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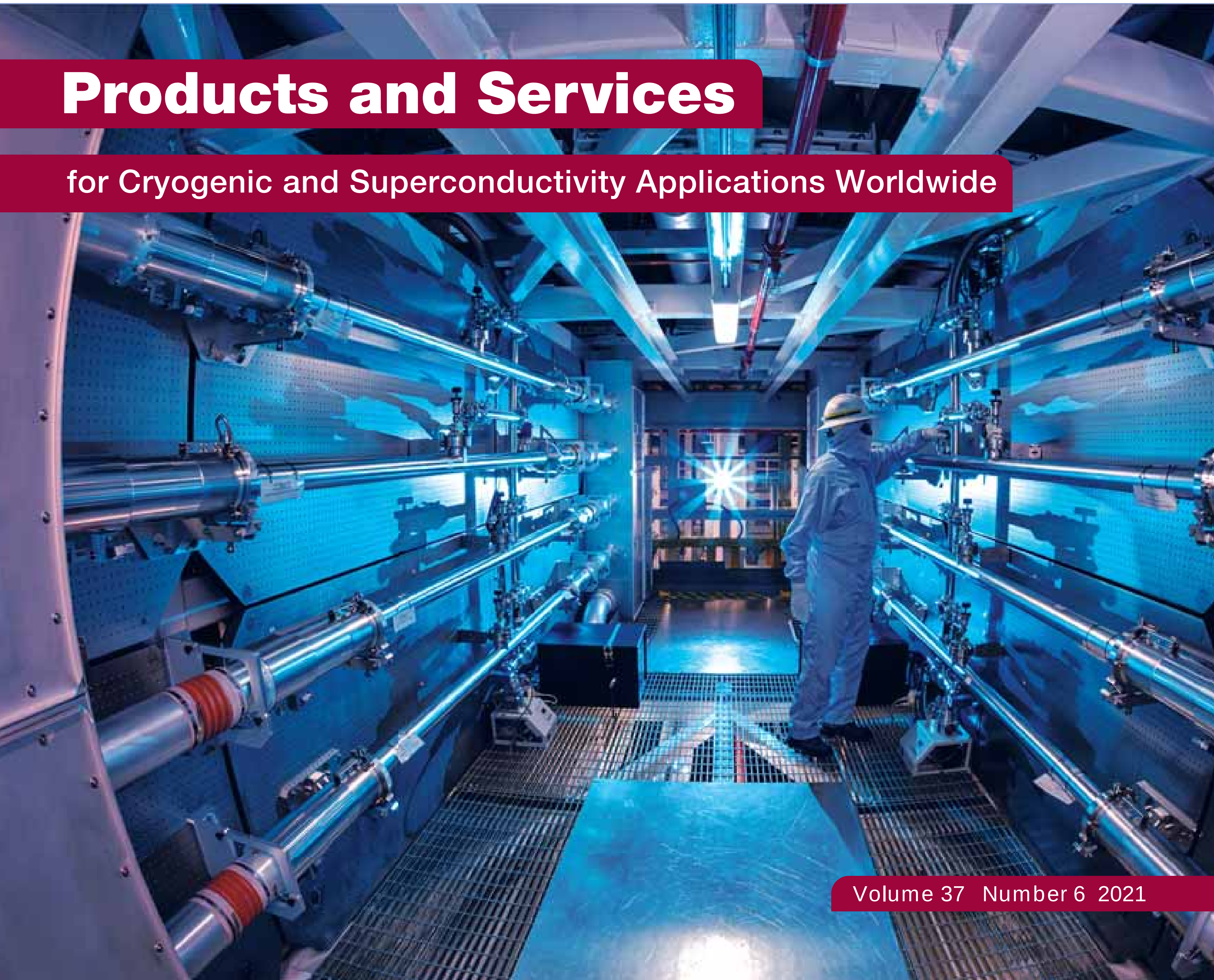

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Preamplifier Support Structure at LLNL

A technician adjusts an optic inside the preamplifier support structure.

Image: Damien Jemison

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The Go-To Place for Cryogenics

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From the Executive Director

As 2021 comes to a close, I want to take a moment to reflect on the eventful and successful year that CSA has had.

The year started with the big announcement that after managing CSA for more than 40 years, Laurie and Werner Huget would be retiring. The Hugets had been a staple in the cryogenic community for a very long time, so this news was a big pill for many to swallow. It was also announced that CM Services, the Association Partnership Company, would be taking over management of CSA. Enter stage left – me!

It seems like just yesterday I was writing my first Executive Director's letter, introducing myself to our readers and members. But here we are – we've almost made it through our first year, and I couldn't be more thrilled with how the year went.

In July, CSA hosted three virtual Short Courses in conjunction with the CEC/ICMC. These courses were very well received and well attended. If you weren't able to attend these courses live, the recordings and materials are available for purchase on the CSA website.

Also in July, we announced the winners of several awards and recognitions. We awarded Dr. Jingyuan Xu the George T. Mulholland Memorial Award for Excellence in Cryogenic Engineering and Benjamin Hansen the Award for Excellence in Cryogenic Operations and Support. We also recognized two individuals as Fellows of CSA: Dr. John G. Weisend II, and Dr. Sastry Pamidi.

In November, CSA hosted the 29th Space Cryogenics Workshop virtually, which was an overwhelming success. I'll be the first to admit that hosting a virtual event is in many ways more difficult than hosting an in-person event. So much more can go wrong technologically that is completely out of our control. But I am happy to say that there were very few technological issues at the virtual SCW. With over 80 people registered and 31 presentations, we were thrilled with the turnout.

In conjunction with the Space Cryogenics Workshop, we announced six winners of the T.H.K. Frederking Space Cryogenics Workshop Student Scholarship. Those winners were: Arpit Mishra, Alireza Moradikazerouni, Lokesh Kumar Meena, Dasari Venkatesh, Joydip Mondal, and Keerthi Raj Kunniyoor.

To top it all off, in the last year CSA has welcomed 12 new Corporate Sustaining Members to the organization. We've also maintained a very high renewal rate – right around 90%.

Looking to the future, CSA has many exciting things happening in the new year. I am happy to announce that CSA will be launching a brand new website early in 2022. This new website will still have all the great content of the old website, but it will have a fresh new look. We will also be implementing a new member database and 'members only' portal. Keep your eyes peeled for more details on the new website in the coming months.

On behalf of everyone here at CSA, we wish you and your families a happy and healthy new year. ■

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CERN Partners with CLS, University of Saskatchewan in Designing the Future of Accelerator Physics

CERN, one of the world's largest and most respected centers for scientific research, the University of Saskatchewan (USask), and the Canadian Light Source are paving the way for a new accelerator for world-class research. The three organizations have signed a Memorandum of Understanding (MoU) for the Future Circular Collider (FCC) Feasibility Study.

Rob Norris, Senior Government Relations, CLS/USask; Frank Zimmerman, FCC Study Deputy Leader, CERN; Patrick Hunchak, USask; Mark Boland, Machine Director, CLS, and Associate Professor, USask; Michael Benedikt, FCC Study Leader, CERN; Tamara Mawhinney, Minister-Counsellor, Permanent Mission of Canada to the United Nations Office; Nadja Schauer, Senior Trade Commissioner, Embassy of Canada to Switzerland; Anders Unnervik, Head of Procurement and Industrial Services, CERN; Emmanuel Tsesmelis, Head of Relations with Associate Members and Non-Member States, CERN.
Image: CERN

CLS, located at the University of Saskatchewan, is a national research facility, producing the brightest light in Canada – millions of times brighter than the Sun – and one of the largest science projects in Canada's history. The CLS and CERN have high-tech facilities that accelerate particles to help scientists probe matter and understand the origins of the universe. These capabilities can also find applications beyond research in fundamental physics, such as helping address global problems like food security, cancer, and climate change.

The international accelerator community sees value in creating a new facility with higher energy capacity, which would allow for even more advanced scientific studies. The higher the energy, the more information to which scientists will have access. CLS, USask and CERN are planning for a future accelerator with sensitivity to energy scales an order of magnitude higher than current accelerators.

In 2020, the European Strategy for Particle Physics Update (ESPPU) requested that the feasibility study of the FCC integrated program be delivered by the end of 2025. The EPPSU stated that "such a feasibility study of the colliders and related infrastructure should be established as a global endeavor and be completed on the timescale of the next Strategy update." CERN, together with its international partners, launched the feasibility study in 2021 with a view to investigate the technical and financial feasibility of the FCC at CERN.

"We warmly welcome CLS and the University of Saskatchewan to this endeavor and we look forward to the ensuing collaboration, thus increasing international co-operation as a prerequisite for success," says Emmanuel Tsesmelis from CERN International Relations.

Ongoing R&D activities, supported by the H2020 FCC Innovation Study, include concrete regional implementation scenarios in collaboration with Host State authorities, accompanied by machine optimization, physics studies and technology R&D.

“These activities offer the vision for a world-leading high energy physics infrastructure for the 21st century, pushing the particle-physics precision and energy frontiers far beyond present limits. The success of the FCC relies on strong global participation, and we warmly welcome the CLS and the University of Saskatchewan joining our efforts and contributing with their expertise in the efficient and sustainable implementation of these machines,” says Michael Benedikt, the FCC Feasibility Study Leader.

The international partners will investigate the feasibility of a future electron-positron collider at CERN, which Canadian scientists would be able to utilize. The physics, engineering and technology of such a pioneering accelerator ring at CERN can be applied to a future ring for the Canadian Light Source community. “Collaboration is key in science,” says Mark Boland, CLS Machine Director and USask Associate Professor in the College of Arts and Science. “We are working together to develop ambitious next-generation accelerator projects.”

Thanks to an ongoing partnership, Canadian researchers and students have access to research infrastructure at CERN. In return, CERN receives their support and expertise. Boland teaches courses on accelerator and synchrotron physics at USask. “With this MoU, USask students will be able to apply the skills they learn from their studies while doing their own research on future CLS and CERN accelerators."

Getting hands-on experience at world-class facilities is invaluable training for these future accelerator physicists. “Being able to help plan for and use a collider like this is a dream come true, particularly working with experts from around the world,” says Patrick Hunchak, who is completing a master’s degree at USask.

Later this month, Hunchak will be at CERN to present in a workshop for students around the world who will be working on the FCC Feasibility Study. In July, researchers and students will gather in Saskatoon, where the CLS and CERN will be hosting an International Accelerator School.

“USask has a mission to deliver research the world needs, and this MoU highlights the power of connecting with partners on the global stage for fundamental research and applied research,” said USask Vice President of Research Baljit Singh. “Working together, we build capacity for discovery that changes lives.”

The possibility of a new accelerator has the partners hopeful for the future of accelerator science and the discoveries it could enable. “Accelerators have already enabled life-saving discoveries. I can’t wait to see what researchers will be able to uncover with an accelerator that is more advanced,” says Boland. ■

Look who's NEW in the Cold Facts Buyer's Guide

Cold Facts Buyer’s Guide is the place to find suppliers in every area of cryogenics and superconductivity. These are the new suppliers added to the Buyer’s Guide since the last issue of *Cold Facts*. Find it online at **csabg.org**.

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www.cryogenicsociety.org/resources/cryogenic_references

Fermilab Sees Record Performance from Next-Generation Accelerator Component

by Lauren Biron, senior writer, lbiron@fnal.gov and Mary Magnuson, writer, mmagnuson@fnal.gov

For several years, three US Department of Energy national labs have worked together to further improve state-of-the-art particle accelerator technology. First tests of a prototype built at Fermi National Accelerator Laboratory (Fermilab, CSA CSM) show the effort has paid off, with a new component setting records.

The technology under development is called a superconducting radio-frequency cryomodule, a high-tech piece of equipment that efficiently speeds up particles. It is a key building block of modern particle accelerators and X-ray lasers. All supported by the DOE Office of Science, Fermilab, Thomas Jefferson National Accelerator Facility (Jefferson Lab, CSA CSM) and SLAC National Accelerator Laboratory (CSA CSM) have pooled their expertise for research and development on cryomodules that will enhance SLAC's X-ray laser, known as the Linac Coherent Light Source (LCLS).

LCLS produces very bright X-ray beams used to provide researchers insights into the atomic structures of cells, materials and biochemical pathways. An upgrade of LCLS to LCLS-II is currently underway. The cryomodules now in development will be part of a future high energy update, called LCLS-II-HE, that will enable even more precise atomic X-ray mapping.

Researchers in biomedical and materials science fields can use LCLS-II and LCLS-II-HE, for example, to study how energy flows in tiny molecules and biochemical systems; how light penetrates and interacts with synthetic materials; and how materials might behave in extreme environments. Importantly, scientists also can use LCLS technology to study the properties of electric fields and how factors such as pressure and magnetism might govern particle interactions.

Assembly of verification cryomodule cold mass prior to insertion into the cryomodule vacuum vessel.
Image: APS-TD process engineering group

The vCM at the Fermilab Cryomodule Test Facility.
Image: APS-TD process engineering group

To produce X-rays, LCLS-II accelerates electrons using superconducting radio-frequency technology. After reaching close to the speed of light, the electrons fly through a series of magnets, called an undulator, which forces them to travel a zigzag path and give off energy in the form of X-rays that are then used for research.

From prototype to production

The high energy upgrade of LCLS-II is the solution to a seemingly impossible task. Researchers wanted to double the energy of the X-ray laser, but the upgrade must be squeezed into a relatively small area between the existing accelerator and another experiment. Current state-of-the-art technology would have required too much room – so the teams had to invent a way to pack more particle punch into their equipment.

Accelerator experts improved the cryomodules in several ways. They used a process called "nitrogen doping" to optimize the molecular makeup of the walls of the superconducting accelerator cavities, the components that accelerate the particle beam. They also developed new procedures to assemble and finish the components. Improving the cleanliness reduces unwanted effects from any contamination on the surface, including errant dust particles.

Fermilab's prototype is a "verification cryomodule." It's proof that the design works as expected, the improved cryomodules will successfully fit in the constrained space, and that final production can begin. It's a strong start to the upgrade that will take place over the next several years and will require 24 new cryomodules: 13 produced at Fermilab and 11 at Jefferson Lab. Researchers improved the cryomodules far beyond current specifications, and the new equipment should result in a 30% improvement to LCLS-II's performance.

"Structurally, if you're looking at the cryomodules from the outside, you won't be able to tell the difference," said John Hogan, senior team lead at Jefferson Lab. "But if we're able to maintain that test performance throughout the whole production, it will give the machine much more energy."

Experts pay attention to quality factor, called Q0, which measures a cryomodule's efficiency – basically, how much excess heat it generates. Superconducting cavities generate about 10,000 times less heat than normal conducting cavities made of copper. But they must be kept at cryogenic temperatures (usually around 2 K), requiring a cryogenic plant. To keep the cryogenic requirements reasonable, many accelerators are operated in a "pulsed mode," with pauses between pulses to reduce the cryogenic load. The nitrogen doping process increases the Q0 so much that it allows the cryomodules in LCLS-II to operate at full tilt without stopping, a feature called "continuous wave mode."

The verification cryomodule achieved a record in this continuous mode; electrons passing through the module will have their energy increased by an incredible 200 million electronvolts. The rapid acceleration within a single cryomodule is what will enable the high energy LCLS-II to reach higher energies in a shorter distance while using fewer cryomodules. The team was also able to maintain the high quality factor, meaning faster acceleration with minimal excess heat.

Fermilab senior team lead Tug Arkan said the prime focus of the high energy upgrade is quality and performance, building on the labs' experience working together. "For LCLS-II, we designed the system, we procured parts, we assembled the parts into the cryomodules, we tested the cryomodules, and then we successfully delivered them to SLAC," said Arkan. "We are starting LCLS-II-HE with the proven success from LCLS-II experience. We will leverage from our successes and from our unwanted outcomes and adapt the lessons learned to LCLS-II-HE."

Jefferson Lab and Fermilab are now assembling the needed cryomodules, which should be complete in 2024. The equipment will be shipped to SLAC and stored until scientists are ready to move them into their positions at the end of the LCLS-II accelerator chain.

Once the team at SLAC installs and commissions the LCLS-II-HE, researchers in everything from biomedical science and molecular physics to renewable energy will find the facility useful.

"LCLS-II-HE will enable higher X-ray energies and better tools and capabilities for the science community," said Greg Hays, the LCLS-II-HE project director at SLAC. "Increased gradient with reduced heat loads will cut the number of required liquid helium refrigeration plants in half and reduce the length of the overall accelerator, allowing it more than double the energy of LCLS-II by making it only 50% longer."

The advances in cryomodule fabrication, installation and operation will also be useful for future particle accelerators both big and small. Many particle accelerators use the same superconducting radio-frequency technology as LCLS-II to accelerate particles, so applying the engineering principles from the LCLS-II-HE upgrade will allow other research teams to create high-performing accelerator cryomodules that create little excess heat and can operate efficiently.

"Higher-gradient performance with lower heat generation will dramatically improve future particle accelerators," Hays said. "It translates to lower construction and operation costs." ■

Over the past three and a half years, some 5,000 tonnes of equipment (tanks, compressors, piping, valves, truck-size electrical motors and Zeppelin-like gas bags) were installed in the cryoplant. Here, one of the three "trains" of helium screw compressors feeding the cold boxes with compressed helium at 20 bar. *Image: ITER*

ITER Takes First Steps Toward Cryoplant Commissioning

Every week since the beginning of November, a tube trailer filled with approximately 4,600 cubic meters (750 kg) of compressed gaseous helium delivers its load to the ITER cryoplant in the south of France. At a later stage, the deliveries will become more massive, as helium is delivered in liquid form in 25,000-cubic-meter (4-tonne) cryogenic containers. Progressively, the helium inventory in the cryoplant will reach the volume required to accommodate the different "clients" inside the tokamak: the lion's share for the superconducting magnets and the cryogenic pumping system, a smaller percentage for the cryostat shielding.

Constituting the helium inventory is a decisive step toward the commissioning of the cryoplant installation. "Over the past three and a half years, we have assembled and installed some 5,000 tonnes of equipment and laid many kilometers of piping – work accomplished through approximately one million work hours and a peak of 200 full-time workers," explains David Grillot, the head of ITER's Cryogenic System Section. "We are now entering the pre-commissioning phase which includes testing and verifying control command systems, performing leak tests, ensuring cleanliness, helium purity and the safety of the equipment."

Like blood in a living organism, helium is at the core of cryoplant operation and performance. "The helium we receive from the tube trailer is extremely pure – no more than 2 ppm (parts per million) of non-helium molecules. In our processes we must remain below 10 ppm, which means that we must create a vacuum in all our tanks and piping before filling them – what we call the 'helium inerting' process."

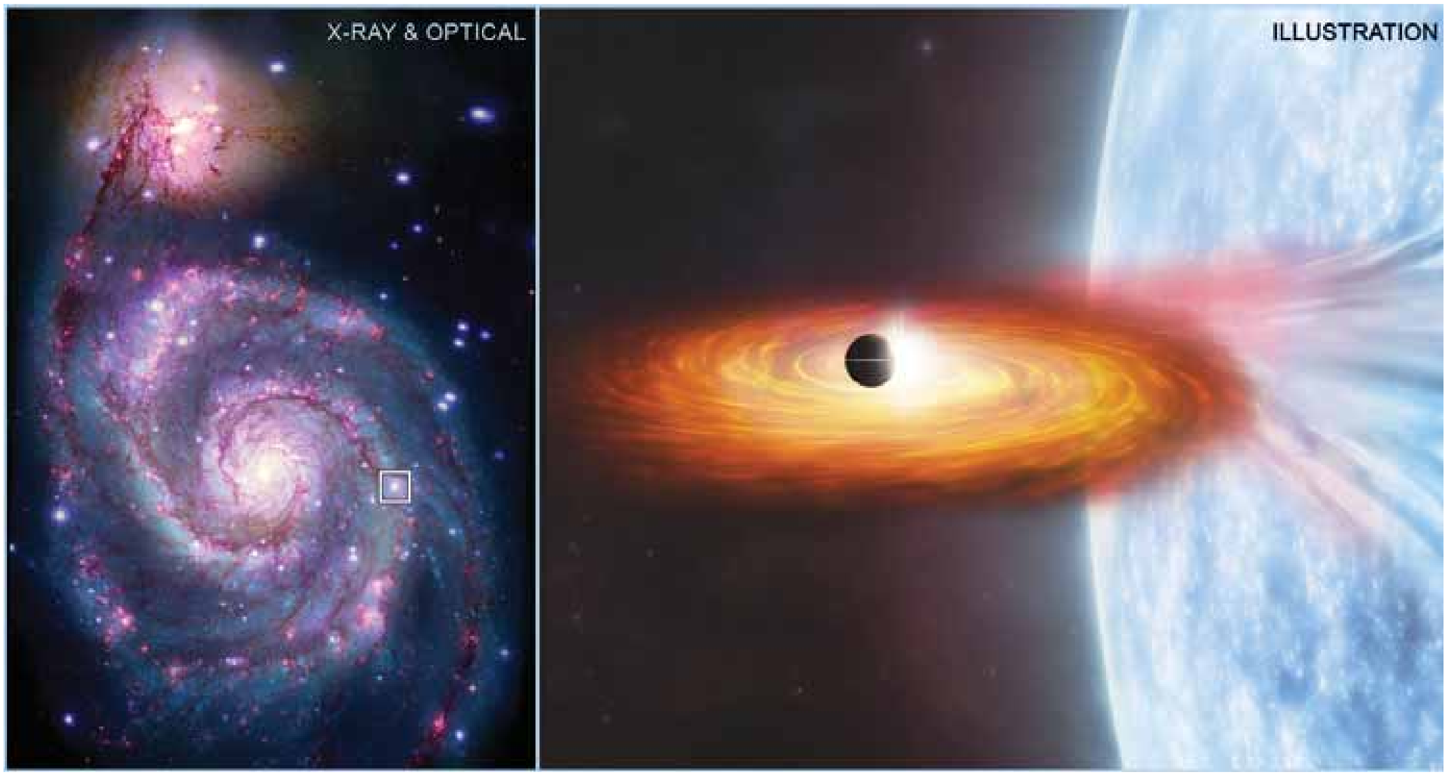
Helium is not the only cooling fluid involved in cryoplant operation. In January 2022, special truck trailers will start delivering what will constitute the first load of liquid nitrogen (400,000 liters) to be used as a pre-cooler in the helium cooling process. During operation phase, an air separation unit will extract nitrogen directly from the air to compensate for the inevitable losses.

The final commissioning sequence of the cryoplant is heavily dependent on the availability of other systems and installations. Compressors, turbines and electrical motors are powerful machines that require considerable cooling power that will only become available when the ITER heat rejection system is fully operational. "Fortunately, a large part of the pre-commissioning can be done without the availability of cooling water," Grillot adds with a smile.

Likewise, the flow of supercritical helium in the Tokamak Building will need to be tested before all magnets are fully installed. Consequently, "bypasses" will be installed to create a closed circuit and verify that the cryogenic system mission can be properly achieved.

Operational acceptance testing will begin in the first months of 2022. "If everything goes well, the cryoplant will be in marching order in 2024," says Grillot. For the head of the ITER Cryogenic System Section, the adventure will have lasted more than 10 years – first as the engineer in charge of design and manufacturing at the French supplier Air Liquide (CSA CSM), then at ITER since early 2016.

But as always, success will be the result of teamwork. In the case of the cryoplant, the Cryogenic Integrated Team brings together the three parties sharing responsibility for the procurement of the cryoplant – the ITER Organization, responsible for the liquid helium plant; Europe, in charge of the liquid nitrogen plant and auxiliary systems; and India, whose contractors are procuring the cryolines, the warm lines and cryodistribution components. ■



A composite image of M51 with X-rays from Chandra and optical light from NASA's Hubble Space Telescope contains a box that marks the location of the possible planet candidate.
Image: X-ray: NASA/CXC/SAO/R. DiStefano, et al.; Optical: NASA/ESA/STScI/Grendler; Illustration: NASA/CXC/M.Weiss

Chandra Sees Evidence for Possible Planet in Another Galaxy

Signs of a planet transiting a star outside of the Milky Way galaxy may have been detected for the first time. This intriguing result, using NASA's Chandra X-ray Observatory, opens up a new window to search for exoplanets at greater distances than ever before. The possible exoplanet candidate is located in the spiral galaxy Messier 51 (M51), also called the Whirlpool Galaxy because of its distinctive profile.

Exoplanets are defined as planets outside of our solar system. Until now, astronomers have found all other known exoplanets and exoplanet candidates in the Milky Way galaxy, almost all of them less than about 3,000 light-years from Earth. An exoplanet in M51 would be about 28 million light-years away, meaning it would be thousands of times farther away than those in the Milky Way.

"We are trying to open up a whole new arena for finding other worlds by searching for planet candidates at X-ray wavelengths, a strategy that makes it possible to discover them in other galaxies," said Rosanne Di Stefano of the Center for Astrophysics, Harvard & Smithsonian (CfA) in Cambridge MA who led the study, which was published in *Nature Astronomy*.

This new result is based on transits, events in which the passage of a planet in front of a star blocks some of the star's light and produces a characteristic dip. Astronomers using both ground-based and space-based telescopes – like those on NASA's Kepler and TESS missions – have searched for dips in optical light (electromagnetic radiation humans can see), enabling the discovery of thousands of planets.

Di Stefano and colleagues have instead searched for dips in the brightness of X-rays received from X-ray bright binaries. These luminous systems typically contain a neutron star or black hole pulling in gas from a closely orbiting companion star. The material near the neutron star or black hole becomes superheated and glows in X-rays.

Because the region producing bright X-rays is small, a planet passing in front of it could block most or all of the X-rays, making the transit easier to spot because the X-rays can completely disappear. This could allow exoplanets to be detected at much greater distances than current optical light transit studies, which must be able to detect tiny decreases in light because the planet only blocks a tiny fraction of the star.

The team used this method to detect the exoplanet candidate in a binary system called M51-ULS-1, located in M51. This binary system contains a black hole or neutron star orbiting a companion star with a mass about 20 times that of the Sun. The X-ray transit they found using Chandra data lasted about three hours, during which the X-ray emission decreased to zero. Based on this and other information, the researchers estimate the exoplanet candidate in M51-ULS-1 would be roughly the size of Saturn, and orbit the neutron star or black hole at about twice the distance of Saturn from the Sun.

While this is a tantalizing study, more data would be needed to verify the interpretation as an extragalactic exoplanet. One challenge is that the planet candidate's large orbit means it would not cross in front of its binary partner again for about 70 years, thwarting any attempts for a confirming observation for decades. "Unfortunately to confirm that we're seeing a planet we would likely have to wait decades to see another transit," said co-author Nia Imara of the University of California at Santa Cruz. "And because of the uncertainties about how long it takes to orbit, we wouldn't know exactly when to look."

Can the dimming have been caused by a cloud of gas and dust passing in front of the X-ray source? The researchers consider this to be an unlikely explanation, as the characteristics of the event observed in M51-ULS-1 are not consistent with the passage of such a cloud. The model of a planet candidate is, however, consistent with the data. "We know we are making an exciting and bold claim so we expect that other astronomers will look at it very carefully," said co-author Julia Berndtsson of Princeton University in New Jersey. "We think we have a strong argument, and this process is how science works."

If a planet exists in this system, it likely had a tumultuous history and violent past. An exoplanet in the system would have had to survive a supernova explosion that created the neutron star or black hole. The future may also be dangerous. At some point the companion star could also explode as a supernova and blast the planet once again with extremely high levels of radiation.

Di Stefano and her colleagues looked for X-ray transits in three galaxies beyond the Milky Way galaxy, using both Chandra and the European Space Agency's XMM-Newton. Their search covered 55 systems in M51, 64 systems in Messier 101 (the "Pinwheel" galaxy), and 119 systems in Messier 104 (the "Sombrero" galaxy), resulting in the single exoplanet candidate described here.

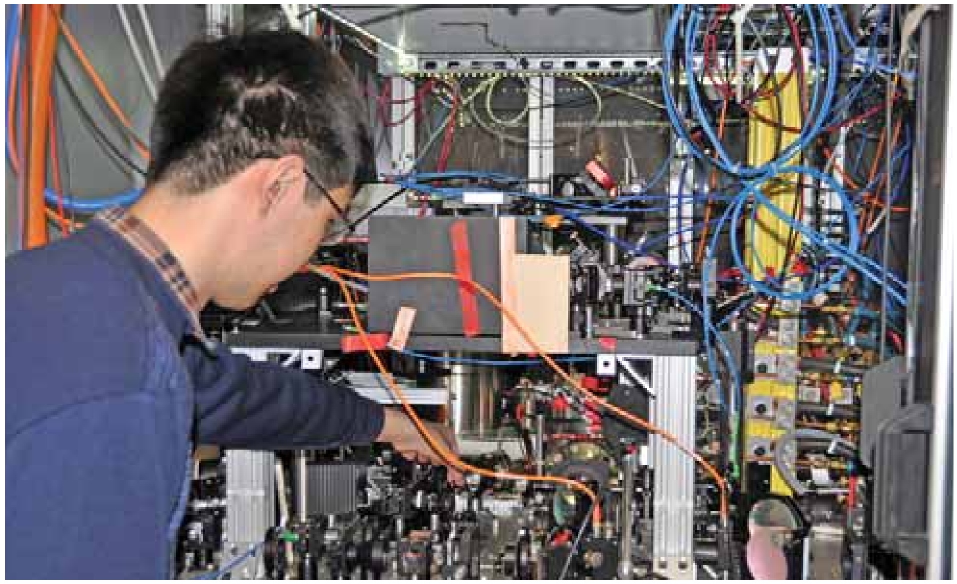
The authors will search the archives of both Chandra and XMM-Newton for more exoplanet candidates in other galaxies. Substantial Chandra datasets are available for at least 20 galaxies, including some like M31 and M33 that are much closer than M51, allowing shorter transits to be detectable. Another interesting line of research is to search for X-ray transits in Milky Way X-ray sources to discover new nearby planets in unusual environments.

The other authors of this *Nature Astronomy* paper are Ryan Urquhart (Michigan State University), Roberto Soria (University of the Chinese Science Academy), Vinay Kashap (CfA), and Theron Carmichael (CfA). NASA's Marshall Space Flight Center manages the Chandra program. The Smithsonian Astrophysical Observatory's Chandra X-ray Center controls science from Cambridge MA and flight operations from Burlington MA. ■

How Ultra Cold, Superdense Atoms Become Invisible

by Jennifer Chu, MIT News Office

A new study confirms that as atoms are chilled and squeezed to extremes, their ability to scatter light is suppressed.



Graduate student Yu-Kun Lu aligns optics for observing light scattering from ultracold atom clouds.
Image: Courtesy of the researchers

An atom's electrons are arranged in energy shells. Like concertgoers in an arena, each electron occupies a single chair and cannot drop to a lower tier if all its chairs are occupied. This fundamental property of atomic physics is known as the Pauli exclusion principle, and it explains the shell structure of atoms, the diversity of the periodic table of elements, and the stability of the material universe. MIT physicists observed the Pauli exclusion principle, or Pauli blocking, in a completely new way: they've found that the effect can suppress how a cloud of atoms scatters light. The team's results, reported November 18 in *Science*, represent the first observation of Pauli blocking's effect on light-scattering by atoms. This effect was predicted 30 years ago but not observed until now.

Normally, when photons of light penetrate a cloud of atoms, the photons and atoms can ping off each other like billiard balls, scattering light in every direction to radiate light, and thus make the cloud visible. However, the MIT team observed that when atoms are supercooled and ultra-squeezed, the Pauli effect kicks in and the particles effectively have less room to scatter light. The photons instead stream through, without being scattered.

In their experiments, the physicists observed this effect in a cloud of lithium atoms. As they were made colder and denser, the atoms scattered less light and became progressively dimmer. The researchers suspect that if they could push the conditions further, to temperatures of absolute zero, the cloud would become entirely invisible.

"Pauli blocking in general has been proven, and it is absolutely essential for the stability of the world around us," says Wolfgang Ketterle, the John D. Arthur Professor of Physics at MIT. "What we've observed is one very special and simple form of Pauli blocking, which is that it prevents an atom from what all atoms would naturally do: scatter light. This is the first clear observation that this effect exists, and it shows a new phenomenon in physics." Ketterle's co-authors are lead author and former MIT postdoc Yair Margalit, graduate student Yu-Kun Lu, and Furkan Top PhD '20. The team is affiliated with the MIT Physics Department, the MIT-Harvard Center for Ultracold Atoms, and MIT's Research Laboratory of Electronics (RLE).

A light kick

When Ketterle came to MIT as a postdoc 30 years ago, his mentor, David Pritchard, the Cecil and Ida Green Professor of Physics, made a prediction that Pauli blocking would suppress the way certain atoms known as fermions scatter light.

His idea, broadly speaking, was that if atoms were frozen to a near standstill and squeezed into a tight enough space, the atoms would behave like electrons in packed energy shells, with no room to shift their velocity or position. If photons of light were to stream in, they wouldn't be able to scatter.

"An atom can only scatter a photon if it can absorb the force of its kick, by moving to another chair," explains Ketterle, invoking the arena seating analogy. "If all other chairs are occupied, it no longer has the ability to absorb the kick and scatter the photon. So the atoms become transparent. This phenomenon had never been observed before, because people were not able to generate clouds that were cold and dense enough."

"Controlling the atomic world"

In recent years, physicists including those in Ketterle's group have developed magnetic and laser-based techniques to bring atoms down to ultracold temperatures. The limiting factor, he says, was density. "If the density is not high enough, an atom can still scatter light by jumping over a few chairs until it finds some room," Ketterle says. "That was the bottleneck."

In their new study, he and his colleagues used techniques they developed previously to first freeze a cloud of fermions – in this case, a special isotope of lithium atom, which has three electrons, three protons, and three neutrons. They froze a cloud of lithium atoms down to 20 microkelvins, which is about 1/100,000 the temperature of interstellar space. "We then used a tightly focused laser to squeeze the ultracold atoms to record densities, which reached about a quadrillion atoms per cubic centimeter," Lu explains.

The researchers then shone another laser beam into the cloud, which they carefully calibrated so that its photons would not heat up the ultracold atoms or alter their density as the light passed through. Finally, they used a lens and camera to capture and count the photons that managed to scatter away. "We're actually counting a few hundred photons, which is really amazing," Margalit says. "A photon is such a little amount of light, but our equipment is so sensitive that we can see them as a small blob of light on the camera."

At progressively colder temperatures and higher densities, the atoms scattered less and less light, just as Pritchard's theory predicted. At their coldest, at around 20 microkelvin, the atoms were 38 percent dimmer, meaning they scattered 38 percent less light than less cold, less dense atoms.

"This regime of ultracold and very dense clouds has other effects that could possibly deceive us," Margalit says. "So we spent a few good months sifting through and putting aside these effects, to get the clearest measurement."

Now that the team has observed Pauli blocking can indeed affect an atom's ability to scatter light, Ketterle says this fundamental knowledge may be used to develop materials with suppressed light scattering, for instance to preserve data in quantum computers.

"Whenever we control the quantum world, like in quantum computers, light scattering is a problem, and means that information is leaking out of your quantum computer," he muses. "This is one way to suppress light scattering, and we are contributing to the general theme of controlling the atomic world."

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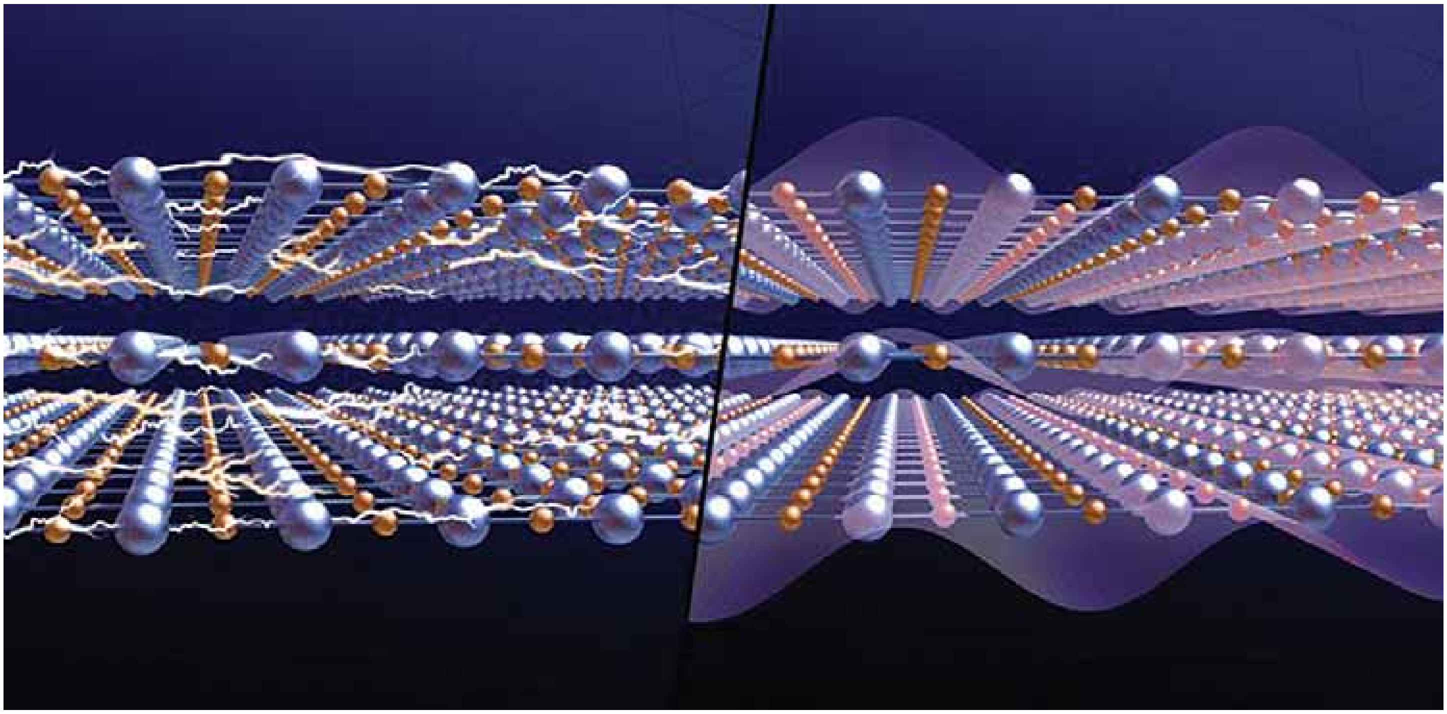
Strange Metal State in High Temperature Superconductors Gets Even Stranger



On the left panel, the copper-oxide planes of the material YBCO are presented in the strange metal phase, where the strong interaction between electrons, the 'quantum entanglement,' is illustrated as lightning. On the right panel, the same planes are presented when the charge density waves appear. Here, the symmetry of the system is reduced by the appearance of these local modulations of the conducting electrons, which cause the suppression of the strange metal phase. *Illustration: Yen Strandqvist*

Researchers from Chalmers University of Technology, Sweden, have uncovered a striking new behavior of the "strange metal" state of high temperature superconductors. The discovery represents an important piece of the puzzle for understanding these materials, and the findings have been published in the highly prestigious journal *Science*.

Superconductivity, where an electric current is transported without any losses, holds enormous potential for green technologies. For example, if it could be made to work at high enough temperatures, it could allow for lossless transport of renewable energy over great distances. Investigating this phenomenon is the aim of the research field of high temperature superconductivity. The current record stands at −130 °C, which might not seem like a high temperature, but it is when compared to standard superconductors which only work below −230 °C. While standard superconductivity is well understood, several aspects of high temperature superconductivity are still a puzzle to be solved. The newly published research focuses on the least understood property – the so-called "strange metal" state, appearing at temperatures higher than those that allow for superconductivity.

"This 'strange metal' state is aptly named. The materials really behave in a very unusual way, and it is something of a mystery among researchers. Our work now offers a new understanding of the phenomenon," says Floriana Lombardi, professor at the Quantum Device Physics Laboratory at the Department of Microtechnology and Nanoscience at Chalmers. "Through novel experiments, we have learned crucial new information about how the strange metal state works."

Believed to be based on quantum entanglement

The strange metal state got its name because its behavior when conducting electricity is, on the face of it, far too simple. In an ordinary metal, lots of different processes affect the electrical resistance – electrons can collide with the atomic lattice, with impurities, or with themselves, and each process has a different temperature dependence. This means that the resulting total resistance becomes a complicated function of the temperature. In sharp contrast, the resistance for strange metals is a linear function of temperature – meaning a straight line from the lowest attainable temperatures up to where the material melts.

"Such a simple behavior begs for a simple explanation based on a powerful principle, and for this type of quantum materials the principle is believed to be quantum entanglement." says Ulf Gran, professor at the Division of Subatomic, High-Energy and Plasma Physics at the Department of Physics at Chalmers. "Quantum entanglement is what Einstein called 'spooky action at a distance' and represents a way for electrons to interact which has no counterpart in classical physics. To explain the counterintuitive properties of the strange metal state, all particles need to be entangled with each other, leading to a soup of electrons in which individual particles cannot be discerned, and which constitutes a radically novel form of matter."

Exploring the connection with charge density waves

The key finding of the paper is the discovery of what kills the strange metal state. In high temperature superconductors, charge density waves (CDW), which are ripples of electric charge generated by patterns of electrons in the material lattice, occur when the strange metal phase breaks down. To explore this connection, nanoscale samples of the superconducting metal yttrium barium copper oxide were put under strain to suppress the charge density waves. This then led to the re-emergence of the strange metal state. By straining the metal, the researchers were able to thereby expand the strange metal state into the region previously dominated by CDW – making the 'strange metal' even stranger.

"The highest temperatures for the superconducting transition have been observed when the strange metal phase is more pronounced. Understanding this new phase of matter is therefore of utmost importance for being able to construct new materials that exhibit superconductivity at even higher temperatures," explains Lombardi.

The researchers' work indicates a close connection between the emergence of charge density waves and the breaking of the strange metal state – a potentially vital clue to understand the latter phenomenon, and which might represent one of the most striking pieces of evidence of quantum mechanical principles at the macro scale. The results also suggest a promising new avenue of research, using strain control to manipulate quantum materials.

The article "Restored strange metal phase through suppression of charge density waves in underdoped $YBa_2Cu_3O_{7-\delta}$" is now available in the journal *Science*. The research was carried out by Eric Wahlberg, Riccardo Arpaia, Edoardo Trabaldo, Ulf Gran, Thilo Bauch and Floriana Lombardi from Chalmers University of Technology, in collaboration with researchers from Politecnico di Milano, University La Sapienza, Brandenburg University of Technology and the European Synchrotron facility. ■

Space Cryogenic Workshop Recap

During a year filled with uncertainty, many were worried about the effects of the pandemic on CSA's biennial Space Cryogenics Workshop (SCW). After much consideration and effort, we are pleased to report the successful execution of our first – and hopefully only – virtual SCW. Hosted virtually on the Remo® online platform on November 15 and 16, the event was two days of presentations, networking and reconnecting with colleagues and friends. Each of the two days was broken up into two groups of presentations, beginning and ending with networking opportunities in Remo's virtual conference room. Co-chairs Amir Jahromi and Mark Kimball moderated all four sessions while CSA's Megan Galeher and Tate Paglia – executive director and editor, respectively – worked as administrators for the sessions. Sponsors included Lake Shore Cryotronics, XMA, Lihan, Eta Space and Ability Engineering Technology, all CSA Corporate Sustaining Members.

After a welcome ceremony including a "Hello" from Laurie and Werner Huget, CSA's past stewards, Day 1's first group was "Missions I," focusing on ongoing, upcoming and future space missions. Presentations from Peter Shirron, Michael DiPirro, Jason Hartwig, William Notardonato and Ramaswamy Balasubramaniam, shared their work: "Performance of the 3-Stage ADR on the Resolve Instrument on the X-Ray, Spectroscopy and Imaging Mission," "Finding and Fixing a Small Low Temperature Leak – A Case Study on XRISM/Resolve," "The Reduced Gravity Cryogenic Transfer Project," "Development of Cryogenic Propellant Depots for Sustainable Space Exploration," and "Gravitational Effects on Liquefaction Systems for Lunar and Mars exploration," respectively.

After a brief networking break, the next session – "Cryocoolers" – featured presentations from Roel Arts, Keisuke Shinozaki, and Shuang Tang. The topic of cryocoolers for space applications was discussed, including developments, testing and advancements of both soon-to-be-launched or currently in-orbit instruments. Presentations, in order of speaker, were "LPT6510 Development up to Flight Model," "Cooling Performances of Joule Thomson Coolers with Straight Heat Exchangers for Space Science Missions," and "Energy Sensitivity of Carrier Transport and Scattering: A New Path for Cryogenic Electronics and Solid State Cryo-Coolers."

After a short lunch break, part two of Day 1 focused on "Experimental Cryogenics." Scott Courts, Wesley Johnson and co-chair Mark Kimball discussed "Stability of Cernox Temperature Sensors Stored at Room Temperature Over a 29 Year Period," Summary of Testing Results for the Structural Heat Intercept, Insulation, and Vibration Evaluation Rig," and "Highly Sensitive Investigation of a Helium Leak in a Cryogenic Valve," respectively.

Then, Adam Swanger, Tom Conboy, Joydip Mondal and Alok Majumdar covered "Cryogenic Fluids I." In order of speaker, presentations were: "Passive Cooling in Aerogel-Based Insulation Systems for Liquid Hydrogen Upper Stage Launch Vehicle Tanks," "Development of a Hybrid Screen Channel Liquid Acquisition Device for Reliable Microgravity Transfer of Cryogenic Fluids," "Numerical Investigation of the Flow-field Due to Oscillating GN_2-LN_2 Interface in Presence of Ultrasound" and "Numerical Modeling of No Vent Filling of a Cryogenic Tank with Thermo-dynamic Vent System Assisted Injector."

Day 2 began with another welcome session and networking before the presentations of "Missions II" began. Mike Meyers and Wesley Johnson presented their works entitled, "Recent Concept Study for Cryogenic Fluid Management to Support Conjunction Class Crewed Missions to Mars" and "Liquefaction of Cryogenic Fluids for Production and Storage of Commodities on Extra-Terrestrial Surfaces."

After a short break, "Cryogenic Fluids II" was presented by Mansu Seo, Sam Darr, Matthew Taliaferro, Keerthi Raj Kunnlyoor, Alireza Moradikazerouni, Arpit Mishra and Niklas Weber. Presentations, in order of speaker, were: "Investigation of Line Chill-down Process with Liquid Oxygen in Ground Launch Complex," "Cryogenic Chilldown Model of Transfer Line with Low-effusivity Coating," "Control Volume Approach to Cryogenic Transfer Line Chilldown Investigation of Quench Flow Boiling Heat Transfer Correlations for Cryogenic Feedline Chill-down Modeling," "Computational Study of Natural Convection in Pressurized Cryogenic Tanks," "Shearing Jets from an Interacting Bubble-pair in the Cryogenic Environment," and "Vapor Bubble Growth in Liquid Methane due to Pressure Reduction in a Microgravity Environment."

After lunch, part two of Day 2 began with "Propulsion." Speakers included Seungwhan Baek, Lokesh Kumar Meena, Feroz Khan, Dylan Sagmiller and Kishan Bellur who gave their presentations entitled: "The Effect of Spray Cooling During the Cryogenic Liquid Pressurization with Helium," "Performance parameter estimation for HTS-magnet based Magneto Plasma Dynamic Thrusters (MPDT)," "Cryogenic System Design for High-Temperature Superconducting Magnets in Applied-Field Magnetoplasmadynamic Thrusters," "Numerical Modeling and Design of a Gaseous Propellant Acquisition System for the Triton Hopper," and "Mass Accommodation Coefficient of Cryogenic Propellants: A Cryo/Neutron Study."

Following these presentations, "Superconductivity in Space Cryogenics" was addressed. Speakers Feroz Khan and Sonja Schlachter presented "Magnetohydrodynamic Enhanced Entry System for Space Transportation (MEESST) as a Key Building Block for Future Exploration Missions" and "High-Temperature Superconductor Harness for Cryogenic Instruments on Satellites," respectively.

We thank all our sponsors, presenters, co-chairs, moderators and, most importantly, attendees for making a virtual Space Cryogenics Workshop just as enriching and rewarding as any in-person event. We look forward to seeing you face-to-face in 2023! A full list of presentations, including abstracts, can be found at **spacecryogenicsworkshop.org/agenda**. ■

GenH2 Manufactures NASA Kennedy Space Center-Licensed Macroflash Test Instrument

GenH2, specializing in commercializing and mass-producing advanced technology solutions, has announced that it is the first and only company currently manufacturing and distributing a new Macroflash test instrument under a technology transfer license from NASA Kennedy Space Center (KSC). The further development and manufacturing by GenH2 will follow more than a decade of internal research use in the space program by chief architect James Fesmire, cryogenic engineer, author of *Cold Facts*' *Clean Energy Future* column, and a leading hydrogen technologies expert.

Fesmire is also the inventor of the Macroflash technology, which was carried out under the umbrella of the KSC Cryogenic Test Laboratory (CSA CSM). Also known as a Cup Cryostat, the compact instrument measures thermal conductivity of materials or complex composites at below-ambient temperatures or subjected to a large temperature difference.

The South Dakota School of Mines & Technology (South Dakota Mines), a science and engineering university in Rapid City SD, is the first to receive the commercialized version of the Macroflash, which will be used in energy, transportation, construction and environmental sectors. It will be employed for such applications as engineered systems, research testing and quality control in manufacturing.

Other potential applications include electrical power and energy storage; refrigeration and cryogens; aerospace and advanced materials construction; and ground and air transportation. "We are pleased to have our own instrument in-house after years of advanced materials collaborative research work with James Fesmire as well as the team at Cryogenics Test Laboratory of NASA Kennedy Space Center," said Dr. David Salem, Director of the Composites and Polymer Engineering (CAPE) Laboratory at South Dakota Mines.

"Accurate thermal performance information, including effective thermal conductivity data, are needed under relevant end-use conditions across diverse industries," said Cody Bateman, a pioneer in cryogenics as well as the founder and CEO of GenH2, which also deploys liquid hydrogen infrastructure solutions. "By mass producing the Macroflash, industry and research institutions have a practical tool for basic testing of common materials or research evaluation of advanced materials and systems."

Advances in new polymers and composites along with growing industrial needs are the impetus for the Macroflash development. Among its many benefits, the Macroflash is compact, easy to use and cost-effective compared to other commercially available thermal test instruments. The device's small size is advantageous for test specimens (typically 75mm in diameter and 6mm in thickness), including solids, foams or powders, that are homogeneous or layered in composition. In addition, multiple tests can be completed in one day, with no costly vacuum chamber setup required.

The Macroflash technology uses liquid nitrogen as a direct heat energy meter and is applicable to testing at a wide range of temperatures from 373 K down to 77 K and under an ambient pressure environment. It operates with a cold side, maintained by liquid nitrogen at 77 K while a heater disk maintains a steady warm-side temperature from ambient up to 373 K.

The steady boiloff of the liquid nitrogen provides a direct measure of the heat energy transferred through the thickness of the test specimen. Nitrogen or other gas is supplied to the instrument to establish a stable, moisture-free, ambient pressure environment. Different compression loading levels can also be conveniently applied to the test specimen as needed for accurate, field representative thermal performance data. The Macroflash is calibrated from approximately 10 mW/m-K to 800 mW/m-K using well-characterized materials.

The Macroflash follows the guidelines of the newly established technical standard ASTM C1774 (Annex A4). For more information, please visit **https://technology.nasa.gov/patent/KSC-TOPS-22, www.genh2.net**. ■

Ability Engineering Technology Introduces Ultra Precise Cryo Valve to Public

Ability Engineering Technology (AET), an Illinois-based manufacturer of equipment used in cryogenic process applications, has announced the introduction of a standard product line of Cryogenic Valves.

According to Matt Resler, Sales Director at AET, "Our cryogenic valves have been successfully used for more than 30 years by our DOE clients, and we only recently decided to make them available for purchase by the larger industrial market."

The AET Valve can be used in multiple orientations and can be paired with various actuator packages. Seat seals are typically Neoflon PCTFE M-400H (aka Kel-F), and Bonnet Teflon O-rings and seals are also available in other materials for special applications and specifications. The valves are rated for liquid hydrogen (-423 °F) and liquid helium (-454 °F) temperatures. The series is also suitable for use in ASME B31.3 piping systems with all welding performed by ASME Section IX Certified Welders. They can also be designed to meet PED, CRN, and other international requirements.

Standard valve sizes are available up to 1", but custom cryogenic valves can be designed and manufactured to meet specific client requirements and applications.

Matt Resler continued, "Our cryogenic valves are carefully engineered for repeatable seals and manufacturing, and we're willing to modify any single component of the valve to meet a customer's needs. For your next cryogenic valve application, keep us in mind." **www.abilityengineering.com** ■

The Ability Engineering Technology's Cryo Valve.
Image: AET

RUAG Space Enhances Climate Data Through 10 Times More Accurate Satellite Navigation

Satellites provide important data on climate and the environment every day. According to initial tests, new software from RUAG Space can determine the real-time position of a satellite in space 10 times more accurately than was previously possible. More accurate positioning data leads to more precise satellite data and helps to avoid space debris.

ESA and NASA's Sentinel-6 environmental satellite. *Image: ESA/ATG Medialab*

Satellites give important data for climate and environmental research, such as how high sea levels are rising or what effects global warming is having on glacier retreats in the Alps. The more precise the satellite data, the more accurate the scientists' predictions. That is why RUAG Space is working on a study for the European Union to determine the position of satellites more precisely, which in turn will enable better satellite data on climate change, for example.

Tests exceeded expectations: Position accuracy down to 10 centimeters

RUAG Space recently conducted its first tests on Earth. This involved testing new software with an existing navigation receiver for RUAG Space satellites under simulated space conditions. "The result was impressive," reported Heinz Reichinger, technical lead engineer for navigation receivers and signal processing. "We were able to determine the satellite's position 10 times more accurately than previously possible." Position accuracy improved from about 100 centimeters to 10 centimeters. "This is a quantum leap in high precision positioning of satellites," Reichinger added. With an accuracy of 10 centimeters, the test results significantly exceeded the original expectations of accuracy of 20 centimeters.

New software processes new Galileo signal

The higher accuracy was achieved with a new software program. In addition to conventional signals, the software can also process an additional position signal from the European Global Navigation Satellite System, Galileo. To determine the exact position of satellites, RUAG Space's latest navigation receivers combine signals from both Galileo and the American GPS system. "We are using the Galileo signal to position satellites that are in space. But there is currently untapped potential in the Galileo satellites as they transmit signals in several frequency bands," explained Martin Auer, who is leading the study at RUAG Space. With the Galileo High Accuracy Service (HAS), Galileo will pioneer a worldwide, free high accuracy positioning service aimed at applications that require higher performance such as drones or autonomous vehicles. This service should be available in 2022. "A software update can be played on navigation receivers already in space as well as receivers we've already delivered to customers and are still on Earth," Auer comments.

The hardware of the devices remains unchanged. ESA, for example, is having the RUAG Space navigation receiver "PODRIX" already delivered for the Sentinel-1C environmental satellite upgraded with this new software for in-orbit validation of the satellite. The Sentinel-1C satellite built by Thales Alenia Space will be launched in 2022.

However, navigation receivers from RUAG Space that process Galileo signals already ensure precise positioning. These include the one for the Sentinel-6 Copernicus satellite, which has been in space since November 2020. It measures the extent of sea-level change and provides important data on coastal areas at risk from sea-level rise. "The more accurately the satellite's position can be determined, the more precise the environmental data it collects and provides. This potentially unlocks new observations and predictions essential to cope with the effects of climate crisis, for example in exposed coastal cities such as Venice," explained Fiammetta Diani, head of market development at the European Union Agency for the Space Programme (EUSPA).

More accurate positioning data avoids satellite accidents and space debris

More accurate data about a satellite's position also helps prevent satellites from colliding in space, thus providing better space situational awareness. When satellites collide in orbit, a lot of satellite debris is created. Due to the high speed in orbit, even the smallest debris particles pose a huge threat to other satellites. "The more precise the position of a satellite is known, the better a potential accident can be predicted, and, for example, evasive maneuvers can be carried out. Our more accurate satellite positioning data helps to avoid space debris," emphasized Reichinger.

New navigation system for satellite swarms

In the coming years, the launch of many swarms of hundreds to thousands of small satellites in low Earth orbit is planned. For such swarms of identical satellites, RUAG Space is developing a low-cost navigation receiver that is lighter and smaller than conventional devices and already includes the new software capable of processing the additional Galileo HAS signals as a standard feature. The new receivers called "NavRix PinPoint" are more cost effective due to the use of standardized electronic components (Commercial Off the Shelf).

At the beginning of 2021, the EUSPA awarded a research contract worth one million euros to RUAG Space. The aim of the study is to increase the positioning accuracy of satellites. The study will be completed in 2022. **www.ruag.com/space** ■

New software from RUAG Space makes it possible to determine the real-time position of a satellite in space 10 times more precisely. *Image: RUAG Space*

Demaco Produces ESS Hydrogen Distribution System

by Sthefani Neves Minela, Sales Engineer, Demaco

Hydrogen is the most abundant chemical element in the universe and the most important feedstock for life. In Greek, the word "hydrogen" is composed of the terms “hydro” and “genes,” which means water generator.

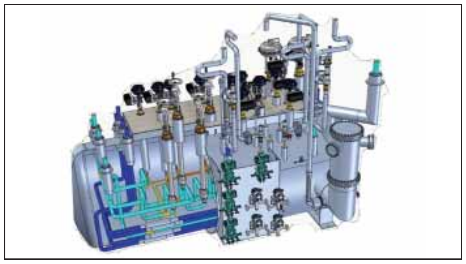
In 1766, the English chemist Henry Cavendish distinguished hydrogen from other flammable gases and identified its properties, but the name hydrogen was given by Antoine-Laurent Lavoisier in 1781. Hydrogen was commonly featured in the design of gas balloons in the 18th century, and then in the 20th century, substantial exploitation of hydrogen propellants in space propulsion systems began.

Hydrogen is not in the free state. It is produced by separating it from the other elements which it is combined with, through the processes that consume energy, called electrolysis and reforming. Unlike carbon-based fuels, hydrogen does not generate harmful waste, as it is fuel that burns cleanly and efficiently, creating an energy cycle that is renewable to the environment.

Hydrogen is used on a daily basis as a liquid gas by many industries for the production of chemicals and electronics, as well as space shuttles, fuel and space capsule propulsion. This work condition requires sophisticated cryogenic systems and insulation techniques.

The use of liquid hydrogen is present in cryogenic systems in part of projects of major value for science and development, such as ESS, ISRO, DLR and ESA of Sweden, India, Germany and Europe, respectively. These institutes are recognized worldwide for their scientific research on planetary exploration, space travel and scientific breakthroughs related to materials, health and the environment.

In cryogenic engineering, the quality of design and manufacture makes an extreme difference in the effectiveness and performance of the equipment throughout its lifetime. These constructions are based on the use of vacuum technology, which maintains the permanence of hydrogen in its liquid state and at the required temperature, according to the application need.



The ESS – Demaco Valve Box. *Image: Demaco*

The European Spallation Source (ESS) is a research facility that aims to be a leader within materials research by using neutrons. For transforming fast into slower neutrons for research, ESS will use subcooled liquid hydrogen as a coolant, and Demaco, which has three decades of experience in the cryogenics and hydrogen industries, is responsible for delivering part of the equipment that will make this project possible.

Demaco is developing the design and will manufacture, test and install a cryogenic valve box, several single transfer lines and required piping that constitutes part of the ESS cryogenic system. The valve box receives hydrogen from the main supply line and distributes it into four supply lines, leading towards the cryogenic moderators. Likewise, the valve box receives the hydrogen return lines, which merge into the main return line.

The illustration presents the 3D model of the valve box for the so-called cryogenic distribution and ortho-para measurement system (OPMS) at ESS. Besides the liquid hydrogen distribution system, the valve box contains a dedicated part used by ESS to measure the ortho-para fraction of the hydrogen returning from the moderators.

Valve boxes are dedicated devices of immense importance in a cryogenic system. The challenges in the execution of the distribution box project are related to the lack of space to accommodate a considerable number of instruments: temperature sensors, flow meters, cryogenic valves and pressure measurement devices, among others. Furthermore, the design solution respects not only ATEX regulations but also extra safety measures, due to the hard pressure requirements combined with a potentially explosive atmosphere.

The design of the transfer lines is not a typical design for single transfer lines, but a complex design. In the ESS project, the single transfer lines have a shared vacuum, one of ESS’ requirements to optimize safety. Due to the pressure drop combined with the use of hydrogen requirements in the design of the transfer lines, special pressure safety valves, special bellows, flexible components, and special Demaco Johnston couplings were selected, in order to keep hydrogen contained. This setup guarantees the reliability of the device. The connection in the monolith vessel (application) is a critical area. Due to the presence of ionizing radiation levels and external vacuum to which the equipment will be exposed, additional analyses have to be performed to assure the equipment's integrity. Moreover, 100% X-ray is applied, not only to the process piping but also to the vacuum jacket (normally this would only be 10%), guaranteeing quality from the beginning to the end of the hydrogen transfer process.

This unique project is possible due to the cooperation between ESS and Demaco cryogenic teams, and Demaco’s professional knowledge that is capable of offering an integral approach from the measurement, design, manufacturing and installation of reliable cryogenic equipment, allowing ESS to increase the excellence of its scientific research. “It's all about cryogenius.” **www.demaco.nl** ■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Cool Cryo Guests

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Our new 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 Tate Paglia at editor@cryogenicsociety.org.

Adiabatic Softening of Stainless Steel at 4 K

Much of the property data for materials at cryogenic temperatures was developed 30 or 40 years ago and is now condensed into tables in handbooks and standards. Thus, fewer people are actively performing these tests, and many may not be aware of some important subtleties of the material behavior and the procedures developed to obtain valid data. This article reviews some of these factors.

As the temperature drops into the cryogenic range, the heat capacity of most materials drops markedly. The heat capacity of a typical 300-series stainless steel drops by about a factor of 2 when dropping from room temperature to 77 K, and then by over another order of magnitude going to 4 K.[1] This extremely low heat capacity at 4 K can have a major effect on the mechanical properties as the deformation of testing generates heat. In turn, these effects must be considered in the mechanical testing procedures. For example, the Scope of ASTM Standard E 23 on notched bar (Charpy) impact testing of metallic materials states (and has stated for over 20 years), "These test methods do not address the problems associated with impact testing at temperatures below -196 ºC (77 K)."[2]

This could perhaps be worded even more strongly because the caution is based on a 1992 study by Tobler et al that made extensive efforts to conduct an accurate impact test at 4 K.[3] They placed the specimen in an insulated tube within the impact machine anvils and cooled it in place with liquid helium. In spite of these precautions to keep the specimen at 4 K, thermocouples on the specimen showed that the temperature spiked significantly as the machine striker induced deformation. They concluded "...convective or conductive heat transfer, or plastic deformation during a test will cause the specimen temperature to rise rapidly. Consequently, valid impact tests of alloys at 4 K cannot be performed according to the procedure outlined in ASTM Methods E 23-88. ... Fracture does not occur at the intended temperature, but at an uncontrolled temperature, since materials with different work hardening rates heat differently. In view of the temperature rise variability and scatter in measurements and property correlations, we conclude that it is not possible to accurately estimate the 4 K fracture toughness of ductile steels, or rank them properly, using Charpy tests." And this is the reason that fracture mechanics specimens are used to assess material toughness below 77 K.

You might not think there would be a problem during tensile testing because the loading rates are orders of magnitude slower. Yet at 4 K, the tensile test record (stress-strain plot) of stainless steels also exhibits serrations (a saw-tooth pattern or "ratchetting") that have been attributed to adiabatic heating. Understanding the source of this behavior will lend to better and safer designs of cryogenic structures.

The phenomenon of serrated yielding has been known since at least the 1950s. It has been observed on a variety of alloys, from fairly pure Armco ingot iron to stainless steels with almost 50% alloy content.[4,5] Sleeswyk attributed it to "anomalous velocity dependence of strain-hardening." A more thorough review of the phenomenon was produced by Rodriguez in 1984.[6] Most studies have concentrated on tensile test data to understand what is happening, but it has also been observed with compact tension specimens at 4 K.[7]

The initial part of a typical stress-strain record of a 4 K tensile test is shown in Figure 1.[8] The strain scale is expanded to

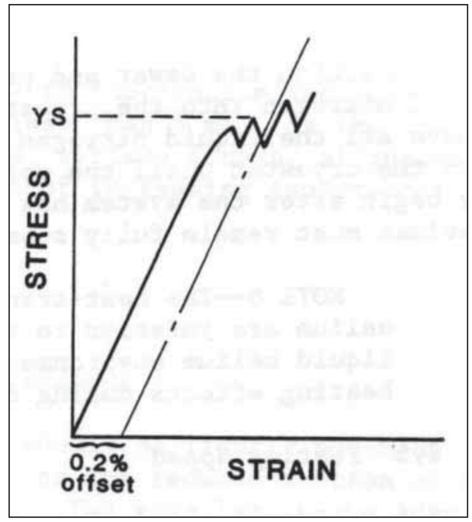

Figure 1. Initial part of stress-strain plot at 4 K showing that serrated yield can occur even before the traditional 0.2% offset yield point. [8]

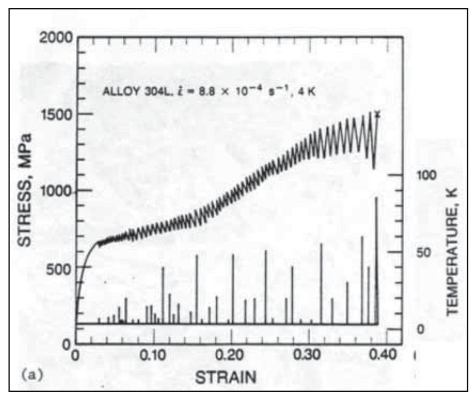

Figure 2. Tensile Stress vs Strain Curve (top) and Specimen Surface Temperature (bottom, with scale to right) for Stainless Steel Alloy 304L at 4 K at a typical strain rate. [9]

show that the serrations can first appear before the traditionally defined start of plastic deformation (0.2 % offset strain).

A complete tensile test plot from a study by Reed and Walsh is shown in Figure 2 to illustrate that the serrations occur over the entire span of the test.[9] Notice that the magnitude of the serrations increases as the stress increases. It seems reasonable to attribute the rough magnitude of the serrations to the elastic strain energy stored in the specimen, and to a smaller extent in the load train and test machine frame.

Further clarification of what is happening comes from the concurrent temperature spikes recorded along the bottom of Figure 2, with the temperature scale to the right. These measurements came from embedded thermocouples and superconducting filaments in contact with the tensile specimen's surface. The temperature spikes vary significantly in height because the thermocouples were not always adjacent to the precise location of the shear band. The average temperature spike was about 50 K and corresponded to a specimen extension of about 0.1 mm.

Reed and Walsh reference another study by Ogata and Ishikawa who studied this heating with a thermocouple embedded in a round tensile specimen.[10] They found that as the strain rate increased, the temperature spikes also increased, sometimes reaching 150 K.

In other words, the serrations result from a cyclic process. The load on the specimen increases (as the load frame follows a programmed strain ramp) until plastic deformation is triggered. This leads to rapid local heating within a shear band, lowering its strength. The resulting sudden extension and load drop arrests when the work-hardening specimen is able to sustain the load, and the specimen quenches back to 4 K. Meanwhile, the load frame continues to move until shear occurs within another band. These cycles continue until the specimen reaches its strain limit and fractures.

This behavior is not familiar to many engineers because most tensile testing is performed near room temperature when there is little change in the strength of the specimen as the shear bands release the elastic strain. It is the interaction of deformation making a significant change in the temperature of a low-heat-capacity material, combined with the strength of the material changing so much with the temperature, to release stored strain energy in a cascade.

Implications

This may seem like interesting trivia for mechanical testing lab personnel, but it could have some important implications in an engineering structure. Many of these early studies were performed on common stainless steel alloys used at room temperature (like 304 and 316), before the powerful strengthening effect of nitrogen was fully realized. Alloys such as 316LN strengthen even more as they are cooled, leading to the possibility of more stored strain and the possibility of higher temperature spikes once the strain bands move. Also, many engineering structures are much larger and more complicated than uniaxial tensile specimens and test machines, and so they may store much more residual strain energy, especially as they are cooled. Add to this the fact that many engineering structures include welds which are notorious for containing residual strain fields.

Engineered structures are usually designed to stay below the yield strength so no plastic deformation can occur. However, Figure 1 shows that serrations can occur even below the classic definition of yield strength. When all the various sources of stored strain (from construction) are added to any strains due to cooling of materials with different CTEs, the elastic loads on regions of the structure could be near the yield point. If additional strain is added by operating loads, some parts of the structure could experience plastic strain. The resulting deformation could cascade as the released heat moves more material into a lower strength state. The deformation will continue until the elastic strain is reduced to a level that balances the strength of the newly work-hardened material, possibly producing greater plastic strain than what was experienced in the short and stiff tensile test frame. In a large structure, you could imagine cases where this might result in a sudden distortion on the order of mm and maybe offset the alignment of some precision structure. The wise design engineer will keep the possibility of adiabatic softening in mind when assessing the behavior of the structure under service load, and include stress relief treatments or other measures to limit the stored elastic strain on the structure.

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[8] Part of Figure 5 from "Tension Testing of Structural Alloys in Liquid Helium," R.L. Tobler and R. P. Reed, in *Materials Studies for Magnetic Fusion Energy Applications at Low Temperatures*, from NISTIR 3944, September 1990, pg. 312.

[9] Part of Figure 1 from "Tension Testing of Structural Alloys in Liquid Helium," R.L. Tobler and R. P. Reed, in *Materials Studies for Magnetic Fusion Energy Applications at Low Temperatures*, from NISTIR 3944, September 1990, pg. 305.

[10] T. Ogata and K. Ishikawa, *Workshop on Standardization of Fracture Toughness Testing of Low Temperature Structural Materials*, National Research Institute for Metals, Tskuba Labs, Sengen, Sakura-mura, Niihari-gun, Ibaraki, Japan, March 1986. ■

Clean Energy Future

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

Hydrogen Storage and Density: Gas vs. Liquid

In the vast array of applications in the world of cryogenics, there are two distinct groups that emerge. In one group is the need for a cold temperature, such as liquid helium for MRI or quantum computers, or liquid nitrogen for freezing strawberries or performing brain surgery. The second group represents the need for the dense storage of molecules such as the entire foundation of the "gases industry." But no subject is hotter than hydrogen storage density for enabling the clean energy transition built around a hydrogen ecosystem.

The leading motivation for liquid hydrogen in the mix of the burgeoning hydrogen economy is simply the density of the hydrogen molecules. There are additional motivations, such as the purity of the molecules feeding the sensitive hydrogen electric cells ("fuel cells"), but let's just take them one at a time to avoid any confusion. Regarding hydrogen storage density, and the question of gas vs. liquid in practical applications, there is some confusion that is easy to correct.

The density of the fluid is one thing. The net usable density of operational systems is another thing. Added to this reality check is that the weight and cost of a real system also matter… a lot. For initial comparison, the densities of four different hydrogen fluid densities are given in Figure 1. The first four are for gaseous hydrogen storage, compressed to either 350 bar or 700 bar, two popular pressures for application in buses and cars, respectively. The second two are for cryogenic storage, including both liquefied hydrogen and cryo-compressed (supercritical fluid) hydrogen. Clearly, cryogenic hydrogen provides the highest storage densities.

Either way – compressing the gas to high pressures or liquefying the gas

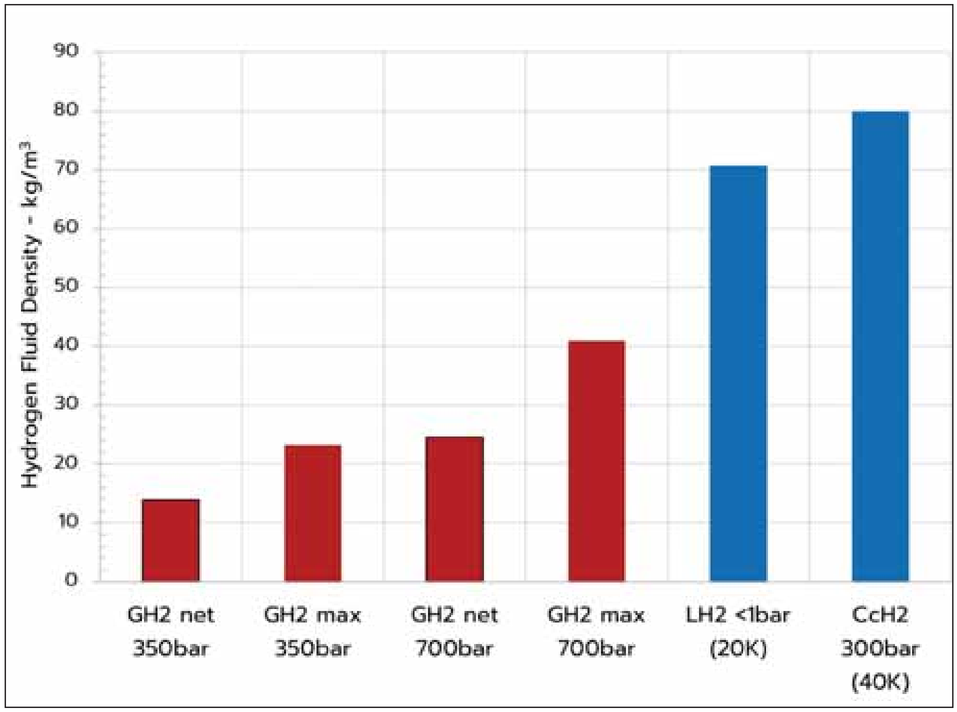


Figure 1. Hydrogen fluid density comparison. *Image: Fesmire*

(through the compression processes of refrigeration) – there is much compression work and heat rejection involved to make it happen.

So far so good, but here comes the confusion: a focus on the fluid density alone hides the reality of what does matter – the net density of the storage system. And added to this reality is the practicality, based on both capital expenditures (CAPEX) and operating expenses (OPEX) costs, of putting that hydrogen to work as needed on-demand, under actual duty cycles, for a given end-use application. To illustrate the net density of the storage system, let's look at storing 30 tonnes of hydrogen in both liquid form and high pressure compressed gas form.

Really? 30 tonnes of hydrogen? That's indeed a lot of hydrogen, but a single mega truck stop (or a hub of several large truck stops) of the future could go through that much hydrogen in a day. The necessary hydrogen storage systems in liquid form and compressed gas form (700 bar) are shown in Figure 2. The net storage density for gaseous hydrogen considers a typical duty cycle for vehicle dispensing. The net storage density for liquid holds close to the fluid density.

The liquid hydrogen storage requires a small, relatively lightweight, low pressure sphere only about 9 meters in diameter. The equivalent 700 bar gaseous hydrogen storage bank would require a field the size of the Eiffel Tower's footprint and weigh about as much at that structure (roughly 10,000 tonnes) or roughly 700x more than the single liquid tank.

There is still more to consider. For use of the high pressure gas, dispensed to the truck tanks at 700 bar, there will be another equal-sized field of massive pressure vessels to serve as the buffer tanks in the cascade of compression up to 950 bar or more. The net storage density for the high pressure gas becomes incredibly poor for large amounts of hydrogen as shown in Figure 2.

Approximately 500 racks, or 1,500 pressure vessels, are required for the equivalent 30-tonne hydrogen storage at 700 bar. And, to reject the tremendous amounts of heat involved with compressing, all this gas would require another field of cooling towers.

Using high pressure gas storage for large-scale hydrogen infrastructure is clearly not a realistic option other than the potential for underground caverns in a few locations around the world.

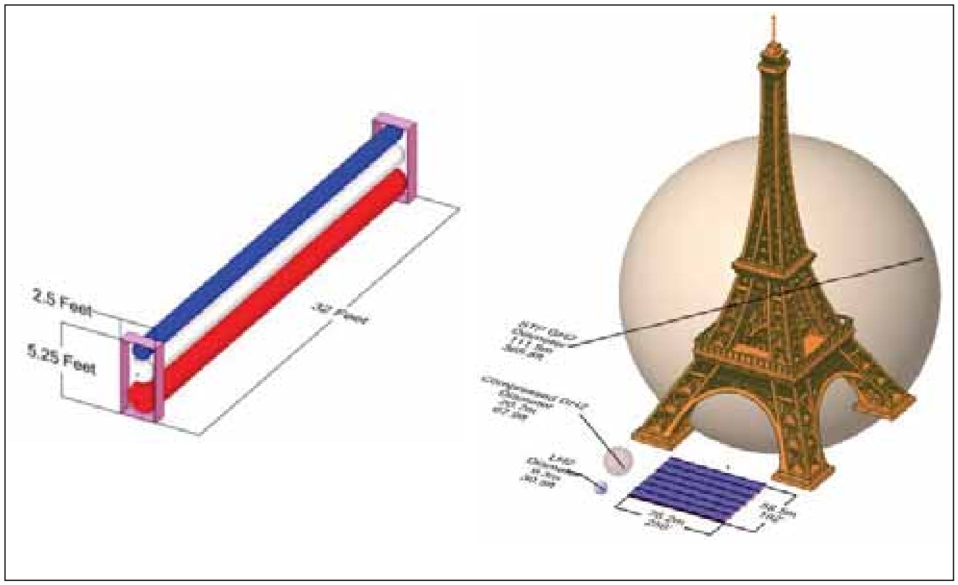


Figure 2. Hydrogen storage system density comparison: single gas storage rack for 0.1 tonne (left); 30 tonnes of storage in different forms (right) is scale with the Eiffel Tower. *Image: J. Ancipink, GenH2*

The liquefaction of hydrogen gas is indeed an energy-intensive process as we know, but gas storage is a non-starter for the needs of larger equipment as well as the hydrogen infrastructure at scale. The largest super-jumbo gaseous hydrogen trailer holds only about 1/3 tonne. For servicing a few dozen small cars per day, the high pressure gas storage approach will get the job done. High pressure gas will likely remain a vital part of hydrogen applications in general, but is extremely limited when more than 1/2 tonne of hydrogen is involved.

Liquid hydrogen is the focus because it is a practical path forward as the world transitions toward clean transportation and clean energy. ■

Cool Fuel

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

Over the Moon for Cryodusting

This story begins about 12 months ago when I wrote the *Cold Facts* column "Making a Splash with Moon Dust," about our fledgling concept to mitigate lunar dust with liquid nitrogen (LN_2) as part of the 2021 NASA Big Ideas Challenge. It was risky writing that article when I did, as NASA had not announced the finalists from the proposal pool. Much like Clark Griswold in the movie *Christmas Vacation* putting a deposit down on a pool before receiving an anticipated Christmas bonus, this story has a lot to unwrap before the end: hacking old medical equipment, 592 individual trials, dressing up Barbie dolls in Nomex suits, a broken-down travel trailer, and the merriest bunch of precocious underclassmen to win a NASA challenge since, well, 2019 when NASA started the Big Ideas Challenge series.

The party got started when NASA selected Washington State University (WSU) as one of seven finalists from the initial pool of 50 applicants. The team threw an actual party, complete with balloons, depicting the ortho-parahydrogen spin-isomers of hydrogen. With a team quickly coalescing, we needed to get to work fast. We knew early on that modeling electrostatically charged volcanic dust in the wake of a Leidenfrost droplet in reduced gravity wouldn't be feasible within the 11-month time frame of the competition. Liquid nitrogen hitting a pile of volcanic ash is analogous to a pyroclastic flow during a volcanic eruption, we're just calling it a cryoclastic flow (see Figure 1). With modeling removed, we needed a way to do rapid and repeatable experimental trials with liquid nitrogen like an astronaut would do, safely.

Figure 1. An example of cryoclastic flow. *Image: Leachman*

Figure 2. The Nomex Barbie. *Image: Leachman*

If you've ever been to the dermatologist to have a wart removed, you've likely seen a hand-held liquid nitrogen dispenser. Don't worry, that device is designed to be safe by forcing vaporization of LN_2 in a controlled fashion to prevent unnecessary burning. We voided all warrantees by boring open the nozzle orifice for direct LN_2 streaming. The hack worked. The team was able to test variable nozzle geometries (flat nozzles work best), variable inclinations (<90° from face down is best), distances from fabric swatch (40 cm is optimal), vacuum levels (works even better under vacuum), and many other variables like regolith or suit simulants. 592 safe trials later we basically found that it didn't matter much what we changed, cryodusting removed the goal of 90% of particles (by mass) below 10 microns from the fabric. What we did not expect was for the effect to get better under vacuum or with repeated cycles.

With a combination of a liquid nitrogen spray bar in the airlock and the handheld dispenser for spot treatment, we had a system that was synergistic when operated together and loosely coupled should either fail. To advance the TRL of both systems we needed a way to conduct a realistic scaled test. 1/6 scale was appropriate for the available vacuum chamber and about the height of a Barbie doll. So, we made a doll-sized space suit out of Nomex shown in Figure 2. Yes, the concept still worked with results like the controlled trials. Along the way we did complete some modeling that showed the Leidenfrost effect still works in reduced gravity, which has also been shown in prior experiments. Now that we were convinced, we just needed to convince NASA's judges.

There are many reasons why I'm a big fan of student competitions like NASA's Big Ideas Challenge series. The combination of something to prove, fear of public embarrassment, and peer-to-peer comparisons with expert feedback does wonderful things. The team flat out cares more with institutional pride on the line and works to achieve a higher level of professionalism. Moreover, blue-collar institutions like WSU can show, yet again, that our best can compete with the best anywhere. NASA gets research results faster, and likely cheaper, than with traditional research programs. It's a perfect tool for solving big sticky challenges needing new concepts tested fast. The significant downside of traditional competitions is that to have a winner, there are many losers.

The Big Ideas Challenge team thought this through too, as every team won an award from a different category. They even had fun by acknowledging unique team contributions. Our team was recognized with awards for "The Most Innovative Use of a Barbie Doll" and "Most Original Regolith Simulant Origin Story." The latter award came after one of our team members launched into the story of finding the Mt. St. Helen's Ash in a barn north of town with a 1969 (same year as the first moon landing) Airstream travel trailer sitting next to it that ended up coming home with me. We had lots of laughs. I couldn't be prouder of the hard work, coachability, kindness and fun of this team. The judges agreed and awarded them the Artemis Award for research most likely to end up on the moon.

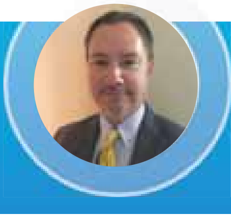
What the judges kept telling us was that the concept is new to the literature. They naturally wanted to know what else this cryodusting concept could be used for. My guess is anything that has stubborn dust where water cannot be used: silicon wafer/chip production, element/material processing, nuclear waste processing, and novel food decorations come to mind. Regardless, cryodusting is a topic to think about when you dust off those old holiday decorations up in the attic. ■

Jobs in Cryogenics

Assistant in Research – Materials Test Engineer
National High Magnetic Field Laboratory

Magnet/Cryogenic R&D Associate
Oak Ridge National Laboratory

Job openings from CSA Sustaining Members and others in the cryogenic community are included online, with recent submissions listed above. Visit **http://2csa.us/jobs** to browse all current openings or learn how to submit your company's cryogenic job to our list of open positions. Listings are free for Corporate Sustaining Members.



by Jonathan R. Stephens, NASA Marshall Space Flight Center, jonathan.r.stephens@nasa.gov

NASA Team Investigates Enhanced Approach for Tank-to-Tank Cryogen Transfers in Micro-Gravity Applications

NASA is putting emphasis on reusable cryogenic systems to enable returning astronauts to the lunar surface, and eventually on to Mars. Such systems will require replenishing cryogens on-orbit via a cryogenic tanker or propellant depot, and potentially on the lunar and Martian surfaces with the utilization of in-situ resources. Replenishing cryogens on-orbit requires a tank-to-tank transfer which presents challenges due to thermal environments and the absence of gravity. If the transfer process is initiated with the receiving tank empty and at atmospheric temperature, it then must be chilled to cryogenic temperatures to enable filling. Likewise, the transfer lines and associated hardware must be prechilled to assure liquid is transferred. Since prechilling results in propellant loss, it is preferred to minimize this process in the interest of saving propellant mass.

To simplify the operations associated with propellant transfer and explore potential mass savings, NASA has been experimenting with a new methodology which uses a Vented Chill/No-Vent Fill (VC/NVF) approach and enhances the process using a 3-D printed spray injector augmented with a Thermodynamic Vent System (TVS).

Transfer methodology

The operations associated with the VC/NVF approach are fairly simple. With an empty receiving tank at ambient temperature and vented to the atmosphere, the process is started by flowing cryogen through the transfer line and into the receiving tank via a spray injector. During this initial phase, cryogens boil off, absorbing energy from the transfer hardware and the receiving tank mass all while chilling the receiving tank ullage space. Boiloff gas is then released through the receiving tank vent port to avoid excessive pressure. This Vented Chill (VC) process continues until the tank temperature decreases to a predetermined "trigger point" value which is an indication to command the receiving tank vent valve closed.

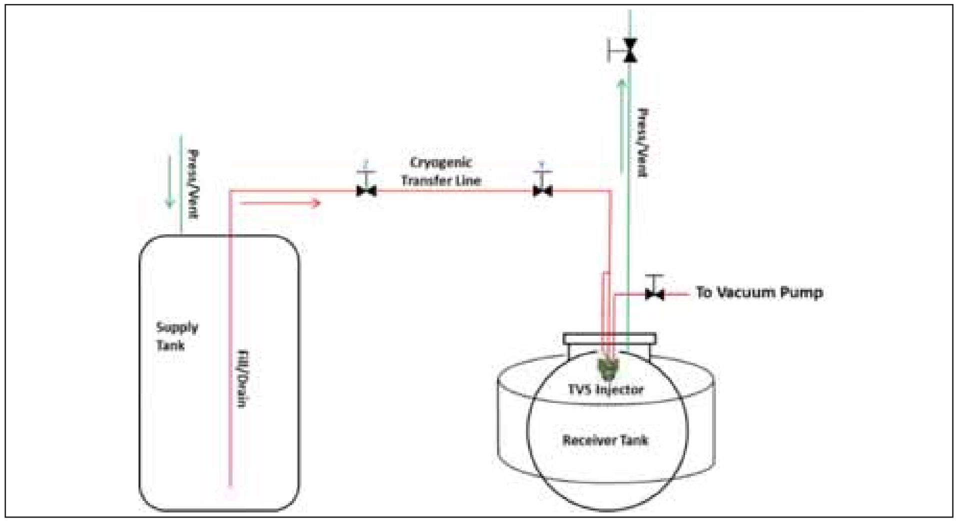


Figure 1. Test Article Setup. *Image: NASA*

If sufficient energy is removed from the receiving tank during the VC process combined with the large spray pattern acting as a heat exchanger absorbing thermal energy resulting in ullage collapse, a successful transfer can ensue filling the receiving tank to near 100% liquid level. If insufficient energy is removed from the receiving tank as a result of setting the "trigger point" temperature too high, then the flow will stall, resulting in a failed transfer. However, it has been demonstrated that a stalled flow can recover when the spray injector TVS is activated and a successful transfer can ensue.[1, 2]

Experimental Setup

The VC/NVF methodology was demonstrated through a series of tests at the NASA Marshall Space Flight Center's (MSFC) Propulsion Research and Development Lab (PRDL). NASA's Vibro-Acoustic Test Article (VATA) served as a liquid nitrogen supply tank while the 62-gallon spherical CRYOgenic Orbital TEstbed (CRYOTE) was used as the receiving tank. Both tanks were insulated, instrumented, and placed on load cells inside a 9' x 20' vacuum chamber. Each had independent pressurization and vent lines and were connected via a single fill and drain line to enable the transfer of liquid nitrogen between the two tanks. The receiving tank was instrumented with external surface thermocouples to monitor thermal conditions during chill and transfer. A simplified schematic of the test article setup is illustrated in Figure 1.

Leveraging the capabilities of additive manufacturing, a spray injector augmented with a TVS heat exchanger was designed, manufactured and installed into the receiving tank. The spray injector accepts subcooled cryogen which passes through an internal coiled heat exchanger before spraying it in an axial and radial pattern into the receiving tank. On a separate circuit upstream of the spray injector, an isenthalpic expansion of liquid cryogen occurs across a Joule-Thomson device, resulting in a cold 2-phase mixture which is introduced via a separate path into the injector. This cold mixture then enters a cavity where it flows over the exterior of the coiled heat exchanger, further subcooling the liquid nitrogen inside. It then passes through a coiled heat exchanger on the external surface of the injector which chills the ullage gas, causing a reduction in receiving tank pressure. A photograph of the 3-D Printed TVS Augmented Spray Injector and an image illustrating the internal flow paths are shown in Figures 2 and 3, respectively.

Figure 2. TVS Augmented Injector. *Image: NASA*

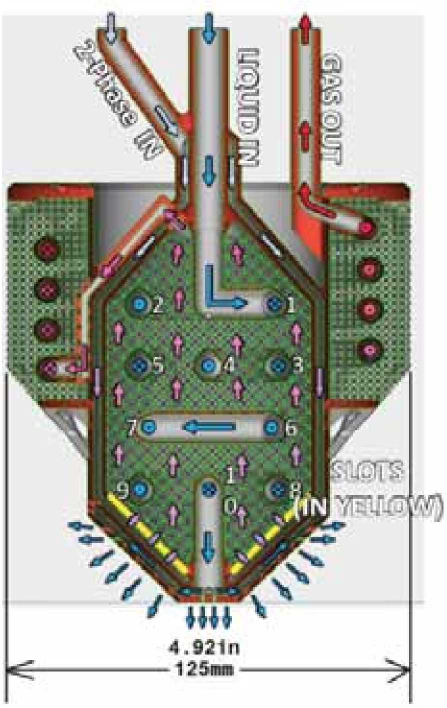


Figure 3. Injector Internal Flow Paths. *Image: NASA*

Results

A series of transfer tests were performed at MSFC using the experimental setup described above. Successful transfers, stalled transfers and recovered transfers were all demonstrated. Located at the 50% liquid level on the receiving tank, an external surface temperature was selected as the transfer "trigger point" which was used as an indication as to when sufficient thermal energy was removed from the system and the receiving tank vent valve could be closed. Each test started with the supply tank filled with liquid nitrogen and pressurized to 45 PSIA, and the receiving tank vent valve commanded open.

To demonstrate a successful fill to near 100% capacity, the "trigger point" value selected was 168 K. Both transfer valves were opened, supplying liquid nitrogen to the receiving tank via the spray injector. This cooled the transfer line, receiving tank and ullage space. As the cryogen absorbed heat, the boiloff gas was vented through the receiving tank vent port until the tank was chilled to 168 K and the vent valve was commanded closed.

The receiving tank pressure initially began to rise, but before it could reach the supply pressure resulting in a stalled transfer, it steadily started to decrease as the ullage collapsed due to the large conical spray of subcooled liquid absorbing energy. The internal pressure continued to decrease until the transfer concluded with the receiving tank near 100% full.

A failed transfer was demonstrated on a subsequent test with an increased "trigger point." Using the same process as the previous attempt, the receiving tank vent was closed when the "trigger point" temperature was chilled to 178 K. Again, the receiving tank pressure initially began to rise and – due to insufficient thermal energy removed during the chill – the pressure continued to rise to the supply pressure resulting in a stalled transfer.

The activation of the TVS heat exchanger proved to be effective in recovering a stalled transfer on another demonstration. Following the same process, the TVS was activated at start and the "trigger point" was set to 260 K. After a brief chill, the "trigger point" was reached and the vent valve commanded to close. The receiving tank pressure immediately increased to the supply pressure, resulting in a stalled transfer. However, with the TVS active, the liquid internal to the injector continued to cool as the injector exterior heat exchanger chilled the ullage space eventually leading to a reduction in pressure and allowing the transfer to recover and fill the receiving tank to 100% full.

Future Work

With the success of these small-scale demonstrations, the team plans to pursue this transfer methodology on a medium-scale propellant tank with a significantly higher heat load. Multiple injectors have been designed with various heat exchanger types (coiled, tube-in-shell, lattice structure, fins) and different spray patterns. The injectors will be instrumented to characterize internal heat exchanger performance. Additional transfer methodologies will be demonstrated as well, in an attempt to quantify potential mass savings associated with the NV/NCF approach. Testing is planned for November 2021 through March 2022.

Acknowledgement

This effort was funded in part by NASA Marshall Space Flight Center and NASA Space Technology Mission Directorate's Technology Demonstration Missions program. It is currently managed as an activity within NASA's Cryogenic Fluid Management Portfolio Project. I would like to acknowledge the Enhanced Cryogenic Transfer via a TVS Augmented Injector team which is comprised of talented engineers from NASA's Glenn Research Center and Marshall Space Flight Center, and Yetispace Inc.

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Cool Cryo Guests

by Hardik Dave, President, CryoHiVac Consulting LLC, hdave@cryohivac.com

Our new 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 Tate Paglia at editor@cryogenicsociety.org.

CryoHiVac Investigates Cryogenic Market, Affordability from Earth to Space

Today's time-sensitive market needs revolutionization of traditional costly technologies. The cryogenic and electronic market development and utilization started from 1970 for commercial applications, and both are fast-growing technologies. There has been significant advancement of electronic products. Nowadays, a small smartphone has much more data storage and processing power capability than large costly computers in the 1970s. Smartphones are now available to most people due to low cost. Due to affordable cost and high utilization factor, the electronic product demand is always increasing. In contrast, cryogenic products are exceptionally expensive, making them inaccessible to most people.

Cryogenic refrigeration is a process of cooling with roots in ancient history. Cryogenic extreme low temperature of 4 K cryopump, cryocooler and high vacuum systems has numerous applications in diverse scientific disciplines such as space industries, on-orbit applications, satellites, cryosurgery, MRI, superconductor, semiconductor, clean energy in the form of thermal fusion, LNG, liquid hydrogen technologies, defense and R&D projects. This article aims to signify the importance of "affordability" for future development of the cryogenic market in the 21st century, to build better human life on Earth and in space!

All details provided in this article are either based on published data or the author's knowledge and judgments formed from his experience. In this short article we will try to understand what real world needs are for future cryogenic market development. If we consider a cryogenic system as the human body, then refrigeration is its heart and high vacuum is its spine.

Space and Satellite Industries: It is forecasted that demand for satellite refueling and on-orbit services may grow more than triple in size to become a $1.4 trillion market within a decade. US commercial space companies like SpaceX, Firefly, Blue Origin, etc. need to consider affordable cryogenic propellant supply systems for on-orbit operations to explore deep space. Successful expansion of space launch and satellite industries requires pivoting away from traditional, costly and complex launch operation technologies. Cryogenic propellants depot and cryogenic/hypergolic propellant fluid transfer systems for on-orbit operation require adoption of new "innovative technology development" for project specific autonomous operation that considers low cost to achieve faster, frequent and affordable space missions. The commercial space market must embrace an approach of "affordability with needed reliability," which is the key to successful missions to the Moon, Mars, and the establishment of human life in space.

Clean Energy / Fusion Energy Market: Cryogenic applications in the thermal fusion energy market is intended to provide cheaper energy to meet our growing energy demand and solve the environment pollution problem. The successful development of this technology will solve the energy problem for several generations to come. There are few organizations currently in the process of making this dream a reality. To achieve fusion energy, the International Thermonuclear Experimental Reactor (ITER) organization based in France is building the world's largest Tokamak that has a doughnut-shaped vacuum chamber to establish plasma and generate very high temperatures of 150,000,00 °C. Cryogenic cooling in the high vacuum chamber is used to maintain stable generation of fusion energy, just like the Sun and stars. This type of challenging technology requires systematic integration of its subsystem operation from initial design (FEED) to achieve maximum efficiency at lowest operation cost. In a Tokamak device, powerful magnetic fields are used to confine and control the plasma, and this advanced R&D must consider affordability with needed project specific reliability that requires optimization of technology for applicable subsystem integration. Similarly, an American company, Commonwealth Fusion Systems in Massachusetts, is developing a Tokamak approach to create low-cost energy. The main challenge remains "affordability with needed reliability." This type of R&D program requires project specific technology optimization during the design approach, utilizing subject matter expert (SME) knowledge and experience to achieve low-cost cryogenic and vacuum system design and operation to create an affordable, clean energy source.

Affordability: For the past 60 years, there has been a significant rise in the global cryogenic market and its advanced technological development. However, the utilization factor remains very low due to the surprisingly high cost of cryogenics applications. We know from the last six decades that cryogenic product costs always increase unpredictably. In the 21st century, the challenge for all of us is to reduce cryogenic system cost and achieve affordability.

The growth of the cryogenic equipment market is forecasted to be about $4.33 billion during 2021-2025. However, the excessive cost of advanced cryogenic technology development may adversely impact the following two multibillion dollar future global markets:

1) Space market: Satellites, in-space simulation and launch vehicles for on-orbit operations

2) Clean energy market: Thermal fusion, LNG, liquid hydrogen technologies

Due to unreasonably high cost, new cryogenic product development cannot compete with current product availability, and the net result is low "product utilization factor." We have enough knowledge and data from early-stage cryogenic R&D carried out by government organizations like NASA, the US Department of Defense and different private industries to know that 21st-century cryogenic market development requires innovative and affordable cryogenic product development to increase the utilization factor, which will result in an increased market demand. Government organizations like NASA had adopted unique approaches from "lessons learned" and procurement of commercial off-the-shelf items to achieve affordability. Another government organization, the National Science Foundation (NSF), is providing great help to new start-up small businesses via the SBIR Phase I program. NSF encourages market research and product commercialization at the early stage, which also requires affordability of new R&D products, to be successful in today's market. NSF focuses on transforming the scientific discovery into potential commercial market opportunity that truly helps to build successful small businesses and benefit the US economy.

In today's time-sensitive and competitive market, there is no single source of information or software available that can provide a complete design solution for complex cryogenic system development. Considering the current market trend for increasing reliance on utilization of engineering software tools and forgetting the experienced workforce of SMEs, it is a well-known fact that many large commercial companies and government organizations are increasing total cost due to missed schedule milestones. Lack of timely involvement of SMEs leads to increased program costs to fix unforeseen program risks/issues late in the program lifecycle. Increased program costs are a significant setback in today's economy.

And last, but not least, "Affordability with needed reliability" is key for the successful growth of future cryogenic markets!

Hardik Dave is the president of CryoHiVac, which provides consulting services for cryogenic and high-vacuum applications to the scientific and high-tech industry. For more information, visit their website at **www.cryohivac.com**. ■

WOMEN *in* CRYOGENICS and SUPERCONDUCTIVITY

Swamini Chopra

Who is your present employer?

Maharashtra Institute of Technology (M.I.T.) in Aurangabad, M.S., India.

What is your title?

I am an assistant professor of research in the department of mechanical engineering.

What projects are you working on now?

Our team is working in the area of material property enhancement by cryogenic treatment. We are working with Sanjay Techno Plast Pvt. Ltd, Waluj (an automotive component manufacturer) to improve the wear performance and deformation resistance of PA 66/GF clutch plate by cryogenically treating the component at different sub-zero temperatures and soaking period combinations. We are also working with Professor Carlone of the University of Salerno, Italy to enhance the mechanical performance and improve the surface quality of UHDPE knee prosthesis by cryogenic treatment.

What accomplishment are you most proud of?

For the last six years, I have been part of a team that has worked extensively in the field of cryogenic treatment of different materials at both the research and the application level. Our team, spread at two locations, Aurangabad and Nagpur, has helped many industrialists in realizing the potential of cryogenic treatment for enhancing different properties of their components. We have also assisted them to successfully incorporate cryogenic treatment into their fabrication processes.

This summer, my mentor, Dr. Kavita N. Pande, and I have taken a leap to set up a small enterprise in the city of Nagpur, M.S. India, offering research, testing and consultancy services in the field of cryogenic treatment of different polymers, metals and ceramics.

What advances for women would you like to see in the fields of cryogenics and superconductivity?

This is an exciting time for women to take up more research opportunities as many research funding agencies and educational institutions across the world are trying to bring more female candidates into their teams. In the field of superconductivity, next generation machines based on superconducting magnets and high temperature superconductors are gaining momentum over the last couple of years. Whereas the use of cryogenics in different fields such as cryogenic machining, cryopreservation, sub-zero cryogenic treatment, cryogen fuels, etc. are now being recognized for actual applications as well, it would be nice to see many smart and intellectual women present their perspectives in these areas and contribute to research and applications to develop a greener and more energy efficient world.

What would be the best approach to getting more women into our field?

The field of cryogenics and superconductivity remain at a research and laboratory level due to the high investment and production costs this work demands. If these costs can be reduced to some extent, it will be very easy to attract many capable and interested candidates, not only women. Sharing their research with people working in actual application areas will encourage female researchers and entrepreneurs to further and increase the potential of this field.

Gargi Menger

Who is your present employer?

Inox India Pvt. Ltd., a leading manufacturer of cryogenic equipment.

What is your title?

I'm an executive of the Cryo Scientific Division in Quality Assurance and Quality Control.

What projects are you working on now?

The most important project I am currently working on is for ITER in the design and manufacturing of Disruption Mitigation System Cryolines. I'm also working at the Raja Ramanna Center for Advanced Technology doing fabrication of horizontal test cryostats with feedcan and a horizontal liquid nitrogen storage container.

What accomplishment are you most proud of?

My accomplishment as a cryogenic quality engineer. I have done various performance tests, NER tests, cold shock/thermal cyclic tests and heat leak tests on cryogenic projects being executed by my division. It's a great challenge and a wonderful experience. The very first project I worked on was a prototype of the ITER cryolines, and with its successful execution we became eligible to bid for the ITER cryolines project.

What advances for women would you like to see in the fields of cryogenics and superconductivity?

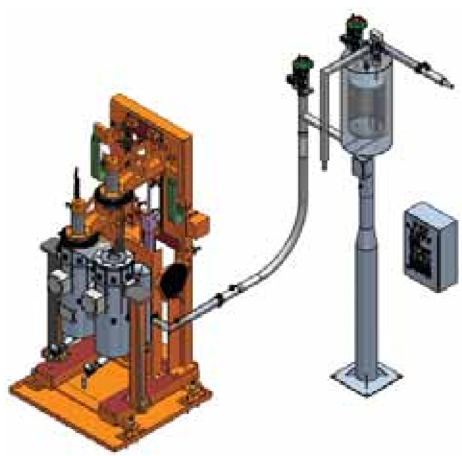
There are many women working at good positions in the fields of cryogenics and superconductivity but they seem to mainly be in research or the design field. With six years of experience in this field, I have come across very few women in fields like quality, production and installation on site. I want to see more women able to explore all fields!

What would be the best approach to getting more women into our field?

One idea is to publish more magazines and articles about this field to educate more women about this wonderful career opportunity. We can educate parents and students and invite women from the cryogenic fields to raise awareness about their exciting careers and possibilities. The women who are in this field can share their own experiences and should give themselves the task of spreading awareness to bring more young girls to cryogenics... just as I did! ■

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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People, Companies in Cryogenics


Image: Jefferson Lab

Latifa Elouadrhiri was presented with the 2021 Jesse W. Beams Research Award, which recognizes especially significant or meritorious research in physics that has earned the critical acclaim of peers from around the world. The award was established by the Southeastern Section of the American Physical Society (SESAPS) in 1973. Elouadrhiri is only the second woman to receive it.

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The **Ariane 5 launch vehicle** that will launch the **James Webb Space Telescope** was moved to the final assembly building at Europe's Spaceport in French Guiana on November 29, 2021. Ariane 5 parts shipped from Europe to French Guiana have been coming together inside the launch vehicle integration building. Webb, now fueled, will soon be integrated on Ariane 5's upper stage and then encapsulated inside Ariane 5's specially adapted fairing.

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Image: DESY / Angela Pfeiffer

Beate Heinemann, Senior Scientist at **DESY** and Professor of Physics at **University of Freiburg**, will take over the High Energy Physics division at DESY as Director on February 1. This was unanimously decided by DESY's supervisory body, the Foundation Council, at its meeting on December 7. Heinemann is the first female director in DESY's history.

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ESA and **Airbus** have signed a contract to move forward with the design and construction of the Atmospheric Remote-sensing Infrared Exoplanet Large-survey, Ariel, planned for launch in 2029. Ariel is the third in a trio of dedicated exoplanet missions conceived by ESA focusing on various aspects of this rapidly evolving subject area. It will follow Cheops, which launched in 2019, and Plato, scheduled for launch in 2026.

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The **Arnold and Mabel Beckman Foundation** today announced the 2022 awardees of its FIB Milling Sample Preparation for Cellular CryoET program. The grant will supply support of $1.5 million per site for the acquisition, development, and maintenance of instrumentation for focused ion beam milling; support for personnel, junior scientists, and training programs; support for data science collaborations within research teams; and/or costs for proposed research programs. Investing in this instrumentation underscores the Foundation's mission of supporting research breakthroughs in chemistry and the life sciences.

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GTT Group, an engineering company expert in containment systems with cryogenic membranes used to transport and store liquefied gas, has announced that its member company **Elogen**, a technological expert at the service of green hydrogen, has entered into collaboration agreement with Université Paris-Saclay, one of the Top 50 of the world's best universities according to Shanghai Ranking. The agreement aims to strengthen their partnership in the field of PEM water electrolysis, which is a promising technology for the production of low-carbon hydrogen.

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Rigetti Computing, a pioneer in full-stack quantum computing, announced a collaboration with **Microsoft** to provide Rigetti quantum computers over the cloud to users of Microsoft's Azure Quantum service. When the Rigetti system becomes available, it will be the largest quantum computer accessible on Azure Quantum. The two companies expect the integration to be completed and available to users in the first quarter of 2022.

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RUAG Space's engineering and production capabilities will play a central role when the **James Webb Space Telescope (JWST)** is launched from the Kourou Spaceport in French Guiana, scheduled for December 22, 2021. In addition to the payload fairing, separation system and on-board computer for the Ariane 5 launch vehicle, the company delivered the antennas for data transmission to Earth, the ground support equipment and three mechanisms for two of the telescope's four scientific instruments.

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Singapore LNG Corporation Pte Ltd (SLNG) and **Linde Gas** have signed a memorandum of understanding to collaboratively explore the feasibility and development of a carbon dioxide (CO_2) liquefaction and storage facility, located adjacent to the SLNG Terminal on Jurong Island, Singapore. The project concept involves using cold energy from the SLNG Terminal's operations to liquefy CO_2, leveraging on the companies' expertise in carbon capture, liquefaction, and cryogenic storage and handling solutions. ■

Meetings & Events

6th Annual LNG Summit USA
March 9-10, 2022
Houston, Texas
http://2csa.us/kr

28th International Cryogenic Engineering Conference and International Cryogenic Materials Conference 2022
April 25-29, 2022
Virtual
http://2csa.us/ks

Foundations of Cryocoolers Short Course
June 27, 2022
Bethlehem, PA
http://2csa.us/kn

ICC 22
June 27- 30, 2022
Bethlehem, PA
http://2csa.us/kn

29th International Conference on Low Temperature Physics
August 18- 24, 2022
Sapporo, Japan
http://2csa.us/ha

ASC 2022
October 23-28, 2022
Honolulu, HI
http://2csa.us/ko

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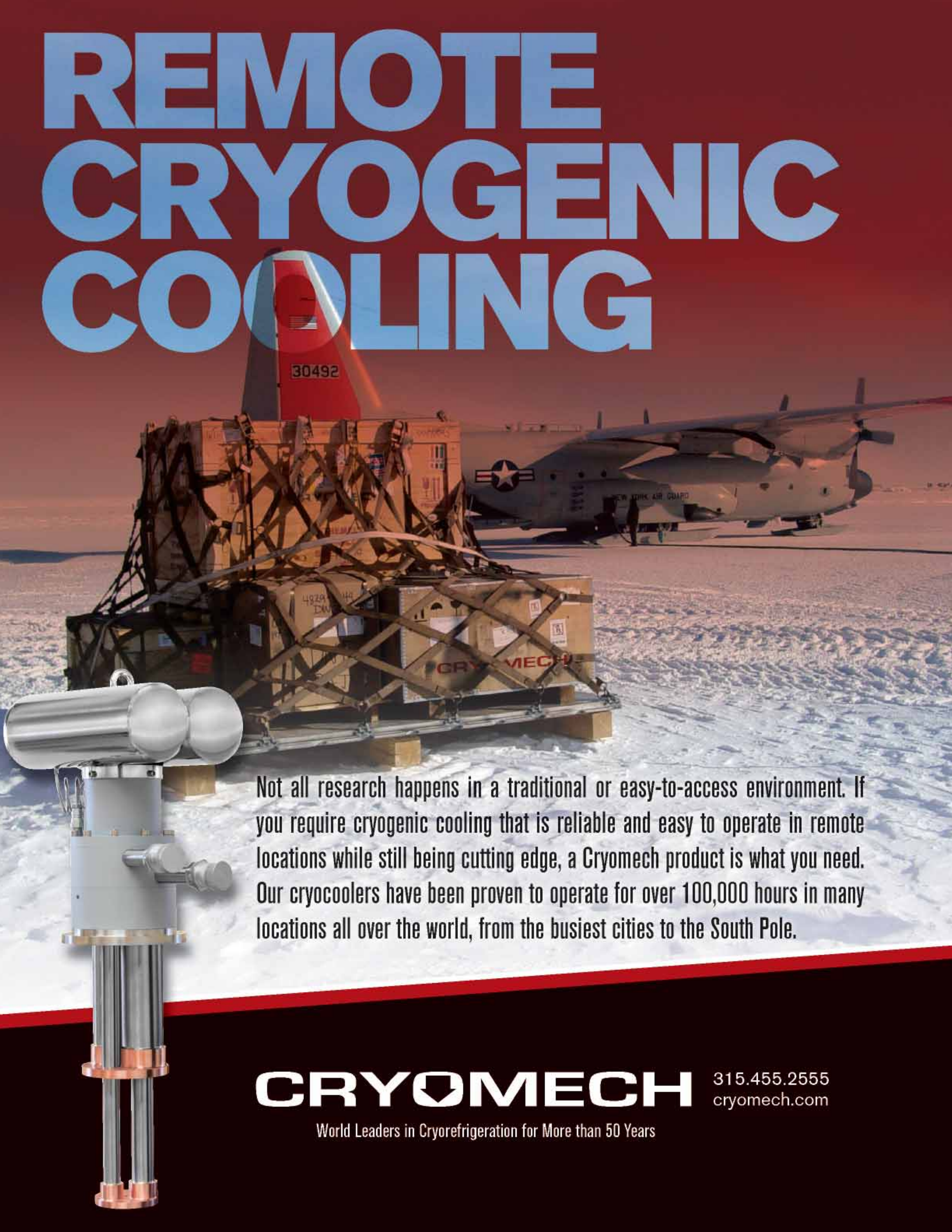
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