Cold Facts INTERNATIONAL

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Cryopreservation Marks Breakthrough for Diabetes Cure | 8

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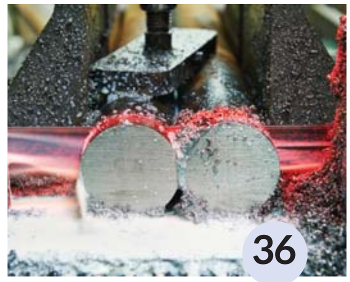

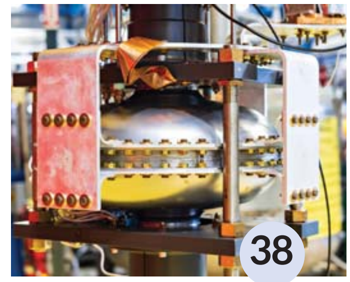

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University of Minnesota College of Science and Engineering Professor John Bischof and mechanical engineering Ph.D. student Lakshya Gangwar use one-of-a-kind pieces of equipment to cryopreserve and rewarm cells, tissues, and even entire organs.
Credit: Rebecca Slater

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From the Executive Director

What an eventful couple of months it has been! Recently, I was joined by ***Cold Facts*** Editor Anne DiPaola in Honolulu, Hawaii, where we attended the Applied Superconductivity Conference (ASC). It was an absolute pleasure to meet so many of our members and colleagues in person – and the fact it was in such a beautiful location was an added plus!

On the first day of ASC, CSA Awards Chairman Chris Rey presented the Roger W. Boom Award. The Boom Award is named in honor of the late emeritus professor from the University of Wisconsin. Dr. Boom's career spanned more than 30 years during which he motivated a great number of young scientists and engineers to pursue careers in cryogenic engineering and applied superconductivity. The spirit of the Boom Award is to recognize young people for their pursuit of excellence, demonstration of high standards and clear communications.

We are thrilled to present this award to Dr. Nusair M. Hasan of the Facility for Rare Isotope Beams. Dr. Hasan is recognized for his outstanding work on the advancement of cryogenic processes and technology, specifically relating to large-scale 2 K and 4.5 K cryogenic refrigeration and critical supporting sub-systems for particle accelerators. Dr. Hasan has also made noteworthy contributions in training and mentoring future generations of cryogenic engineers.

Later in the week, the CSA Board of Directors met in person for the first time since before the pandemic. During the meeting, the board approved our impressive slate of nominees for the CSA board election which will take place in the coming month. If you are a member of CSA, expect to receive an email soon to place your vote.

Throughout the entirety of the conference, we had many conversations with event attendees. There seemed to be a common theme in our conversations – organizations are struggling to find qualified candidates to fill open positions. CSA wants to do all we can to combat this issue. If your organization is hiring, I encourage you to post the job to CSA's Job Center at **https://cryo.mcjobboard.net**. Job postings are free for members. If you are currently seeking employment, I invite you to post your resume to our Job Center at **https://cryo.mcjobboard.net/jobs/resume-upload**. CSA's Job Center is a helpful tool, but we understand it won't solve the root cause of the issue. In 2023, CSA plans to increase our outreach to colleges and universities that might not currently have any cryogenics-related courses. We hope such efforts will grow the workforce in the long-term.

Lastly, I want to remind everyone to mark your calendars for the 30th Space Cryogenics Workshop which is taking place on July 16-18, 2023, at the Outrigger Kona Resort and Spa in Kailua-Kona, Hawaii! We hope to see many of you there. For full details, visit **spacecryogenicsworkshop.org**.

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

Life Sciences & Testing Labs

University of Minnesota College of Science and Engineering Professor John Bischof and mechanical engineering Ph.D. student Lakshya Gangwar use one-of-a-kind pieces of equipment to cryopreserve and rewarm cells, tissues and even entire organs. *Credit: Rebecca Slater*

Pancreatic Islet Cryopreservation Marks Breakthrough for Diabetes Cure

by Rhonda Zurn, director of communications and marketing, College of Science and Engineering, University of Minnesota

Engineering and medical researchers at the University of Minnesota Twin Cities and Mayo Clinic have developed a new process for successfully storing specialized pancreatic islet cells at very low temperatures and rewarming them with a laser and gold nanoparticles, enabling the potential for on-demand islet transplantation. The breakthrough discovery in cryopreservation is a major step forward in a cure for diabetes.

According to the Centers for Disease Control and Prevention, diabetes is the seventh leading cause of death in the United States, accounting for nearly 90,000 deaths each year. Despite 100 years of therapeutic development since the discovery of insulin, current diabetes therapies, such as continuous glucose monitors, insulin pumps and closed-loop systems, remain a treatment for the condition rather than a cure of the disease.

Cryopreservation of specialized pancreatic islet cells by Professor John Bischof and his team is part of a larger effort involving cryopreservation methods led by the University of Minnesota Twin Cities. *Credit: Rebecca Slater*

Pancreatic islet cell transplantation, a process where doctors take groups of cells from a healthy pancreas and transfer them to a recipient who then begins to make and release insulin on their own, is one method being explored to cure diabetes. However, a limitation of this approach is that transplants from a single donor are often insufficient to achieve insulin independence in the recipient. Frequently, two, three or more donor-islet infusions are required, which adds risks associated with repeated surgical interventions and multiple rounds of strong immunosuppression induction.

A common strategy for overcoming the donor supply problem is to pool islets from multiple donors, achieving high islet dosage with a single infusion, but this process is limited by the inability to safely store islets for long periods of time. Previous research has shown storage to be limited to 48 to 72 hours before transplantation. While some groups have shown the feasibility of culturing islets for extended periods (weeks to months), the majority have reported reduced islet recovery and loss of endocrine function over time.

The breakthrough from the research done by the University of Minnesota Twin Cities and Mayo Clinic provides a new method of islet cryopreservation that solves the storage problem by enabling quality-controlled, long-term preservation of the islet cells that can be pooled and used for transplant.

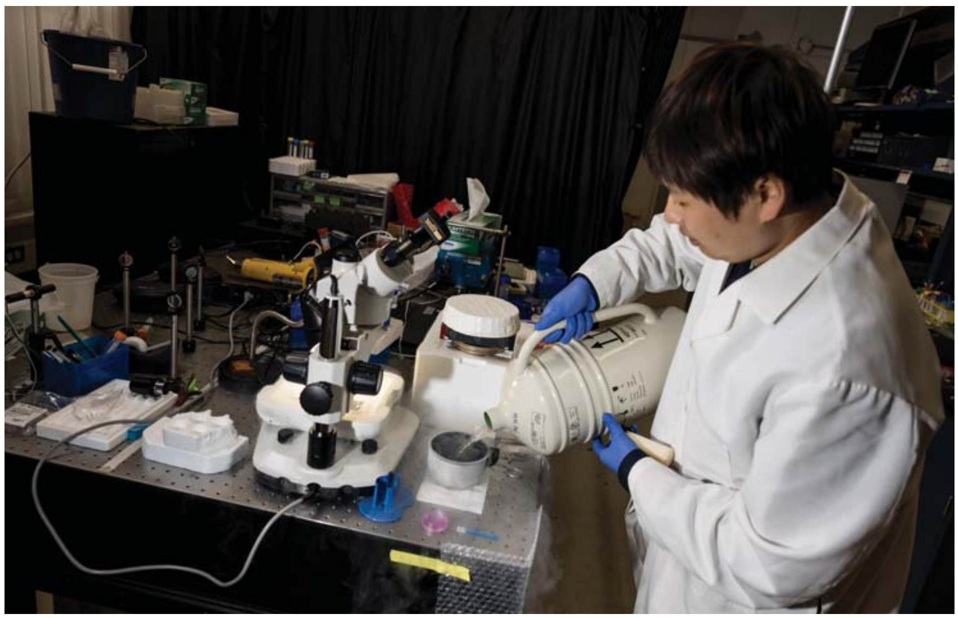
By using a specialized cryomesh system, excess cryoprotective fluid is removed, which allows rapid cooling and rewarming on the order of tens of thousands of degrees per second while avoiding problematic ice formation and minimizing toxicity. The new cryopreservation method demonstrates high cell survival rates and functionality (90% for mouse islet cells and about 87% for pig and human islet cells), even after nine months of storage. Storage with this potential cryopreservation approach is theoretically indefinite. Furthermore, in mice, the transplantation of these cryopreserved islet cells cured diabetes in 92% of recipients within 24 to 48 hours after transplant. The results suggest that this new cryopreservation protocol may be a powerful means of improving the islet supply chain, allowing pooling of islets from multiple pancreases, and thereby improving transplantation outcomes that can cure diabetes.

"Our work provides the first islet cryopreservation protocol that simultaneously achieves high viability and function in a clinically scalable protocol," said John Bischof, Ph.D., a Distinguished McKnight University Professor in mechanical engineering and director of the University of Minnesota's Institute for Engineering in Medicine. "This method could revolutionize the supply chain for islet isolation, allocation and storage before transplant. By pooling cryopreserved islets before transplant from multiple pancreases, the method will not only cure more patients, but also make better use of the precious gift of donor pancreases."

Researchers also pointed out that this method can be scaled up to reach large numbers of people worldwide who suffer from this progressively debilitating disease. "Despite decades of research, islet transplantation has remained just around the corner; ever with great promise, but never quite within reach. Our technique for cryopreserving islets for transplantation could be a significant step towards finally achieving that lofty goal," said Erik Finger, MD, Ph.D., associate professor of surgery at the University of Minnesota Medical School, M Health Fairview.

This research is part of a larger effort involving cryopreservation methods led by the University of Minnesota. In 2020, the University of Minnesota and Massachusetts General Hospital were awarded $26 million over five years from the National Science Foundation to create the Engineering Research Center for Advanced Technologies for the Preservation of Biological Systems (ATP-Bio). ATP-Bio aims to achieve major bioengineering breakthroughs by developing and deploying the technology to "stop biological time" through temperature control — that is, to "biopreserve" or "cryopreserve" numerous biological systems. ATP-Bio includes 30 senior personnel from seven institutions across the US and Canada.

One strategy for overcoming the donor supply problem is to pool islets from multiple donors, achieving high islet dosage with a single infusion. Storage with the cryopreservation approach demonstrated by University of Minnesota Twin Cities researchers is theoretically indefinite. This would allow pooling of islets from multiple pancreases and thereby improve transplantation outcomes that can cure diabetes. *Credit: Rebecca Slater*



University of Minnesota Twin Cities College of Science and Engineering postdoctoral fellow Zongqi Guo is part of a team that has developed a new process for successfully storing specialized pancreatic islet cells at very low temperatures and rewarming them, enabling the potential for on-demand islet transplantation for diabetes patients. *Credit: Rebecca Slater*

CryoRobot Provides Peace of Mind to Hopeful Families

About 12 percent of American women ages 15 to 44 have difficulty getting pregnant or carrying a pregnancy to term, according to the federal Centers for Disease Control and Prevention. Many struggling with infertility turn to assisted reproductive technology.

With growing numbers of men and women choosing to freeze (or cryopreserve) their sperm, eggs and embryos, patients have more control than ever over when to begin building a family. This freedom to manage a personal reproductive timeline reflects incredible advancements in technology. Kindbody, a nationwide fertility and wellness service, offers state-of-the-art cryopreservation techniques and vitrification in order to increase success rates for patients.

Among the technologies they use is the TMRW Life Sciences CryoRobot to ensure an ideal preservation environment and risk reduction, and to give patients peace of mind. TMRW's CryoRobot is the first and only automated platform for the management, identification and storage of the frozen eggs and embryos used in vitro fertilization (IVF).

Dr. Amber R. Cooper, a director of IVF at Kindbody, says that prior to the CryoRobot's addition, the IVF process was entirely manual and not without hiccups. "Issues that have plagued fertility clinics through the years include embryo mix-ups, incorrect transfers of embryos and catastrophic failures resulting in the loss of thousands of irreplaceable eggs and embryos. However, TMRW's technology automates and digitizes the entire process, which helps reduce the risk for human error and, more importantly, allows the clinic to individually track eggs and embryos 24/7 through remote monitoring, sensors and state-of-the-art software." TMRW's proprietary, Overwatch, provides the 24/7 monitoring, giving complete assurance as to the safety of specimens under clinic care.

TMRW Life Sciences CryoRobot. *Credit: TMRW Life Sciences*

Using the new technology from TMRW, Kindbody can constantly monitor specimens on-site and remotely, while patients can check in on their individual specimens, accessing information on real-time storage conditions. Cooper says the ability to obtain this level of specific information provides "peace of mind for patients as it pertains to their precious tissue."

Although the introduction of CryoRobot is new, the concept has been building momentum for several years. "Robotics has been a growing area of interest in how automation can assist in storing, retrieving and monitoring IVF tissue," Cooper says. "Typically, cryogenic IVF tissue is monitored using traditional hardwired systems that rely solely on human observations. When the TMRW company originally approached us, it provided an opportunity to stop and evaluate how the introduction of their system could help provide an even greater level of security for our ever-growing patient population. It is this type of forward thinking that will help patients achieve their family goals safely and efficiently," she says.

The TMRW cryo specimen management platform's key features include:

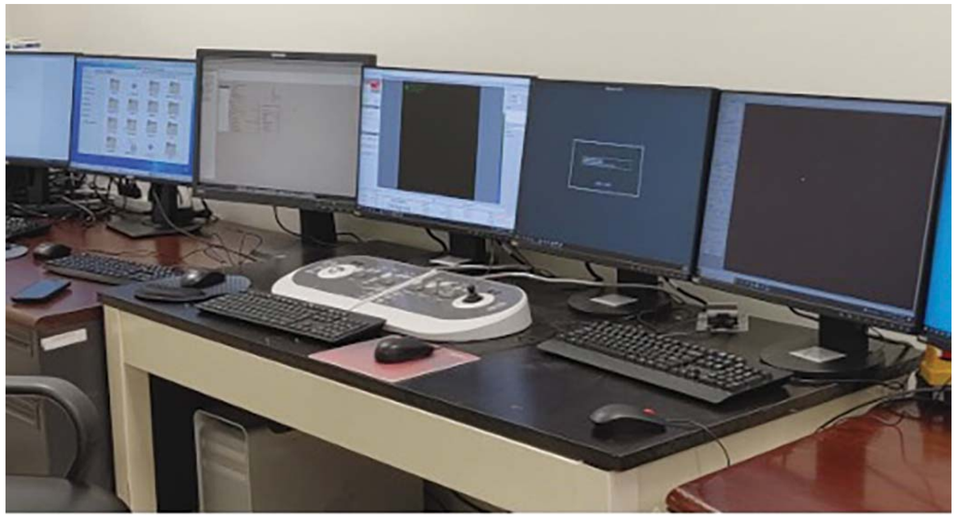
- Proprietary labware with industry-leading thermal properties and fully automated robotic storage to maintain safe cryogenic temperatures for specimens at all times.
- Unique digital identification for each patient using advanced radiofrequency labware, enabling clinics to identify and track specimens, creating an unbreakable track-and-trace audit trail.
- 24/7 remote monitoring through Overwatch, which performs thousands of system performance checks every day, enabling the system to proactively predict clinic and specimen safety.
- Fully encrypted, HIPAA-compliant software, providing the highest level of privacy and security to both patient and clinic data.

Since the birth of the first IVF baby over 40 years ago, reproductive medicine has progressed with numerous breakthroughs and discoveries, but the management of frozen specimens has not seen the same level of advancement. Current methods are manual, analog and labor-intensive. TMRW brings technology and automation to the process, providing digital identification and tracking of specimens and complete traceability of the frozen eggs and embryos of every patient. "We are proud to provide this cutting-edge solution and deliver unparalleled transparency, traceability and security, dramatically reducing risk and providing peace of mind during what is a deeply personal journey for fertility patients," said Tara Comonte, CEO of TMRW. "TMRW's solution enables clinics to meet the growing demand for fertility services and safely care for the resulting exponential increase in the number of specimens under their management."

UT Health Invests in Cryo-EM with State-of-the-Art System

by Will Sansom, UT Health

UT Health San Antonio has invested in a powerful new tool to solve disease riddles at the molecular level by adding a state-of-the-art cryo-electron microscopy (cryo-EM) laboratory to their campus. Investing more than five million dollars over the next three years through funds from multimillion-dollar grants made by the Cancer Prevention and Research Institute of Texas and additional funding by The University of Texas System Science and Technology Acquisition and Retention, UT Health San Antonio has procured scientist recruits, completed renovations of laboratories, and purchased the instrumentation necessary to develop the high-tech campus addition.



A cryo-EM control room at UT Health San Antonio. *Credit: UT Health*

Cryo-EM is complementary to existing structural biology technologies at UT Health San Antonio. X-ray crystallography, for example, exposes a protein crystal to X-rays, diffracting the X-ray beam in directions according to the protein's structure. Nuclear magnetic resonance spectroscopy, meanwhile, demonstrates the behavior of an atom nucleus when it is placed in a powerful magnetic field. Experts can infer structure from the behavior they observe.

"Some protein targets, however, are too small to be visualized by existing techniques or have flexible, wiggly regions that impede the crystal formation," explains Dr. Elizabeth Wasmuth, Ph.D., assistant professor of biochemistry and structural biology. She joined UT Health San Antonio this year after participating in cryo-EM studies of prostate cancer conducted at multiple institutions in New York. "Cryo-EM flash-freezes proteins on thin layers of ice within milliseconds and barrages them with electron beams, generating biologically useful information."

"We are essentially molecular photographers," says Shaun Olsen, Ph.D., associate professor of biochemistry and structural biology and director of the Structural Biology Cores Facilities at UT Health San Antonio.

Dr. Lijia Jia, Ph.D., examines the cryo-EM instrument. *Credit: UT Health*

"Some people take pictures of buildings. We take pictures of proteins and want to see what they look like in three dimensions."

"We look at molecules in levels of detail that are unparalleled," adds Dr. Wasmuth. "Basically, it is like being able to see a dime on the surface of the moon. That is the level of resolution that the techniques and tools of structural biology allow us to see about molecules inside cells and inside our bodies."

According to Dr. Wasmuth, having a cryo-EM system also allows doctors and scientists to observe drug targets that couldn't be visualized by other methods. "The second week the cryo-EM facility became functional, we were able to solve the structure of a complex of proteins involved in DNA damage repair at impressively high resolution."

Cryo-EM has boomed in the last decade due to advances in technology. Better microscopes, stronger optics, and high-tech computer programming have allowed new discoveries. UT Health San Antonio's cryo-EM system, a Glacios outfitted with a cutting-edge detector (Falcon 4) and energy filter (Selectris) is poised to make an impact on the studies developing in multiple facilitates.

It will help investigators of the Mays Cancer Center study tumors. It will help investigators of the Glenn Biggs Institute for Alzheimer's and Neurodegenerative Diseases study dementia and, at the same

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UT Health Invests in Cryo-EM... Continued from page 11

time, help faculty of the Sam and Ann Barshop Institute for Longevity and Aging Disorders study age-related diseases. Finally, among several other disciplines and applications at UT Health, it will also aid researchers of the Greehey Children's Cancer Research Institute in their study of childhood cancers.

The process of acquiring and implementing such instrumentation and technology is an arduous task even for the most sophisticated medical facility. "A cryo-EM system is extremely sensitive, and we had to go through a process with the facilities and maintenance people to make sure there was no electromagnetic or vibrational interference," Dr. Olsen said.

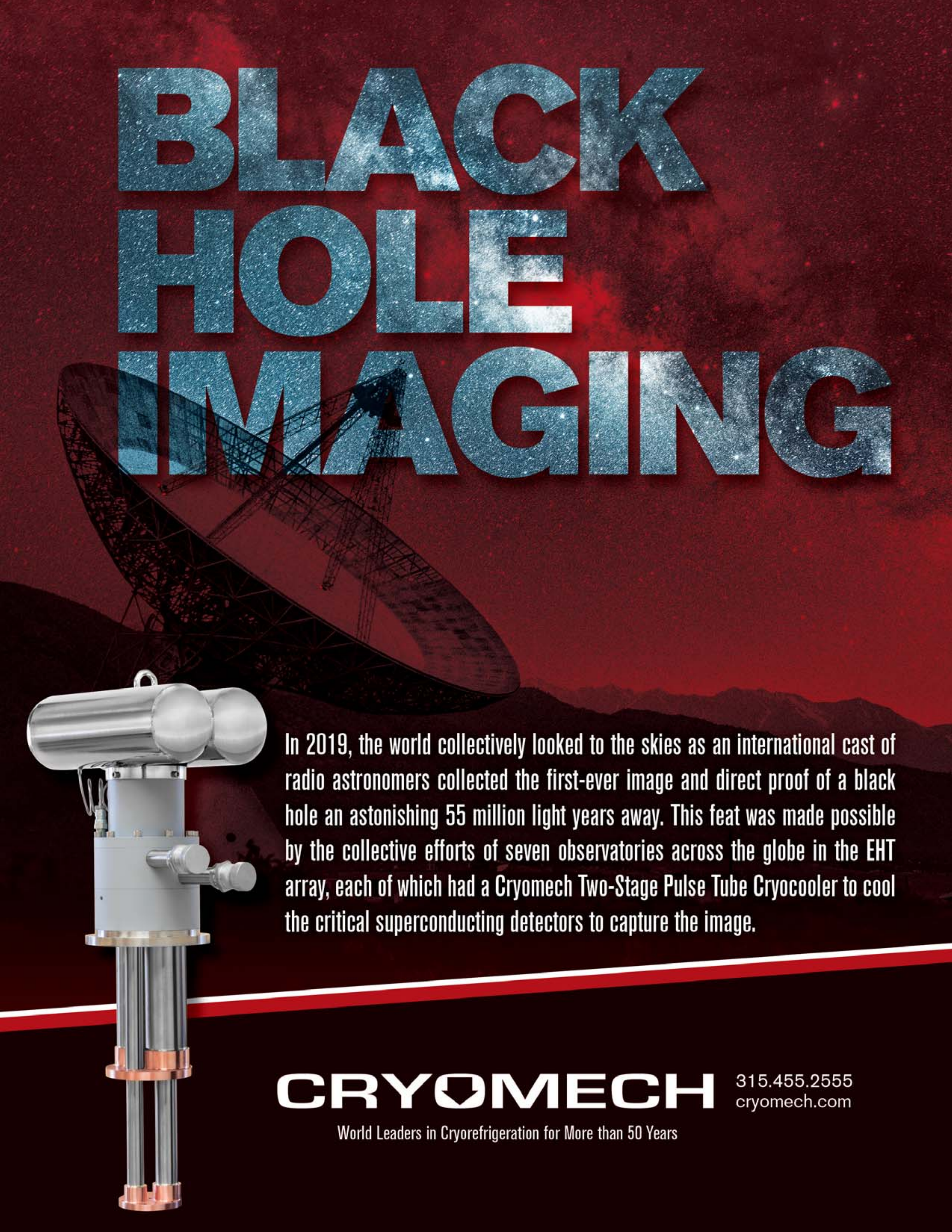
Once the cryo-EM system arrived, getting it into the building required ingenuity. It was shipped in two pieces, but even so, the giant pieces cleared the door space and hallway by mere inches. Next, because the cryo-EM microscope is so sensitive to vibrations and electromagnetic interference from air conditioners, centrifuges and other sources, the scientists needed a particular type of ceiling tile in the room. Delivery of the tiles was delayed by several weeks because of supply chain issues. Ultimately, however, overseeing the use of the technology requires expertise.

Dr. Lijia Jia, Ph.D., manages a NASA-like quality control room with multiple computers, monitors and the cryo-EM system, which includes an electron gun that aims the beams at flash-frozen protein samples. Doctors like Jia are in high demand for his rare skill set. Specially trained in New York on all aspects of the system, he possesses the crucial ability to precisely align the microscope for target acquisition.

"He can troubleshoot any issues and knows how to process data and prepare samples," Dr. Wasmuth explains. "He is a five-million-dollar man."

Much like the space telescopes in Chile, Hawaii and West Texas are indispensable shared resources for astronomers, cryo-EMs are invaluable shared resources for structural biologists. "One data set from two days on the cryo-EM system will be about five terabytes," Dr. Wasmuth notes. "A terabyte is one trillion bytes of information. This is clearly not something grandma's computer can handle. It requires a graphic processing unit to render graphics at high speed."

Sifting through the data requires graphics cards, something people who mine Bitcoin and Ethereum cryptocurrencies also need. The price of the cards escalated after the pandemic market fluctuations. "There was increased mining activity and people were buying loads of graphics cards, says Dr. Olsen. "So, yes, there have been many supply chain issues and installation setbacks, but we've gotten what we need to start changing lives."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In 2019, the world collectively looked to the skies as an international cast of radio astronomers collected the first-ever image and direct proof of a black hole an astonishing 55 million light years away. This feat was made possible by the collective efforts of seven observatories across the globe in the EHT array, each of which had a Cryomech Two-Stage Pulse Tube Cryocooler to cool the critical superconducting detectors to capture the image.
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Hydrogen Technology

Cryomotive team with the first generation cryogas onboard H_2 storage system. *Credit: Cryomotive*

Cryomotive Hits Significant Milestone in Cryogas, Cryo-Compressed Hydrogen Pressure Vessels

by Hannah Mason, CompositesWorld

Hydrogen mobility startup Cryomotive, located in Taufkirchen, Germany, has reached an important milestone in its roadmap to develop and produce its Cryogas cryo-compressed hydrogen (CcH_2) pressure vessels, designed to carry CcH_2 at a density of 72 grams per liter or more to enable long-haul trucks and buses a range of more than 1,000 kilometers per tank.

Founded in October 2020, Cryomotive aims to enter its technology into the market for small-series applications in 2024. Working toward this goal, Cryomotive has recently received and commissioned a new, automated winding machine from Mikrosam of Prilep, Macedonia, and its first full-size liners for heavy-duty truck tanks are ready to be reinforced with a proprietary carbon, fiber-reinforced composite.

Cryomotive's first generation cryogas onboard H_2 storage system will consist of two insulated pressure vessels to store up to 80 kilograms of cryogenic H_2 gas, generated by either cryo-compressing liquid hydrogen (LH_2) or by cryo-cooling gaseous hydrogen (GH_2). The integrated first generation Cryomotive frame mounted cryogas CcH_2 storage system will be able to provide GH_2 in a well-defined temperature range with an adjustable pressure up to 3 MPa (30 bar), suitable to power any fuel cell or hydrogen internal combustion engine powertrain.

As reported by AutoFutures in January 2022, Cryomotive's technology is being developed as part of the 3.5-year CryoTruck consortium project, begun at the start of 2022 and funded by the German Federal Ministry for Digital and Transport. Additional consortium partners include commercial vehicle manufacturer MAN Truck & Bus (Munich, Germany) and vehicle retrofitter Clean Logistics (Winsen, Germany). The goal of the project is reported to be the development of a high-capacity, cryogenic hydrogen gas storage system with fast-refueling technology, aiming for a range of 1,000 kilometers per tank fill and a refueling time of 10 minutes.

Dimitar Bogdanoski, sales manager at Mikrosam, says, "We're happy to have Cryomotive as our customer. It shows how filament winding machines with a lot of flexibility to go from development to full production scale are essential in enabling a greener energy future."

Off-Grid Hydrogen Energy Maximizes Power of Steam

by Robert Price, authorized inspection supervisor, Bureau Veritas, and Brent Woodall, media director, Ssastar Communications

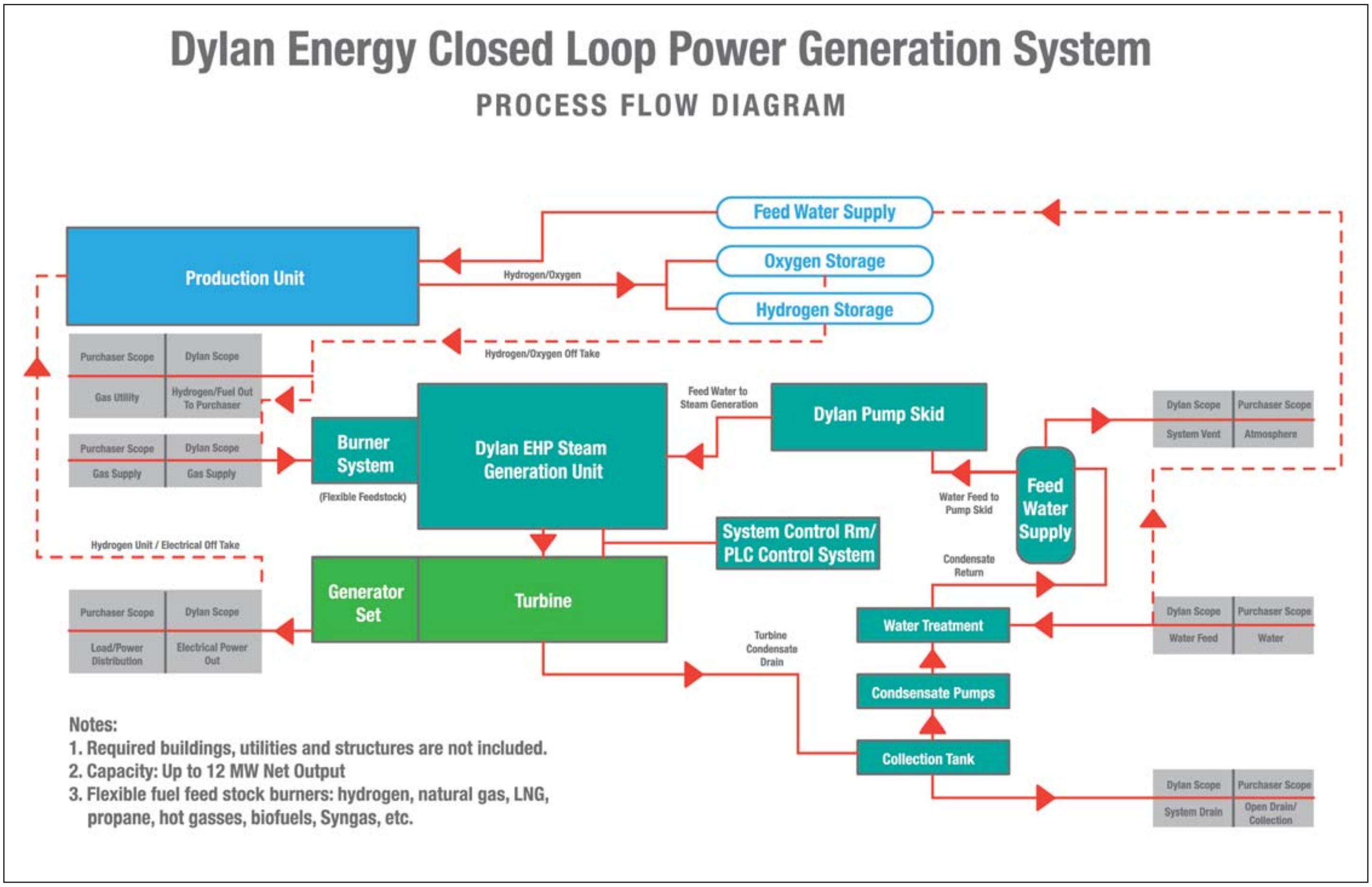

Figure 1. *Credit: Dylan Energy*

Dylan CHP LLC has researched, developed, and patented advanced steam generation technology, utilizing hydrogen to generate clean energy electricity. The Dylan System is based on extreme heat preservation (EHP), the heart of the Dylan patent that allows the Dylan Energy-Efficient System to achieve nameplate steam output while consuming only a small fraction of the hydrogen. Dylan's flexible EHP technology can easily be retrofitted to burn other fuels including natural gas, LNG, flare gas, landfill gas, MSW, or other traditional fuels as feedstock that more conventional systems require. Dylan continues to engineer its system to maximize quality, energy efficiencies and reliability to its customers.

The Dylan System generates low-pressure saturated steam within a closed loop circulating architecture. Within the Dylan System environment, a circulating liquid is heated to the desired steam temperature, which is then released to drive steam turbine-based electrical generation technology. Steam then condenses back to liquid, is recirculated, and again efficiently converted back to steam. The Dylan System can produce electricity from steam-driven turbines ranging from 6 MW (*with spare-steam generating capacity to go to 12 MW*) and can easily scale incrementally in parallel to 100 MW and above. This is proprietary and patent-pending technology that can only be obtained from Dylan Energy and is significantly more efficient than existing technology.

Engineered Solution

Dylan's revolutionary patented technology is an engineered solution. Due to its extreme heat preservation technology, Dylan can produce electricity, on or off-grid, very efficiently and at a low cost. Dylan and its partners have identified rural communities that are getting gouged by the local utilities due to scarcity of supply and/or lack of public infrastructure. In many cases, there can be over 100 miles of transmission lines coming from a substation, which makes entire rural communities totally reliant on the volatility of these limitations and/or imbalances in the event of a single point of failure (i.e., loss of power

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Off-Grid Hydrogen Energy... Continued from page 15

Research and Development Facility. *Credit: Dylan Energy*

lines or transformers from lightning strike or weather, shortage of power at the end of the distribution lines, etc.) and without a redundancy loop or backup. Through a collaborative process, Dylan can design a properly sized system to allow clean, dependable, efficient and affordable energy to schools, local governments, businesses and the public, while also assisting in balancing electrical loads on the national grid.

Dylan's engineered solution uses its patented and tested technology for producing steam with a flexible fuel feedstock burner at significantly less BTUs per pound of steam than historical boilers. Based on certified engineer reports and testing of the Dylan steam generation technology, the results (input of fuel BTUs and output of steam at different pressures and temperatures) were then utilized to coordinate with engineers from other proven steam turbine technologies and gen-sets to establish an engineered solution as outlined in Figure 1. A 13 MW Gross Dylan System will net 12 MW of electricity after parasitic electricity is utilized to run the Dylan.

All production units are designed and constructed to meet or exceed:

1) Application and code requirements per the federal government or managing code department by location (specialized national and international code compliance by Bureau Veritas).

2) NEMA electrical codes.

3) Explosion proof per Class I, Group C/D, Div. II.

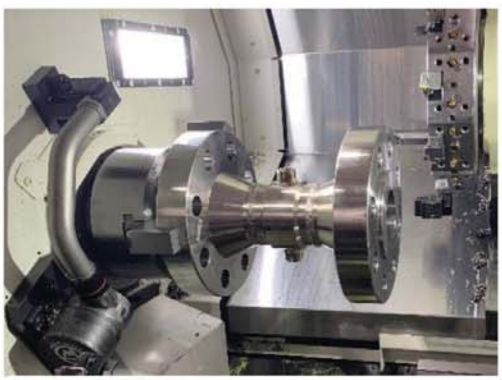
4) UL-approved control panels and any other codes that are applicable and as advised by the Dylan engineering department.

The Dylan Energy Solutions for Today's Energy Crisis:

- Clean, efficient, off-grid energy solution that maximizes the power of steam
- Researched, developed, patent and patent-pending Extreme Heat Preservation (EHP) engineering
- Constant, consistent, and reliable energy, regardless of time and conditions, unlike solar and wind
- Capable of powering neighborhoods, small towns and large-scale facilities, all off-grid
- Deliverable to remote areas to meet military, disaster relief, and third world needs
- Flexible clean fuel stocks (i.e., hydrogen, natural gas, LNG, etc.)
- Offers flexibility for use in conjunction with the grid to reduce electric load
- Offers scalable and customizable design based on energy needs
- Uses only 20% of the fuel that other energy sources require
- Meets California's high EPA standards
- Provides new jobs and replaces outdated, failing infrastructure






Partnership Brings Ground-Based, End-to-End and On-Site LH2 Infrastructure

by Sandra Lukey, Shine Group

Fabrum (CSA CSM), an industry leader in zero emissions transition, and British engineering consultancy Filton Systems Engineering (FSE) have joined forces with GKN Aerospace to help shift aviation towards hydrogen flight with end-to-end, hydrogen fuel system technology. This collaboration leverages FSE's aerospace capability in fuel systems and designing fuel, air, hydraulic, inerting and engine systems, with Fabrum's cryogenic and fuel tank storage technology and expertise in hydrogen fuel systems. GKN Aerospace is a multi-technology, tier 1 aerospace supplier. With 38 manufacturing locations in 12 countries, GKN serves more than 90% of the world's aircraft and engine manufacturers. The technology born from the collaboration is a game-changer for aviation innovators and researchers, enabling liquid hydrogen production on demand as close as possible to the point of use, storage and containment, and a paradigm shift from liquid hydrogen produced at large-scale plants and transported to the site of use.

Fabrum liquid hydrogen unit. *Credit: Fabrum*

The announcement coincides with FSE's upgrade to its existing hot and cold fuel test facility, which now offers both gaseous and liquid hydrogen in a commercial test environment in Bristol, England. The test facilities enable aerospace companies to produce and test liquid hydrogen as a fuel for hydrogen test flights, with FSE providing further support towards certification for flight status. Fabrum developed the ground-based, end-to-end liquid hydrogen production solution for the test facility, including hydrogen conditioning, liquefaction and liquid hydrogen storage. Further upgrades are planned, including combining Fabrum's cryogenic technologies with a membrane-free electrolyzer to remove dependence on gaseous hydrogen supply.

At the FSE test facility, a ground-based demonstrator of a 2.4 kW liquid hydrogen system has been jointly designed with GKN Aerospace and built by FSE under the Innovate, UK-funded Safe Flight project. This end-to-end system demonstrates the feasibility of liquid hydrogen as an aircraft fuel source and addresses many of the safety concerns raised by the introduction of such a novel fuel. The project has developed storage and dispensing technologies, optimized purging systems, and integrated fuel tank design with distribution on aircraft (including vaporization and conditioning) all the way through supplying a fuel cell with gaseous hydrogen at the required temperature and pressure over a range of electrical loads representative of a typical flight.

"The successful adoption of zero emission fuels requires both ground-based infrastructure developments for liquid hydrogen provisioning at airports and for the aircraft that will use it," explained Fabrum CEO Dr Ojas Mahapatra. "Point-of-use liquid hydrogen production is the most economical short- to medium-term solution to enable zero emission flight. With FSE, we're taking refuelling solutions to the aviation industry, right through to the onboard fuel cell."

Filton Systems Engineering Commercial Director Ben Richardson is proud to see FSE's hydrogen solutions become a reality. "We've combined our expertise to achieve significant liquid hydrogen milestones. Together, we've already delivered breakthrough test facilities with ready access to hydrogen on site and on demand. We see this as a vital asset to aerospace and other industrial sectors. If hydrogen is going to be developed as an alternate fuel source, there is now a facility in the UK where product development can be performed safely and with a continuous supply of liquid hydrogen."

Also coming onboard is US-based NI (previously National Instruments) to lend its expertise from involvement in recent space programs. "They are providing gauging and control hardware and methodologies to solve the challenges associated with the control and instrumentation of such a challenging and relatively unknown fuel," adds Richardson.

Fabrum's managing director and co-founder, Christopher Boyle, says the company's partnership with FSE is powerful as it leverages Fabrum's years of experience delivering components into aviation for future flight, including superconducting motors and battery technology for electric airplanes. "We're excited to now tie our aerospace and hydrogen systems together for actual flight and full certification with FSE. We've always believed hydrogen is the ideal alternative fuel for aviation."

How to Avoid a Tank Collapse

by Wil Ferch, principal of Nordstern Associates LLC, ferch.wil@gmail.com

The industrial gas industry produces the elemental components of "air" (nitrogen, oxygen, and argon) that are used in other industries as part of their processes. Once separated from air, each element exists as an extremely cold cryogenic temperature liquid. Typical liquid temperatures are −185° C. Large, field-erected tanks are used to store these liquids, and these tanks range from 100,000 gallons to over 2,000,000 gallons in size. API-620/Appendix Q standards, or their equivalent, are the routine guiding design documents. These tanks are built as flat-bottom, domed-top tanks, typically with stainless steel inner containers, carbon-steel outer containers, and the top/side insulation space between these tanks filled with three to five feet (radial dimension) of granular perlite insulation. The inner tank sits on a sandwich structure of Foamglas® insulation and concrete. During cooldown and commissioning, these tanks need to be dried, inerted, and brought down to very cold temperatures to allow product to be introduced. If done incorrectly during cooldown, these tanks risk vacuum collapse. This article discusses the details surrounding one such occurrence.

Case Study Specifics

A client with a 450,000-gallon liquid oxygen tank attempted cooldown using their historical procedures, which had been used successfully before. These tanks are often built to a design pressure of one to five psig, yet are very weak in any sort of vacuum condition. The tank must first be prepped for cooldown until it is sufficiently dry and inert. The typical process for cooldown is to introduce end-product into the tank, typically through a top connection, to lessen top-to-bottom temperature differential and metal stress, compared to bottom entry. Various methods can be employed, either cold gas entry or momentary 'spurts' of liquid, with defined interruption between applications to allow product vaporization and temperature normalization. In almost all cases, the supply line (and control valves) used for this step is very small (one to three inches in diameter), enabling good volumetric control

Example of a tank collapse. *Credit: European Industrial Gases Association*

of the incoming cold gas/liquid. In this case, however, they were forced to use a 12-inch diameter line. Externally, the client still used a small (two-inch diameter) line from the liquid source to the tank's 12-inch diameter line connection, believing this would provide the fine degree of control they needed for the incoming cold fluid. At some point during the cooldown process, the dome collapsed into itself and dropped nearly six feet. With inner and outer containers connected at the top/center through a manway, this connection caused both the outer and inner tank top dome to collapse, as the inner tank suffered the actual vacuum condition.

Probable Causes

There are a number of probable causes for the collapse. Differences of opinion exist between the client company and the external consulting service employed to investigate, but certainly any or all of the following were contributors:

- **Lack of operational discipline**—Tank pressures and temperatures were monitored by the control room throughout the process. Screen capture recordings of the process indicated that the tank suffered multiple dips into a vacuum condition prior to a large, final vacuum condition, which then caused the inner container to collapse. Staff did not mention any unusual conditions, but interviews with personnel indicated a major management push to get the work done, which was severely behind schedule.

- **An abnormally large internal supply line within the tank (12-inch diameter line)**—This more than likely accumulated a large volume (800 gallons) of cold liquid, rendering well-controlled smaller input volumes via the external two-inch diameter supply line ineffective. Small incremental spurts of liquid that were introduced could have vaporized and lifted a much larger quantity of stored liquid within this 12-inch line to spill into the main tank. It was found later that the lower tank penetration of this 12-inch line through the outer tank sidewall also showed excessive external ice accumulation, indicating insufficient insulation in this area and subsequent heat leak. Either heat leak or ineffective input liquid control contributed to unusually large amounts of liquid entering the inner tank during cooldown.

- **Cold fluid applied to a warm tank causes the fluid to vaporize and create pressure**—This continues but not throughout the process. At some point, there is a cold-gas atmosphere that exists within the tank, and any (excessive) subsequent addition of liquid causes the gas contents to condense, which would vacuum-collapse the tank instantaneously. Although the tank was protected by vacuum relief valves, the instantaneous nature of the condensation/vacuum condition creates an enormous flow requirement that no vacuum relief valve (regardless of size) can process. To illustrate the violence and uncontrolled nature of the collapse, there is a YouTube film clip showing a similar (purposeful) tank collapse of a railway tanker: **https://youtu.be/2WJVHtF8GwI**

Application

Although this case study was for an industrial gas product application, the same failure can occur in other industries and products, such as LNG (a cryogenic fluid at − 162° C) and various oil/gas scenarios where large tanks are often steam-cleaned internally before poor weather affects the plant site.

MicroSensor Provides Options for Cryogenic Storage Tank Monitoring

by Emily Magee, freelance writer

Due to the rapid development of the industrial sector, various industrial gases, such as nitrogen, oxygen, carbon dioxide, argon, hydrogen, helium and acetylene, which are gaseous at normal temperatures and serve as the foundational raw materials for contemporary industry, are now completely indispensable to the operation process. Industrial gases have a broad range of applications in a variety of sectors, including metallurgy, steel, medical treatment, petroleum, chemical industry, electronics, environmental protection, building materials, glass, construction, food and beverage equipment, just to name a few. However, gas requires stricter regulations for technologies related to preparation, container handling, storage and transportation, due to the hazardous outcomes when gas is stored incorrectly and unmonitored. Such faulty conditions can lead to disasters, such as excessive pressure and release of vapors that can travel to an ignition source.

Real-time monitoring of the pressure values in the manufacturing, storage, supply, and use of industrial gases is accomplished through a variety of pressure transmitters, differential pressure transmitters, and other sensing and monitoring instruments. Gas production equipment and storage tanks are also realized through supporting systems. To guarantee safe production, enhance process management and increase automation, gas cylinders must be automatically monitored and adjusted to maintain pressure values within the typical range.

Cryogenic Storage Tank Monitoring

Cryogenic tanks are used in cases where large quantities of gas need to be stored in liquid form. The tank is divided into two fundamental parts, an inner and outer vessel, insulated from one another by a combination of insulating materials. Of utmost importance to the safety of the tank is a pressure regulation system. Its purpose is to ensure that the cryogenic tank always operates at a constant pressure that is set with the user's needs in mind.

A pressure regulation system's purpose is to ensure that the cryogenic tank always operates at a constant pressure that is set with the user's needs in mind. *Credit: MicroSensor Co., Ltd.*

The MPM489FL pressure transmitter.
Credit: MicroSensor Co., Ltd.

When monitoring the storage tank, the pressure transmitter is primarily used to gauge the liquid level of liquid gas. The most popular and reliable method for determining the liquid level in cryogenic storage tanks is differential pressure measurement, using a differential pressure transmitter to measure the pressure difference between the tank's top and bottom. The height of the liquid level will ultimately be calculated from the recorded pressure value. To verify that the system is operating safely, the pressure sensor may also be used to detect the tank's absolute pressure as well as the pressure before and after the cryopump.

MicroSensor Corporation, a research and development group of pressure sensors and transmitters for a variety of industries, typically employs an MDM4901FL differential pressure transmitter for measuring oxygen pressure. The device uses an isolation diaphragm made of stainless steel 316L that is filled with fluorinated oil for enhanced stability and safety. The MPM489FL pressure transmitter is also available for use in this application. Fluorinated oil is used in the product's sensing component, and the grease-prohibited production method is used. It can detect and gauge absolute pressure. With short-circuit and reverse polarity protection, the MPM489FL is secure, dependable and simple to use.

A dispersed silicon piezoresistive differential pressure sensor, as well as a stainless steel 316L isolation diaphragm, are both components of the MDM4902FL I2C digital differential pressure transmitter. The product has a fluorinated oil filling for improved stability, a wide operating temperature range, high accuracy, steady performance and easy adjustment. The docking and expansion are made simple by the I2C digital output standard. A high-precision, high-stability differential pressure transmitter with a broad range and intelligent output is the MDM3051S-DP transmitter. It can be used to measure the flow of a medium like gas or steam as well as the liquid level, density, pressure, and flow.

Since the 1970s, MicroSensor Corporation has engaged in the research and development of pressure sensors and transmitters designed around piezoresistive measurement principles. Using its rich experience, MicroSensor provides intelligent systems to sectors as diverse as industrial automation, hybrid and electric vehicles, oil and gas, marine, energy and utilities, communications and many others. **www.microsensorcorp.com**

Exploring SLS Rocket Engines and Artemis I

by Lee Mohon, NASA staff writer

The Space Launch System (SLS) rocket engines are high-performance machines that are exposed to extremely low temperatures, extremely high temperatures and pressures during fueling and flight. During launch, more than 700,000 gallons of liquid hydrogen and liquid oxygen must be delivered at a consistent temperature and pressure from the SLS core stage tanks to the four RS-25 engines. Liquid hydrogen fuel flows into the engines at the cryogenic temperatures of −423° F, and liquid oxygen at −297° F.

Before this massive amount of fuel is delivered to the engines, SLS engineers chill down the engines to thermally condition them to receive the propellant. The engine thermal conditioning is "kick-started" by delivering liquid hydrogen to the engines at the same time the liquid hydrogen core stage tank is being filled. This procedure was developed during core stage Green Run testing when all four engines were chilled and ignited, just as they are during launch. By doing this early in the launch countdown, engineers can evaluate data and ensure that the engine components are sufficiently saturated with super cold liquid hydrogen that chills them before they proceeded with terminal countdown leading to launch.

Cooling down the engines in advance, a process called prechill, is an important step before launch as it ensures that critical engine components, such as pump bearings, are chilled down to the temperatures required for operation. The core stage "bleed valve" allows hydrogen to flow through the engines and thermally condition them by starting to chill them down. Via the bleed valve, the propellants flow through the engines' turbopumps, bearings, nozzles and other components without being combusted. It is important that the cryogenic liquid hydrogen is maintained at a consistent temperature as it flows through the engine turbopumps. If liquid hydrogen warms, it turns to gas and can form bubbles that cause an issue with thermally conditioning the engine.

During engine chilling, engineers evaluate multiple sources of data from the SLS core stage, the engines and the ground systems, including pressure and thermal data, to ensure the engines are thermally conditioned and ready to be filled with propellant and ignited during the terminal countdown right before launch. During the terminal countdown starting at T-30 seconds, the flight computers are controlling the rocket and monitoring all its systems, and the launch is controlled by the autonomous launch sequencer, or ALS. The flight computers monitor data from numerous flight data sensors and will stop the launch if they detect that the engines are not thermally conditioned and ready for ignition.

The four RS-25 engines on NASA's Space Launch System rocket produce more than 2 million pounds of thrust. The four RS-25 engines last fired during the core stage Green Run hot-fire test at NASA's Stennis Space Center near Bay St. Louis, Miss., in March 2021. *Credit: NASA/Robert Markowitz*

Artemis I is a flight test to launch SLS and send Orion beyond the moon and back to Earth before future missions with a crew. After standing down on the Artemis I launch attempt Saturday, September 3, 2022, due to a hydrogen leak, teams decided to replace the quick disconnect interface seal between the liquid hydrogen fuel feed line on the mobile launcher and the SLS rocket while at the launch pad. On September 21, the launch director confirmed all objectives had been met for the cryogenic demonstration test, and teams began to proceed with critical safing activities and preparations for draining the rocket's tanks.

The four main objectives for the demonstration included assessing the repair to address the hydrogen leak identified on the previous launch attempt, loading propellants into the rocket's tanks using new procedures, conducting the kick-start bleed, and performing a pre-pressurization test. The new cryogenic loading procedures and ground automation were designed to transition temperature and pressures slowly during tanking to reduce the likelihood of leaks that could be caused by rapid changes in temperature or pressure. After encountering the leak early in the operation, teams further reduced loading pressures to troubleshoot the issue and proceed with the demonstration test. The pre-pressurization test enabled engineers to calibrate the settings used for conditioning the engines during the terminal count and validate timelines in advance to reduce schedule risk during the countdown on launch day.

At the time of this publication, NASA targeted the next launch attempt of the Artemis I mission for Monday, Nov. 14, with liftoff of the SLS rocket carrying the Orion spacecraft planned during a 69-minute launch window that opens at 12:07 a.m. EST. All information used in this article is attributed to NASA.

Cool Cryo Guests

by Nils Tellier, PE, EPSIM Corporation (www.epsim.us)

Our Cool Cryo Guest feature highlights articles submitted by industry experts. We encourage you to send in your work for possible inclusion in a future issue. For consideration, please contact Anne DiPaola at editor@cryogenicsociety.org.

Limited Series: Tips for Cryogenic Air Separation Units

Welcome to this new limited-series column in ***Cold Facts***. The purpose of this series of articles is to provide tips for cryogenic air separation units (ASUs), particularly in consideration of increasingly high energy costs. Our goal is to help plant owners and operators locate and solve issues that might improve the reliability, production or energy efficiency of their plants. Each column will address a specific ASU area, from air compression and purification to cold box product compression and storage.

Air compression tips

Apart from the recycle compressor on a liquefier, the main air compressor is the largest energy consumer in an ASU. Its purpose is twofold: one, increase the pressure of the feed air to meet the operating pressure of the main condenser in the cold box, and two, control the mass flow of air to the cold box. Performance degradation of the main air compressor results in higher power bills and possibly lower oxygen production.

Figure 1: Two-stage inlet air filter for a 120 TPD ASU. *Credit: Nils Tellier*

Low suction pressure

Low suction pressure forces the air compressor to work harder and burn more energy to meet the desired discharge pressure and flow. Starting with the inlet, a typical two-stage filter has a pressure drop of the order of three in WC. If the pressure drop is allowed to reach 10 in WC, the compressor power consumption will increase by approximately one percent. The main causes are design or maintenance issues of the inlet air filter and suction line.

Given today's high cost of energy, it is worth revisiting the inlet filter maintenance schedule, its design and sizing. Likewise, it is possible to derive the pressure drop across the entire suction piping by counting the number of elbows on the suction line and checking the piping length and diameter.

Each inch of water pressure drop has a power cost impact. At 15 cents/kWh, reducing the suction pressure drop by three in WC can save annually over $5,000 per MW of compressor power. While in most cases the compressor inlet filter and piping are designed and sized adequately, there may be instances where a small capital upgrade can yield long-term savings.

High discharge pressure

The air compressor discharge pressure is dictated by the main condenser operating pressure, plus any obstacle on the warm air circuit such as the aftercooler, the chiller tower, the front-end purification or a cold box isolation valve. Reducing the pressure drop between the compressor discharge and the lower column in the cold box yields significant energy savings.

On the maintenance and operation, the most obvious areas are the compressor inter- and aftercoolers, the chiller tower (if applicable), the adsorbers' media and dust filters and any valve on the air circuit to the cold box. Chiller towers, when running too cold, can plug up because of the precipitation of calcium carbonate (CaCO3) on the packing rings. Adsorber media, alumina and molecular sieve restrict airflow over time as they turn to dust.

On the capital aspect, it may be worthwhile reconsidering equipment pressure drops that were industry-standard years ago and reviewing the cost/benefit of upgrading some equipment like the front-end purification.

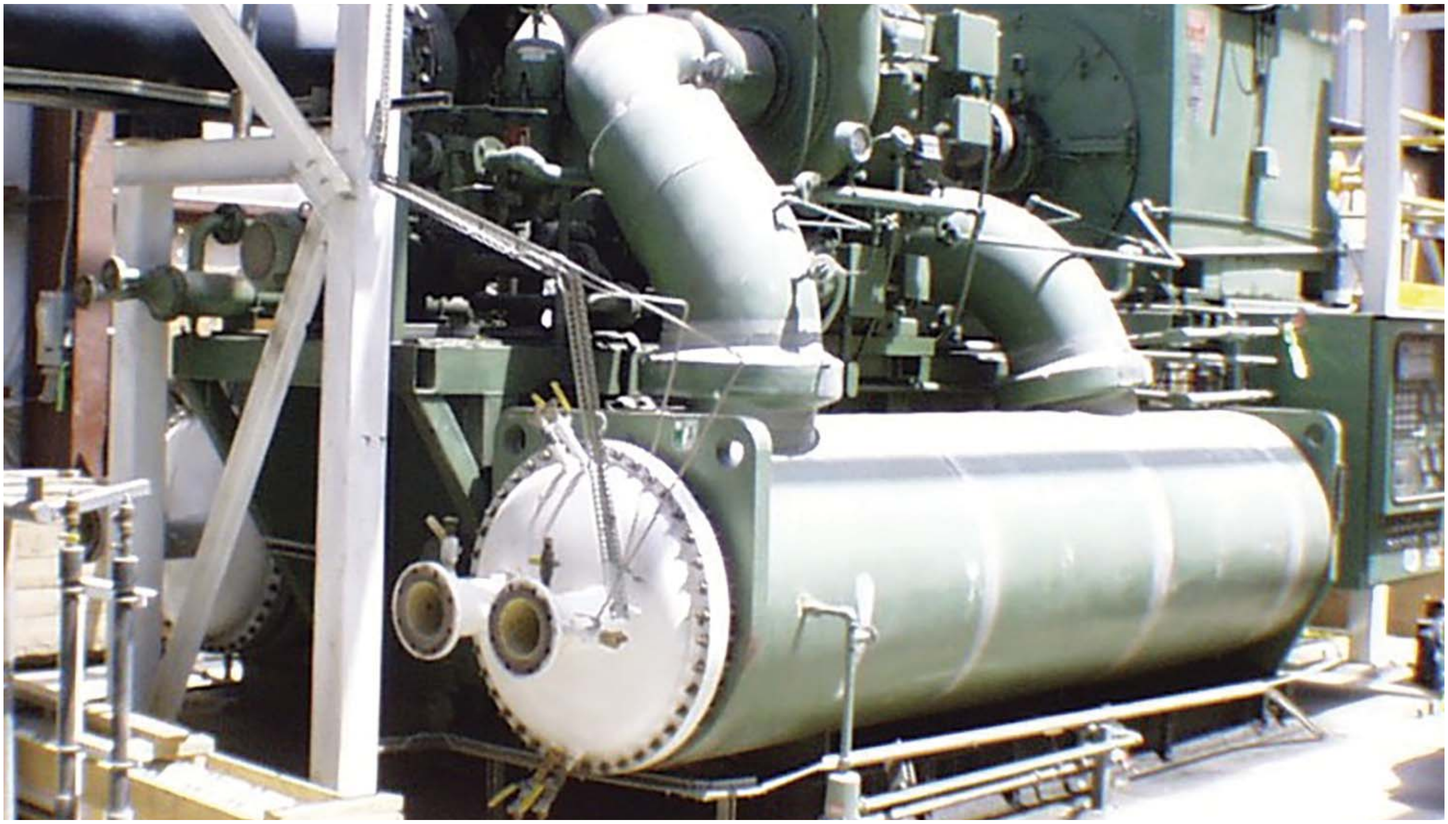


Figure 2: ASU main air compressor during installation. *Credit: Nils Tellier*

An excessive discharge pressure will open the surge valve and create parasitic air loss.

Air Loss

Air loss is another energy cost driver. Some leakage is necessary by design—for example, seal air for the labyrinth seals, instrument air for the valve actuators and vented air during the adsorbers depressurization. The former two could be lessened by tapping into an alternative source of dry gas such as medium-pressure nitrogen, if available. The latter can be reduced by extending the adsorbers' cycle time if possible.

Accidental air losses include broken cooler tubes after the compressor third stage, where air leaks inconspicuously into the cooling water, condensate traps and bypasses, piping flanges and valve glands.

An additional source of a significant air leak may be the vent valve for surge protection. If the valve is located before the aftercooler, a telltale indication would be a high-silencer temperature. Potential reasons that can lead to a leaking surge valve include: seat out of adjustment or actuator out of calibration, surge control, acting prematurely, or excessive discharge pressure. In the latter case, the problem may be intermittent, as in during the adsorbers switch.

Conclusion

This qualitative review on the energy optimization of an ASU front end is intended to help plant owners/operators identify opportunities for energy cost reductions with minimal capital expenditures. My next article will address additional tips on the air compressor.

Cryo Bios

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

William M. Fairbank

William M. Fairbank

Born February 24, 1917

Died September 30, 1989
Palo Alto, California

William Fairbank was an extremely inventive physicist. In addition to making fundamental discoveries in cryogenics and superconductivity, his studies led to a number of important technological applications in these fields. As a professor, Fairbank also had a large impact on science through the students whom he trained and inspired during his career in academia.

Fairbank was born in Minneapolis and earned his undergraduate degree in chemistry at Whitman College in Washington state. Upon graduation in 1939, he started graduate studies in physics at the University of Washington. In 1941, with the entry of the US into World War II, he interrupted his studies and moved to Massachusetts Institute of Technology to assist in the development of RADAR systems. After the end of the war, he resumed his studies, moving to Yale University in the areas of cryogenics and superconductivity. While at Yale, Fairbank, working with his brother Henry and Yale Professor C.T. Lane, made one of the first detections of second sound in He II. The first detection of second sound was made in Moscow by V. Peshkov a couple of years earlier. (Recall that second sound had been predicted by L. Tisza (***Cold Facts*** Vol. 37, #4) as a result of his two-fluid model of He II.)

A notable aspect of the Yale team's experiment was the method for detecting second sound. Rather than looking for temperature waves like Peshkov did, the team realized that the temperature waves of second sound would produce periodic evaporations of vapor at the surface of a He II bath. The team then detected these bursts of vapor acoustically with a microphone in the helium vapor space. The use of clever techniques to make difficult precision measurements would be a hallmark of Fairbank's career. Fairbank's thesis topic was not second sound but rather it was the surface resistance of superconducting tin at microwave frequencies. This topic, which is a nice extension of his RADAR work at MIT, would become more important once he moved to Stanford University. Fairbank earned his Ph.D. in Physics in 1948 and became an assistant professor of physics at Amherst College.

Fairbank was recruited to Duke University as an associate professor, championed by Fritz London (***Cold Facts*** Vol. 38, #3), then also at Duke. While at Duke, Fairbank and his team made a number of fundamental discoveries in cryogenics. They showed that a mixture of ^{3}He and ^{4}He will spontaneously separate into a ^{3}He-rich zone atop a ^{4}He-rich zone at 0.9 K. This development was vital to the creation of dilution refrigerators. Fairbank made precise measurements of the specific heat of helium at the transition point to He II. This point is known as the lambda point due to the shape of the specific heat versus temperature curve at the transition temperature of 2.2 K. The specific heat rises to a very sharp point at this temperature, and it was this very narrow region that Fairbank and his team measured precisely. Fairbank also made measurements of the nuclear magnetic susceptibility of ^{3}He, continued work on second sound and contributed to a hydrogen bubble chamber particle detector design while at Duke.

In 1959, Fairbank moved to Stanford University where he remained for the rest of his career. His research at Stanford was extremely productive, encompassing topics such as superconductivity, free electron lasers, biophysics, gravitational wave detectors and additional studies in He II and solid ^{3}He. Three examples of his research are illustrative.

The first example of Fairbank's illustrative work at Stanford is what is likely Fairbank's most fundamental discovery: magnetic flux quantization in a superconducting ring. (This was also discovered nearly simultaneously by a group in Germany.) The second example is an extension of Fairbank's earlier work on superconducting radiofrequency cavities. This work led to the development of the world's first superconducting linear accelerator (SCA) by a Stanford team including Fairbank, T. Smith, P. Wilson, H. Schwettman and M. McAshan. The SCA was the forerunner of much larger machines built later at Jefferson Lab, DESY and SNS. The last example of his illustrative work at Stanford is Gravity Probe B (GPB). This experiment is one of the longest and most difficult projects in which Fairbank participated.

The objective of GPB was to use a satellite to make precision measurements of two predictions from Einstein's theory of general relativity. Both of the effects studied result from interaction of Earth with spacetime. The presence of the earth deforms spacetime, in effect causing gravity, and the rotation of the earth drags some spacetime with it. The concept of GPB is straightforward: the GPB satellite contains a telescope that is attached to gyroscopes. The spin axis of these gyroscopes is aligned with the guide star to which the telescope is pointed. Classical physics predicts that if the gyroscopes do not experience any external forces, their spin axis will remain aligned with the star. Any deviations from this would be a result of general relativity.

While the GPB concept was straightforward, the implementation was not—particularly the requirement that the gyroscopes experience no external forces. The effect of general relativity is quite small, so any possible external forces, as well as instrument noise, had to be made very close to zero. GPB was first proposed to NASA by Leonard Schiff, Robert Cannon and William Fairbank in 1962. Shortly afterwards, they were joined at Stanford by Francis Everitt. GPB was not launched until 2004. Between 1962 and 2004, several hundred people contributed to the GPB project at Stanford and Lockheed Martin. During this time, important technological developments were made in areas including superconducting films, the use of helium in space, superconducting quantum interference devices (SQUIDS), development of near perfect spherical gyroscopes and advanced GPS technology. At its heart, GPB was a cryogenic system containing 2,441 liters of superfluid helium at 1.8 K. (See Figure 1.)

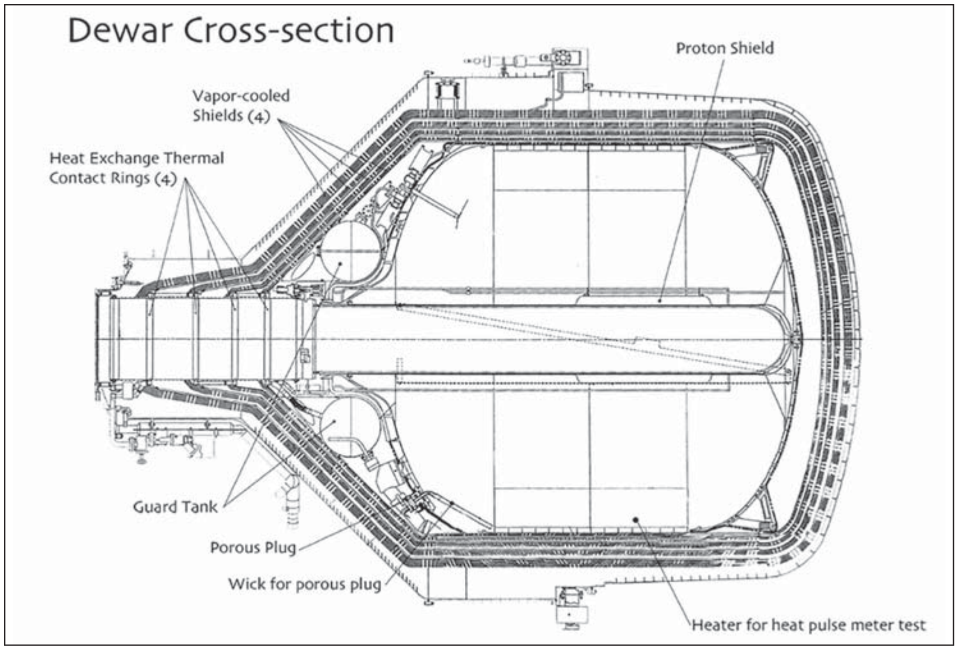


***Figure 1** **Cross-section of the Gravity Probe B dewar. Note the use of porous plugs for venting into space and the multiple vapor-cooled thermal shields. This dewar contained approximately 2,400 liters of He II.** Credit: Stanford University*

One of GPB's most important contributions was the training of scientific staff. A total of 79 Ph.D. dissertations at Stanford and 13 from other institutes in a range of topics are associated with GPB. In addition, many physicists, engineers and postdocs gained experience on the GPB project. GPB had a successful 17-month science mission and measured the predicted deformation of spacetime to within a 0.25% precision and the dragging of spacetime by the rotating Earth to within a 19% precision.

During his career, Professor Fairbank graduated 58 Ph.D. students at Duke and Stanford. His distinctions included being elected to the National Academy of Sciences and winning the Fritz London Prize. In celebration of Fairbank's 65th birthday, his colleagues organized a seminar on his work. The resulting talks were collected into the book *Near Zero: New Frontiers of Physics* (J. D. Fairbank, B. S. Deaver, C. W. F. Everitt, P. F. Michelson, eds. Freeman, 1988), which provides a good sense of Fairbank's interests and accomplishments.

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

All the Hydrogen Miracles

In 2009, Department of Energy Secretary and Nobel Laureate Steven Chu slammed hydrogen fuel technology in an interview with the ***MIT Technology Review***, "...if you need four miracles, that's unlikely: saints only need three miracles."[1] Shortly after, he attempted to eliminate the hydrogen fuel technology office — this was the world I entered into hydrogen research. Nearly a decade later, it suddenly feels like hydrogen is getting a chance. But many are rightly skeptical. Given the focus of this ***Cold Facts*** on liquid hydrogen, it's time to take stock of the hydrogen miracles already underway and the miracles we're still waiting for. The question comes down to how long we'll be waiting.

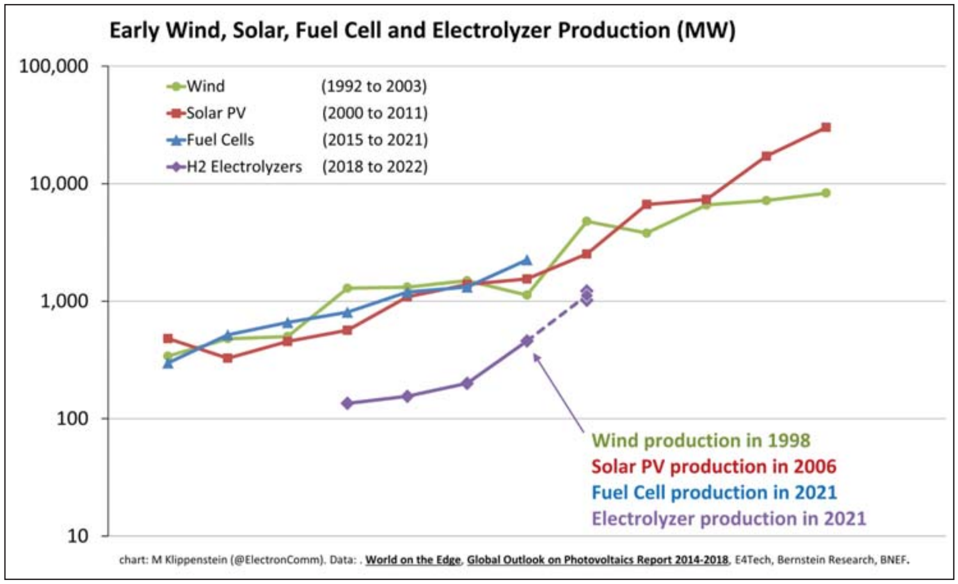


***Figure 1:** Year-over-year increase in wind, solar, fuel cell and electrolyzer production capacity.* *Credit: Matthew Klippenstein, Canadian Hydrogen Fuel Cell Association*

Miracle #1: Green Liquid Hydrogen Production

In 2009, Steven Chu was a little misleading when he said the majority of the hydrogen we get is from fossil fuels. Approximately 80% of all US hydrogen production is used in petroleum refining and ammonia production, so of course hydrogen was fossil-based.[2] The seismic shift that has happened since 2009 is the ramp rate of green hydrogen electrolysis from water and renewable electricity, shown in Figure 1. Year over year, the increase in adoption is starting to outpace the rapid growth in wind and solar power experienced over the first decade. With large-scale investments into regional hydrogen hubs coming over the next few years, this trend is anticipated to accelerate. How long before the miracle of the majority of our liquid hydrogen being green? If Plug Power's targets are realized: 2028.[3] Any bets on what will happen if the DOE succeeds in its primary EarthShot to realize 1 kg of green hydrogen production for $1 in 1 decade?

Miracle #2: Liquid Hydrogen Storage and Delivery

In 2010, approximately 80-90% of small merchant hydrogen distribution was through cryogenic liquid tanker trucks.[4] With over 50 years of liquid hydrogen tanker trucks operating over US highways, it's shocking to learn that not a single death has been associated with liquid hydrogen.[5] It's just as shocking for many to learn that in 2020, approximately 30% of the nation's groceries were moved via hydrogen fuel cell forklifts powered by this liquid hydrogen.[6] It's easy to see why most commercial hydrogen is distributed in this form. What's not easy to see is why Chu and others were avoiding mention of liquid hydrogen back in 2009. Was it the fact that liquefaction consumes 30% of the energy content of the fuel? Was it the boiloff losses that occur with a stored cryogen? Was it the difficulties of transferring, sloshing and ullage volume collapse? Regardless, I'm optimistic that we'll see fundamental research opportunities for hydrogen liquefaction and zero-vent storage in the coming years. The theoretical minimum liquefaction energy for hydrogen is 7-11% of the energy content of the fuel, which is in line with petroleum refinery efficiencies.[7] Liquid hydrogen origami fuel bladders could eliminate sloshing problems.[8] Small-scale and efficient coolers and liquefiers could provide enough active cooling to eliminate venting.[9] I'm optimistic that in the next 5-10 years we'll realize the miracle of zero-vent, zero-loss liquid hydrogen storage and tankage systems. We've been neglecting basic research into liquid hydrogen for so long that a little bit is likely to go a long way.

Miracle #3: Convenient Liquid Hydrogen Testing

Just last month, I was in a planning meeting where the inconveniences of liquid hydrogen testing were brought up as a primary limitation to wide-scale adoption. In 2009, it was true that to be in the liquid hydrogen game you needed a 16,000-gallon storage dewar parked outside and a six-figure budget. This is no longer the case. In July, a team from my lab drove an eight-foot cube of a shipping container down to a field in Oregon, combined water and electricity to make liquid hydrogen, transferred the liquid hydrogen into a 3D-printed fuel tank and flew a drone into the sky.[10] Anywhere you have electricity and water you can now make liquid hydrogen. That might make liquid hydrogen the most convenient fuel over the majority of our planet.

Figure 2: Dawn of convenient liquid hydrogen at the Pendleton, Ore. Unmanned Aerial Systems flight range.
Credit: of Zach Zoller, Insitu

Miracle #4: Public Acceptance of Liquid Hydrogen

This last miracle may be the most daunting given the recent history, but reasons for optimism exist. Washington state recently passed two bills related to hydrogen technology, with the entire House and Senate unanimously approving the bills with all but two nay votes.[11] It may be that hydrogen is one of the few topics that politicians can agree upon these days. Conversations with many I've had in industry over the years are starting to quietly change as well.

How long before the miracle of green liquid hydrogen powering humanity? Time will tell. It's a breeze to imagine floating wind turbines, below the horizon on the ocean, slowly accumulating liquid hydrogen from seawater. It's uplifting to think about liquid-hydrogen-fueled aircraft, trains, trucks and shipping vessels. It's reassuring to think about zero-boiloff liquid hydrogen as backup power for data centers, hospitals and other critical infrastructure. I know this for sure: miracles have had nothing to do with hydrogen's technological progression over the last decade. Liquid hydrogen has been working all along, despite little federal investment. It's time to invest in the fundamental research necessary to make liquid hydrogen technology the best it can be.

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by Matthew Deans, Wesley Johnson, Ed Canavan, Weibo Chen, and Jason Hartwig

Small Business Opportunities in Cryogenics at NASA

NASA invests in multiple programs that advance new cryogenic technologies. Two such programs, the NASA Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs [1], are specifically oriented toward small businesses and small businesses partnering with research institutions. Phase I SBIR/STTR contract awards for idea generation may lead to Phase II prototype developments and to other continued development mechanisms/awards, demonstrations, infusions and commercialization opportunities.

Recent SBIR/STTR solicitations have included calls for a range of cryogenic technologies:

- Propulsion applications, such as Z10.01 Cryogenic Fluid Management
- In-space cryogenic instrument applications, such as S16.07 Cryogenic Systems for Sensors and Detectors
- Non-Earth surface processing of industrial gasses, such as T14.01 Advanced Concepts for Lunar and Martian Propellant Production, Storage, Transfer and Usage
- Mechanisms and electronics that operate in cryogenic environments, as well as applications for cryogenic fuels on aircraft, are among other needs that appear as well.

Historically, NASA releases new SBIR and STTR Phase I solicitations annually [2], opening in January with submissions due about 60 days later. In 2022, Phase I award selections were announced May 26. Phase II awards are typically awarded in the calendar year following the year of the Phase I solicitation release. Past Phase I and Phase II awardees can be found in the SBIR and STTR award search tools [3].

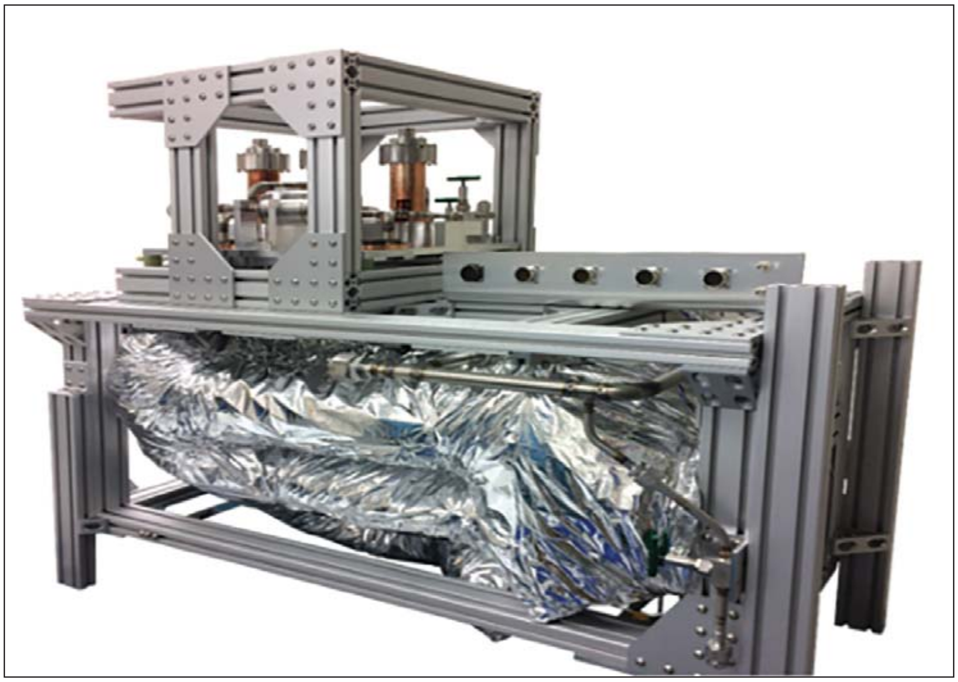

Figure 1: 20W / 20 K cryocooler in Creare's clean room. *Credit: Creare, Inc*

Beyond Phase II, NASA SBIR/STTR awardees are eligible for various mechanisms to continue to develop, infuse and commercialize technologies. Many of these mechanisms provide cost-matching, where small businesses obtain one or more investors from NASA or other government agency projects/programs, industry (for aerospace or commercial applications), or venture capital investors and then apply for 1:1 cost matching from NASA SBIR/STTR. These awards can be an effective way to continue the development of the technology for NASA's needs, while also broadening and advancing it for a range of applications. Cryogenic/fluid technologies started within the SBIR/STTR pipeline have not only seen use in NASA programs and across the aerospace industry, but they have also had recent crosscutting and spin-off applications in terrestrial transportation and

Figure 2: Integrated multilayer insulation being installed on a tank at NASA Glenn Research Center. *Credit: NASA*

industrial manufacturing applications, among others. For more details on these opportunities, see the SBIR website [4].

Additionally, because selection under the Phase I solicitation satisfies competition requirements, SBIR/STTR awardees are eligible for further awards related to their SBIR/STTR technologies on a sole source basis. This feature significantly simplifies and shortens the process and lead time for a follow-on contract award. Recent developments funded through these mechanisms include high capacity cryocoolers at both 20 K (This is discussed in ***Cold Facts***, vol 4 – see image in Figure 1) and 90 K from Creare; integrated multilayer insulation (see Figure 2) systems from Quest Thermal Group; and radiation-hardened high power, low-cost cryocooler electronics (HP-LCCE) from Iris Technology Corporation (see Figure 3).

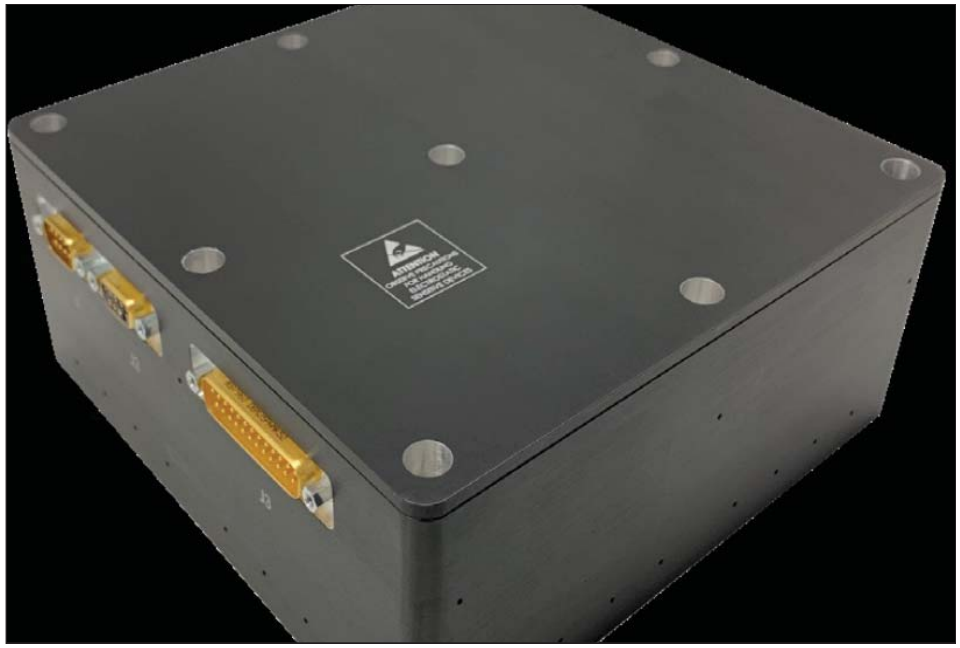

Figure 3: Iris Technology Corporation's HP-LCCE for Regenerative Cryocoolers. The nominal output power is 200W and the mass of the controller is about 1.8 kg. The control electronics is designed to tolerate radiation levels up to100 krad.
Credit: IRIS Technology

With support from NASA SBIR, Iris Technology developed affordable radiation-hardened control electronics for space cryocoolers [5]. In addition to the basic function of converting bus DC power to appropriate AC power to drive the linear compressors, the control electronics has input power ripple filtering to reduce the electric disturbance to the input power bus and active vibration control technology to reduce cryocooler exported vibrations by adjusting the driving voltage to one of the opposing pistons in the compressor assembly. The HP-LCCE is independent of the cryocooler type, allowing it to be integrated with cryocoolers from multiple manufacturers. Iris' CCEs have been selected to drive the cryocoolers for the Mapping Imaging Spectrometer (MISE) and Mass Spectrometer in NASA's Europa Clipper mission. Iris' CCE is also selected for the cryocooler in NASA's High-resolution Volatiles and Minerals Moon Mapper (HVM3) mission.

Similarly, with support from NASA SBIR, Quest Thermal Group, along with their partners, Ball Aerospace, developed the novel integrated multilayer insulation (IMLI) system [6]. IMLI and its derivatives rely on discrete spacer technologies as opposed to netting to keep the reflective shields within the MLI blanket separated. This yields a more structurally rigid blanket compared to a traditional blanket and can be used to support thermal shields within blankets or even lightweight vacuum jacketed concepts. IMLI has flown on multiple NASA missions, including the Robotic Refueling Mission #3, Lucy (mission to the asteroid belt and several asteroids caught in Jupiter's orbit), and Green Propellant Infusion Mission. Quest has also partnered with several prime contractors supporting various stages of NASA's Human Lander System.

NASA's SBIR program is an excellent path for small businesses to engage with NASA to address specific high-priority technology gaps while supplementing their internal research and development activities, helping them bring new products to market.

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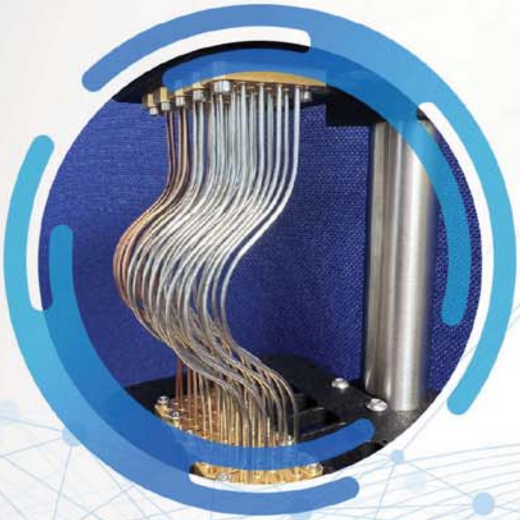

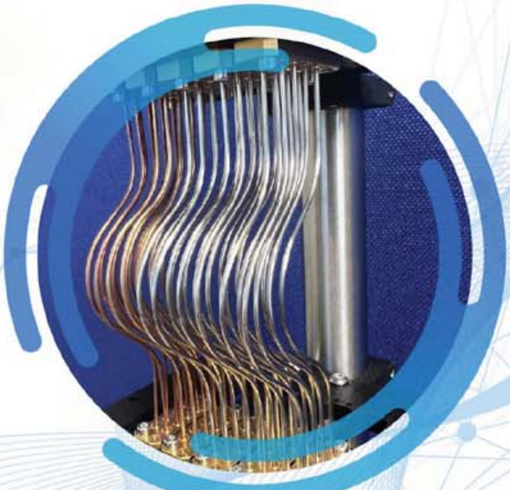

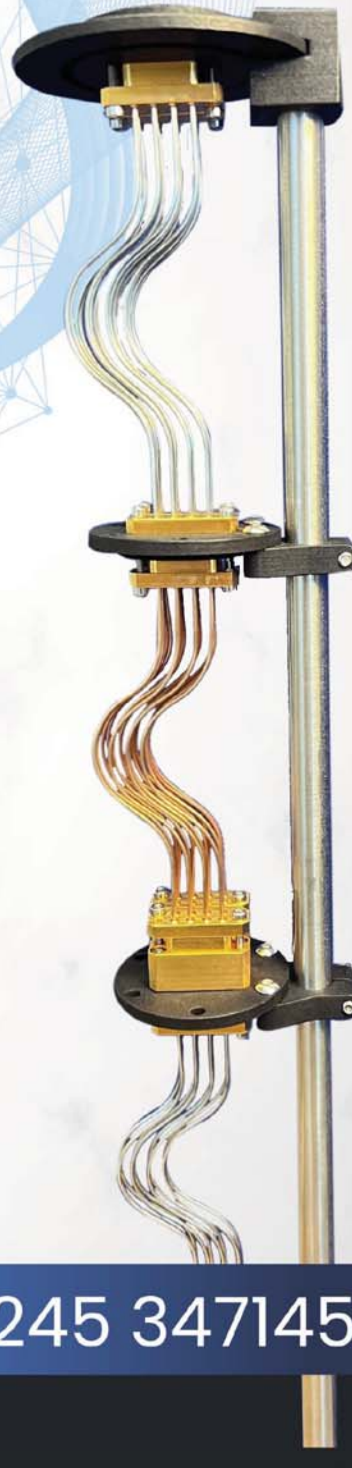

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Hydrogen Liquefaction System Developed from Stirling Cryogenerators

by Francesco Dioguardi

***2019 Stirling Cryogenics hydrogen reliquefier for Cold Neutron Source at RID**. Credit: Stirling Cryogenics*

Stirling cryogenerators have been widely used since the 1960s and 1970s for the production of LH_2 at various institutes and research laboratories all over the world. In materials sciences, small-scale production was used to study the properties and behavior of LH_2 and its effect on materials.

In scientific devices, Stirling cryogenerators have been used as LH_2 reliquefiers to create cold neutron sources and to run H_2/D2 distillation columns. Today, some of these vintage machines are still in use. For example, the one at the National Institute of Cryogenic and Isotope Separation in Romania was installed in 1973 and still operates today.

With the accelerated interest in a carbon-free society over the last few years, hydrogen and liquid hydrogen have come to the center of attention again. Many large, green H_2 gas production facilities are being built or planned, and many for liquefaction purposes. Based on the same trusted two-stage Stirling cryogenerators used for more than 40 years, Stirling Cryogenics has designed a range of system sizes, from a small laboratory-scale unit producing 5 kg/day of LH_2 and up to 400 kg/day containerized systems for industrial scale – all only needing H_2 gas and electric power as input, producing converted para LH_2 into a transfer vessel.

Hydrogen Liquefier Concept

The two-stage cryogenerator is available as a one-cylinder machine for liquefaction of 5 kg/day and as a four-cylinder machine for 30 kg/day of LH_2. Incoming hydrogen gas is cooled to 80 K in the first stage and then liquefied at 20 K in the second stage. The liquid flows into a transfer vessel by gravity, from which the LH_2 is transferred to the storage tank. A Stirling Cryogenics LH_2 system will include all necessary internal piping, instrumentation, a transfer vessel and system control. All systems are built according to ATEX or other relevant coding. Optionally, catalytic ortho-para conversion, containerization and GH_2 inlet gas purification can be offered. Stirling cryogenerators can also be supplied as modules to a system integrator, building the total system with the cryogenerators as the core.

For larger capacities, a number of cryogenerators are put in parallel. The design concept of the larger Stirling systems is that all cryogenerators will run independently of each other. Should one of the cryogenerators be offline, the liquefaction capacity of the other machines remains available. The second advantage is that the liquefaction capacity is easily adaptable to the momentary availability of H_2. The number of operational cryogenerators can easily be adapted by just turning them on or off. Because a Stirling cryogenerator will start producing LH_2 within 20 minutes of warm start-up, the system can react swiftly when GH_2 flow increases again.

LH2 Boiloff Reliquefaction

Besides the production of LH_2 from H_2 gas production, the two-stage Stirling cryogenerator can also be used as a reliquefier for boiloff gas of a storage tank, preventing the blow-off of cold GH_2. For such a setup, the cold GH_2 is not fed to the cryogenerator, but the 20 K cooling power is transported into the storage tank.

Transport of the cooling power is done using Stirling's CryoFans, creating a cold He gas loop connecting the 20 K heat exchanger of the cryogenerator with the reliquefaction heat exchanger built in the top side of the LH_2 vessel. The evaporated GH_2 will then remain inside the vessel.

Stirling Cryogenics is available to discuss the design set-up of a project-specific Stirling system for LH_2 reliquefaction and BOG systems. **www.stirlingcryogenics.eu**

Paragraf is Changing the Game with Cryogenic Hall Sensors

by Matt Enderle, Paragraf Communications

Due to limitations in size and power dissipation, many prevalent measurement methods are incompatible with low temperature applications. Hall effect sensors have emerged as the superior option because of their compact size and low-power requirement. Until now, conventional Hall sensors have themselves been limited by material capabilities and the quantum Hall effect (QHE). Paragraf®'s Cryogenic Graphene Hall Sensors (GHS-C), however, enhance the ability of companies that make and/or use superconducting magnets to conduct continuous measurements in low temperature and high-field environments. This means ending the reliance on factory calibration or current-to-field measurements to evaluate these systems. With its patented graphene deposition process, Paragraf averts limitations by producing the GHS-C, which achieves operation in temperatures down to mK and field measurements of over 30 T.

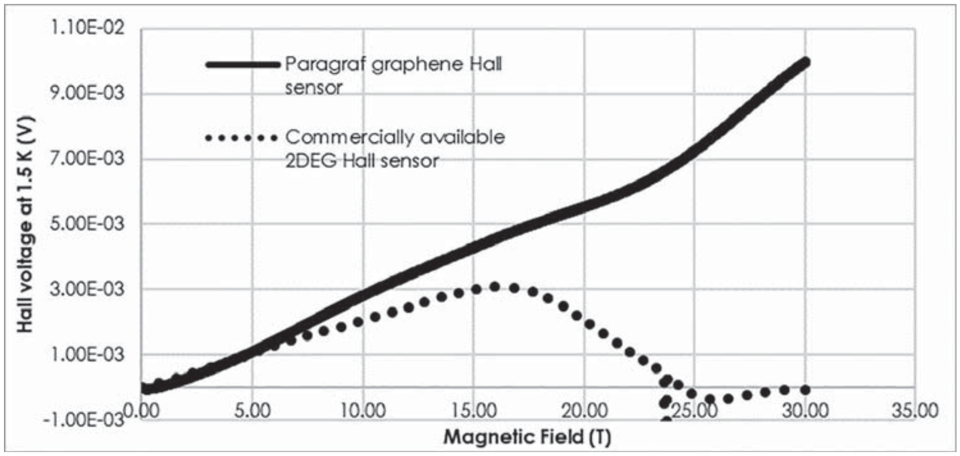
Graphene and Robustness

Conventional Hall effect sensors can experience thermal expansion and contraction of their components when moving between high and low temperatures, leading to degradation of materials and failure of the sensing function. In contrast, owing to its two-dimensional structure, graphene is an exceptionally flexible and robust material, capable of withstanding extreme temperatures and temperature shocks.

Paragraf's GHS-C makes use of that flexibility, while enhancing the overall material strength of the sensor. Using a patented technique, they incorporate the graphene layer into the sensor in a structurally sound and contamination-free manner. This produces a sensor with a superior, highly durable construction.

The QHE

The QHE involves a loss of linearity for voltage outputs above a particular field strength in low temperatures. Once sensors



This chart illustrates that Paragraf's GHS-C maintains its linearity in high-field environments well beyond the capability of a common Hall sensor. *Credit: THFML*

Paragraf GHS mounted on an Oxford Instruments' Proteox development fridge. *Credit: Paragraf* encounter fields above that threshold, the corresponding readings increase in plateaus and sharp inclines, rather than in a continuous, proportional trend line. This makes the device unusable as a cryogenic magnetic field sensor. Unique to Paragraf's graphene deposition is a technique that enables them to modify the sensitivity of the sensors. Through experimenting with the construction process of the GHS-C, Paragraf has found it can delay the onset of QHE so that it is producing sensors that maintain their linearity up to ~30 T, as demonstrated at The High Field Magnet Laboratory in Nijmegen, The Netherlands.

Ease of use

The Paragraf GHS-C's ability to operate at low temperatures means that it does not require the use of additional inserts to protect it. This allows for enhanced flexibility in locating a device within the sample loader. The very low-power dissipation (a few nanowatts) and the development of the line of smaller sensors means that the device can be placed closer to the field of interest while having the accuracy of its measurements improved.

GHS-C Benefits

Paragraf's GHS-C offers a number of advantages over conventional Hall sensors in cryogenic environments. The small form factor eases installation, and the low current requirement prevents interference with cryogenic operations. The 2D nature of graphene provides very high-resolution and eliminates the planar Hall effect to which conventional sensors are prone. The sensors are able to operate at temperatures down to millikelvin temperatures – with no room temperature inserts – while maintaining their linearity of measurement even in fields of 30T and higher.

Applications

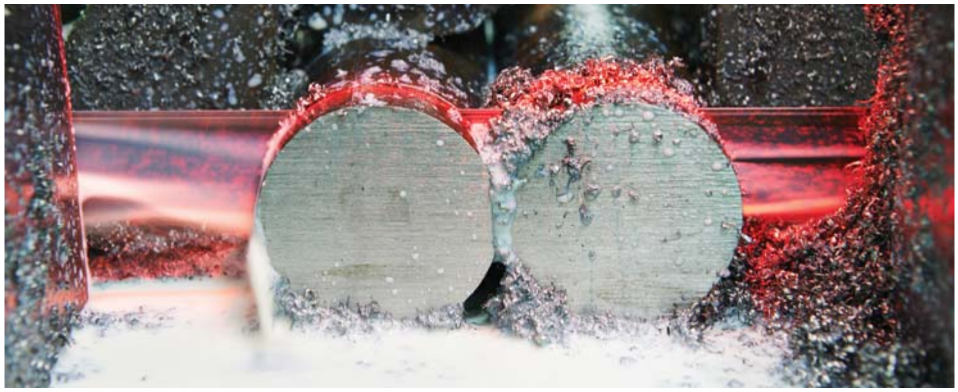
Paragraf GHS-C sensors can be employed across a range of cryogenic applications. They are capable of monitoring the operations of quantum computers that require extremely low temperatures. Similarly, they can be used to map superconducting magnets and circuits, to accurately calibrate magnets, to monitor magnet drift, and to identify flux pinning. The sensors can be built into superconducting magnet coils (in active or persistent mode) or onto sample stages designed for cryogenic use. Further, the same sensor can be employed on both the inside and outside of a shield to characterize the shielding materials and the superconducting magnet. Rosie Baines, a Paragraf scientist, recently gave a presentation to the Graphene Council explaining more about the value of Paragraf sensors in extreme environments. (To view her presentation, go to **youtu.be/fSqs-SWL0Kg**.)

Paragraf harnesses graphene to create the next generation of sensors. It is the first company to mass produce graphene-based Hall effect sensors that measure magnetic fields using less power and achieving greater sensitivity than conventional Hall sensors. Paragraf's sensors have unique advantages for a spectrum of applications that include industrial automation and manufacturing, automotive and transportation, consumer electronics, research, computing and healthcare applications. **www.paragraf.com**

CryoEdge Solves an Ancient Problem with a Cutting-Edge Solution

By Dan Krč

Ever since the Stone Age, people have searched for the most effective ways to cut and shape materials for best use. This quest has most recently resulted in revolutionary breakthroughs and developments like lasers, plasma beams, and water jets as cutting instruments. Despite these advances, the overwhelming majority of cutting tasks still require metal with a sharpened edge, which has one key undesirable trait: it wears out and gets dull. Not so with CryoEdge, a sales and service company based in the Spokane, Washington area. CryoEdge's essential issue goes back to prehistoric times: how can we cut things better and make the tools we use for cutting last longer?



Because of the high demands placed on bandsaws for cutting large diameters of steel and plate aluminum, they are vulnerable to rapid wear and are an area of specific interest for CryoEdge. *Credit: © Dmitry Kalinovsky | Dreamstime.com. Rights of reproduction purchased by CryoEdge*

This is where metallurgy enters. Societies that use metal have known for centuries that it can be enhanced by a combination of heat treatment and quenching (cooling in a medium), often repeated several times in alternating sequence. Quenching can be done in a variety of ways in numerous types of fluids, but with the advent of modern techniques, results advance to new levels by using compressed gases in a liquid state, optimizing effects at the molecular level and changing metals in ways our ancestors couldn't have imagined.

When CryoEdge founder John Alcamo learned of these new methods, he had already been in the saw- and tool-servicing industries for more than 35 years and had operated a conventional sales and sharpening operation, ProCut Saw & Tool, for the majority of that time. "I realized this was a game-changer," says Alcamo about his decision to invest in a process of cryogenic treatment that began with bandsaws and cold saws for his existing customers.

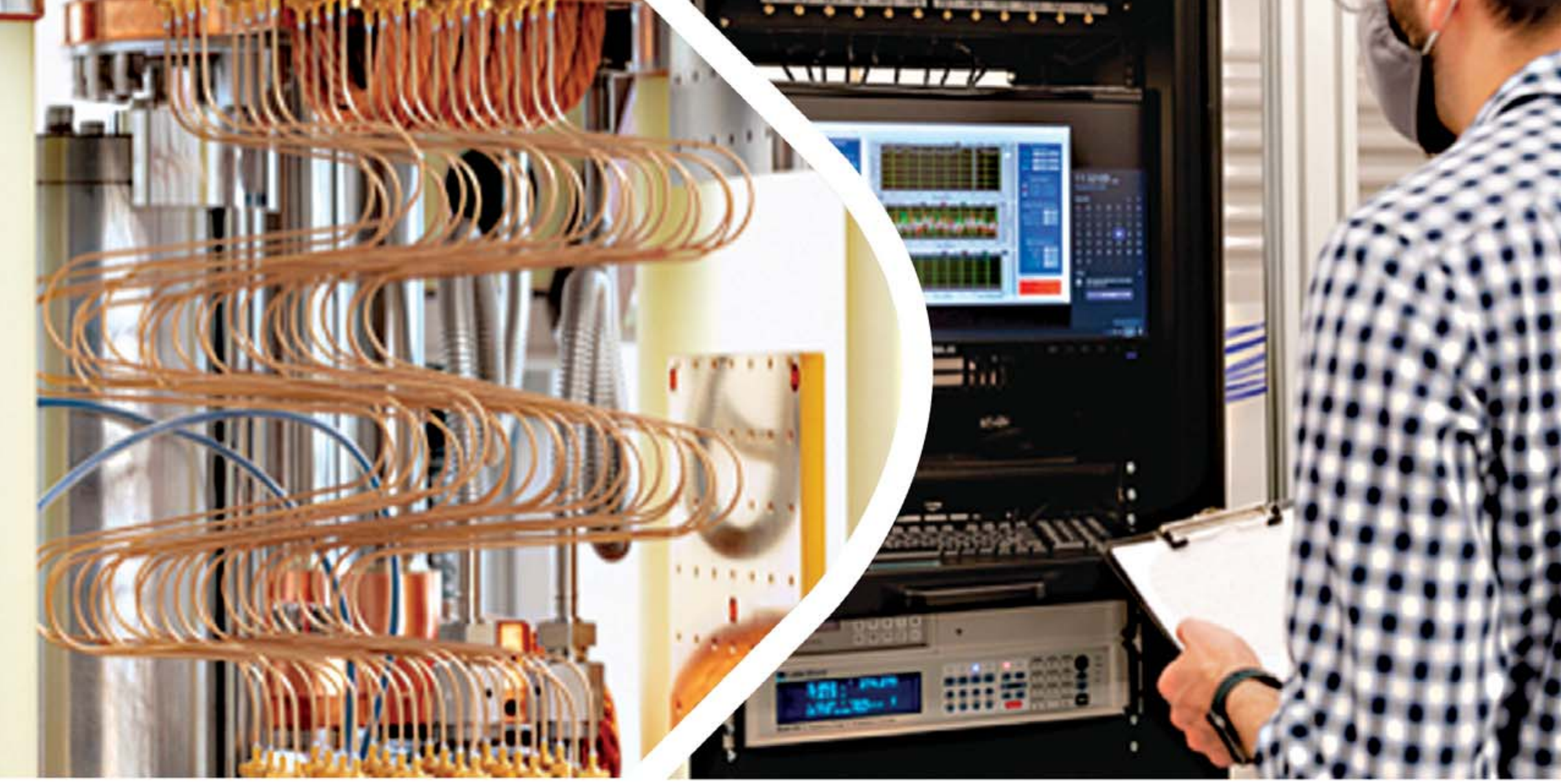
Alcamo readily admits that his mind is practical rather than theoretical where it concerns the exact molecular changes that the CryoEdge process brings about. "There are a lot of scholarly studies out there—material testing, charts, diagrams of molecular lattice, research about proportions of austenite and martensite, and how they affect the usable life of the metal. When it comes down to it, the reason I know I've got a tested process that works is because of the positive feedback I get from customers and the repeat orders. (For those interested in pursuing the research, CSA hosts the Cryogenic Treatment Database, an online database that contains scientific and informational articles related to cryogenic treatment. Find it at **2csa.us/ctd.**)

One repeat customer is Andy Drouhard, lead machinist for Utec Metals Inc., a manufacturer in Spokane Valley. "I get a lot more out of the treated tools," he says. "I'm cutting some large-diameter, difficult-to-cut steels. Historically, with my previous blades, when we cut those, I would not get straight cuts. Now, I'm getting very true cuts with the treated blades, and these pieces are going directly into the lathe; so a truer cut means it's a lot easier to machine. I've been running this saw for 17 years, cutting big steel. I would not get this amount of life from any other blade I've run. When you go back and measure the square inches of all these cuts, it was a significantly larger amount of material cut."

Cryogenic treatment of metals has been performed since as early as 1937 when Russian researcher A.P. Gulyaev documented his findings in an article entitled "Improved methods of Heat-Treating High-Speed Steels to Improve the Cutting Properties," published in a Soviet journal called Металлург (*Metallurg*, i.e., "*Metallurgist*"). More recent literature points to NASA's development of cryogenic applications as a key factor in yielding the techniques that are in use today and which are still being refined. As for its own process, though CryoEdge is prohibited by the terms of a license agreement from disclosing exact details, Alcamo acknowledges that the treatment involves temperatures below −300° F as part of a several-step quenching procedure that is time-consuming and meticulously regulated in a controlled, carefully monitored sequence.

As CryoEdge grows, Alcamo finds interest from unexpected industries. A chance meeting with Jamie Blackhart, CEO of Advisor Tactical Products, LLC and a firearms industry veteran, introduced Alcamo to that industry's unique history with cryogenic metal treatments, particularly for maintaining the fine precision necessary for the best rifle barrels.

Alcamo finds the diverse new business avenues challenging but rewarding. "Our slogan is 'Changing tools from the inside out,'" he comments. "Now we're doing the same thing to our business." **www.cryoedge.com**



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Cryocooler Conduction-Cooled SRF Accelerator Design for Industrial Applications

by Dr. Mauricio Suarez, Fermilab Deputy Head of Technology Development and Industry Engagement and Head of IARC

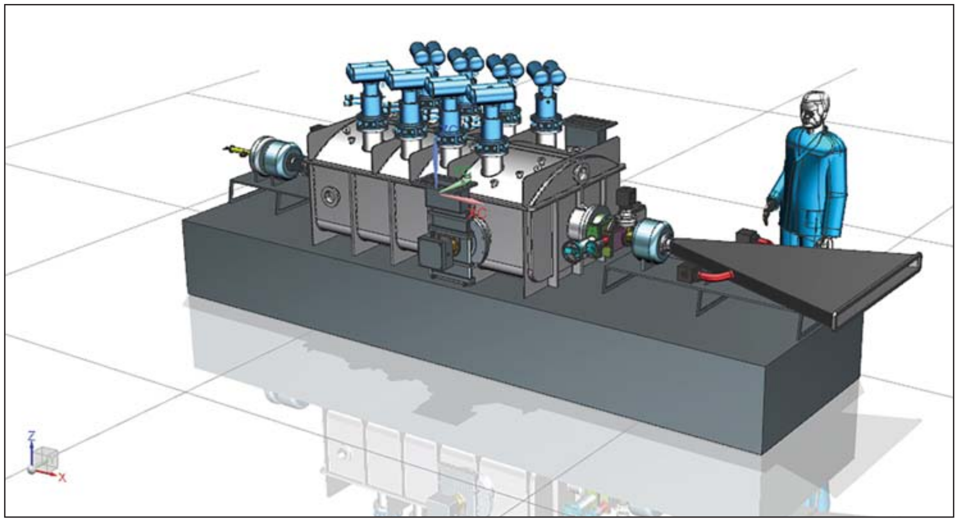

Figure 1: CAD rendering of the compact, high-power SRF e-beam accelerator designed by Dhuley and team, supported by HEP Accelerator Stewardship. The overall size is ~4 m long (end to end), ~2 m wide and ~2 m tall. *Credit: Fermilab*

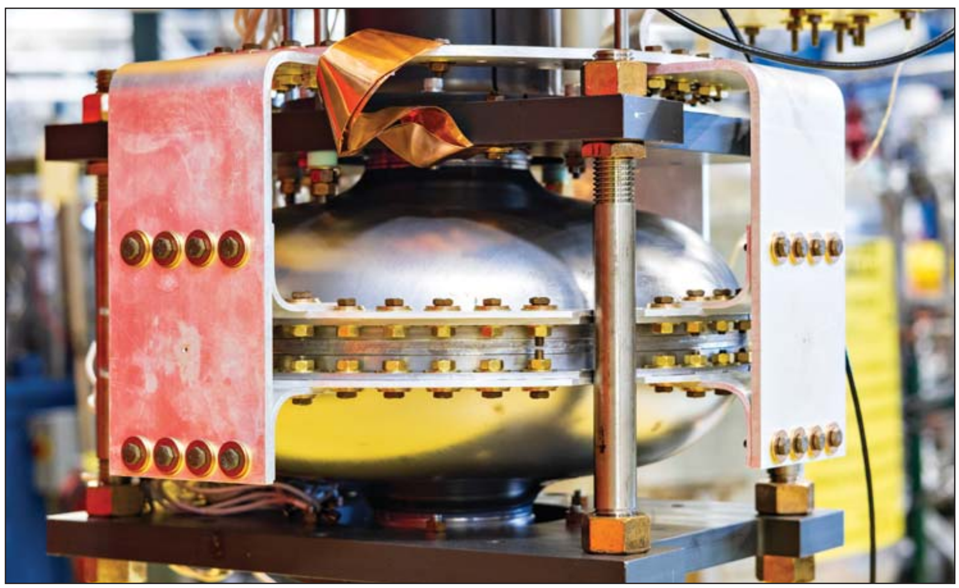

Figure 2: Photograph of the conduction-cooled SRF cavity. *Credit: Martin Murphy, Fermilab*

Principal Investigator Dr. Ram Dhuley has led R&D efforts at the US Department of Energy's Fermi National Accelerator Laboratory (Fermilab) to design a cryocooler conduction-cooled SRF accelerator for e-beam irradiation treatment of wastewater.

Electron beam (e-beam) particle accelerators using the superconducting radiofrequency (SRF) cavity technology are a frontier tool for basic energy and nuclear science research. The extremely small surface resistance of SRF cavities compared to their normal conducting counterparts enables continuous wave (CW) operation, which, in turn, allows attaining high-average power e-beams at lesser wall-plug electricity consumption. This unique advantage also makes SRF e-beam accelerators attractive for industrial applications, such as e-beam irradiation treatment of industrial and municipal wastewater, medical device sterilization, asphalt pavement curing, rapid setting of 3D-printed concrete, high throughput metal additive manufacturing, and more. A meter-long SRF machine with a 10 MV/m average accelerating gradient can produce e-beams of enough energy for these applications.

SRF accelerators need cryogenic systems in the 2-4.2 K temperature range – a need that is presently met using immersion cooling in liquid helium. While the cost and complexity of liquid helium infrastructure can be managed for fundamental research SRF accelerators, industrial installations may find such liquid helium infrastructure to be cost prohibitive and resource intensive. Therefore, simpler and more reliable cryogenic systems are needed to stimulate the adoption of SRF accelerators in the industrial arena.

Dr. Ram Dhuley, a senior cryogenics engineer within Fermilab's Applied Physics and Superconducting Technology Division (APS-TD) and also matrixed into IARC at Fermilab, was awarded a High Energy Physics (HEP) Accelerator Stewardship grant by the US Department of Energy to lead the technical design and cost modeling of a high-power e-beam SRF accelerator using simplified cryogenics systems. The end application of this accelerator is the e-beam irradiation treatment of municipal and industrial wastewater at the scale of several million gallons per day (MGD). One key aspect of the HEP Accelerator Stewardship program is to develop innovative solutions to critical problems by providing grants for use-inspired R&D. Such R&D is focused on the topics of interest identified by the federal stakeholders of the stewardship program, one of which was using simplified cryogenics to make SRF accelerators accessible for industrial applications with a cost target.

Dr. Dhuley served as principal investigator for a team comprising Fermilab experts and industrial partners, including General Atomics and Euclid Techlabs LLC, to create a reference design for a 10 MeV energy, 1 MW average power e-beam SRF accelerator. This e-beam power can treat up to 12 MGD of wastewater – the typical load of a mid-sized municipal wastewater treatment plant. (Figure 1 shows a CAD rendering of the accelerator.)

The accelerator design hinges on two core technologies perfected at Fermilab over several years of research, development and extensive testing. The first technology, pioneered at Fermilab by Dr. Sam Posen, is the Nb_3Sn SRF cavity [1]. This cavity has a thin layer of Nb_3Sn superconductor grown on the RF surface of a bulk niobium cavity. Whereas niobium cavities operate more efficiently near 2 K, the low dissipative properties of Nb_3Sn allow these cavities to achieve comparable performance near 4 K. This allowable 4 K operation brings these cavities into the working temperature range of closed-cycle cryocoolers. However, the challenge still remains to design and optimize the thermal coupling between the cavity and cryocoolers. The second technology, dubbed as conduction cooling for SRF, solves this challenge.

Conduction-cooling for SRF, pioneered by Dr. Dhuley, essentially eliminates liquid helium around the cavity that results into a dramatically simpler cryogenic system that is ideal for industrial settings. The technology comprises a high-purity aluminum link that connects the niobium cavity body to one or more 4 K cryocoolers. The initial R&D phase of conduction-cooling for SRF saw extensive testing and characterization of the bulk conductivity of pure aluminum and its thermal contact resistance with niobium [2]. Following this, the aluminum link geometry was optimized from the thermal conductance and manufacturability considerations [3], resulting in a cavity-link cryocooler assembly depicted in Figure 2. This conduction-cooled SRF cavity was then tested on a new experimental setup to successfully achieve the target average CW accelerating gradient of ~10 MV/m [4, 5]. The CW accelerating voltage at this gradient stands as the highest recorded to date on an SRF cavity without using liquid helium. It is worthwhile to further highlight that this breakthrough technology has already seen widespread adoption in accelerator projects at universities, other national labs and private industry. See [6-8] for examples.

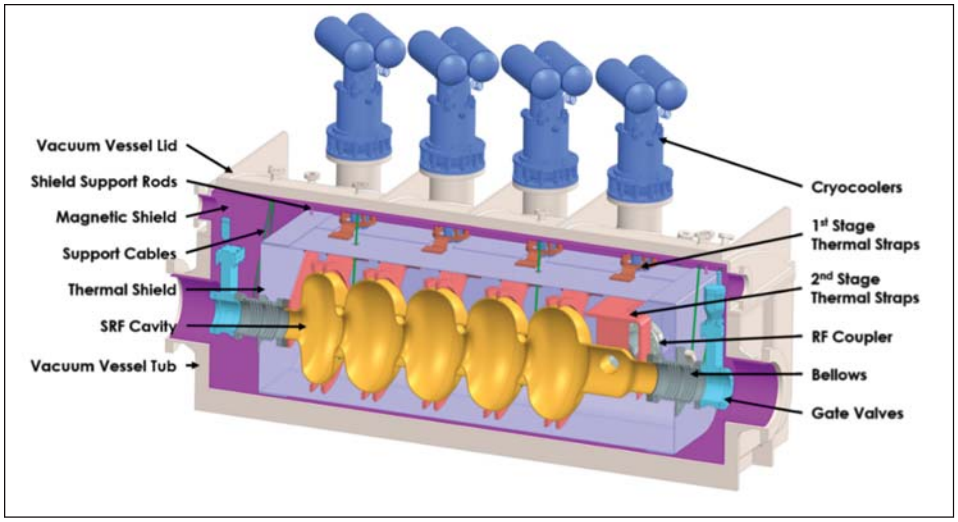

Figure 3: The conduction-cooled SRF cavity integrated with the accelerator cryostat. *Credit: Fermilab*

In addition to the above two core technologies, the accelerator designed by Dr. Dhuley and team comprises a thermionic electron source, low-loss fundamental power couplers, thermal and magnetic shields and a vacuum vessel engineered to ASME standards. The accelerator design relied on several expertise areas of Fermilab APS-TD, including electron injector design, beam transport simulations, cavity RF design, power coupler design and more. Euclid Techlabs LLC aided with multiphysics simulations on the conduction-cooled SRF cavity to verify its thermal performance. General Atomics engineers provided expertise with the design and integration of the accelerator cryostat, as schematically shown in Figure 3, and estimating the cost for building and operating the e-beam accelerator. The staff of Office of Partnerships and Technology Transfer conducted the literature review while the staff of IARC at Fermilab formulated a business case for the Stewardship proposal and provided project management support.

The design report by Dr. Dhuley (lead author) and team is available as a peer-reviewed paper in the journal *Physical Review Accelerators and Beams* [9]. The compact accelerator technology and its applications are covered by multiple US patents, both issued and pending.

This research was funded by a HEP Accelerator Stewardship grant to Dr. Ram Dhuley by the US Department of Energy. This article has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the US Department of Energy, Office of Science, Office of High Energy Physics.

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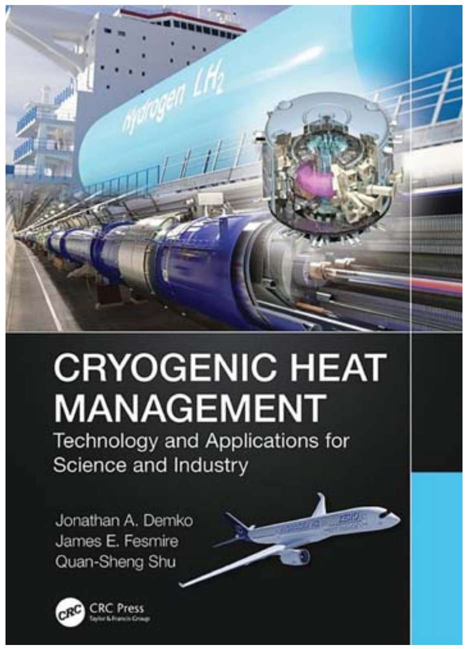
Industry Reviews of *Cryogenic Heat Management: Technology and Applications for Science and Industry* by Jonathan Demko, James E. Fesmire and Quan-Sheng Shu, recently published

Review by Robert Duckworth, CSA member, Senior R&D Staff & Fusion Technology Group Leader, Oak Ridge National Laboratory

The best compliment I can give a technical book, especially one on cryogenics, is whether it can answer the following question affirmatively: if I had a time-sensitive project and suddenly lost internet access or regular access to my bookshelf of cryogenic source materials and had to rely on just two to three books to help me, would this book be one of my selections?

Many of us in the last two years have had to make just such a decision. As I left my office at Oak Ridge National Laboratory to begin working from home in March 2020, my backpack held the following titles: ***Cryogenic Heat Transfer*** by Randall Baron, ***Case Studies in Superconducting Magnets: Design and Operational Issues*** by Yukikazu Iwasa, and ***Cryogenic Process Engineering*** by Klaus Timmerhaus and Thomas Flynn. If ***Cryogenic Heat Management: Technology and Applications for Science and Industry*** had been available in 2020, it would have competed for backpack space with those other titles, which I have owned since I started my research career in 1996 at the University of Wisconsin.

Cryogenic Heat Management provides a sound layout that serves a range of readers, from students and early-career engineers or scientists interested in an introduction to the topic to senior-level personnel interested in the content of a specific chapter. For those starting out, a refresher on basic thermodynamic and heat transfer concepts (Ch. 1) and insulation theory and applications (Ch. 2 and



3) is provided before the authors put forth different applications in the later chapters. These chapters stand alone well as each has its own brief introduction before working through examples that cover space-related and large-scale applications of large helium, hydrogen or nitrogen cryogenic systems. The authors represent the technical details and motivation behind different theories and approaches to each topic well, with timely illustrations, examples and relevant references at the end of each chapter. The reasonable number of references encourages further exploration without the possibility of going down too many rabbit holes. The diversity of cryogenic topics across these chapters is of great value; the authors address topics that are often consolidated in higher-level design treatments, where their enjoyable details can be lost.

Having focused on cryogenics and applied superconductivity since my college years, I am grateful to have spent time with each of the authors. Their style and experience, which I have had the privilege of seeing in action, come across clearly in this book and in a diverse collection of cryogenic applications and resources that I would gladly recommend to any new staff member or engineer in the field looking to design cryogenic equipment. This book won't solve all their issues or mine because we are fortunate to have a strong and growing international cryogenic manufacturing community. However, it will provide a great starting point for asking better questions and getting to more timely solutions.

....

Review by Professor Carlo Pagani, University of Milano and INFN Emeritus Scientist

Cryogenic Heat Management is a very useful reference for scientists and engineers working with low temperatures and facing the various obstacles of heat management. This field is huge and spans from high energy physics experiments to space technology and from the transport and storing of liquid gases to their management by the final users. Depending on the application in terms of temperature, size and project specifications, different solutions have been implemented, making use of a large variety of materials and technologies.

Based on their great experience in the field and after a clear introduction on heat transfer, the authors address in the first chapters of the book the general problem of cryogenic heat management by discussing separately a few common topics: insulation, supports, thermal shields, transfer pipes, storage vessels and vacuum. This choice is quite efficient and makes clear the comparison among the different solutions, each one tightly linked to its specific project. Comparative tables, pictures and schematics, together with a consistent bibliography, guide the reader. In each chapter, the specific common topic is addressed through real examples from first-class applications taken from aerospace, large science infrastructures, and from nuclear fusion, but they also draw from the management and clean transport of the huge quantity of Liquefied Natural Gas found around the world. Comparison with more common applications in medicine and industry are always part of the discussion.

The second part of the book (chapters 8-13) is dedicated to instrumentation, cryogenic measurements and a few special topics, discussing their importance and crucialities. I found of particular interest the discussion on current leads and RF couplers. These items are crucial in some important applications, but both represent an unavoidable penetration that creates a direct connection from the cold-mass and the room temperature.

Finally, the description of thermal switches and special cryostats for extreme applications are noteworthy as well. This final part of the book is very interesting and completes the knowledge transfer from the expert authors to the readers, who are expected to be involved in the design, choice or operation of a cryogenic apparatus where a deep understanding of cryogenic heat management is crucial. ■

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Product Showcase

This Product Showcase is open to all companies and related manufacturers offering new or improved products for cryogenic applications. We invite companies to send us short releases (150 words or fewer) with high-resolution JPEGs of their products to editor@cryogenicsociety.org.

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A full line of transfer and recirculation pump models are available in 1.25-inch, 1.5-inch, 2-inch, 3-inch and 4-inch port sizes for industrial and food processing systems, refrigeration, process plants and transport loading and unloading. Capacities range from 5 to 300 GPM (19-1,134 L/min) with working pressures up to 525 psi (36.2 bar) and operating temperatures down to −30° F (−34° C). **www.gasequipment.com/pages/industrial_gas.html**

FormFactor

JDry-600 Cryogen-Free Dilution Refrigerator

FormFactor's JDry-600 cryogen-free dilution refrigerator is now available for quantum computing and other applications. Proven, made-in-USA technology delivers temperatures down to 9 mK, with the high cooling power needed for multiple-qubit applications (600 and 17 microwatt usable cooling power at 100 mk and 20 mK respectively). The JDry-600 provides a low-vibration, light-tight environment with up to 12 ISO100 ports and a 10 K plate to thermalize experimental services. It is designed for long-term continuous operation and requires no external cryogens or compressors. For ease of use, operating modes include manual, automated and remote, including scripting. **www.formfactor.com**

Spectrum Valves

Cryogenic Cam Butterfly Valve

Dimensions of cryogenic valves change when subjected to extreme temperature service. Even small dimensional changes can cause a disc to separate from its seat, resulting in valve leakage. The Cryogenic Cam Butterfly Valve's constant closing force between the disc and seat at any temperature prevents valve leakage by combining the rotation movement of a typical butterfly valve with the translation movement of a typical globe. From a 100% open position, the shaft and disc act as a single-fixed assembly, rotating approximately 90 degrees until one edge of the disc contacts the seat when the valve is almost closed. When the disc cannot rotate any further, the shaft can. The further rotation of the cam-shaped shaft causes the disc to translate and wedge into the seat with extreme force, creating a leak-tight seal. The pneumatic rack-and-pinion actuator ensures that constant force is always applied throughout a 500° F temperature range. **www.spectrumvalves.com**

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The RAD-0002-ZR Oxygen Deficiency Alarm for Low Temperature protects staff in enclosed areas near storage cylinders of nitrogen, argon, ammonia, chlorine, propane, nitrous oxide, helium, argon or other inert gases. This device is commonly used in hospitals, laboratories, pharmaceuticals, cryogenics, process cooling, freezers, manufacturing, food and beverage and research facilities. The oxygen deficiency safety monitor will stay accurate at temperatures as low as −50° C without needing maintenance, and it does not require zero calibration. This device's sensor has a life expectancy of over 10 years, it has three user-configurable alarms that meet all OSHA codes, and it even has an audible and flashing alarm for the sensor and remote display that reaches up to 90db. Learn more about this device and other gas detection solutions at **www.CO_2Meter.com**

Stirling Cryogenics

CryoFans Range van 3

To thermally connect a cold source with an application that is at some distance or has a large surface, a flow of cold helium can be used as thermal fluid. Stirling Cryogenics has a range of so-called CryoFans for flows from 0.1 to 45 m^3/h and a larger range from 300 to 450. The CryoFans' design is for a maximum static pressure of 30 barg and temperatures down to 15 K. To avoid any rotational seals, the high-speed motor is placed inside of the pressure hull, however, and works at ambient temperature being connected to the impeller via an elongated shaft. The range of CryoFans is available for use in systems cooled, for example, by a bath of liquid gas. All brands of cryocoolers use a clip-on heat exchanger and are integrated in Stirling's own cryogenerators. **https://stirlingcryogenics.eu**

Velan France

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Velan France is a world leader in valves for nuclear, LNG, cryogenic and space applications. With its field experience and technical expertise, Velan can supply any major project requiring first-class quality and perfect reliability. The company's high-performance cryogenic bellows-sealed control valves are used for superconductivity applications, particle accelerators, nuclear fusion facilities, rocket launching pads, helium and hydrogen liquefiers, transfer lines and process systems, bringing high thermal efficiency with low heat in leaks and withstanding of differential thermal expansions during all normal and transient operation modes down to 1.2 K. High tightness performances are guaranteed during a minimum of 10,000 full travel cycles at full design pressure. Thanks to tight tolerances of seats and plugs, high rangeability allows JT effects. **www.velan.com**

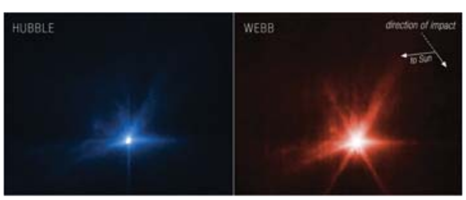
People & Companies in Cryogenics

Web Industries Inc. (CSA CSM), a global provider of contract converting and turnkey manufacturing services in the medical, aerospace, personal and home care, and industrial sectors, has promoted **Kathrin Doyle Arena** to the position of vice president of human resources. In her new role, Arena will focus on fostering the company's employee-owner culture, helping to sustain and grow the business in the United States and globally.

Credit: Web Industries

....

Two of **NASA's** great observatories, the **James Webb Space Telescope** and the **Hubble Space Telescope**, captured views of a unique NASA experiment designed to intentionally smash a spacecraft into a small asteroid in the world's first-ever in-space test for planetary defense. These observations of NASA's **Double Asteroid Redirection Test (DART)** impact mark the first time that Webb and Hubble simultaneously observed the same celestial target.



Credit: Science: NASA, ESA, CSA, Cristina Thomas (Northern Arizona University), Ian Wong (NASA-GSFC); Joseph DePasquale (STScI) Jian-Yang Li (PSI); animation: Alyssa Pagan (STScI)

On September 26, 2022, at 7:14 pm EDT, DART intentionally crashed into Dimorphos, the asteroid moonlet in the double-asteroid system of Didymos. It was the world's first test of the kinetic impact mitigation technique, using a spacecraft to deflect an asteroid that poses no threat to Earth, and modifying the object's orbit. DART is a test for defending Earth against potential asteroid or comet hazards.

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The President of India, Droupadi Murmu, inaugurated **the Integrated Cryogenic Engine Manufacturing Facility of Hindustan Aeronautics Limited (HAL)** in Bengaluru on September 27, 2022. Addressing the gathering, the president said that inauguration of the facility is a historic moment for the whole country to have a state-of-the-art facility to manufacture cryogenic engines.

Credit: President's Secretariat

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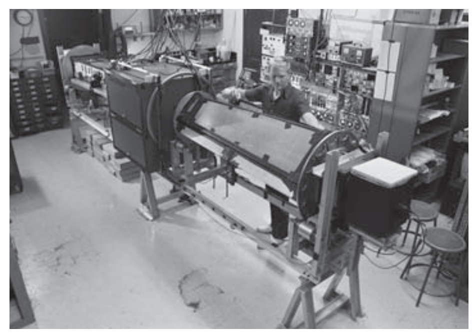
Cryoport, a global leader in temperature-controlled supply chain solutions for the life sciences industry, announced it has entered into a strategic relationship with **BioLife Plasma Services**, part of the global biopharmaceutical company Takeda, intended to provide consistent, high-quality cellular starting material for use in the manufacture of life-saving cellular therapies. By bringing together BioLife Plasma Services' proficiency in apheresis collection and their donation center infrastructure with Cryoport's life sciences' world-class capabilities and expertise in temperature-controlled supply chain solutions for the biopharmaceutical industry, the companies aim to establish a standardized, integrated apheresis collection, processing and distribution solution for cellular therapies. Importantly, the new platform will leverage the cryo-processing expertise of Cell Matters, which Cryoport acquired in late July 2022.

....

Zero Point Cryogenics has been awarded a contract to build an ultralow temperature dilution refrigerator — a piece of equipment that enables researchers to explore the possibilities of quantum technology for testing — by the National Research Council of Canada. The test will be funded through the Innovative Solutions Canada Testing Stream program, which partners with small and medium-sized Canadian businesses to award contracts to innovators who are developing novel solutions. The contract was awarded by Public Services and Procurement Canada.

....

The Royal Swedish Academy of Sciences has awarded the **2022 Nobel Prize in Physics** to **Alain Aspect**, **John Clauser**, and **Anton Zeilinger** "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science." Clauser was a postdoctoral researcher at the Department of Energy's Lawrence Berkeley National Laboratory and UC Berkeley from 1969 to 1975. He conducted this research in the early 1970s with the late Stuart Freedman, who was then a graduate student and who would become a world-renowned physicist in Berkeley Lab's Nuclear Science Division and professor of physics at the University of California at Berkeley. Their work addressed whether quantum mechanics or a competing theory best explained what happened in the quantum world. In the 1980s, Alain Aspect performed more precise tests that closed some of the potential loopholes in the earlier experiment, again validating quantum mechanics. Anton Zeilinger further explored entanglement and made the first demonstration of quantum teleportation in 1997.



John Clauser with the quantum mechanics experiment he and Stuart Freedman built to test Bell's theorem in the 1970s. *Credit: Steve Gerber/Berkeley Lab*

....

Dr. Nusair Hasan of the **Facility for Rare Isotope Beams** was recognized with CSA's 2022 Roger W. Boom Award at the Applied Superconductivity Conference in Honolulu for his outstanding work on the advancement of cryogenic processes and technology, specifically relating to large-scale 2 K and 4.5 K cryogenic refrigeration and critical supporting sub-systems for particle accelerators. Dr. Hasan has also made noteworthy contributions in training and mentoring future generations of cryogenic engineers.

Courtesy of Dr. Nasair Hasan

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Engineers and technicians from the **National High Magnetic Field Laboratory** (CSA CSM) were recognized with a **2022 R&D 100 Award** for the design and construction of the 32 Tesla Superconducting Magnet. The R&D 100 recognizes revolutionary ideas in science and technology, and the 32T, all-superconducting magnet is the world's most powerful and first of its kind. Funded by the National Science Foundation's Division of Materials Research and the state of Florida, the magnet is composed of an outer set of traditional commercial low temperature superconducting coils and a novel set of inner coils made from a high temperature superconductor, consisting of a combination of yttrium, barium, copper and oxygen. MagLab scientists, engineers, technicians and other staff worked to develop entirely new techniques for insulating, reinforcing and de-energizing the novel inner coils, techniques that were essential because of its unique and complex electromagnetic and mechanical aspects.

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The **Phoenix Company of Chicago** announces the launch of its redesigned website, **www.phoenixofchicago.com**. With a sleek, modern design and a new, user-friendly interface featuring improved navigation and search functionality, their updated website provides visitors an intuitive way to learn about The Phoenix Company of Chicago's RF/microwave solutions, view their expanded product line and download technical resources.

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Thermo Fisher Scientific Inc. introduced the Thermo Scientific Glacios 2 Cryo-Transmission Electron Microscope (Cryo-TEM), a powerful microscope with new automation and high-resolution imaging capabilities designed to help cryo-electron microscopy researchers of varying experience levels accelerate structure-based drug discovery. This advanced, fast and cost-efficient method for drug design may enable customers to accelerate the pace of research for debilitating disorders like Alzheimer's, Parkinson's and Huntington's diseases, as well as research for cancer and gene mutations.

....

CB&I, a US designer and builder of storage facilities, tanks and terminals, joined hands with a major South Korean shipyard, **Daewoo Shipbuilding & Marine Engineering (DSME)**, to apply liquid hydrogen storage tanks to large carriers. A DSME official said that the partnership with CB&I would contribute to realizing the large size of liquefied hydrogen carriers. "The combination of our shipbuilding technology and CB&I's storage tank technology will help the domestic shipbuilding industry maintain its world's top position in the field of large liquid hydrogen carriers." CB&I provided NASA's new liquid hydrogen storage sphere that will be the world's largest liquid hydrogen storage unit. The company is also involved in a group led by Shell to develop a liquid hydrogen storage technology for tanks used at import and export terminals.

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Meetings & Events

BCC Introductory Cryogenics Course
November 23-24
Warrington, England
http://2csa.us/linkbcryo

The 35th International Symposium on Superconductivity
November 29-December 1
Nagoya, Japan
http://2csa.us/la

European Cryogenic Days 2023
March 28-29, 2023
Darmstadt, Germany
http://2csa.us/lb

Cryogenic Engineering Conference/ International Cryogenic Materials Conference (CEC/ICMC)
July 9-13, 2023
http://2csa.us/lc

Space Cryogenics Workshop
Space Cryogenics Workshop
July 16-18, 2023
spacecryogenicsworkshop.org

EUCAS 2023: 16th European Conference on Applied Superconductivity
September 3-7, 2023
Bologna, Italy
http://2csa.us/lf

MT-28: International Conference on Magnet Technology
September 10-15, 2023
Aix En Provence, France
http://2csa.us/lg

Mitsui & Co., Ltd and **Quantinuum** signed a strategic partnership agreement to collaborate in the delivery of quantum computing in Japan and the Asia-Pacific region. Mitsui, a digital transformation company, and Quantinuum, a world leader in quantum computing, hardware and software, will jointly pursue quantum application development and provide value-added services to organizations working across a variety of quantum computing domains.

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