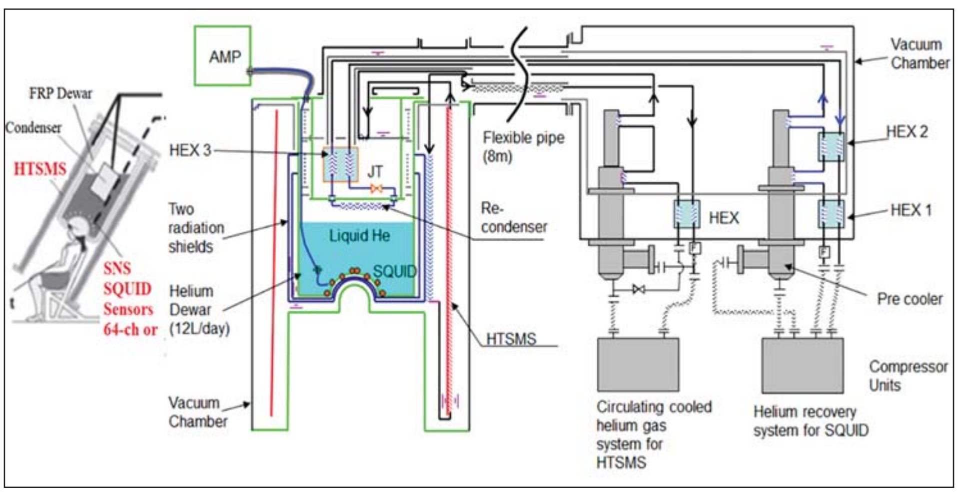


Figure 5: Diagram of the zero boiloff cooling system for HTSMS, SQUID, dewar shield and re-condenser; and the SQUID array is composed of 64 radial gradiometers, upgradable to 128.[5] Credit: K. Narasaki et al

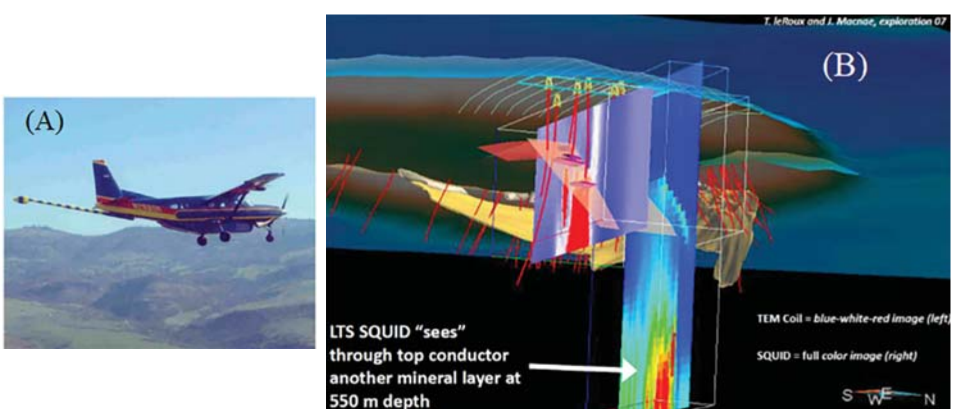


Figure 6A: HTS SQUID in flying.[1] *6B: LTS SQUID found out new mining at a depth of 550m.*[2] Credit: R. Fagaly (A) and T. leRoux (B) and M. Kiviranta

employed in the readout and measurement process of SC qubits. The Josephson effects are just one of the many approaches to building quantum computers, but they show promise in scalability and controllability.

Non-destructive testing (NDT) and magnetic microscope SQUIDs are employed for detecting and evaluating defects or anomalies in materials for quality control and structural integrity assessments. Eddy current techniques in DC SQUID systems are utilized to image defects deep beneath the surface using relatively low frequencies. The application of an improved DC SQUID system for detecting Ti inclusions in Nb sheets has been successfully tested.[6] Additionally, magnetic microscopes are now available in the market for special applications.

Geophysics, astrophysics and cosmology SQUIDs are utilized in investigating Cosmic Microwave Background (CMB) radiation and various astrophysical phenomena, including dark matter research and gravitational wave detection.[3,7-9] Microwave SQUID multiplexing has been planned for reading out these detector arrays. Figure 6A displays HTS planar gradiometers used in geological exploration flights,[1] while the right side illustrates an LTS SQUID system identifying a useful mineral layer at a depth of 550m beneath topsoil/rock layers (Figure 6B).[2] European scientists also initiated the project E-SQUID (development of SQUID-based multiplexers for large infrared-to-X-ray imaging detector arrays in astronomical research from space) to develop the best readout solution for such detectors.

Medical devices and magnetoencephalography (MEG) Mobile MEG developed by Sumitomo Heavy Industries (SHI) employs an HTS magnetic shield (HTSMS) and SNS-type SQUID sensors (series arrays).[4] The HTSMS and SQUID are cooled by a zero boiloff cooling system, which consists of a circulating cooled helium gas system for cooling the HTSMS below a temperature of 90 K and a helium recovery system for cooling the SNS-type SQUID sensors to LHe temperature as shown in Figure 5.[5] Narasaki et al. introduced the achievement of the first measurement of neuron current in the brain by using SHI's MEG in 2018. The zero boiloff cooling system consists of two closed-cycle cooling subsystems. The dewars are made of a fiber-reinforced plastic (FRP).

Magnetic resonance imaging (MRI) SQUIDs can be employed in MRI systems to detect the weak magnetic signals generated by nuclear spins in the body to enhance the sensitivity of MRI.

Noise thermometer The use of Johnson noise thermometry can measure the mK temperature range, serving as an absolute thermometer without requiring calibration if all circuit parameters are independently measured or calibrated at a specific point. It operates effectively from some mK to 4.2 K, featuring a highly linear temperature range from several mK to about 1 K. One of the early works on noise thermometry involves the design and construction of a noise thermometer using two commercially available SQUID systems, as shown in Figure 4.[4] The thermometer is cooled by a dilution refrigerator, and signals are directly coupled through a SC flux transformer to an RF SQUID at 4.2 K.

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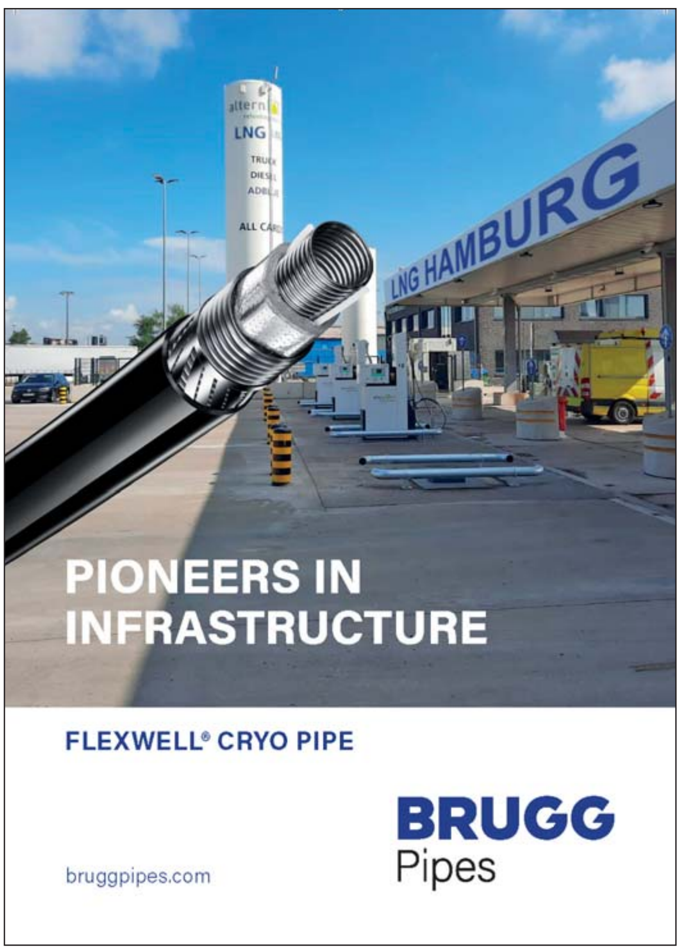

Clean Energy Future

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

The Boiloff of Liquid Hydrogen from Storage Tanks

In cryogenics and the emerging clean energy world that is reliant on liquid hydrogen, the term "boiloff" gets used a lot these days, somewhat like barbecue sauce at a summer picnic. Variations include boiloff rate (BOR), normal evaporation rate (NER), heat leakage rate, heat transmission, heat load, heat leak and heat ingress. Other than the jargon term boiloff, these terms are fairly synonymous. NER is given in percent of steady-state loss per day from a tank that is ½ to ¾ full (or as otherwise stated). But what does it really mean, and how is it quantified for useful engineering purposes in designing and operating LH_2 tanks? To start, we can look at the basic terms of heat transmission and cryogenic insulation.

LH2 shown at NBP: Understanding "boiloff" in the clean energy transition involves distinguishing between evaporation losses of liquid hydrogen from tanks and the larger transfer losses of liquid between tanks with terms like heat flow rate and heat transmission playing key role. *Credit: James Fesmire*

To compare different thermal insulation systems, a clear and consistent definition of *heat transmission* is needed. Heat transmission is a steady-state process after thermal equilibrium has been achieved between two fixed boundary temperatures (hot and cold). Heat transmission is expressed in joules per second or watts (W). The goal is to minimize the heat transmission into the liquid hydrogen inside the tank by using a high performance, evacuated thermal insulation system designed and built according to the specific operational needs.

Heat transmission measurements are directly obtained by the boiloff calorimetry method. Standard terms and definitions from ASTM C1774 are given as follows:

- Heat flow rate (Q) — rate of heat energy being transferred to a system or heat transmission (J/s or W)
- Heat flux (q) – heat flow rate, under steady-state conditions, through a unit area, in a direction perpendicular to the plane of the thermal insulation system (W/m^2)
- Effective thermal conductivity (Ke) — the thermal conductivity through the total thickness of the insulation test specimen between specified boundary temperatures and in a specified environment (mW/m-K). The insulation test specimen may be one material, homogeneous or non-homogeneous, or a combination or stack-up of materials.
- System thermal conductivity (Ks) — the thermal conductivity through the total thickness of the insulation test specimen and all ancillary elements such

as packaging, supports, getter packages, enclosures, etc. (mW/m-K).

The basic calculations for heat transmission are developed in the following sections:

The goal of any thermal insulation system is to minimize the *total* heat transmission into the tank. The total heat leak is given by the following simplified equation (Eq. 1):

$$Q_{total} = Q_{solid\ conduction} + Q_{gaseous\ conduction} + Q_{convection} + Q_{radiation} \quad \text{Eq. (1)}$$

The heat flow rate (Q), also known as "heat leak," is calculated as given in Eq. (2), and the effective thermal conductivity (ke) is further calculated in Eq. (3):

$$Q = \text{m-dot} * h_{fg} = k_e * A_e * \Delta T/\Delta x \quad [\text{J/s or W}] \quad \text{Eq. (2)}$$

$$k_e = Q /(A_e * \Delta T/\Delta x) \quad [\text{mW/m-K}] \quad \text{Eq. (3)}$$

Where:
- m-dot is the mass flow rate [g/s]
- h_{fg} is the heat of vaporization [J/g] at the Normal Boiling Point (NBP)
- A_e is the effective area for heat transmission [m^2]
- ΔT is the temperature difference [K]
- Δx is the total thickness of the insulation [m]

The heat flow rate (Q) includes all modes of heat transmission (radiation, solid conduction, gaseous conduction, and convection). While solid conduction is usually fixed, the test environment determines the relative amounts of the other components of heat transmission. The heat flux (q) per unit area is calculated as follows:

$$q = Q/A_e \quad [\text{W/m}^2] \quad \text{Eq. (4)}$$

Now, for real LH_2 storage tanks, we need to convert the boiloff rate into the heat leakage rate to make it truly useful. There are two cases: open system or closed systems. In an open system (vented to atmosphere), the heat ingress causes a loss of product. In a closed system (vent valve is closed), the heat ingress causes a continual rise in pressure. From the standard ISO 21014:2019 *Cryogenic vessels – Cryogenic insulation performance* the following definitions are given:

- Heat-leak rate (Q): quantity of *heat being transmitted per unit time* from the ambient air to the contents of the inner vessel.
- Holding time for an open system: time expected to elapse, for a specified degree of filling, from the initial filling level until the vessel is empty (no more liquid).
- Holding time for a closed system: time elapsed, for a specified degree of filling, from establishing the initial filling condition until the pressure has risen to the set pressure of the relief device.

For static tanks, the liquid and vapor system will become stratified, which affects the evaporation of the liquid. For transportable vessels, the holding time is determined without the effects of stratification. Tests under this standard are to be performed at 50% capacity, which introduces further complications called ullage vapor heating that must be taken into account in the case of LH_2 tanks.

To calculate the Q from a NER, we simply multiply the mass flow rate by the heat of vaporization, just as in Eq. 2. Consider the following example: for a 10,000 kg capacity LH_2 tank with an NER of 1.0%/day or 100 kg/day or 1.157 g/s, the heat leakage rate is:

$$Q = (1.157 \text{ g/s}) * (446 \text{ J/g}) = 516 \text{ J/s} = 516 \text{ W}$$

Note that this calculation is based on the normal boiling point (NBP) of LH_2 (that is, 20.3 K and ambient pressure). Given a NER for any cryogenic tank, ask if it is derived from a test or an analysis. While NER addresses the steady-state condition, the much more substantial "boiloff" losses from cooldown and transfer operations represent highly transient conditions which are handled differently. Key parameters include: tank ullage pressures (and the corresponding higher liquid temperatures) and tank liquid levels [for both supply tank and receiving tank]; transfer pressure range, steady-state or transient conditions, mobile or stationary equipment. The boiloff term is widely used and casually tossed around, but it introduces important questions that must be addressed in specific to the operation.

Cool Fuel

by Dr. Jacob Leachman, Associate Professor, Washington State University, jacob.leachman@wsu.edu

Harnessing Hydrogen Thermoacoustic Instabilities

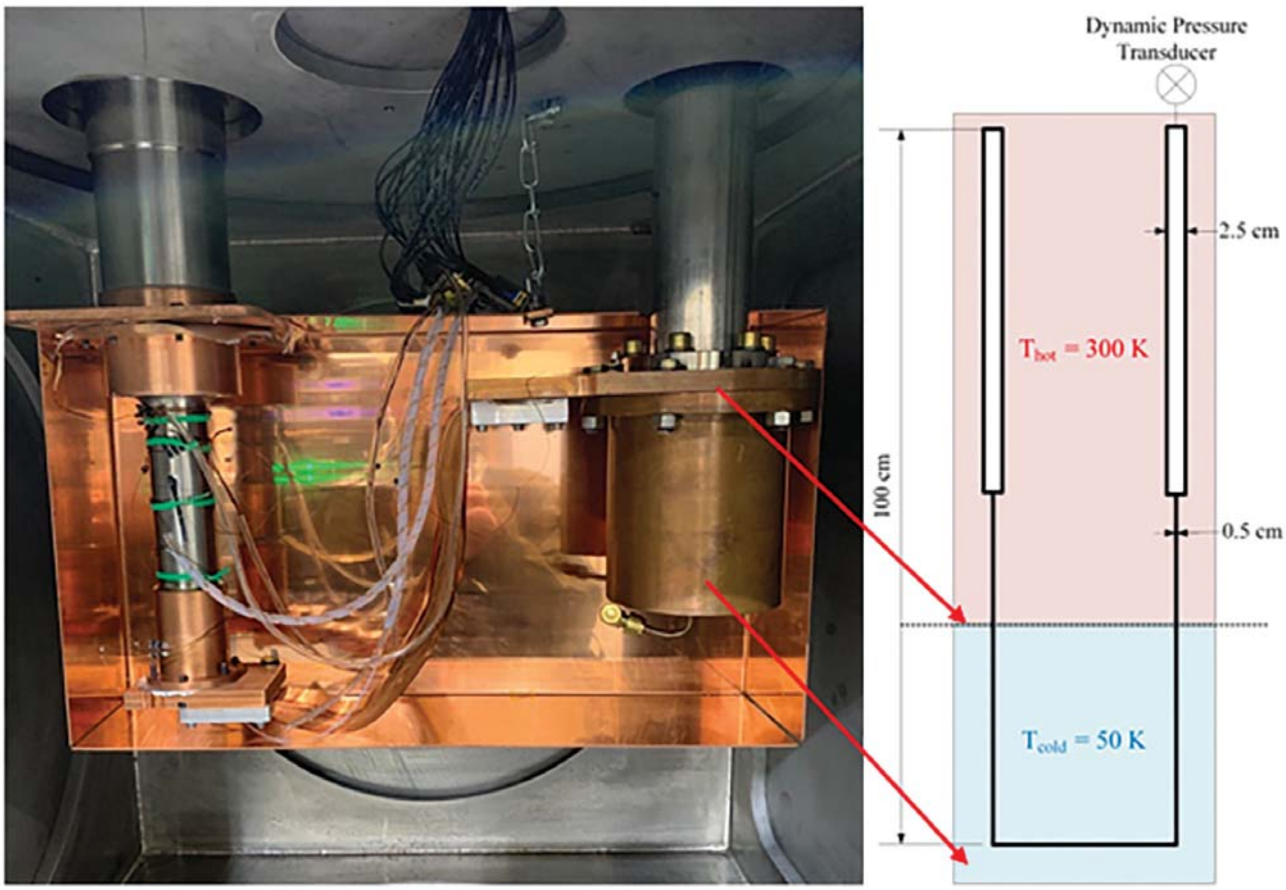

***Figure 1:** (Left) Cryostat for creating a controlled temperature environment to measure thermoacoustic instabilities in hydrogen. (Right) Conceptual schematic.* *Credit: Matt Shenton*

In the early days of setting up the HYPER laboratory, we were commissioning a new cryostat when we observed something troubling. The needle on a Bourdon tube gauge measuring the pressure inside a cryogenic vessel blurred through approximately a 20-degree arc. When I first saw this, my immediate thought was that I'd worked too long and needed to go home. But then I remembered something I was taught years earlier.

Discovered in 1949 by Jan Taconis in 1949, high-frequency pressure oscillations occur whenever a column of fluid has a sufficiently large temperature gradient for the expansion and contraction of random fluid motions to create enough bulk flow to become cyclic. Flash forward to today, and thermoacoustics is the topic of an active NSF grant with my colleague Professor Konstantin Matveev and Matt Shenton, a Ph.D. student in the HYPER Center.

Our first challenge was to carefully measure the thermoacoustic behavior of cryogenic hydrogen. During our search of the literature, we were shocked to discover that nearly all of the experiments had focused on helium; only a few measurements with hydrogen were available, and those seemed to be in passing due to the historical difficulties of working with cryogenic hydrogen. Matt set up the system shown in Figure 1 that uses a cryocooler to create the temperature gradient necessary to initiate thermoacoustic instabilities. Over several months, Matt compared helium versus normal hydrogen oscillations in a 0.5-cm tube over various pressures, including the vapor, supercritical and liquid regimes.

What Matt discovered through his measurements is that thermoacoustic

▶ *continues on page 36*

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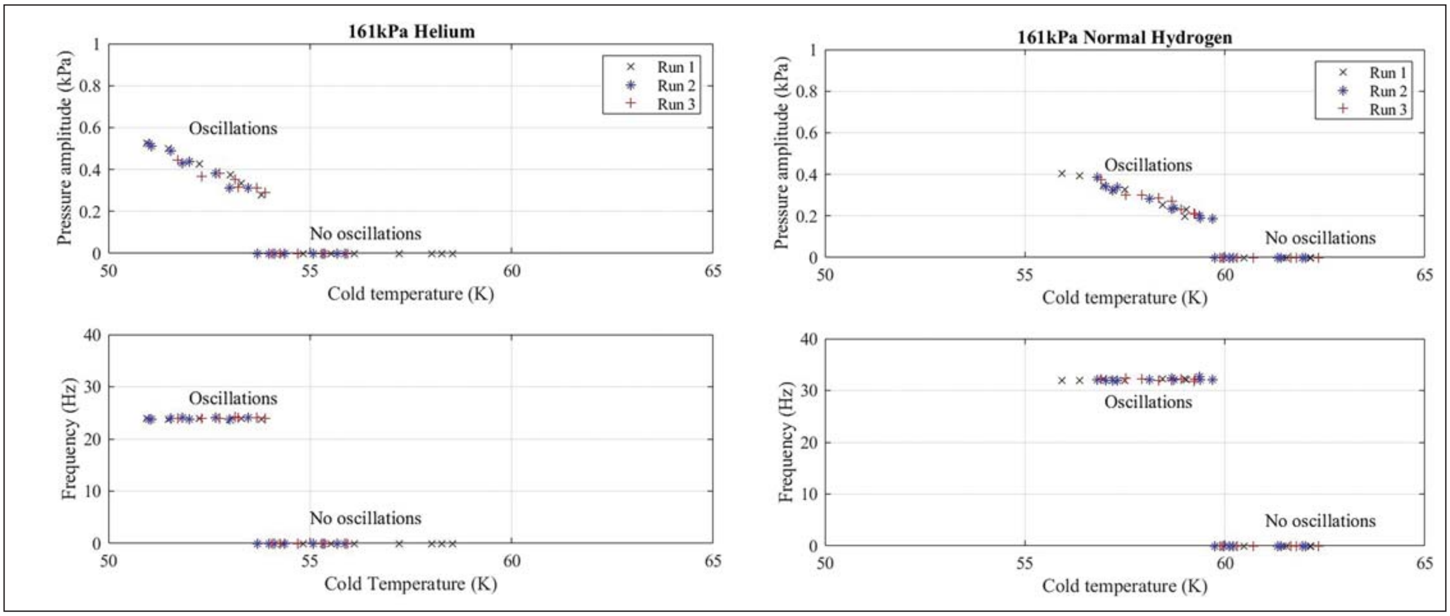

Figure 2: Thermoacoustic pressure amplitude and frequency versus cold temperature for helium (left) and normal hydrogen (right). *Credit: Matt Shenton*

instabilities are easier to initiate in hydrogen than in helium. The onset temperatures, oscillation frequencies and pressure amplitudes are higher with hydrogen than with helium for identical setups. This makes sense as the sound speed is higher and the viscosity is lower for hydrogen than helium. Figure 2 shows a plot with some of these measurements for comparison. What should be noticed is that the frequencies of thermoacoustic instabilities are significant, potentially exceeding 100 Hz. This means that most run-of-the-mill pressure transducers are sampling at frequencies far too low for detection. Of course, you could get lucky like I did years ago and have a Bourdon tube gauge in the right location for the needle to blur.

Thermoacoustic instabilities can be modeled, controlled and harnessed for useful applications. Increasing the volume of the warm end and the sharpness of temperature gradients both tend to increase instabilities. Flow obstructions, losses or extra volumes strategically placed at key points tend to decrease instabilities. One challenge with modeling is that most of the traditional theory is based on ideal gas property assumptions. Our two-phase and supercritical tests pushed the boundaries of these simplified assumptions and showed that we still see thermoacoustic instabilities in these conditions. Computational fluid dynamics (CFD) tools seem to help in these situations.

Konstantin's models indicate that hundreds of watts can be transferred at large oscillation amplitudes. This has important implications for the design of liquid hydrogen storage tank penetrations that are not often discussed or considered by industry. Given the ability to control these instabilities via valves and other mechanisms near the tube entrance into the tank, someone could develop a handy heater or vaporizer using this technique. Applying the pressure oscillations to the system enables the same phenomena to pump heat from cold to hot for cooling.

Given the relatively higher performance of hydrogen thermoacoustics than helium, perhaps the time has come to even consider hydrogen as a working fluid in cryocoolers. But that would require convincing people that there remains a lot more to discover.

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Pulsar Helium Confirms Groundbreaking Helium Find

by Thomas Abraham-James President, CEO and Director, Pulsar Helium Inc.

In an exciting development for helium exploration, Pulsar Helium Inc. has confirmed a significant discovery of helium during its operations at the Jetstream #1 appraisal well in the Topaz helium project located in Minnesota. This discovery marks a significant milestone, not only for Pulsar Helium but also for the burgeoning helium industry.

On February 28, the Jetstream #1 well reached a total depth of 2,200 feet. As the drilling progressed, helium shows were detected between depths of 1,750 to 2,200 feet, with helium concentrations measuring up to 12.4%. These findings were authenticated by on-site mass spectrometer readings. The well, upon reaching total depth, underwent conditioning with air to eliminate residual drill fluid. Subsequently, the well commenced natural gas flow, enriched with helium. Over a five-hour cleanup period, the mudlog gas composition revealed an increase from 3.7% to 5.1% helium. However, these measurements are considered conservative due to potential dilution from atmospheric contamination during the drilling process.

Topaz is located in Minnesota and is a helium discovery in a new helium province where Pulsar is the first mover. It has been drilled and flowed with 10.5% helium, with only trace hydrocarbons present. *Credit: Pulsar Helium*

Thomas Abraham-James, president and CEO of Pulsar Helium, expressed his excitement about the discovery and pledged to keep stakeholders updated as further results emerge. Despite encountering challenges such as loss of circulation and returns while drilling, the precise origination depth of the gas remains to be determined. Baker Hughes, responsible for collecting and processing comprehensive wireline logs, is currently analyzing the data to provide clarity on this aspect. The geological consistency observed throughout the well, characterized by interchanging troctolite/anorthosite formations, suggests promising prospects for further exploration.

The gas compositions were meticulously examined by an independent surface logging team employing a quadrupole mass spectrometer. Samples collected during the drilling process will be subjected to comprehensive analysis in specialized gas laboratories to ascertain molecular composition and eliminate atmospheric contamination. While the Jetstream #1 well concluded drilling at a depth of 2,200 feet, 50 feet more shallow than planned, logistical constraints imposed by impending spring load restrictions necessitated timely completion. Moving forward, a well testing package is slated for implementation, including flow testing, pressure buildup programs and collection of pressurized gas samples for laboratory analysis.

Pulsar Helium ensures compliance with the State of Minnesota's exploratory boring regulations, underscoring its commitment to responsible exploration practices. With projects like Topaz in Minnesota and Tunu in Greenland, Pulsar is emerging as an industry leader in helium exploration. As the helium industry gains momentum, Pulsar Helium's latest discovery may be a turning point for helium, with promising economic opportunities and technological advancements on the horizon.

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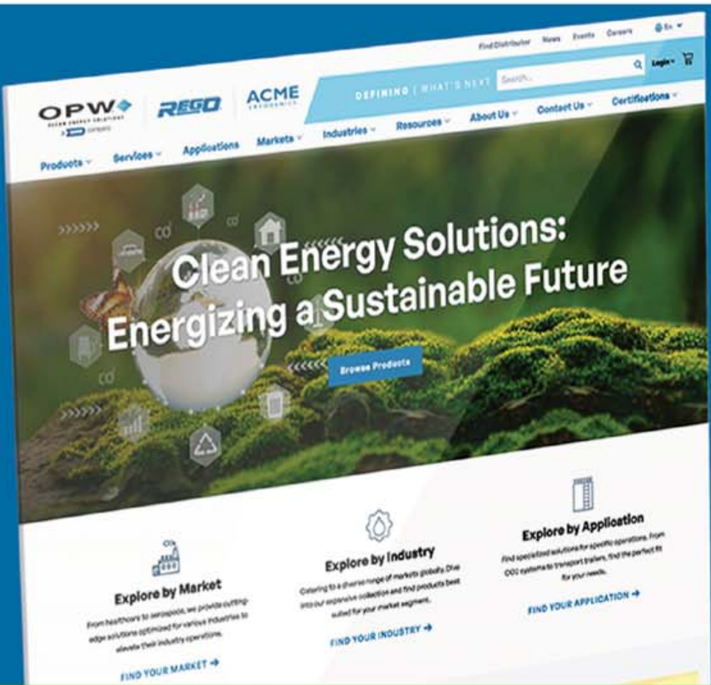

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Quantum Design Explores Quantum Frontiers with Precision Measurements

by Rick Hapanowicz, Quantum Design

Since 1982, Quantum Design has been providing lab-ready scientific instruments to colleges, universities, government and corporate laboratories around the world. Instruments include the DynaCool® Physical Property Measurement System (PPMS), the MPMS3® SQUID Magnetometer and VersaLab® Physics Education System. The OptiCool® is a large volume, low vibration, low temperature and high magnetic field cryogen-free environment for magneto-optical investigations. The FusionScope® is a correlative microscopy system for scanning electron microscopy (SEM), atomic force microscopy (AFM) and elemental imaging of materials. These instruments are made in the US and were designed and developed by Quantum Design's engineering team in San Diego, Calif.

This collage shows the instruments produced by Quantum Design. Many new materials have been analyzed in Quantum Design systems including superconductors, quantum magnets, thermoelectrics, magneto-caloric, two-dimensional and many other material classes. *Credit: Quantum Design*

The MPMS3® SQUID Magnetometer is Quantum Design's flagship instrument for magnetic measurement. This is the highest sensitivity, commercial magnetometer with thousands of installations around the world. The DynaCool® and VersaLab® systems have over 20 experimental measurement options. These options allow researchers to quickly measure the electrical, magnetic, thermal and optical properties of materials. Figure 1 shows the instruments produced by Quantum Design. Many new materials have been analyzed in Quantum Design systems including superconductors, quantum magnets, thermoelectrics, magneto-caloric, two-dimensional and many other material classes.

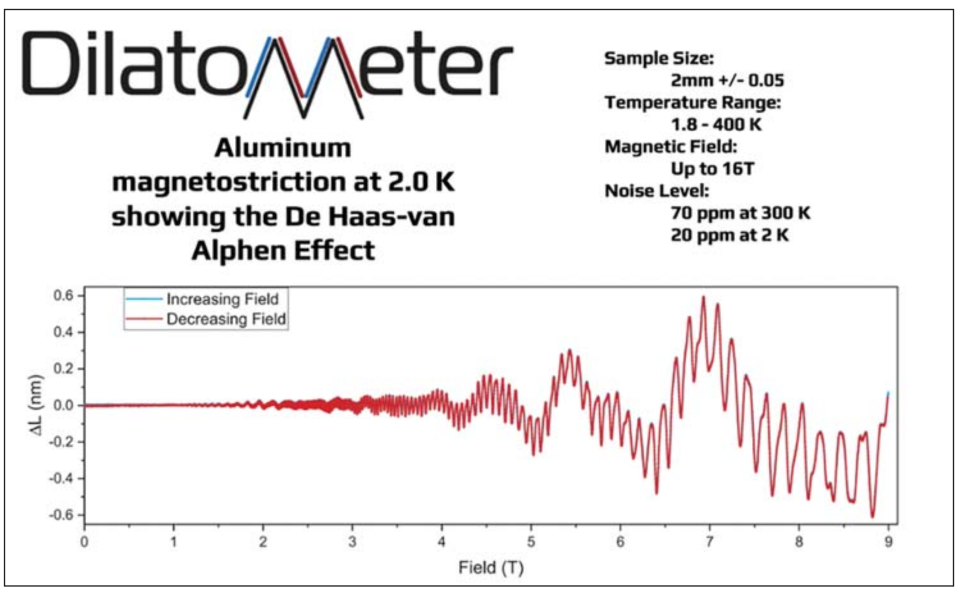


Figure 2: Ultrasensitive ratiometric capacitive measurement provides picometer resolution of the thermal expansion of material. The example shows the magnetostriction of aluminum at 2 K. *Credit: Quantum Design*

Quantum Design's precision measurement systems allow researchers to test the quantum limit. The quantum limit is the crossover when classical mechanics can no longer describe the behavior of a material and the quantum mechanics behavior of the electron dominates the effect. An example of this is illustrated in Figure 2, with data collected using the PPMS dilatometer measurement option. This ultrasensitive ratiometric capacitive measurement provides picometer resolution of the thermal expansion of material. The example shows the magnetostriction of aluminum at 2 K. The oscillation of the thermal expansion of the aluminum at low temperature and changing applied magnetic field is quantum mechanical in nature and is described as the De Haas-van Alphen effect. Another example of the quantum limit is the Quantum Hall effect, shown in Figure 3, showing field-dependent transverse and longitudinal transport measurements for a GaAs 2-D electron gas system at 2 K with 1 μA sourced excitation current in the van

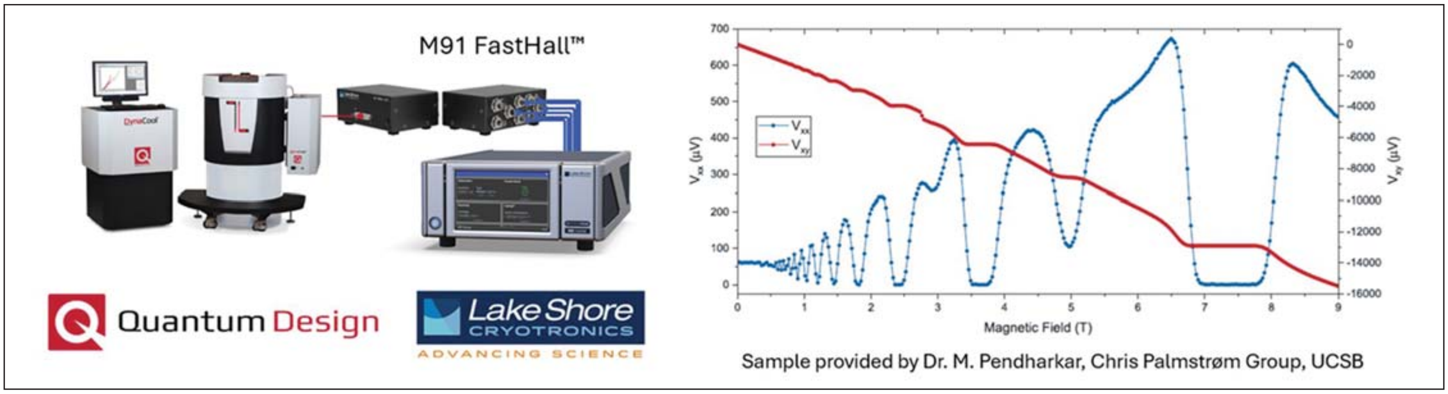


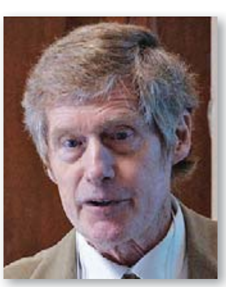
Figure 3. This figure shows field-dependent transverse and longitudinal transport measurements for a GaAs 2-D electron gas system at 2 K with 1 μA sourced excitation current in the van der Pauw geometry. *Credit: Quantum Design*

der Pauw geometry. This measurement was performed in the PPMS DynaCool® coupled with the Lake Shore Cryotronics M91 FastHall™ measurement system. The M91 Fast Hall system provides researchers with the ability to make rapid measurements and calculate the Hall and mobility parameters of samples. Plateaus in the transverse channel demonstrate the integer quantum Hall effect and correspond to where the Fermi level falls in an area of localized states between neighboring Landau levels. (Sample provided by Dr. M. Pendharkar, Chris Palmstrøm Group, University of California, Santa Barbara).

Recently, Quantum Design has further expanded its measurement platforms to include the OptiCool® and FusionScope®. The OptiCool® provides a large volume, cryogen-free, ultralow vibration cryostat that combines low temperatures (1.7 K), high magnetic fields (±7 T) and ample optical access from eight optical windows along multiple axes. The addition of easy nanopositioner integration, multiple window and fiber feedthrough options, internal objective mounting hardware, and rapid temperature stage results in a highly versatile platform that allows for experiments that would be impossible in other cryostats. The ultralow vibrations further enable cryogenic high-magnetic field microscopy studies. The FusionScope® is a correlative microscopy platform that combines the complementary strengths of AFM, SEM and energy-dispersive X-ray spectroscopy (EDS). Seamlessly image your sample, identify areas of interest, measure your sample and combine your imaging data in real time. Quantum Design's microscopy offerings have now allowed the company to take materials characterization from the bulk to the nanoscale.

Quantum Design instruments are found in the world's leading research institutions and have become the reference standard for a variety of magnetic and physical property measurements. Quantum Design instruments are cited in and provide the data for more scientific publications than any other instrument in the fields of magnetics and materials characterization. This means that each year, hundreds of scientific publications, advancing the science of materials, use data generated from Quantum Design instruments.

In addition to Quantum Design's efforts in building precision scientific instrumentation, the company is also active in improving hands-on experimental learning for STEM students. Quantum Design launched The Discovery Lab Initiative, which seeks to partner colleges and universities with leading technology companies to develop new curricula emphasizing hands-on experiential learning. By introducing industry-standard research instruments, students are inspired to "take theory into practice," thereby better training themselves to be successful in the next stage of their scientific careers. Quantum Design created Discovery Teaching Labs to promote this collaborative effort between industry and academics. **discoveryteachinglabs.com**, **www.qdusa.com**



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QuantumPURE is a powered filtration system designed to purify impure helium from airships. It efficiently removes contaminants through compression, purging and safe ejection, ensuring clean helium is returned via a dedicated fill line. Its optimized design fits various operational needs, minimizing costs. With user-friendly features, it allows for one-person operation and easy transportation, either skid- or trailer-mounted. Field-replaceable valves and seals ensure convenient maintenance. The system offers flexibility with electric or diesel-powered compressors and minimizes helium loss by venting air and water efficiently. QuantumPURE provides a reliable solution for helium purification, facilitating seamless operations with its practical design and versatile functionality. **www.quantum-h2-technology.com**

Connection Solutions for IT Cooling

Stäubli

Discover Stäubli's advanced Connection Solutions for IT Cooling, redefining digital infrastructure in the era of escalating online activity and data flow. As computing power expands, liquid cooling becomes essential for efficient heat dissipation and energy optimization. Stäubli's technology ensures seamless integration and operational continuity, with non-spill connectors enabling hassle-free maintenance and protection of IT systems. Compact and adaptable, Stäubli's quick-release solutions optimize heat transfer fluid management across diverse environments, guaranteeing flawless sealing for long-term reliability. Heat-exchanger connections efficiently dissipate server heat, ensuring equipment integrity and optimal performance. Emission-control couplings and refrigeration connectors uphold operational continuity, enhancing efficiency while minimizing energy costs. **www.staubli.com**

Gas Handling System Generation 2

Bluefors

Earlier this year at the American Physical Society March Meeting, Bluefors announced a next generation gas handling system that brings more flexibility, usability, functionality and safety to operating dilution refrigerators. The new hardware comprises multiple modular units, based around a new core unit that utilizes top industrial solutions. The core unit adopts an easy-access, lockable front door design and the latest generation of pumps and sensors. The system has been designed as a modular platform that can be easily upgraded to add more features and functionality. Gas Handling System Generation 2 also introduces an all-new touch screen Control Software Generation 2 that makes the operation of Bluefors cryogenic measurement systems more intuitive. The new control software offers expanded remote access and simplifies operation for less experienced users through fully automatic, intelligent automation – while providing greater access to diagnostic data for those who need it. **www.bluefors.com**

Qubit-in-a-box 0 (QiB0)

ConScience

These devices feature qubits coupled to resonators, bonded and packaged with easy-to-connect SMA connectors, perfect for benchmarking and calibration. The standard setup includes four fixed-frequency transmon single qubits (3-5 GHz) and two hanging resonators (6-7 GHz). The qubits have a lifetime, T1, up to 80 microseconds and the quality factor of the resonator is approximately one million. Product features include four isolated qubits with T1 ranging from 50 to 90 microseconds on average and exceeding 100 microseconds in some cases, four readout resonators coupled separately to each qubit, two hanging resonators with Qi greater than 0.5×106, an oxygen-free copper case and female SMA connectors for RF connections. **www.con-science.se**

Beyond Gravity Leaps Forward in Satellite Monitoring

by Christian Thalmayr, Senior Global Communications Manager, Beyond Gravity

Beyond Gravity, a leading space supplier, expands its expertise into space data services with the launch of its new Space Situational Awareness (SSA) solution. This innovative service, leveraging over six years of data collection, offers unparalleled accuracy and insights into more than 10,000 active satellites, promising to enhance faster decision-making for institutional and commercial customers alike.

SSA services include the ability to monitor, track and predict the location and behavior of satellites orbiting Earth. They are vital for the safety, security and sustainability of space activities, enabling the avoidance of collisions, reporting of interference and prediction of unforeseen events. Leveraging more than six years of data collection from diverse sources and building on a partnership with a trusted ally, Beyond Gravity is now launching a new SSA solution distinguished by its outstanding accuracy and superior data quality, designed to meet specific requirements with unparalleled flexibility and adaptability. This SSA product tracks satellite overflights with exceptional accuracy and offers its users comprehensive footprint intelligence, revealing details about the satellite's onboard technology and instruments. This empowers users with an in-depth understanding of a satellite's capabilities.

Beyond Gravity's Space Situational Awareness (SSA) solution delivers technical insight into over 10,000 satellites. Screenshot of the SSA application, showing the (mock-up) technical information and footprint of a satellite over Europe. *Credit: Beyond Gravity*

Accelerating Decision-Making

Beyond Gravity's latest offering caters to the varied demands of commercial or institutional customers alike, the latter including security units, disaster response teams or governmental agencies. In mere seconds, the online platform delivers comprehensive intelligence about a satellite's activities, including potential observation, including potential observation, listening, or interference capabilities within specific regions and timeframes. Such rapid access to data significantly supports operational decision-making processes. By leveraging the high-precision satellite intelligence provided, it enables users, for instance, to swiftly organize aid following natural disasters or secure national and global interests. Oliver Grassmann, executive vice president of Beyond Gravity's Satellites division, emphasizes, "Our new SSA solution is designed to create great added value for our customers, for example, by significantly speeding up decision-making. It identifies satellites with necessary capabilities that will fly or have flown over a specific area with unprecedented accuracy, allowing emergency services to swiftly access this information. This can notably expedite the rescue of individuals identified through satellite imagery."

Trusted and Customizable

The Beyond Gravity SSA solution is a product that keeps longstanding and collaborative partnerships in mind, Grassmann explains, "Our SSA platform, informed by millions of data points and daily satellite capability monitoring, delivers unmatched operational and technical insight into over 10,000 satellites. It ensures a secure, seamless experience for governmental and commercial stakeholders alike." He adds, "Customizable and adaptable, our solution is already benefiting a broad spectrum of partners through enhanced data interoperability, such as for Command-and-Control systems and map layering (e.g., KML)."

Data: The Modern Era's Oil

With the introduction of its SSA solution, Beyond Gravity is broadening its product range and entering the expanding market for space data services. This move aligns with the anticipated growth of the global space economy, which is expected to surpass a trillion US dollars by the 2040s, alongside a significant increase in demand for data solutions. CEO André Wall underscores this opportunity, stating, "Leveraging our four decades at the forefront of space technology, we're poised to capture additional growth for Beyond Gravity in the dynamic data market. We've developed a unique data solution that creates outstanding value for our customers by providing unparalleled insights into satellite capabilities. Our solution demonstrates how space technology can significantly enhance life on Earth, underscoring the critical role of space data across diverse industries."

www.beyondgravity.com

People & Companies in Cryogenics

Credit: : NASA JPL

Leslie Livesay has assumed the position of deputy director at **NASA's Jet Propulsion Laboratory (JPL)**, marking her as the first woman to hold this role in JPL's history. With over 37 years of experience at JPL, Livesay has led various teams in developing technologies and flight systems for planetary, Earth science and astrophysics missions. She brings a wealth of expertise, having served in multiple key positions including project manager for the Kepler space telescope mission and associate director for Flight Projects and Mission Success. Livesay, who holds degrees in applied mathematics and electrical engineering, has been recognized with prestigious awards such as the Carl Sagan Memorial Award and NASA's Exceptional Achievement Medal.

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OPW has launched a new website, **opwces.com**, as the digital home for its Clean Energy Solutions business unit, featuring renowned brands like RegO® Products and Acme Cryogenics. This user-friendly platform offers easy navigation and access to a wide range of industrial gas, LNG and hydrogen solutions across various markets and industries. Meanwhile, **regoproducts.com** will remain active as the primary hub for RegO propane energy products, with plans for an upcoming remodeling to enhance customer access and resources.

Image courtesy of OPW/Acme Cryo

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Chart Industries and **GasLog LNG Services** are teaming up to investigate the establishment of a commercial-scale liquid hydrogen supply chain. This collaboration seeks to capitalize on GasLog's advancements in liquid hydrogen vessel technology and Chart's expertise in cryogenics and large-scale liquefaction solutions. The initiative aims to support GasLog's involvement in forthcoming projects to develop a commercial-scale liquid hydrogen supply chain from the Middle East to Europe and Asia. Leveraging over 158 years of hydrogen experience, Chart will contribute its expertise in compression, liquefaction, refrigeration technologies and cryogenic operations to ensure the safety and efficiency of the supply chain.

Image courtesy of Splash247

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The **UK Space Agency** is opening new headquarters at the Harwell Science Campus' Space Cluster in Oxfordshire and regional offices in Scotland, Wales, and the Midlands as it works to support the space sector across the UK. Aligned with the government's Levelling Up strategy, the expansion will enable the agency to collaborate more closely with the UK's thriving space sector, while promoting regional skills and job opportunities to deliver increasingly ambitious missions and capabilities. The new HQ at Harwell is due to open in June, while offices at William Morgan House in Cardiff and Space Park Leicester will open in April. The office at Queen Elizabeth House in Edinburgh will open later in the summer.

Quad 2 at the Harwell Science Campus' Space Cluster in Oxfordshire. Credit: UK Space Agency

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Maybell Quantum has secured a $25 million funding round led by Cerberus Capital Management, L.P. With this investment, Maybell plans to expand manufacturing, establish a new production facility and enhance its MayQ Labs. The partnership with Cerberus underscores the strategic importance of quantum capabilities for national security.

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Carbon America is introducing its FrostCC™ cryogenic CO_2 separation method at the National Carbon Capture Center, marking a significant advancement in carbon capture technology. Unlike traditional methods, FrostCC operates without external refrigerants, instead utilizing a novel process of compressing and expanding flue gas flow with heat integration, making it more energy-efficient and environmentally friendly. The technology has the capability to freeze CO_2 and other pollutants, storing the captured CO_2 as a liquid for easier transport and storage. With potential applications across various industries, including power plants and manufacturing facilities, FrostCC has the promise to substantially reduce carbon emissions.

Meetings & Events

BCGA Annual Conference 2024
May 16
Worsley Park, Manchester
https://bcga.co.uk/conference

CSA's Foundations of Cryocoolers Short Course
June 3
Madison, Wisconsin
www.cryogenicsociety.org/foundations-of-cryocoolers-short-course-2024

23rd International Cryocooler Conference
June 3-6
Madison, Wisconsin
https://cryocooler.org

IEEE Workshop on Low Temperature Electronics
June 3-6
Cagliari, Sardinia, Italy
https://wolte16.org

FCC Week
June 10-14
San Francisco, California
https://fccweek2024.web.cern.ch

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