Application Note

A Comparison of Physical Property and Performance Characteristics of Lake Shore Cernox Resistance Temperature Sensors with Commercially Available Thick Film Resistors

General Information

Thick film resistance temperature sensors have been used experimentally in the laboratory for a number of years. This material is offered in a variety of compositions – bismuth ruthenate, ruthenium oxide and ruthenium dioxide. In fact, packaged ruthenium dioxide sensor devices are now available commercially.

The basic RuO_2 device material, as are all the compositions mentioned above, is now supplied commercially by third parties that produce this material for purposes other than thermometry. These third party suppliers can and will vary the production process of the material without regard to the resulting effects on the material's thermometry characteristics. One company marketing RuO_2 sensors has been forced to make adjustments to technical sales bulletins over time to reflect changing material characteristics. For example, over a span of only nine months, the documented nominal resistance of this company's 1 kΩ resistors at 0.02 K changed from 74 kΩ to 133 kΩ. Using the corresponding sensitivity of 4.5 MΩK, this produces a ΔT of only 13 mK at a temperature of 20 mK. For another sensor, the difference is 0.083 K at 1.5 K.

In contrast, Lake Shore manufactures Cernox sensors from pure materials, and will retain in-house control over production. The needs of the thermometry community are Lake Shore's primary concern.

1. Resistance Versus Temperature Characteristics

Typically, companies marketing RuO_2 sensors currently offer devices with room temperature resistance values of 1 kΩ and 100 kΩ. These sensors are packaged in a 0.093" diameter by 0.2" long copper enclosure. For the 1 kΩ model, one company recommends that you use 60 µV excitation (AC resistance bridge) for the temperature range 0.02 K to 4.2 K, and a DC excitation current of 10 µA for the range 4.2 K to 20 K. The corresponding RuO_2 data sheet does not list a calibration above 20 K for this model, so most of the information herein is presented with an upper temperature limit of about 20 K. For the 100 kΩ model, a DC excitation current of 10 µA is recommended for the entire temperature range from 1.5 K to 300 K. However, as will be shown later, this causes significant self-heating. A vastly different resistance versus temperature characteristic is obtained if 10 µA excitation is used instead of the 1-3 mV excitation which is typical for NTC devices.

Figure 1 below shows the resistance versus temperature characteristic for RuO_2 sensors (dashed lines) and the Cernox family of resistors (solid lines). The 100 kΩ thick film resistor was calibrated at the manufacturer's recommended 10 µA. Notice the curve turning over at the low end due to self-heating.

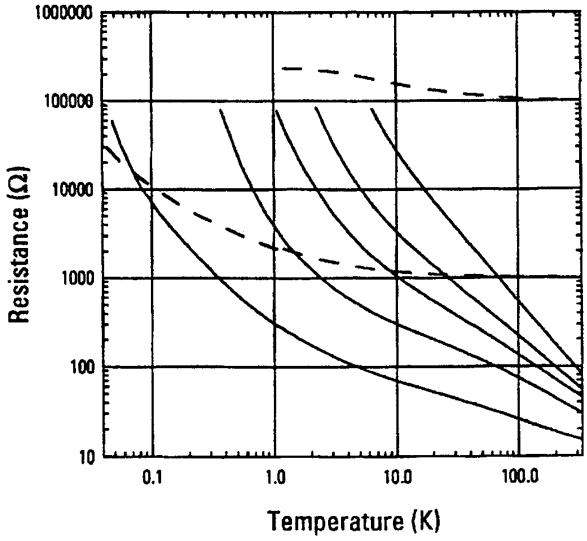

Figure 1. R vs T for RuO_2 sensors and Lake Shore's Cernox Sensors.

2. Power and Self-Heating

The signal from a temperature sensor can be made larger by increasing the power dissipated in the sensor. A larger signal to noise ratio provides better temperature resolution. The power dissipation can be increased only until the sensor self heats significantly above the object or environment whose temperature is to be measured. The acceptable power dissipation is determined by the thermal resistance between the temperature sensor and its environment. Lower thermal resistance allows higher power dissipations and thus higher signal levels and better temperature resolution. Self-heating due to excessive power dissipation decreases the accuracy of a temperature measurement and should be avoided.

A test for self-heating in RuO_2 sensors (both 1 kΩ and 100 kΩ models) was performed. The sensors were purchased as packaged by the manufacturer in a hermetically sealed, small metal cannister. The sensors were mounted in the copper block of a Lake Shore calibration probe. Two different excitation methods were used: 1) constant current excitation of 10 μA as recommended by the manufacturer, and 2) current adjusted to produce an output signal in the 1-3 mV range, a technique commonly used to minimize self-heating while providing a usable signal. The deviations between the two excitation methods were on the order of 25 mK in the 1.2 - 20 K temperature range and 1.5 K in the 20-300 K range for the 1 kΩ sensor. These deviations probably indicate the repeatability limits for the calibration of a 1 kΩ RuO_2 sensor. The resistances of the 100 kΩ sensor were significantly affected by the excitation method below 20 K, as shown in Figure 2, indicating that self-heating is a problem.

The resistance differences from the 100 kΩ sensor were converted to temperature deviations using the manufacturer's standard curve and plotted in Figure 3. The interchangeablity of such temperature sensors would be limited since the self-heating depends on exactly how the sensor is mounted and on the thermal contact between the object whose temperature is to be measured and the ultimate heat sink. This point will be addressed in more detail in Section 5.

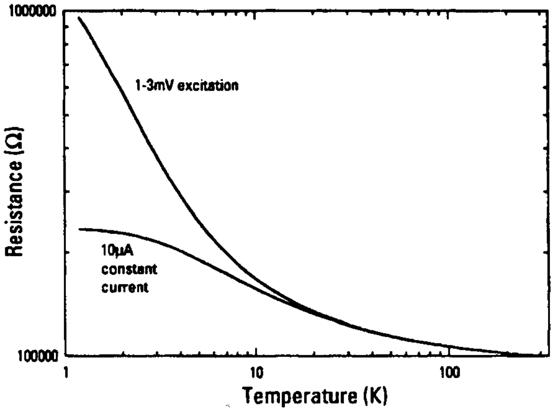

Figure 2. Resistance versus temperature comparison for a 100 kΩ RuO_2 sensor when read at 1-3 mV excitation (upper curve), or read at constant 10 μA current (lower curve).

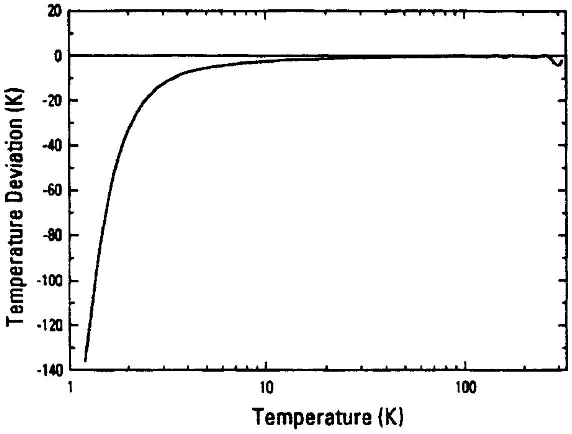

Figure 3. Temperature error for a 100 kΩ RuO_2 sensor resulting from self-heating when using a 1-3 mV excitation versus a 10 μA excitation baseline.

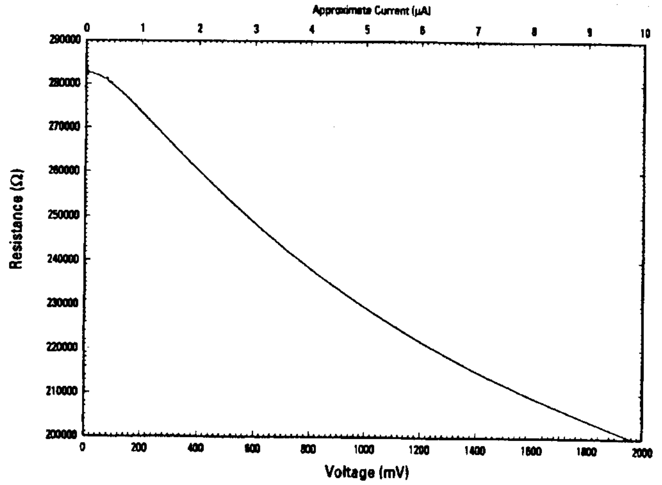

Figure 4. Self-heating error in a 100 kΩ RuO_2 sensor as a function of excitation voltage (current) at 4.2 K.

3. Sensitivity.

In terms of sensitivity, the RuO_2 sensors have a higher signal sensitivity (measured in Ω/K) in some temperature ranges. However, remember that the RuO_2 sensors have a room temperature base resistance of either 1 kΩ or 100 kΩ upon which any measurement must be made. The signal sensitivity scales with the resistance. For example, doubling the resistance will double the signal sensitivity. A more useful measure is either (1/R) (dR/dT) or (T/R) (dR/dT). The second expression is the dimensionless sensitivity. This quantity is also equal to d(logR)/d(logT). The number is useful because it is independent of the geometry of the sensorand depends only on the material. Figure 5 shows the signal sensitivity for both the 1 kΩ and 100 kΩ RuO_2 devices (dashed lines) and Lake Shore's Cernox sensor family (solid lines). The RuO_2 sensors have been operated at (manufacturer recommended) 10 µA constant current. Once again the curve is turning over at the low end indicating the presence of significant self-heating in the 100 kΩ device.

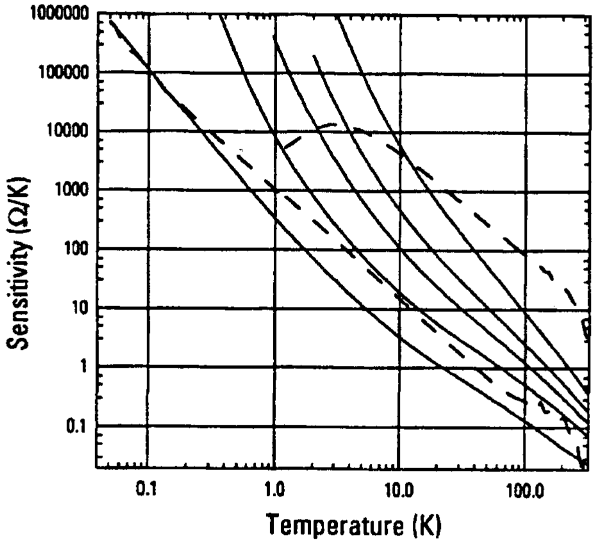

Figure 5. Signal sensitivity versus temperature for RuO_2 sensors and Lake Shore's Cernox sensors.

Plotted as signal sensitivity, the RuO_2 devices compare favorably with the Cernox sensors. However, when you examine them in terms of dimensionless sensitivity, the Cernox sensors are better. Figure 6 plots specific sensitivity as a function of temperature for the same sensors plotted in Figure 5. In Figure 6, the Cernox sensor models (solid lines) shown are CX-1010, CX-1030, CX-1050, CX-1070 and CX-1080, from top to bottom. The RuO_2 sensors are shown as dashed lines with the 1 kΩ device curve extending to 50 mK, and the 100 kΩ sensor curve ending at 1.5 K.

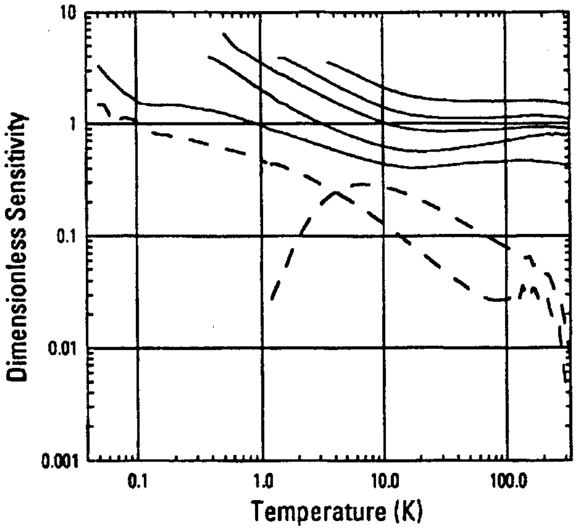

Figure 6. Dimensionless sensitivity versus temperature for RuO_2 sensors and Lake Shore Cernox sensors.

4. Accuracy.

Table 1 lists one manufacturer's RuO_2 accuracy specifications (taken from published data sheets). These data sheets compared the accuracy of their RuO_2 devices with Lake Shore carbon-glass sensors. The comparison was unfavorable to the RuO_2 sensors. In fact, the RuO_2 data looks even worse when compared with the Cernox sensor family. The accuracy specifications for the two Cernox sensors represented in Table 1 were calculated from operating specifications in Lake Shore's calibration facility.

Table 1. Accuracy specification for representative RuO_2 and Cernox sensors.

Temperature (K)	Accuracy Specification (mK)			
	1 kΩ	100 kΩ	CX-1030	CX-1080
< 1.5	4	NA	5	NA
1.5	4	50	6	NA
4.2	10	50	7	30
10	100	100	9	35
20	100	100	20	40
50	NA	200	35	45
100	NA	400	55	45
200	NA	500	100	75
300	NA	500	150	100

5. Interchangeability.

Interchangeability of sensors is one area where, at least initially, thick film sensor devices may offer appeal to users. In Table 2 below, interchangeability data, (taken from a manufacturer's published data sheets), is shown for 1 kΩ and 100 kΩ RuO_2 devices.

Unfortunately, the data represented in Table 2 (taken from the manufacturer's sales bulletins) could not be corroborated with test data taken at Lake Shore for these same sensors. Figures 7 and 8 show the deviation of three 1 kΩ and three 100 kΩ sensors from the manufacturer's mean curve. The tolerance band for the 1 kΩ sensor is plotted and labelled in Figure 7. The tolerance band for the 100 kΩ device would not have been visible in the plot in Figure 8 as it is only 2 K at 300 K.

Table 2. Interchangeability of representative RuO_2 sensors.

Temperature (K)	Interchangeability	
	1 kΩ	100 kΩ
0.02	±0.003	NA
1.5	±0.06	±0.2
4.2	±0.1	±0.2
20	±0.6	±0.3
77	NA	±0.75
100	NA	±1.5
300	NA	>2

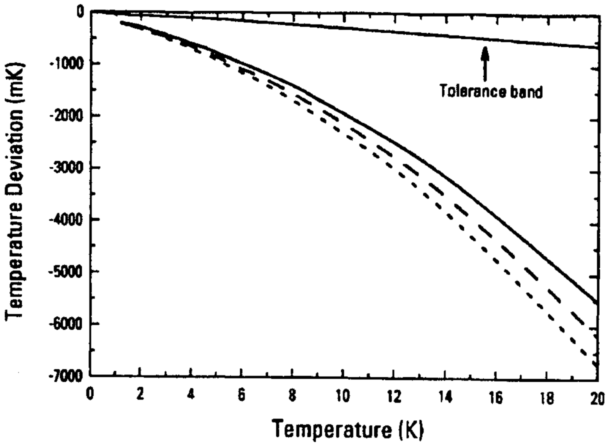

Figure 7. Comparison of three 1 kΩ RuO_2 sensors to their standard curve. The tolerance band is labelled.

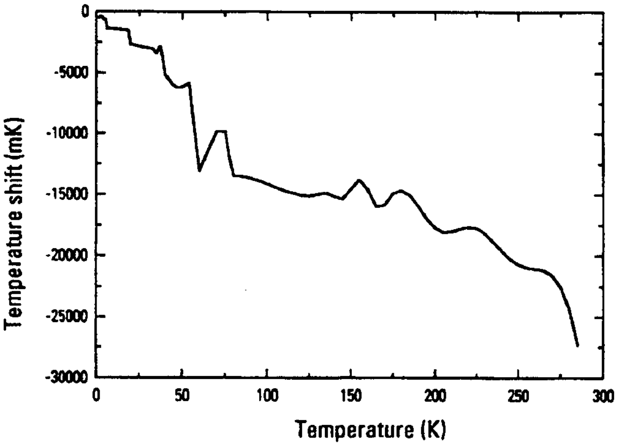

Figure 8. Comparison of a standard 100 kΩ sensor with its standard curve. The tolerance is 2 K at 300 K.

6. Magnetic Field Response

There is a significant amount of data in literature regarding the use of RuO_2 material in magnetic field applications. Generally the results have been favorable. The published magnetic field dependency data for representative RuO_2 1 kΩ and 100 kΩ sensors is shown in Tables 3 and 4.

Table 3. Magnetic field-induced temperature error for 1 kΩ RuO_2 sensors.

Temperature (K)	Field-induced temperature error (K)		
	2 T	8T	14T
0.080	0.0015	0.007	0.010
0.140	0.002	0.012	0.018
0.28	0.005	0.026	0.040
1.3	0.023	0.110	—
4.2	0.042	0.330	—
16	—	0.600	—

Table 4. Magnetic field-induced temperature error for 100 kΩ RuO2 sensors.

Temperature (K)	Field-induced temperature error (K)		
	2 T	8T	14T
0.080	0.0015	0.007	0.010
0.140	0.002	0.012	0.018
0.28	0.005	0.026	0.040
1.3	0.023	0.110	---
4.2	0.042	0.330	---
16	---	0.600	---

The values for the 100 kΩ devices were probably obtained with the sensor operated at 10 µA. It is probable that the sensor was self-heating to the point that the actual temperature of the sensor element was much higher than the registered value, yielding a temperature shift effect that was artificially lower than it should have been. Further, the manufacturer's published data is calculated using ΔR/R instead of ΔT/T. Because of the generally low dimensions less sensitivities of RuO_2 sensors in general, the more commonly used ΔT/T temperature shift values would be much higher. ΔR/R versus ΔT/T specifications can be manipulated,and must be attended to by the customer.

Complete magnetic field data for the Cernox family of temperature sensors is not yet available. In most instances, the magnetic field shift will decrease as the temperature increases. Typical data for Cernox sensor models CX-1030 and CX-1070 is presented in Tables 5 and 6.

Table 5. Typical magnetic field-induced temperature errors for Lake Shore model CX-1030 sensors.

Temperature (K)	Magnetic field-induced temperature error (K)			
	2 T	7 T	10 T	20 T
1.9	0.040	0.110	0.125	0.170
2.6	0.020	0.080	0.090	0.120
4.2	0.004	0.030	0.017	-0.011

Table 6. Typical magnetic field-induced temperature errors for Lake Shore model CX-1070 sensors.

Temperature (K)	Magnetic field-induced temperature error (K)			
	2 T	7 T	10 T	20 T
2.2	0.000	0.001	0.001	0.002
2.7	0.004	0.002	-0.010	-0.014
4.2	0.004	-0.013	-0.042	-0.100

7. Radiation Response.

Although radiation data is available for Cernox sensors, the corresponding data for $Ru0_2$ devices is limited to the 1 kΩ sensors at this time. In general, the $Ru0_2$ sensors we tested behaved similarly to carbon-glass in terms of their usefulness in radiation. The Cernox sensors behave better than both under exposure to gamma radiation. Figures 9 and 10 illustrate the shift in temperature for $Ru0_2$ and Cernox and sensors as a function of temperature after a 10 kGy (1 Mrad) exposure to a Co-60 source with irradiation occurring at 4.2 K.

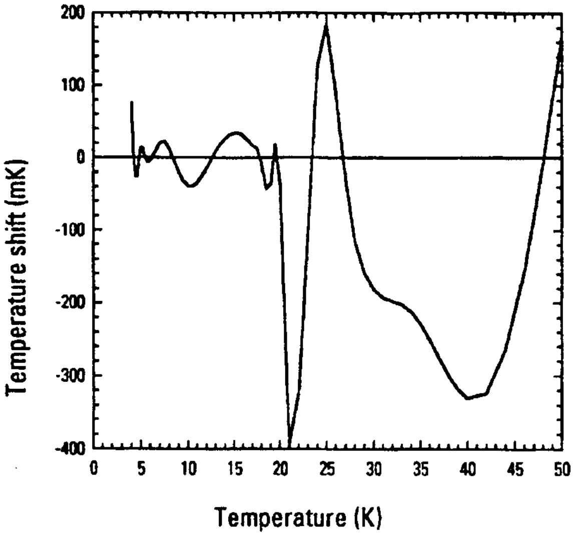

Figure 9. Temperature shift for a 1 KΩ $Ru0_2$ sensor after exposure to 10 kGy (1 Mrad) gamma radiation from a Co-60 source. Irradiation performed at 4.2 K.

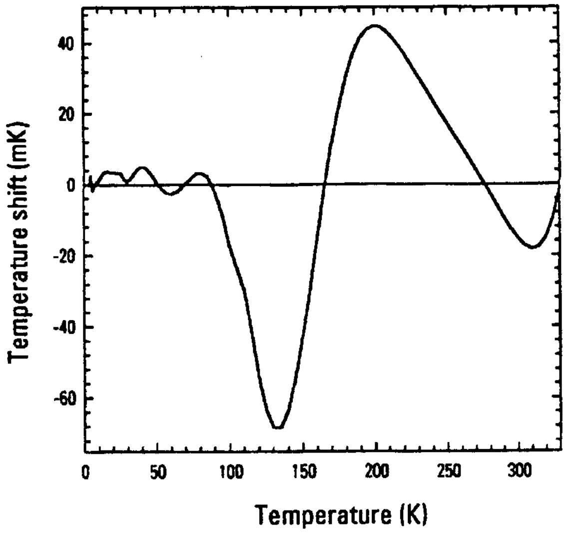

Figure 10. Average temperature shift for 14 Cernox sensors under exposure to 10 kGy (1 Mrad) gamma radiation from a Co-60 source. Irradiation performed at 4.2 K.

8. Stability/Repeatability.

Limited information is available on long term stability or repeatability from manufacturers of Ru0$_2$ sensor devices. There exists anecdotal data that such devices are stable at low temperatures. However, "stable" is not quantified. Three each of the 1 kΩ and 100 kΩ Ru0$_2$ sensors were given 10 fast thermal cycles from 305 K to 4.2 K with the resistance measured after each cycle. Over the last six cycles, the three 1 kΩ devices repeated to 2 mK, 45 mK and 26 mK respectively. The three 100 kΩ sensors repeated to 441 mK, 69 mK and 98 mK respectively. Comparison values for Cernox sensors are presented in Table 7. Several users of Ru0$_2$ sensors have indicated that these devices require approximately 50 thermal cycles from room temperature to LHe temperature for conditioning before becoming stable.

Table 7. Short term repeatability for Ru0$_2$ sensors and Cernox sensors.

Model	Repeatability
1 kΩ	2, 45, 26
100 kΩ	441, 69, 98
CX-1030	±3
CX-1080	±3

Long term stability test results for Cernox sensors will be continually updated, but accelerated test data is currently available. We perform 200 fast thermal shocks between 305 K and 77 K. It is assumed that this simulates the effect of aging. In reality calibrated sensors should be slowly cooled and warmed for maximum stability. Similar data is available for both Ru0$_2$ and Cernox sensors.

The estimated long term stability for the Ru0$_2$ sensors is presented in Figures 11 and 12.. The estimated long term stability of Cernox sensors is shown in Figure 13. Results are typical for a Cernox sensor after 200 thermal shocks from 305 K to 77 K.

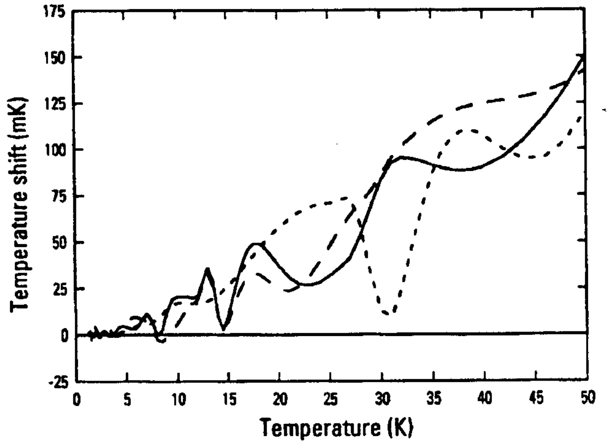

Figure 11. Temperature shift for three 1 kΩ Ru0$_2$ sensors after 200 thermal shocks from 305 K to 77 K.

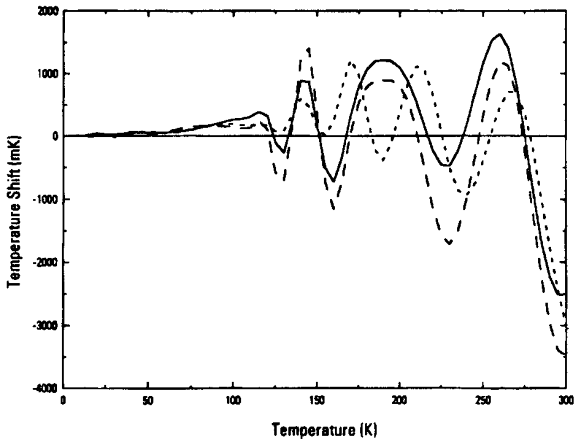

Figure 12. Temperature shift for three 100 kΩ Ru0$_2$ sensors after 200 thermal shocks from 305 K to 77 K.

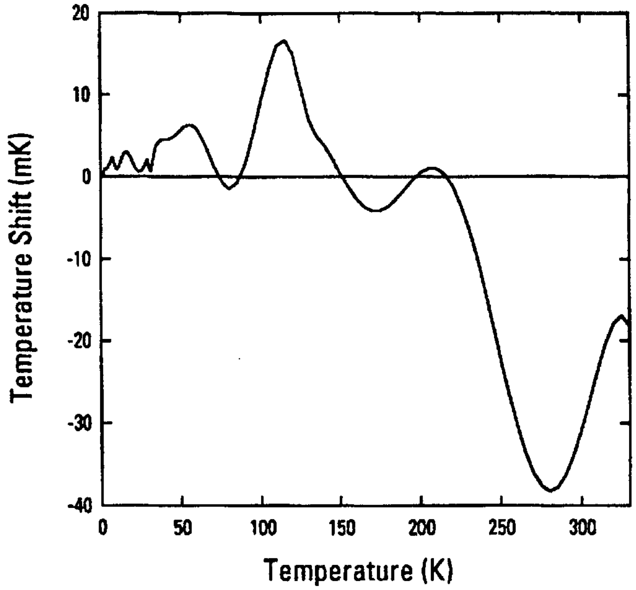

Figure 13. Typical calibration shift for a Cernox CX-1030 sensor after 200 thermal shocks from 305 K to 77 K.

9. Thermal Time Response

The thermal response time is the characteristic time for a temperature sensor to respond to a step change in its thermal environment. While the electronic response time depends mainly on the material and circuit components, the thermal response time depends upon the packaging and mounting as well as the materials.

The thermal response times were measured in liquid using either two sensors of the same type (i.e. bare chips) with one used as a heater or one sensor and a DT-470-SD diode used as a heater. Note that the Cernox sensors used in this experiment were sputtered onto an alumina substrate. We are in the process of switching to all sapphire substrates which should produce much faster time response performance. The response times are likely to be faster when sapphire substrates are used. Thermal response times for the RuO_2 sensors and the Lake Shore Cernox sensors are presented in Table 8 at various temperatures and for various packages (Cernox)

Table 8. Thermal response times for RuO_2 and Cernox sensors at 4.2 K, 77 K and 273 K.

Model	Thermal Response Time (msec)		
	4.2 K	77 K	273 K
1 kΩ (can)	500	1,300	NA
100 kΩ (can)	12,000	Too noisy	Too noisy
CX-1030 (Bare Chip)	1.5	50	135
CX-1030 (-SD package)	15	250	800
CX-1030 (can)	44015	1,000	1,000

10. Electronic Time Response

The electronic time response is the most fundamental limit on how quickly the sensor will respond. The thermal response time is limited by the packaging, while the electronic response time depends upon the makeup of the sensor material itself.

Our measurements were made with a Keithley Model 224 current source with a characteristic rise time of about 1 msec. The sensors were placed in either LHe or LN_2 and connected into the circuit with the current output off. The voltage response as a function of time was measured as the current output was turned on. The results of these tests for RuO_2 and Cernox sensors are shown in Table 9. Higher resistance devices produce somewhat slower response times because there is more electrical insulator material in their composition.

Table 9. Electronic response times for RuO_2 and Cernox sensors at 4.2 K and 77 K.

Model	Electronic Response Time (msec)	
	4.2 K	77 K
1 kΩ (can)	2	2
100 kΩ (can)	4	2
CX-1030	2	2
CX-1080	6	2

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