Cernox™ Resistance Temperature Sensors for High Energy Physics Applications

S. Scott Courts, PhD
Applications Scientist
Lake Shore Cryotronics, Inc.
Westerville, OH 43082 U.S.A.

ABSTRACT

The cryogenic temperature sensing requirements of superconducting magnets used in high energy physics accelerators present a unique challenge. The sensors must operate at cryogenic temperatures below 4.2 K with low magnetic field-induced calibration offsets at fields ranging to 10 T. They must provide high resolution with fast response times to detect potential superconducting magnet quenches. The sensors must be stable over time and thermal cycling with low radiation-induced calibration offsets up the anticipated accumulated dose over the lifetime of the accelerator. This combination of unique requirements severely limits temperature sensor choices for monitoring superconducting magnets. Cernox™ resistance temperature sensors, manufactured by Lake Shore Cryotronics, Inc., were specifically designed and developed for the purpose of monitoring superconducting magnets used in high energy accelerator facilities and meet the criteria required for this application. This work details performance specifications for Cernox resistance temperature sensors with regard to their suitability for high energy physics applications.

BACKGROUND

The application of cryogenic technology to high energy physics has enabled accelerators to achieve energies unimaginable just a few decades ago. The higher magnetic fields resulting from superconducting magnets have allowed for reduced physical size of circular and linear accelerators while increasing their capability. The application of superconducting magnets to accelerators has been a major driving force in development of better supporting technology in all fields of cryogenics.

Among the most important advancements related to cryogenic technology is in thermometry. There are two main applications for cryogenic thermometry in high energy physics: 1) monitoring superconducting magnets, and 2) monitoring liquefaction and distribution of cryogens. Of these two uses, monitoring superconducting magnets is more critical and has more stringent requirements. Sensors used for this application should possess a number of attributes, including magnetic field insensitivity, radiation hardness, high resolution for detecting small temperature changes, fast thermal response time in order to detect impending magnet quenches, and good long-term stability.

The fact that so many different cryogenic thermometer types have been available over the last 20 years highlights the issue that most of these thermometer types have drawbacks in one form or another. Platinum resistance thermometers are extremely stable, but their temperature response limits them to use above 13 K. Germanium resistance thermometers also show excellent stability, but their temperature response limits their use to a maximum temperature of 100 K. Rhodium iron resistance thermometers cover the 0.65 K to 400 K temperature range but perform badly in magnetic fields. Carbon glass resistance thermometers cover the 1.4 K to 325 K temperature range and perform well in magnetic fields but have considerably worse long-term stability compared to platinum, germanium, rhodium iron resistance thermometers. Diodes, both silicon- and gallium arsenide-based, can cover the entire 1.4 K to 500 K temperature range, but have limited use in high magnetic fields.[1]

Lacking a good solution for cryogenic thermometry in high energy applications, in 1989 the U.S. Department of Energy funded a three-phase research project to develop a radiation hard temperature sensor for the 4 K to 80 K temperature range in support of the Superconducting Super Collider that was planned for construction in the United States. This research resulted in the development and commercialization of Cernox™ resistance thermometers that are both radiation hard and are magnetic field insensitive. Performance characteristics of Cernox sensors relative to their application to high energy physics are detailed in the following sections.

CERNOX™ RESISTANCE THERMOMETERS

Fabrication

Cernox resistance thermometers were developed and commercialized by Lake Shore Cryotronics, Inc.[2, 3, 4] based on the work of Yotsuya et al.[5] The devices are completely fabricated at Lake Shore Cryotronics starting with pure materials including zirconium, gold, platinum, molybdenum, and sapphire. Lake Shore maintains the process expressly for the manufacture of Cernox cryogenic temperature sensors.

The sensing film is composed of a conducting zirconium nitride (ZrN) embedded in a non-conducting zirconium oxide (ZrO) matrix fabricated via reactive sputtering. The thin films are deposited onto 50 mm diameter, 0.203 mm thick sapphire substrates that were chosen for their high thermal conductivity at cryogenic temperatures. Sensing bodies are defined using standard photolithography techniques. After defining the sensing bodies, contact metallization is added on the top surface and also patterned using standard photolithography. The top layer of the contact metallization is gold, allowing for direct gold wire ball bonding to the device. Metallization is also added to the bottom surface to allow solder attachment of the die chip. The substrate is diced to produce final die chips 0.81 mm wide × 1.02 mm long × 0.203 mm thick as shown in Figure 1. These die can be calibrated and used at the bare chip level for minimal mass or packaged into a number of configurations to form a more robust sensor and facilitate mounting.

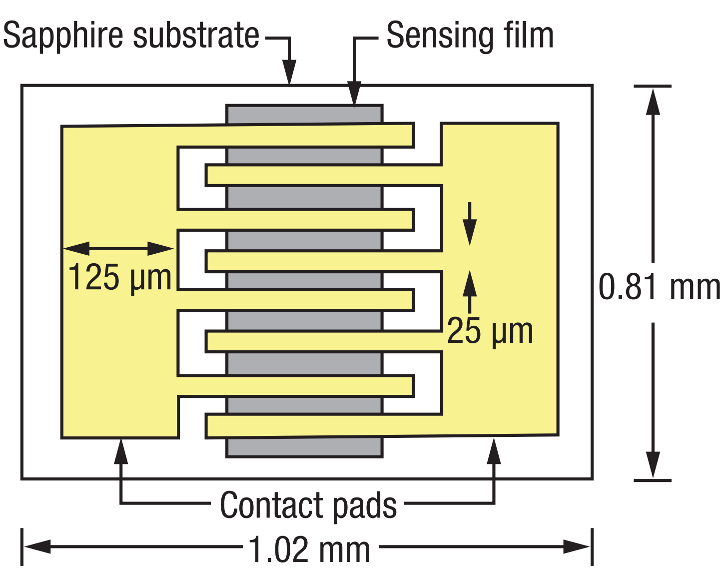


FIGURE 1. *Cernox thin-film cryogenic temperature sensor bare die and electrical trace dimensions.*

Temperature Response

The resulting ZrN/ZrO thin film devices have a negative temperature coefficient that can be adjusted by varying the ratio of ZrN to ZrO. Five commercial models are available that optimize the temperature sensitivity for operation as low as 0.1 K and as high as 420 K. The model designations, model temperature ranges, and typical applications for each model are given in Table 1. The resistance vs. temperature response and the sensitivity vs. temperature response curves for these commercial models are shown in Figures 2 and 3, respectively. Detailed information is available at the manufacturer's website or product catalog.[6]

	Temperature range	Typical application
CX-1010	0.1 K – 420 K	Dilution refrigerator
CX-1030	0.3 K – 420 K	He-3 refrigerator
CX-1050	1.4 K – 420 K	Pumped He-4 system and cryo refrigerator
CX-1070	4 K – 420 K	Open He-4 system and cryo refrigerator
CX-1080	20 K – 420 K	Cryo refrigerator

TABLE 1. *Cernox model designation, temperature range, and typical application.*

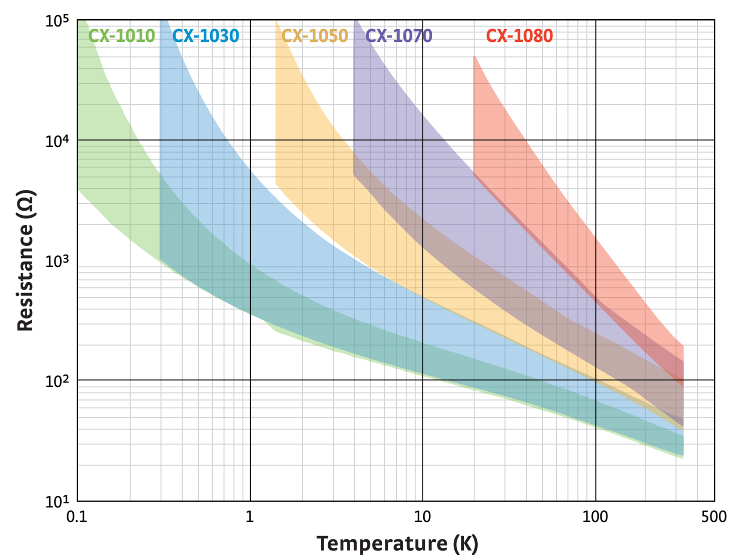


FIGURE 2. *Resistance vs temperature response of the five commercially available Cernox models.*

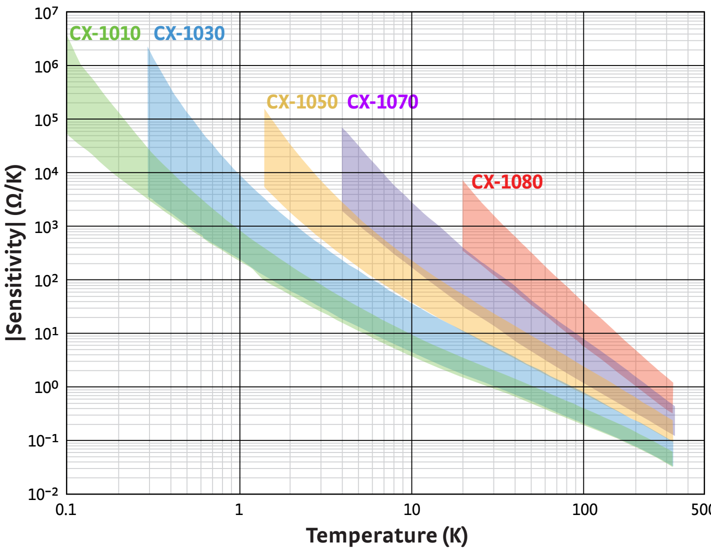


FIGURE 3. *Sensitivity vs temperature response of the five commercially available Cernox models.*

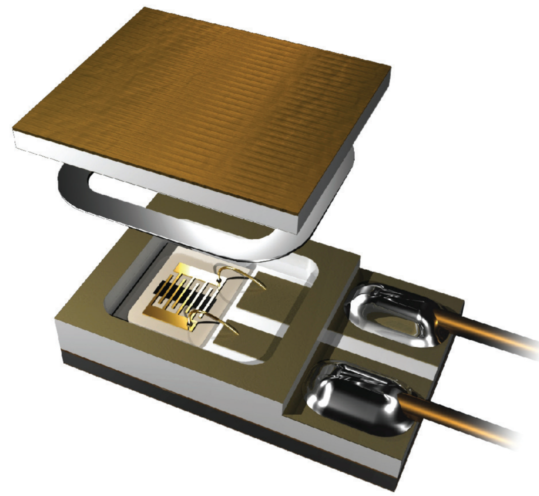


FIGURE 5. *Isometric view of the Cernox SD commercial package.*

Packaging

Cernox sensors can be used as a die chip, which minimizes mass, but most applications benefit from the placement of the die chip into a package. Packaging provides greater protection for the thin film/electrical contacts and facilitates mounting. The most common Cernox package is the SD package shown in cutaway view in Figure 4 and isomeric view in Figure 5. The SD package (approximately 3.2 × 1.9 × 1.1 mm) contains a cavity in which the Cernox die chip is soldered to the top surface of the sapphire package base. The sapphire package base, sapphire die chip substrate, and solder connection provide a high thermal conductivity connection to the sensing film. Electrical connection is made via two 25 µm gold wires that are ultrasonically wire bonded from the die chip contacts (one per pad) to the interior package bond pads. Feedthrough traces connect the interior package bond pads to the exterior package bond pads. The cavity is sealed using a solder preform and alumina lid to form a hermetic seal. The sealing process takes place in a commercial sealing oven, allowing water vapor and air to be pumped away prior to sealing. The standard external leads are bare copper soldered to the exterior bond pads using Sn63/Pb37 solder.

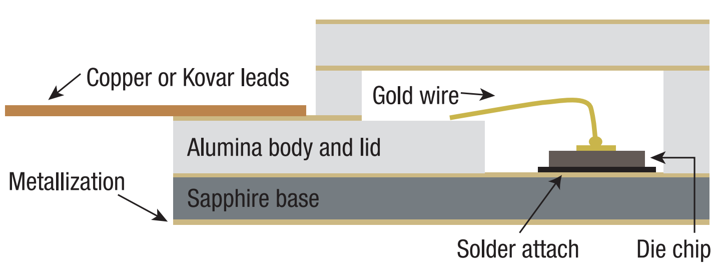


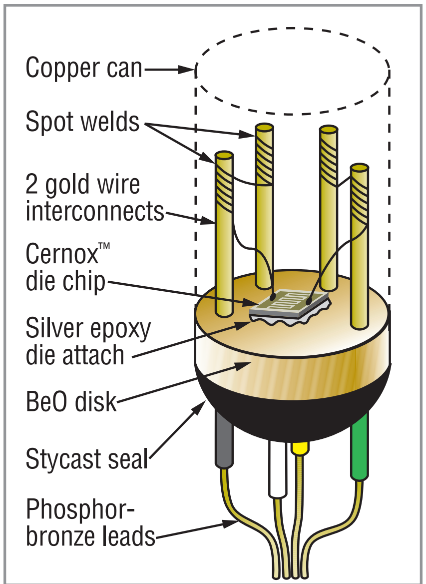
FIGURE 4. *Cutaway view of the Cernox SD commercial package.*

Independent of the sensor within the package, the SD package design is very robust and is commonly used in high reliability applications including aerospace missions. The package has been qualified many times to environmental tests (2,000 thermal shocks from LN_2 to room temperature), and mechanical tests including constant acceleration per MIL-STD-750 (Method 2006, 20,000 Gs), mechanical shock per MIL-STD-883 (Method 2014, Condition H), random vibration per MIL-STD 202 (Method 214, Table II, Condition H), drop tests of 4 m onto a granite block, and pressurization to 17 MPa (170 bar).

The second most common package for Cernox sensors is the AA can, a 3 mm diameter × 8 mm long gold-plated copper can. This package is a traditional cryogenic temperature sensor package that has been used extensively for decades for sensors such as germanium and carbon glass sensors as well as Cernox. In this package the Cernox die is silver epoxied to a beryllium oxide cylinder that serves as a header. Phosphor bronze lead wires are inserted through four holes passing through the beryllium oxide cylinder and epoxied in place using Stycast® 2850. Gold wires are ball-bonded to the top surface contacts of the Cernox chip. The other end of the gold wire is wrapped first around one phosphor bronze wire for current connection and then around a second phosphor bronze wire for voltage detection. The gold wire is spot welded to the phosphor bronze posts for electrical connection. This assembly is inserted into the gold-plated, copper can and epoxied into place using Stycast® 2850. A cutaway view of this package is shown in Figure 6.[6]

FIGURE 6. *Cutaway view of Cernox AA can package.*

The SD and the AA can Cernox packages are both basic packages. Adapters are available for both of these basic packages that facilitate mounting the sensor to the experiment, accommodating installations where the sensor may be clamped on, bolted on, screwed on, or inserted into. Some adapters also include heat sinking features that intercept heat leaking along the electrical leads. More details on both the basic packages and the associated adapters can be found at the manufacturer's website.



Calibration Accuracy

Above 0.65 K, temperature sensors are calibrated in accordance with the International Temperature Scale of 1990 (ITS-90). The calibration accuracy of a temperature sensor is a function of multiple parameters, starting with the accuracy of the thermometers used to calibrate the sensor under test. These working standard thermometers require traceability to primary thermometers normally maintained by national standards laboratories, and every calibration step removed from the primary thermometer standards introduces additional uncertainties into the calibration of the sensor under test. Additionally, all other instrumentation used in the calibration (voltmeters, current sources, resistance standards) require the same chain of traceability to national standards. Proper uncertainty analysis requires the inclusion of the long-term stability of the instrumentation between calibration cycles along with the noise contained within the measurement. Thermal design of the calibration probe with regard to heat leak (electrical wiring, pumping lines, optical radiation) and heater placement is important as the calibration block temperature non-uniformity introduces another source of calibration error. Excitation levels must be carefully chosen to avoid self-heating the working standard thermometer or the sensor under test, and these effects are magnified in vacuum versus liquid calibrations below 4.2 K. The parameters vary by calibration facility according to their thermometer standards, calibration instrumentation, and probe design. Finally, the equivalent temperature errors resulting from errors in the measurement of resistance (i.e., voltage) is dependent upon the temperature dependent sensitivity of the sensor under test.

For traceability to the ITS-90, Lake Shore maintains approximately 30 platinum, rhodium-iron, and germanium resistance thermometers calibrated by the National Institute of Standards and Technology in the United States, the National Physical Laboratory in the United Kingdom, and the Physikalisch-Technische Bundesanstalt in Germany. These secondary thermometer standards are used to calibrate standards-grade working thermometers for everyday use in calibration systems. Instrumentation includes an Agilent model 3458A digital voltmeter, a Keithley model 224 programmable current source, Guildline model 9330 standard resistors in decade steps, and a Keithley matrix switching system containing model 7067 4-wire, low thermal EMF scanner cards. For Cernox sensors calibrated in the Lake Shore temperature calibration facility, the resulting Cernox accuracies are given by model in Table 2.

Temperature (K)	Uncertainty (± mK) by model				
	CX-1010	CX-1030	CX-1050	CX-1070	CX-1080
1.4	4	4	4	—	—
4.2	4	4	4	4	—
10	5	5	4	4	—
20	10	9	8	8	8
30	13	11	9	9	9
50	18	14	12	12	11
100	29	22	17	16	14
300	78	60	46	45	36
400	124	94	74	72	60

TABLE 2. *Uncertainty of Cernox sensors calibrated in the Lake Shore temperature calibration facility*

When determining performance with regard to test treatments, it is important to view the test results with regard to the calibration accuracy that can be achieved by the lab performing the calibration.

Resolution

The resolution available from a temperature sensor is a function of the sensor resistance, sensor sensitivity, and the instrumentation performing the measurement. Over the 1.4 K – 325 K temperature range a typical Cernox excitation would be 10 mV. This excitation balances good resolution and accuracy against the self-heating of the sensor. Typical cryogenic instrumentation such as the Lake Shore Model 336 temperature controller or Model 224 temperature monitor can resolve resistance to about 1 part in 100,000 at a nominal 10 mV excitation. Using this resolution as a baseline and typical Cernox response curves, the resolution can be calculated and is shown in Figure 7 for CX-1050, CX-1070, and CX-1080, which are models most useful above 1.4 K. Note that the saw tooth response for each model is indicative of the resistance range changes that would be observed using typical cryogenic temperature monitors or controllers. As the input resistance range changes, there can be an abrupt change in the instrument resolution. The increasing sensitivity of Cernox sensors with decreasing temperature yields better resolution at lower temperatures, with sub-millikelvin resolution easily achievable below 30 K.

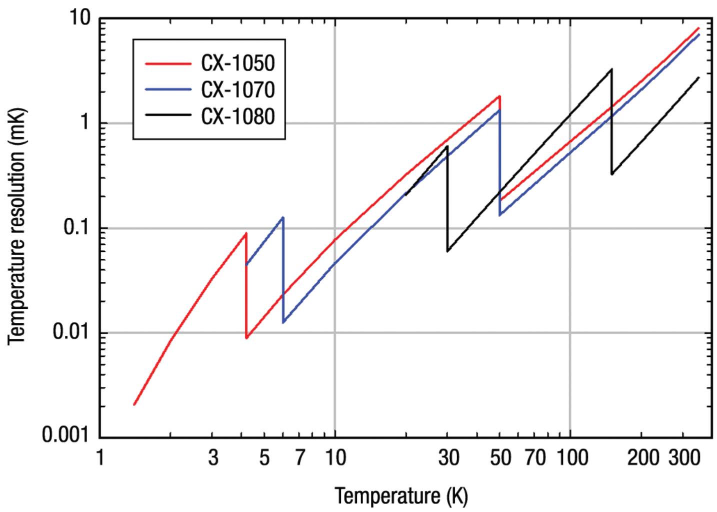


FIGURE 7. *Resolution as a function of temperature for Cernox CX-1050, CX-1070, and CX-1080 sensors. Calculations are based on Lake Shore Model 336 Cernox specifications.*

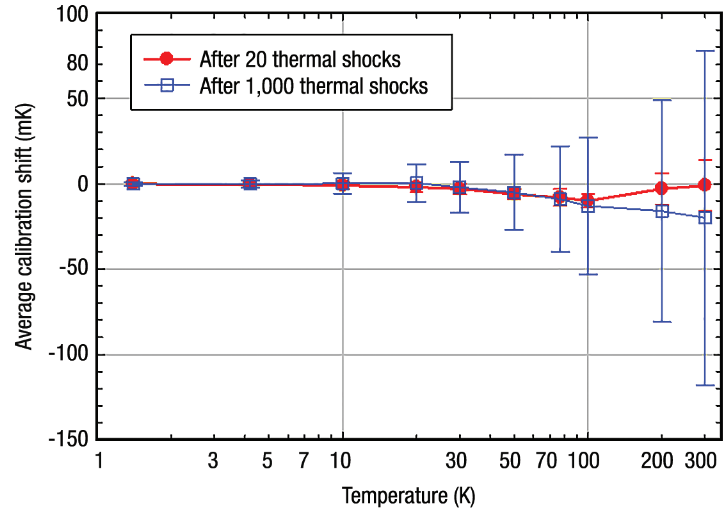


FIGURE 8. *Average calibration shift of 23 CX-1050-SDs after 1,000 thermal shocks from room temperature into liquid nitrogen (~77.35 K).*

Temperature (K)	Average calibration shift (standard deviation) after number of shocks						
	20	40	60	100	250	500	1000
1.4	-0.1 (1)	-0.2 (1)	-0.2 (1)	-0.1 (1)	0.4 (0.5)	0.1 (1)	-0.1 (1)
4.2	-0.3 (1)	-0.2 (2)	-0.1 (2)	-0.5 (2)	1 (2)	0.2 (4)	-0.1 (2)
10	-1 (2)	0.1 (6)	-1 (4)	-1 (4)	1 (5)	1 (10)	0.2 (6)
20	-2 (3)	-1 (11)	-2 (7)	-2 (7)	1 (9)	1 (17)	0.4 (11)
30	-3 (3)	-1 (16)	-4 (10)	-4 (10)	-0.1 (13)	-1 (24)	-2 (15)
50	-6 (3)	-3 (26)	-10 (15)	-9 (15)	-4 (20)	-4 (36)	-5 (22)
77	-8 (5)	-1 (37)	-15 (21)	-13 (21)	-5 (30)	-7 (49)	-9 (31)
100	-10 (4)	-0.4 (46)	-20 (26)	-19 (28)	-8 (38)	-10 (59)	-13 (40)
200	-3 (9)	12 (77)	-18 (43)	-19 (44)	-2 (63)	-11 (93)	-16 (65)
300	-1 (15)	21 (111)	-8 (62)	-4 (59)	19 (87)	-11 (136)	-20 (98)

TABLE 3. *Cernox average calibration shifts and standard deviation after thermal shocking.*

Stability

The stability of a cryogenic temperature sensor takes on many different meanings. It can refer to the short-term stability upon thermal cycling, the long-term stability after repeated thermal cycling, the long-term stability over a period when the sensor is kept at cryogenic temperature, or even the long-term stability after storage at room temperature. For the majority of users, the most detrimental treatment they perform is thermal cycling a temperature sensor. During thermal cycling, the many materials that compose the sensor contract, and the differential contraction induces mechanical stress at the interfaces of differing materials. Most importantly, the stresses occur between the sensing material and support structure and manifest themselves as a hysteresis or small calibration shift with each thermal cycle.

Various work has been performed to characterize the stability of Cernox sensors. Researchers at CERN assembled a thermal cycling apparatus to measure the stability of various temperature sensors including Cernox being considered for use for the Large Hadron Collider. In their work, they found average submillikelvin offsets for Cernox sensors below 4 K after 10, 25, and 50 thermal shocks from room temperature to 4.2 K.[7]

Lake Shore conducted a similar test by thermally shocking 23 Model CX-1050-SDs 1,000 times from room temperature into liquid nitrogen. Recalibrations were performed after 20, 40, 60, 100, 250, 500, and 1000 thermal shocks. The average calibration shifts as a function of temperature after 20 thermal shocks and after 1000 thermal shocks are shown in Figure 8, while the data for all recalibrations are given in Table 3. These data show that even after 1,000 thermal shocks, the average Cernox calibration shift is only -0.1 mK with a standard deviation of 2 mK for temperatures from 1 K to 4.2 K.[8]

Certain cryogenic temperature sensor applications require the acquisition of the sensors long before they will be used. Examples include aerospace missions such as the James Webb Space Telescope, where assembly and testing can take years to complete prior to launch, or accelerators, where the sensors must be installed during construction and installation of the superconducting magnets used for controlling the path of the particles. In these cases, the stability of the sensors over time stored nominally at room temperature is important. Researchers at Lake Shore have monitored a group of Cernox sensors for over 15 years to quantify their long-term stability.[9] These sensors are periodically recalibrated but are otherwise stored at room temperature. These data in Figure 9 show that the average calibration drift over 15 years is less than ±5 mK for the critical temperature range of 1.4 K – 30 K.

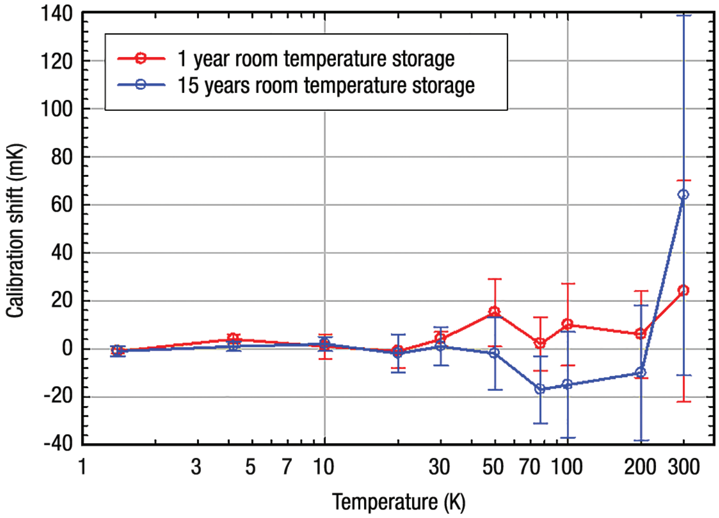


FIGURE 9. *Average calibration shift of a test group of Cernox sensors after 1 year storage at room temperature and after 15 years storage at room temperature.*

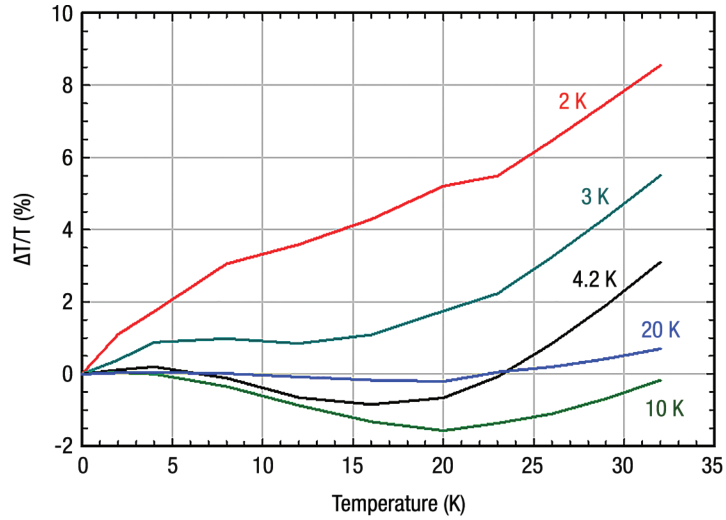


FIGURE 10. *Magnetic field induced calibration shift ΔT/T (%) as a function of temperature and field for Model CX-1050 sensors.*

Response Time

In applications involving superconducting magnets, a main concern is that the magnet can heat localized portions of the superconducting wire, leading that portion to become normal. Due to the high current typically powering the magnet, this normal portion of wire then dissipates a significant amount of heat, causing the remainder of the superconducting wire to become normal, which quickly results in a magnet quench. This type of occurrence is extremely dangerous when multiple superconducting magnets are joined in tandem because a quench in one magnet propagates to adjacent magnets with tremendous magnetic field energy released on a time scale of seconds. Monitoring the magnet temperature with a temperature sensor that has a fast enough response time to allow intervention to prevent magnet quenches is crucial. Measurements of the time response in an open liquid helium bath of CX-1050-SDs yield a 1/e time response of 0.004 s and a 90% time response of 0.008 ms.

Magnetic Fields

The critical application for cryogenic temperature sensors in high energy applications is their use in monitoring superconducting magnets used to steer and focus the particles. To that end, any sensor chosen for this application must have reasonably low magnetic field-induced calibration offsets at the operating temperatures. Much work has been performed characterizing Cernox sensors in magnetic fields[10, 11, 12] with the most complete being that of Brandt, et al.[13], who measured the magnetoresistance of 11 Cernox sensors taken from 9 different source wafers over the 2 K – 286 K temperature range in fields up to 32 T. Their results show that the calibration offsets, ΔT/T (%), are less than 3.2% in fields up to 10 T for temperatures above 2 K. These data are shown in Figure 10.

Radiation Resistance

Cryogenic temperature sensors used to monitor superconducting magnets in accelerator facilities are exposed to radiation. While the exposure is not intentional, it invariably occurs and the accumulated dose over the lifetime of the accelerator can be considerable. Complicating the situation is the ability of some sensor types to accumulate damage during cold irradiation and then thermally anneal some or most of the damage during warm up periods for the facility.

As stated earlier, Cernox temperature sensors were developed specifically for use in an accelerator. During the development and testing phase, the devices were irradiated to the expected total dose levels expected in their use in the Superconducting Super Collider. Irradiation was performed to 10 kGy using a cobalt-60 source and separately to 10^{12} n/cm^2 using a full spectrum pool reactor. During irradiation the sensors were held at 4.2 K in a LHe bath. The irradiation probes were designed to allow for calibration during warming. During this process, the sensors were held at 20 K, 80 K, and 330 K for 8 hour periods with subsequent recooling to 4.2 K to examine the sensors for thermal annealing effects. No evidence of thermal annealing was observed for these Cernox sensors.[14, 15, 16]

Due to their radiation hardness, Cernox sensors have been used in numerous space and accelerator applications, with each application having a specific performance requirement. For this reason, the effects of radiation on Cernox sensors has been measured and reported by many groups using gamma, neutron, and proton radiation with all results showing that Cernox possesses excellent radiation hardness. [17, 18, 19, 20, 21]

Typical Cernox performance in radiation data are shown in Figure 11. These Model CX-1050-SD data were measured by researchers at Lake Shore using the facilities at The Ohio State University Nuclear Reactor Laboratory. The gamma irradiation was performed at room temperature using a cesium-137 gamma source with a dose rate of 0.0075 Gy/s to a total dose of 10 kGy. The neutron irradiation was performed using a pool reactor operating at 50 W, generating a full spectrum of neutron energies from 10^{-10} to 10 MeV at a flux of 2.1×10^{11} n/cm^2/s to a total fluence of 10^{14} n/cm^2. These data show less than 10 mK offsets for temperatures less than 10 K. For the gamma radiation, the offset scales as +0.05% of temperature. For neutron radiation, the offset is less than ±35 mK across the 1.4 K – 325 K temperature range, with better performance at low temperatures.

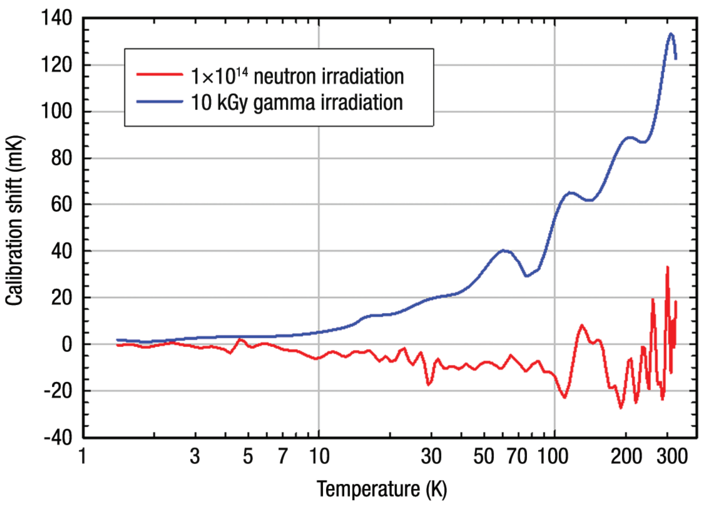


FIGURE 11. *Calibration shift induced on Model CX-1050 Cernox sensors by room temperature irradiation at 1×10^{14} n/cm^2 (red line) and 10 kGy gamma radiation (blue line).*

SUPPLY RELIABILITY

Lake Shore Cryotronics, Inc. has manufactured Cernox temperature sensors since 1989 and has offered them commercially since 1993. Lake Shore is ISO 9001 certified and maintains a quality system to ensure a consistent process through acquisition of pure materials, film deposition/patterning, sensor assembly, quality control testing, and finally calibration. All test and measurement equipment is calibrated and traceable to national standards. The Cernox process is maintained to explicitly manufacture Cernox sensors to ensure ongoing availability and reliability of the Cernox family of cryogenic temperature sensors.

CONCLUSIONS

The characteristics of Cernox cryogenic temperature sensors have been studied for over 25 years. The results of these studies show a wide range temperature sensor with high calibration stability and low calibration offsets induced by magnetic fields or radiation. This combination of attributes make Cernox sensors well suited for applications such as monitoring superconducting magnets in high energy physics accelerators, where sensor performance in high magnetic fields and high radiation is crucial.

REFERENCES

1. T.J. Quinn, Temperature, page 45. Academic Press, London, 1990, 2nd Edition.
2. Lake Shore Cryotronics, Inc., Westerville, OH, 43802, USA.
3. P.R. Swinehart, S.S. Courts, and D.S. Holmes, Metal oxy-nitride resistance films and methods of making the same, U.S. Patent No. 5367285, 1994.
4. D. S. Holmes, S. S. Courts, and P. R. Swinehart, “Electrical Properties of Metal-Oxy-Nitride Nanocomposites,” in Proceedings of the Micro Materials Conference, Micro Mat ’97, edited by B. Michel and T. Winkler, Druckhaus Dresden (GmbH) Press, NY (1996) pp. 678 – 683.
5. T. Yotsuya, M. Yoshitake, and J. Yamamoto, “New type cryogenic thermometer using sputtered Zr-N films,” Appl. Phys. Lett. 51 (1987) 235 – 237.
6. www.lakeshore.com.
7. Ch. Balle, J. Casas, J. M. Rieubland, A. Suraci, F. Togny, and N. Vauthier, “Influence of Thermal Cycling on Cryogenic Thermometers,” in Advances in Cryogenic Engineering, edited by Quan-Sheng Shu, Kluwer Academic/Plenum Publishers, NY (2000) pp. 1817 – 1823.
8. S.S. Courts and J.K. Krause, “Reliability and Stability of Three Cryogenic Temperature Sensors Models Subjected to Accelerated Thermal Cycling,” in Advances in Cryogenic Engineering, Vol. 57, edited by J.G. Weisend II, et al, American Institute of Physics, Melville, NY (2012) pp. 515 – 522.
9. S.S. Courts and J.K. Krause, “Effects of Room Temperature Aging on Two Cryogenic Temperature Sensor Models Used in Aerospace Applications,” in “Advances in Cryogenic Engineering,” Vol. 57B, edited by J.G. Weisend II, et al, American Institute of Physics, Melville, NY (2012) pp. 1329 – 1336.
10. H.D. Ramsbottom, S. Ali, D.P. Hampshire, “Response of a new ceramic-oxynitride (Cernox) resistance temperature sensor in high magnetic fields,” Cryogenics, 36(1), 1996, pp. 61 – 63.
11. G Heinea and W Lang, “Magnetoresistance of the new ceramic ‘Cernox’ thermometer from 4.2 K to 300 K in magnetic fields up to 13 T,” Cryogenics, 38(4), 1998, pp. 377 – 379.
12. G. G. Ihas, L. Frederick, J. P. McFarland, “Low Temperature Thermometry in High Magnetic Fields,” Journal of Low Temperature Physics, 113(5 – 6), 1998, pp. 963 – 968.
13. B. L. Brandt, D. W. Liu, and L. G. Rubin, “Low Temperature Thermometry in High Magnetic Fields. VII. Cernox™ Sensors to 32 T,” Rev. Sci. Instr., 70(1), 1999, pp. 104 – 110.
14. S. S. Courts, D. S. Holmes, and P. R. Swinehart, “Neutron and Gamma Radiation Effects on Cryogenic Temperature Sensors” in “Temperature: It’s Measurement and Control in Science and Industry,” Volume 6, Part 2, edited by J. F. Schooley, American Institute of Physics, New York (1992) pp. 1237 – 1242.
15. S. S. Courts, P. R. Swinehart, and D. S. Holmes, “Radiation Resistant Cryogenic Temperature Sensor for the 4 K to 80 K Range,” Department of Energy final report for contract number DE-FG02- 90ER81074 (1994).
16. S. S. Courts and D. Scott Holmes, “Effects of Cryogenic Irradiation on Temperature Sensors” in “Advances in Cryogenic Engineering,” Vol. 41B, edited by P. Kittel, Plenum Press, NY (1996) pp. 1707 – 1714.
17. Junquera, T, Amand, J. F., Thermeau, J. P., and Casa-Cubillos, J., “Neutron irradiation tests of calibrated cryogenic sensors at low temperatures” in Advances in Cryogenic Engineering 43A, edited by P. Kittel, New York: Plenum Press, 1998, pp. 765 – 772.
18. Amand, J. F., Casa-Cubillos, Junquera, T, and Thermeau, J. P., J., “Neutron irradiation tests in superfluid Helium of LHC Cryogenic Thermometers” in Proceedings of the 17th International Cryogenic Engineering Conference (ICEC), IOP, Bristol, 1998, pp. 727 – 730.
19. S. S. Courts and C. J. Yeager, “Gamma Radiation Induced Calibration Shifts In four Cryogenic Thermometer Models,” in “Advances in Cryogenic Engineering,” Vol. 49A, edited by J. Waynert, American Institute of Physics, NY (July 2004) pp. 404 – 411.
20. T. Tominaka, H. Okuno, J. Ohnishi, N. Fukunishi, H Ryuto, M. Ohtake, K. Ikegami, A. Gogo, and Y. Yano, “Radiation effects on cryogenic temperature sensors of Cernox, CGR and PtCo,” IEEE Transactions on Applied Superconductivity, 14(2), 2004, pp. 1802 – 1805.
21. T. Barnette, Yu. P. Filippov, N. V. Mokhov, N. Nakao, A. L. Klebaner, S. A. Korenev, J. C. Theilacker, J. Trenikhina, and K. Vaziri, “Radiation Requirements and Testing of Cryogenic Thermometers for the ILC,” in Advances in Cryogenic Engineering, edited by J.G Weisend II, et al., American Institute of Physics, Melville, NY (2008).

Scott Courts, PhD

Dr. Scott Courts is an Applications Scientist at Lake Shore Cryotronics and has been active in the field of cryogenics for more than 30 years.

Dr. Courts received his BSc in Physics from Marshall University and a PhD in Experimental Solid State Physics from The Ohio State University in 1988. While at OSU, he studied the transition to superfluid turbulence in two-fluid flow of helium-II.

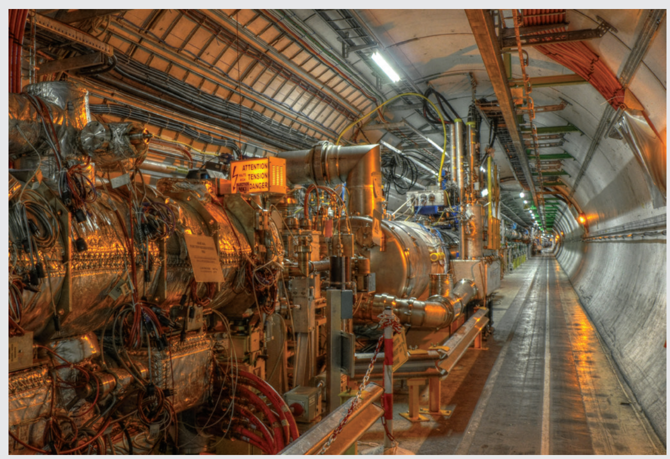
In 1989, Dr. Courts joined Lake Shore as a Senior Scientist in the company's Sensor R&D Division. In this position, much of his focus was on developing thin-film thermometer materials exhibiting high ionizing radiation tolerance and low magnetoresistance offsets for use in accelerator applications. This work led to the development of Lake Shore's highly regarded Cernox™ cryogenic temperature sensors.

Dr. Courts then moved to Lake Shore's manufacturing engineering group in 2001 to fill the role of Applications Scientist and work on improving sensor products, processes, and testing. He has also served as Technical Director for the Lake Shore thermometer calibration facility and worked to extend the calibration range capabilities to its current 20 mK lower limit and up to 900 K at the upper end. Currently, he serves as a metrologist/scientist with the responsibility of maintaining Lake Shore's traceable thermometry scales.

A member of the American Physical Society and the Cryogenic Society of America, Dr. Courts has published over 35 articles on cryogenics/thermometry and served as a reviewer for various journals and proceedings. He has also taught short courses on cryogenic thermometry and instrumentation in both public and private settings for the past 20 years.

Reference Projects

Lake Shore cryogenic temperature sensors have been used in a large number of high energy physics projects, including:



Accelerators

- LHC at CERN—Switzerland
- SNS at Oakridge National Lab—U.S.
- SLAC at Stanford—U.S.
- LCLS and others at Fermilab—U.S.
- Advanced Photon Source at Argonne National Lab—U.S.
- FAIR—Germany
- SRF LINAc at IFMIF
- STF at KEK—Japan
- FEL at DESY—Germany
- CEBAF Linac at Thomas Jefferson Nat'l Lab—U.S.
- Superconducting Ring Cyclotron at Riken—Japan

Fusion Reactors

- ITER—France
- NIF at Lawrence Livermore National Lab—U.S.
- KSTAR—Korea
- W7x at Max Planck—Germany

Other

- ALMA radio telescope—Chile
- Dozens of unmanned research satellites (NASA, etc.)

Lake Shore CRYOTRONICS