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# Cold Facts

The Magazine of the Cryogenic Society of America, Inc.

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# Zero Resistance Zone

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

## SQUID: From Nobel Prize to Most Sensitive Quantum Instruments

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

### Amazing Josephson Effects

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

$$I = I_0 \sin \phi \text{ and } \frac{\partial \phi}{\partial t} = \frac{2e}{h} V$$

where  $I_0$  - critical current,  $\phi$  - phase difference between of the Cooper pairs to the two superconductors, and  $V$  is the voltage across the junction. If the voltage is constant, the

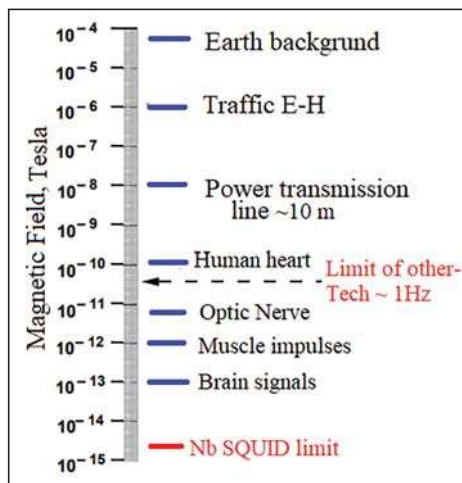


Figure 1: Magnetic signal levels vs both other-Tech & SQUID. Edited by: Shu and Demko

phase difference is a linear function of the time,

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

gives an oscillating current,

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

so-called AC Josephson effects. Broadly speaking, Josephson effects occur when two superconductors (either bulk or film) are connected through a “weak link,” such

as a bridge that allows the passage of electrons (supercurrent). Practically, there are four types of tunneling junctions: 1., Tunnel oxide (SIS) junction with an insulation layer of 10 – 20 Å; 2., Proximity (SNS) Junction; 3., Constriction (microbridge) junction; and 4., Point contact Junction.

### SQUID Sensor

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

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

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

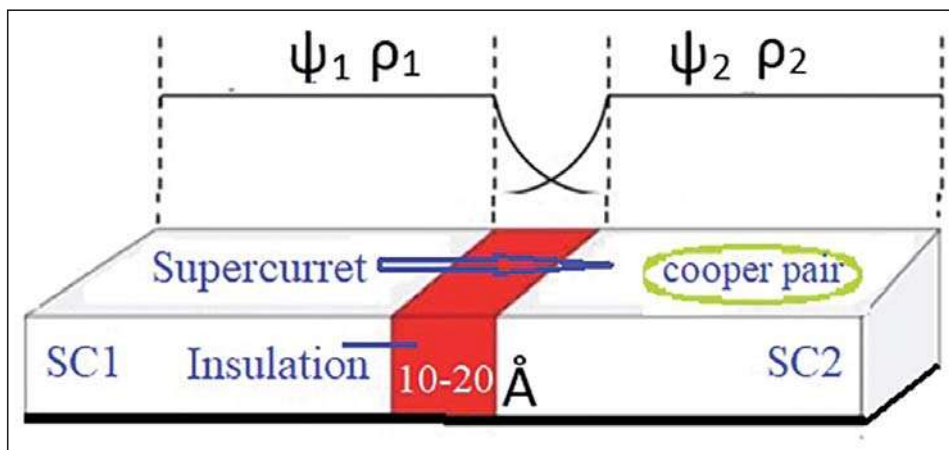


Figure 2: A Josephson junction: Cooper pairs are tunneling through insulation barrier. Credit: Shu and Demko

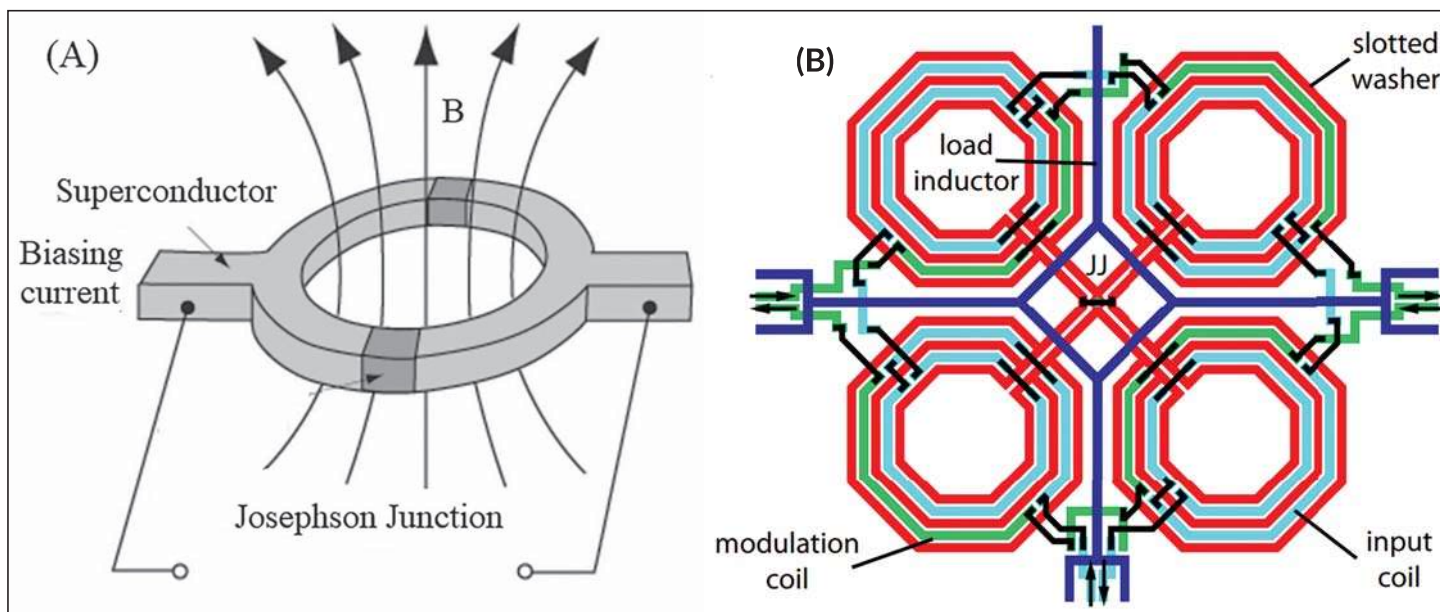


Figure 3A: Sensor of a SQUID. B: a RF-SQUID for the RF-SQUID multiplexer.<sup>[3]</sup> Credit: (A) Shu, (B) Demko.

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

Initially, the Josephson junction is made of low temperature superconductors (LTS), such as niobium (Nb) or lead (Pb) alloys. These devices work only at low T with LHe or 4.2K cryocooler. With development of high temperature superconductor (HTS), the SQUID made of HTS, like YBCO or other HTSs, which work with LN<sub>2</sub> or 77 K cryocoolers.<sup>[1]</sup>

## Design Methodology of SQUID System

In general, a complete SQUID system comprises three main sections: the signal detection/pickup section, the SQUID sensor with an input coil and the control electronics/data acquisition system. The SQUID sensor and signal pickup system operate in a cryogenic environment, while the electronics and data system are located at room temperature. Figure 4 (lower) presents a sketch of the noise thermometer evaluation system with SQUIDs, pickup coils, dilution refrigerator, etc.<sup>[4]</sup> Depending on the nature of the tasks assigned to the SQUID, the channels for pickup and sensors can be single, multiple, or numerous. HTS SQUIDs are convenient for the use of LN<sub>2</sub>, but their sensitivities are normally several times lower

than those of LTS SQUIDs (in NDE case, normally sensitivity <10 fT/√Hz for LTS and <100 fT/√Hz for HTS).

Both LHe and LN<sub>2</sub> dewars are constructed from specially selected materials (such as FRPs) to minimize their magnetic interactions with the SQUID sensors and detection coils. Dewars capable of 90° and even 180° operation are available.<sup>[1]</sup> The tailed dewars can have the spacing between the outside surface of the tail and the detection system (tail gap) as small as ~3 mm in some cases. There is a wide range of detection coil configurations used for DC, AC and pulse measurements as shown in Figure 4 upper.<sup>[1]</sup>

Key to any measurement is ensuring that the detection circuitry (coils) is optimized for the measurement being performed. Axial gradiometer coils offer excellent resolution and reasonable noise rejection for nearby sources: they can be shaped as symmetric, second-order gradiometers and asymmetric gradiometers as shown in Figure 4 (upper).<sup>[1]</sup> Planar gradiometer coils can be constructed as radial gradiometers and 'double-D' planar gradiometers, which offer excellent spatial resolution. Synthetic gradiometers can be extended to more sophisticated schemes for improvement in LTS and HTS systems. As a design tradeoff, if spatial resolution is most important, the area of the SQUID loop can be optimized for the desired spatial resolution. Figure 5 shows a

Magneto-Encephalography (MEG) system which serves as an exceptional example to illustrate the complete cryogenic temperature zone of a SQUID system.<sup>[5]</sup> This system comprises a cryogenic system (dewar/cryocoolers), 64 channels of SQUID sensors & pickup coil arrays and its entirety.

## SQUID Applications

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

## Quantum computer

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

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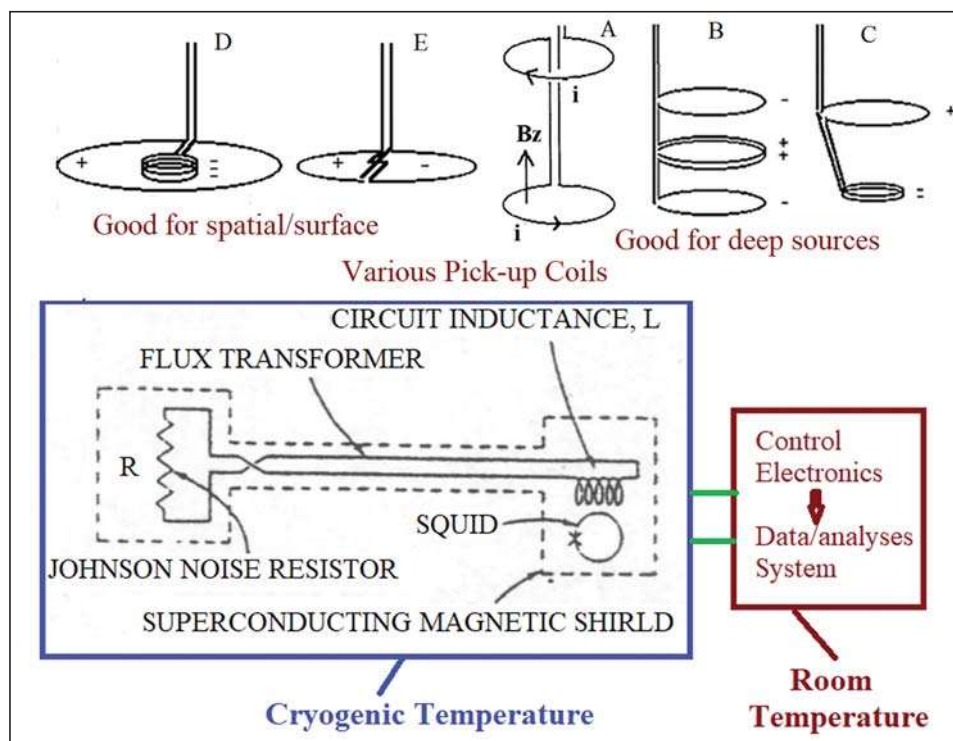


Figure 4: Block diagram of a SQUID system studying noise thermometer.<sup>[4]</sup> Credit Q-S. Shu, J. Harrison et al. and various configurations of pickup coils<sup>[1]</sup> and Fagaly

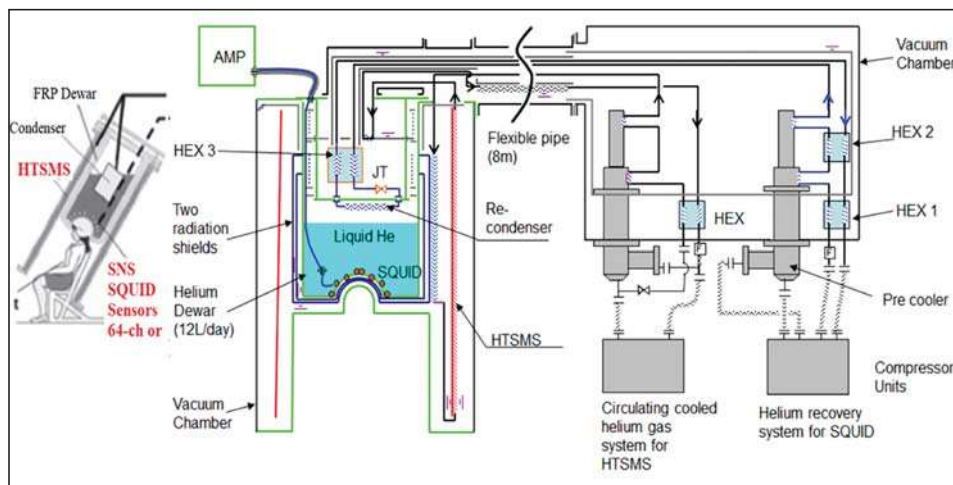


Figure 5: Diagram of the zero boiloff cooling system for HTSMS, SQUID, dewar shield and re-condenser; and the SQUID array is composed of 64 radial gradiometers, upgradable to 128.<sup>[5]</sup> Credit: K. Narasaki et al

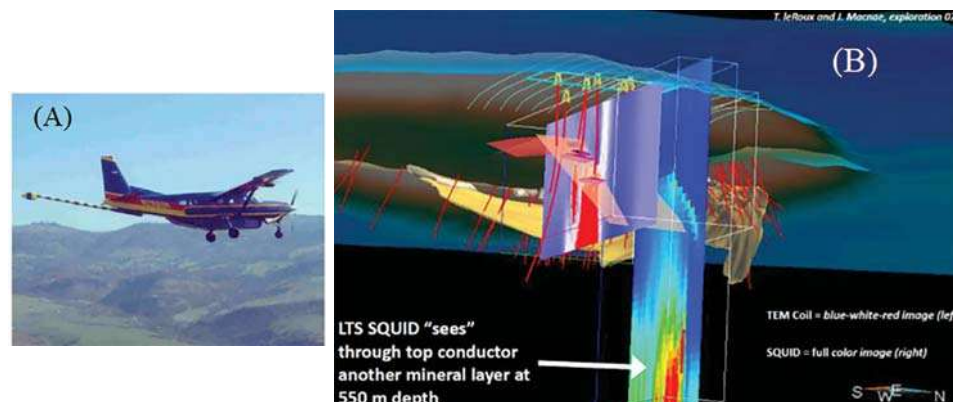


Figure 6A: HTS SQUID in flying.<sup>[1]</sup> 6B: LTS SQUID found out new mining at a depth of 550m.<sup>[2]</sup> Credit: R. Fagaly (A) and T. leRoux (B) and M. Kiviranta

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

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

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

**Medical devices and magnetoencephalography (MEG)** Mobile MEG developed by Sumitomo Heavy Industries (SHI) employs an HTS magnetic shield (HTSMS) and SNS-type SQUID sensors (series arrays).<sup>[4]</sup> The HTSMS and SQUID are cooled by a zero-boiloff cooling system, which consists of a circulating cooled helium gas system for cooling the HTSMS below a temperature of 90 K and a helium recovery system for cooling the SNS-type SQUID sensors to LHe temperature as shown in Figure 5.<sup>[5]</sup> Narasaki et al. introduced the achievement of the first measurement of

neuron current in the brain by using SHI's MEG in 2018. The zero boiloff cooling system consists of two closed-cycle cooling subsystems. The dewars are made of a fiber-reinforced plastic (FRP).

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

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

coupled through a SC flux transformer to an RF SQUID at 4.2 K.

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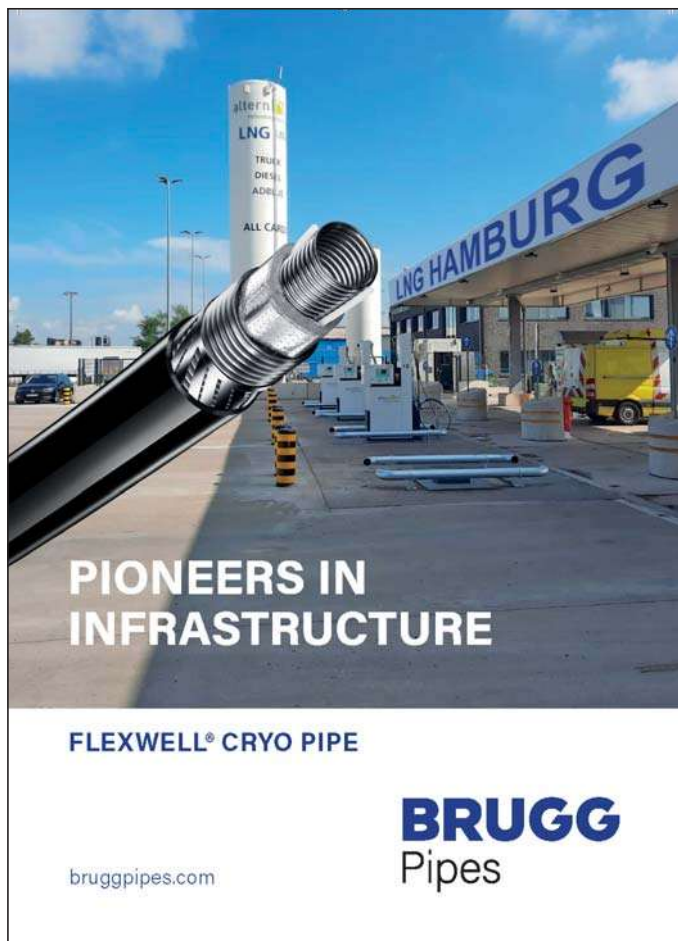
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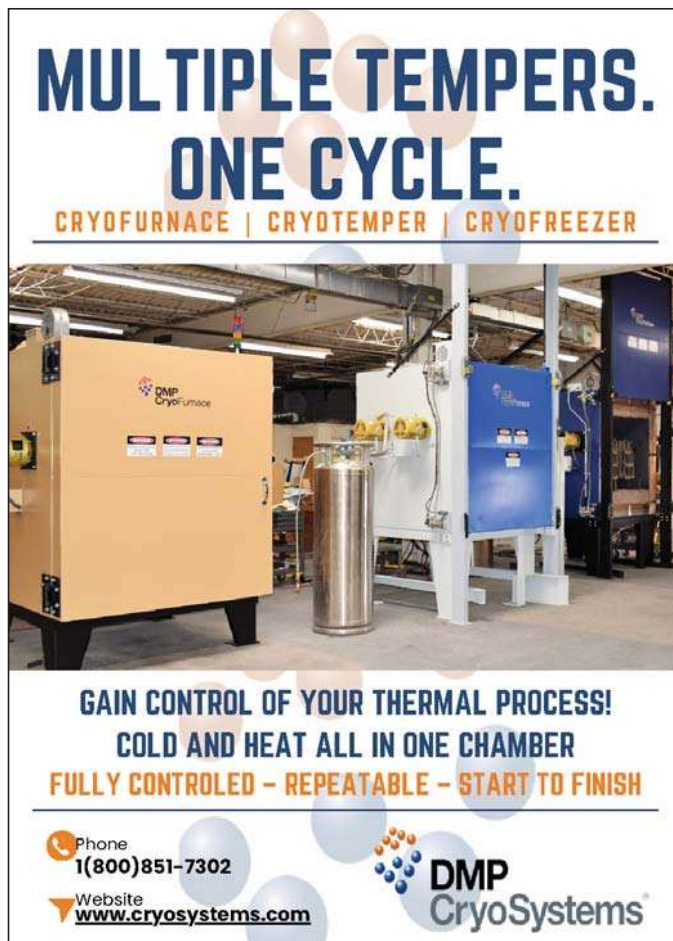


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