

Mechanical robustness of cryogenic temperature sensors packaged in a flat, hermetically-sealed package

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Abstract. Much of the work to develop internationally recognized temperature scales over the past 50 years was performed with thermometers whose sensing elements were constructed from platinum wire, rhodium-iron wire, or doped germanium elements. For high stability, the best results were obtained when the sensing element was strain-free mounted which reduced the effects of temperature-induced mechanical stress and deformation. Unfortunately, the devices were still highly susceptible to mechanical damage, and, barring a catastrophic mechanical shock, damage to the temperature sensors could go unnoticed as it could continue to operate with degraded accuracy. While not at the same level of stability as standards grade thermometers, many of the most commonly used cryogenic thermometers today are far more resistant to mechanical handling. This work examines the calibration offsets on three models of cryogenic temperature sensors resulting from mechanical shock and vibration. The models tested in this work were all obtained from Lake Shore Cryotronics, Inc., and included Cernox™ resistance thermometer models CX-1050-SD and CX-1050-AA, and a diode temperature sensor model DT-670-SD. Mechanical treatments were performed via a simple drop test (heights 20 cm, 50 cm, 1 m, and 4 m), random vibration per MIL-STD-202, Method 214, Table 2, Condition H, and mechanical shock per MIL-STD-883, Method 2002, Condition B. Each sensor was calibrated pre- and post-mechanical treatment and the effect of the treatment on each test sensor was quantified in terms of the equivalent temperature calibration shift. This work details the calibration shift of each sensor type following each treatment type over the 1.4 K to 325 K temperature range. No effects from the testing were discernable for Cernox and diode sensors packaged in the -SD package, a flat, hermetically sealed package, while small calibration offsets of less than 0.15% of temperature at higher temperatures were observed for Cernox sensors packaged in the -AA package, a gold-plated copper can.

1. Introduction

Ironically, simply using a cryogenic thermometer can be detrimental to its stability. During its use, strain between the sensing element and its support structure can occur due to mismatches in their respective temperature coefficients of expansion. In practice, this strain is evidenced as an offset in calibration with thermal cycling resulting in reduced stability, hysteresis, and in severe cases, catastrophic failure. Historically, the most stable cryogenic thermometers were constructed so that the temperature sensing element was supported in a manner that minimized the temperature-induced strain between the sensing element and support structure. While providing superior stability, however, this strain-free mounting resulted in temperature sensors that were easily damaged by mechanical vibration and shock, and cryogenic temperature sensors as a whole acquired a reputation for being very fragile. These sensors, including wire-wound platinum, wire-wound rhodium-iron, and



germanium resistance thermometers, were labeled standards grade thermometers due to their high stability and were critical to the development and dissemination of internationally recognized temperature scales over the past 50 years.

While the highest stability is necessary for some applications including temperature scale development and dissemination, many applications benefit from a trade off between decreased stability and increased robustness. For example, the sensing element of a thin film temperature sensor is intricately attached to its supporting substrate which acts as a buffer between the sensing thin film and the packaging. This direct mechanical support of the sensing film allows the sensor to withstand greater mechanical shock and vibration but slightly compromises the overall stability of the sensor. This work examines the robustness of three models of cryogenic temperature sensors with fully supported sensing elements over the 1.4 K to 325 K temperature range. Results were analysed in terms of the temperature calibration shift observed from pre- to post mechanical shock treatment.

2. Experiment

Three models of cryogenic temperature sensors available from Lake Shore Cryotronics, Inc. (Lake Shore), were tested in this work. [1] The included models are Cernox™ resistance thermometer (CxRT) models CX-1050-SD and CX-1050-AA, and the diode temperature sensor (DTS) model DT-670-SD. Detailed information for each sensor is available from the manufacture. [2]

For each model tested, 20 devices of that model were calibrated over the 1.4 K – 325 K temperature range in one of six 1 K – 325 K cryostat calibration systems in Lake Shore's temperature calibration facility. The calibration uncertainty is given in Table 1 as a function of model and temperature. The 20 samples were then divided into 5 groups of 4 devices each. Samples were then subjected to a simple drop test mimicking the effect of being dropped during installation onto an experiment. Each group was assigned to one of four drop heights of 20 cm, 50 cm, 1 m, and 4 m, and the devices were dropped onto a 30 cm × 30 cm × 10 cm thick granite block manufactured by The L. S. Starrett Company. [3] The fifth group acted as a control group. All devices were then recalibrated with the “undropped” control group used to establish a baseline stability for the model.

In order to provide a precise indication of the mechanical treatment, the sensors were subjected to defined mechanical tests. Following recalibration, the devices were divided into two new groups of 10 sensors each with each new group consisting of 2 samples from each of the initial drop height groups. The first of these two groups was subjected to random vibration per MIL-STD-202, Method 214, Table 2, Condition H, while the second group was subjected to mechanical shock per MIL-STD-883, Method 2002, Condition B. [4, 5] These two tests are typical qualification tests for cryogenic temperature sensors models intended for aerospace use, and were both performed by DfR Solutions. [6] Following the random vibration or mechanical shock treatment, each group was given a final recalibration. In each case, the data for each individual sensor was analysed as the calibration shift between pre- and post-treatment calibrations. Given that multiple calibration systems were used, offsets of up to twice the calibration accuracy could be observed without damage actually occurring.

Table 1. Calibration uncertainty by model and temperature.

Temperature (K)	Uncertainty (mK) by model	
	CX-1050 (-SD or -AA)	DT-670
1.4 K	4	7
4.2 K	4	5
10 K	4	6
20 K	8	9
30 K	9	31
50 K	12	37
100 K	17	32
200 K	33	34
300 K	46	35

3. Data and Results

3.1. CxRT Model CX-1050-SD

For the model CX-1050-SD, the Cernox die chips (nominally $0.97 \text{ mm} \times 0.76 \text{ mm}$) were packaged into a flat, hermetically sealed package shown schematically in Figure 1. The package consists of a sapphire base with alumina sides and lid. The sensing die chip is metallurgically bonded to a metallized pad within the package cavity on top of the sapphire base using Au/Ge solder. Electrical connection from the chip to the feedthrough traces are made using $25 \mu\text{m}$ diameter gold wire. The total length of each internal gold wire interconnect is less than 0.75 mm . The lid is attached using a Au/Sn solder seal to form a hermetic enclosure for the die chips. For external electrical connection, copper leads were soldered to the external package bond pads using 63 Sn / 37 Pb solder.

During the drop test, each sensor was dropped with its leads directed vertically upward with the expectation that this orientation would impart the greatest mechanical shock. Following the drop test, each device was examined under microscope (3x-10x) for external package damage such as chipping or cracking, but no damage was observed on any of the devices. All devices were then recalibrated. The results were analyzed as calibration shift as a function of drop height, but no statistically significant differences were observed between the five test groups. For that reason the results for all 20 CX-1050-SD devices are combined and shown in Figure 2 where the average calibration shift is plotted as a function of temperature. The gray region extending above and below the average calibration shift plot indicates one standard deviation about the average calibration offset. The measured deviations are all within the calibration uncertainty at each temperature, so no discernible effects can be attributed to the drop tests.

Following the drop test and recalibration, the 20 sensors were separated into a random vibration group or mechanical shock group and subsequently tested. Devices were recalibrated and the data were analyzed as calibration shift as a function of random vibration or mechanical shock exposure. As before, no statistically significant differences were present for either of the treatments as the measured offsets were well below the calibration uncertainties. Additionally, no correlation was found between the height from which the sensor was dropped during the first test and the calibration offsets induced by the secondary treatment of vibration or mechanical shock. The combined results of the random vibration and mechanical shock treatment are given in Figure 3. Five different models of Cernox sensors are available in the -SD package with only the sensing film being modified. For that reason, these results obtained for the model CX-1050-SD are expected to apply to the CX-1010-SD, CX-1030, CX-1070, and CX-1080 models as well.

3.2. CxRT Model CX-1050-AA

The second model tested for mechanical robustness was the CxRT model CX-1050-AA. Referring to Figure 4, this package consisted of the Cernox die chip silver epoxied to a beryllium oxide cylinder. Phosphor bronze lead wires were inserted through four holes passing through the beryllium oxide cylinder and were epoxied in place using Stycast 2850. Gold wires are ball-bonded to the top surface

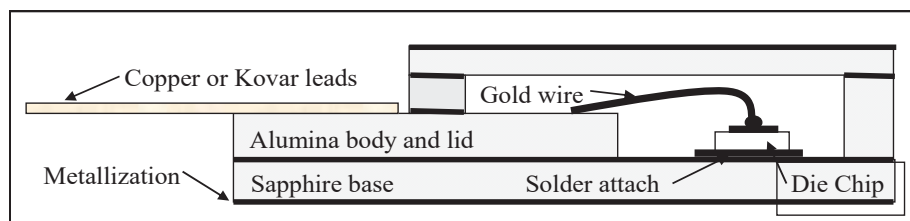


Figure 1. Cut away side view of the -SD package used for the CX-1050-SD and DT-670-SD devices tested in this research. The overall size of the package is approximately 3 mm long \times 2 mm wide \times 1 mm tall with nominal 20 mm lead length.

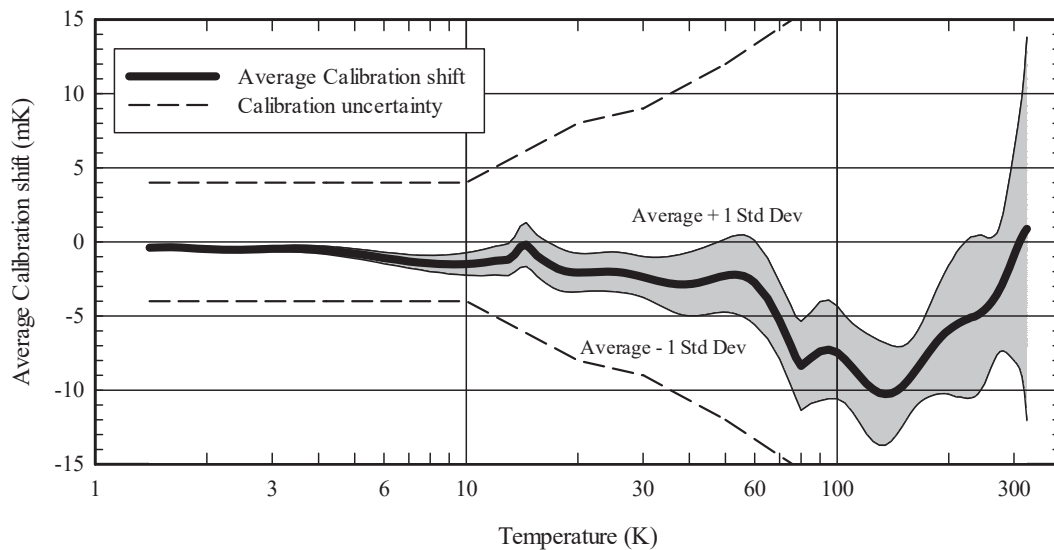


Figure 2. Effects of the of the drop test on 20 CxRT model CX-1050-SDs. The shaded area indicates one standard deviation on either side of the average calibration offset.

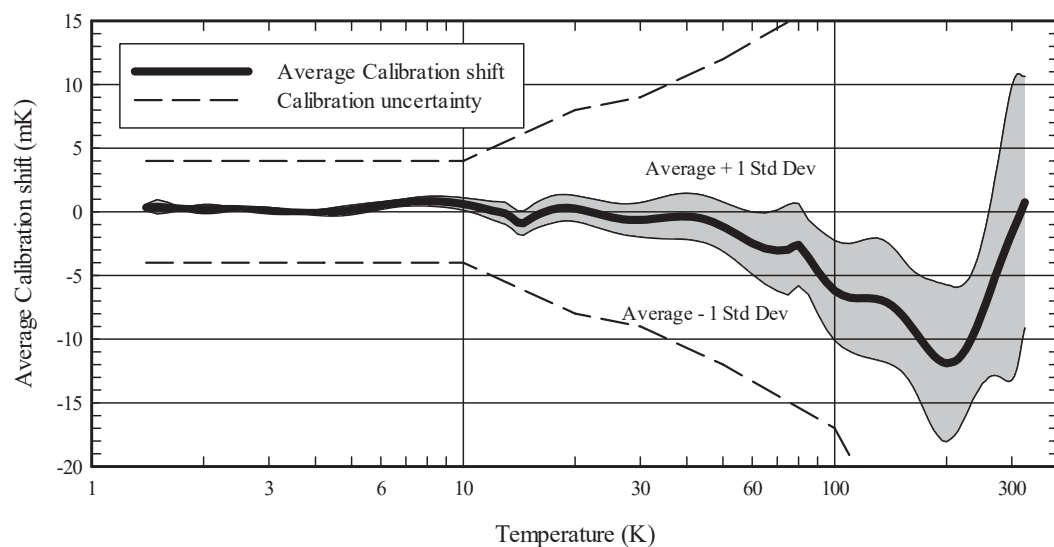


Figure 3. Effects of the of the random vibration and shock test on 20 CxRT model CX-1050-SD. The shaded area indicates one standard deviation on either side of the average calibration offset.

contacts of the Cernox chip. The other end of the gold wire is wrapped first around one phosphor bronze wire for current connection and around a second phosphor bronze wire for voltage detection. These gold leads are spot welded to the phosphor bronze wire for a permanent electrical connection. A Teflon sleeve (not shown) covers the interior wire posts to prevent electrical shorting to the outer copper can. This assembly is inserted into a 3 mm diameter \times 8 mm long gold-plated, copper can and epoxied into place using Stycast 2850.

As with the model CX-1050-SD devices, during the drop test each sensor was dropped with its leads directed vertically upward with the expectation that this orientation would impart the greatest

mechanical shock. Following the drop test the CX-1050-AAs were recalibrated over the 1.4 K to 325 K temperature range. Analysis of the calibration offsets shows larger offsets than observed for the model CX-1050-SD, but still within calibration uncertainty error bars. The magnitude of the offsets did not correlate with the drop height. There is a definite trend toward negative calibration offsets and the offsets show larger scatter which may be indicative of deformation of the internal connecting gold wires which would produce the negative temperature shift as observed in the results if slightly stretched. The combined average calibration shift is shown in Figure 5 with the gray shading indicating one standard deviation about the average calibration shift.

As before, the 20 sensors were then divided into two groups with each group consisting of 2 control sensors plus two sensors from each of the four drop test height groups. The first group was subjected to random vibration testing while the second group was subjected to mechanical shock. Following random vibration, the sensors were recalibrated. At this point, calibration shifts were observed that exceeded levels that could be explained by mere calibration uncertainties. The individual calibration offsets along with the group average and ± 1 standard deviation shading are shown in Figure 6. It's apparent that the average offset is skewed by the large deviations of

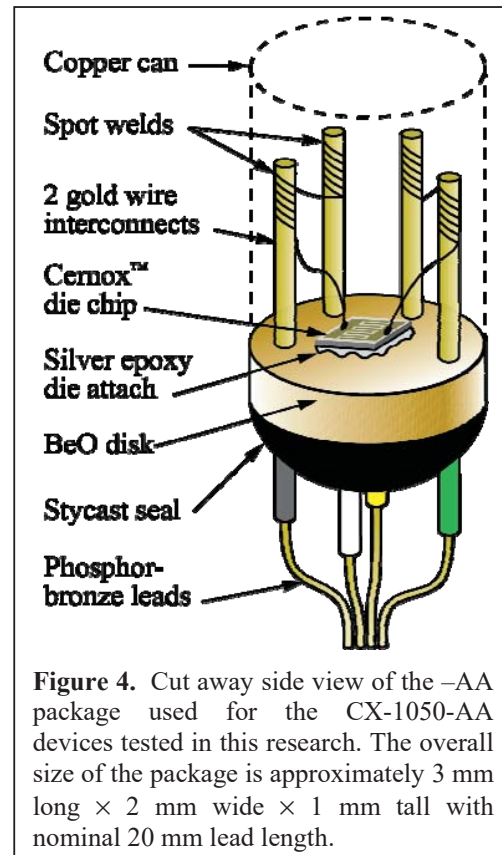


Figure 4. Cut away side view of the -AA package used for the CX-1050-AA devices tested in this research. The overall size of the package is approximately 3 mm long \times 2 mm wide \times 1 mm tall with nominal 20 mm lead length.

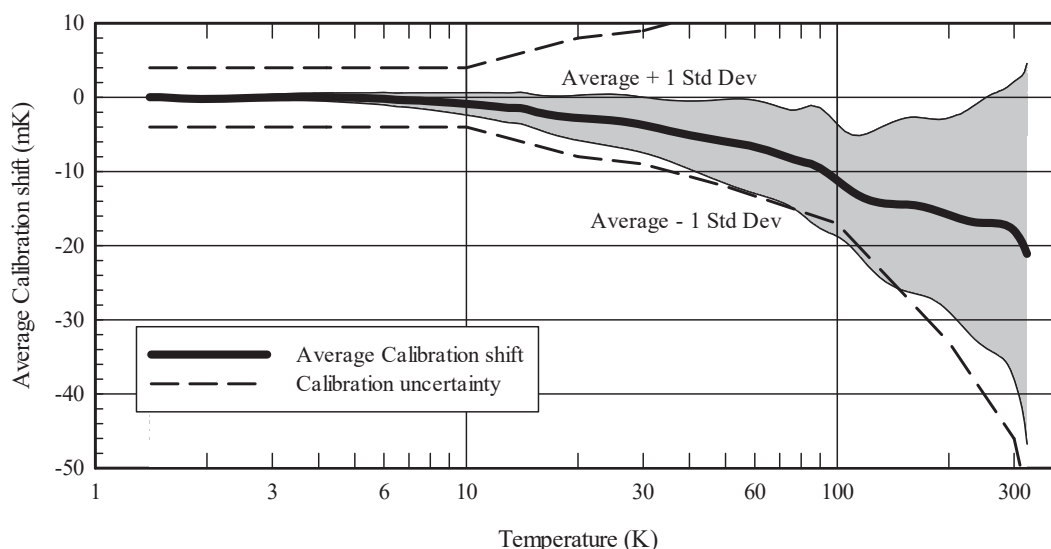


Figure 5. Effects of the of the drop test on 20 CxRT model CX-1050-AAs. The shaded area indicates one standard deviation on either side of the average calibration offset.

two devices, one from the 20 cm drop height group and one from the drop height control group which indicates that the initial drop height did not correlate with subsequent behavior in random vibration. Individual calibration offsets were all less than 0.15% of temperature at higher temperatures.

The second group of CX-1050-AAs was subjected to mechanical shock. Subsequent recalibration again showed calibration offsets that could not be explained in terms of calibration uncertainty. The individual calibration offsets along with the group average and ± 1 standard deviation shading are shown in Figure 7. As with the random vibration group, the average calibration for the mechanical shock group is skewed by a three devices. These were not, however, devices dropped from the highest level in the first test indicating the behaviour under shock was not correlated to the initial drop height. Individual calibration offsets were all less than 0.1% of temperature at higher temperatures.

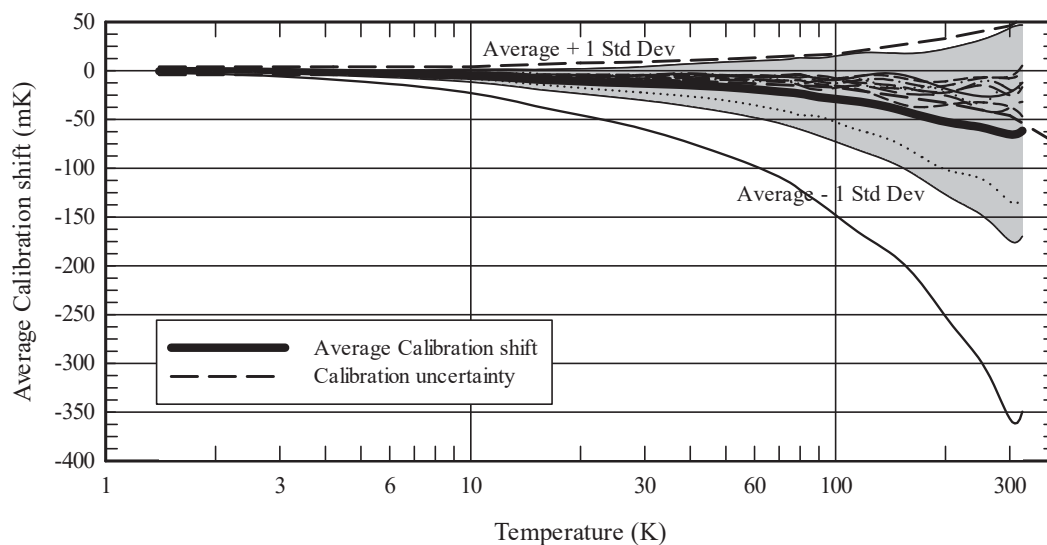


Figure 6. Effects of the of the vibration test on 10 CxRT model CX-1050-AAs. The shaded area indicates one standard deviation on either side of the average calibration offset.

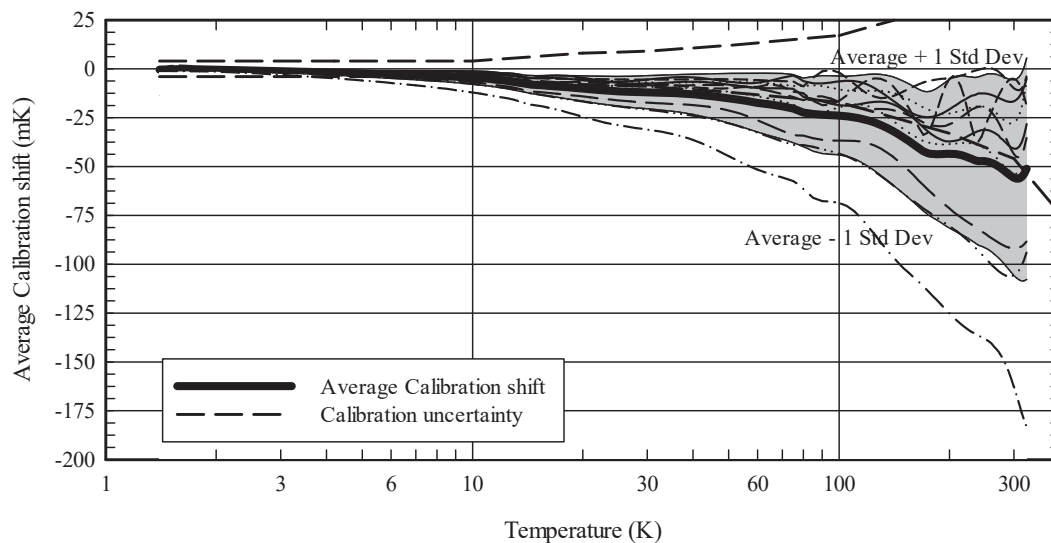


Figure 7. Effects of the of the mechanical shock test on 10 CxRT model CX-1050-AAs. The shaded area indicates one standard deviation on either side of the average calibration offset.

3.3. DTS Model DT-670-SD

For the model DT-670-SD, the nominally $0.41 \text{ mm} \times 0.43 \text{ mm}$ die chips were packaged into the same flat, hermetically sealed package used for the model CX-1050-SD and shown schematically in Figure 1. The only difference between the two packages was that the DT-670-SD had brazed Kovar external leads as part of the base package instead of soldered copper leads.

As with the CX-1050-SD, the leads for the each DT-670-SDs were oriented vertically upward during the drop test to impart the greatest mechanical shock. Each device was visually examined following the drop test under microscope (3x-10x) and no external package damage as observed. The devices were recalibrated and the results analyzed as calibration shift as a function of drop height. No statistically significant effects were observed for any of the drop heights, so the data is presented as combined average calibration offset for all devices as a function of temperature in Figure 8 with one standard deviation indicated in gray. It was noted that while the group average calibration shift is small, the standard deviation does increase with decreasing temperature, especially below 10 K. This effect is attributed to the relatively high power dissipation, about $15 \mu\text{W}$, used to read the devices in this temperature range resulting in device self-heating. The increased scatter is a result of the non-repeatability in mounting with regard to thermal connection which leads to a slightly different self-heating characteristic with each mounting.

Following the drop test and recalibration, the devices were separated into the random vibration group and the mechanical shock group and those tests completed. Results were analyzed initially based on the random vibration or mechanical shock treatment, but no effects were discernible due to either treatment. For that reason, the combined average calibration shift for all devices is given in Figure 9 with one standard deviation indicated in gray.

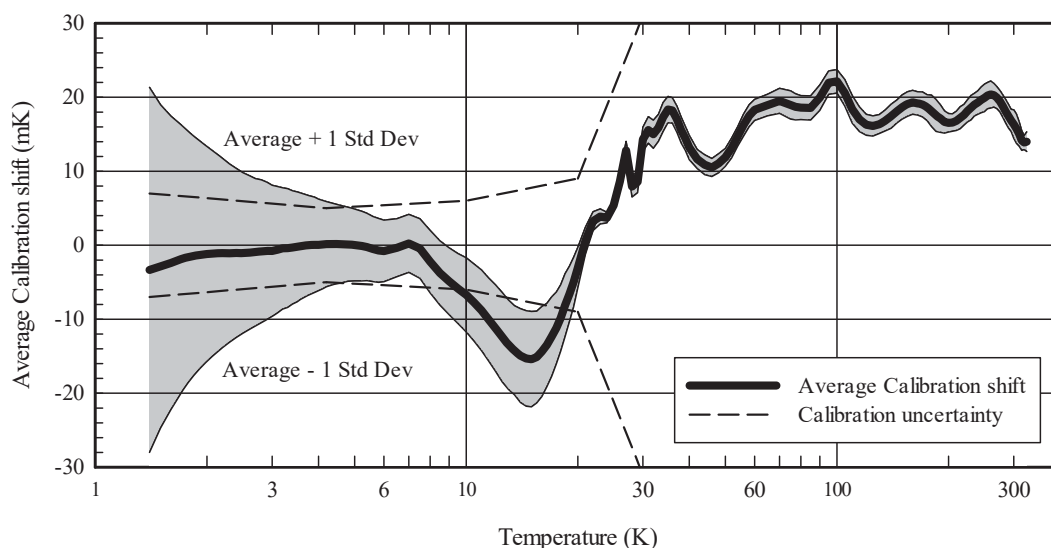


Figure 8. Effects of the of the drop test on 20 DTS model DT-670-SDs. The shaded area indicates one standard deviation on either side of the average calibration offset.

4. Conclusions

This work has examined the robustness of three models of cryogenic temperature sensors manufactured by Lake Shore Cryotronics, Inc., when exposed to three types of mechanical shock: 1) a drop test from heights of 20 cm, 50 cm, 1 m, and 4 m; 2) random vibration per MIL-STD-202, Method 214, Table 2, Condition H; and 3) mechanical shock testing per MIL-STD-883, Method 2002, Condition B.

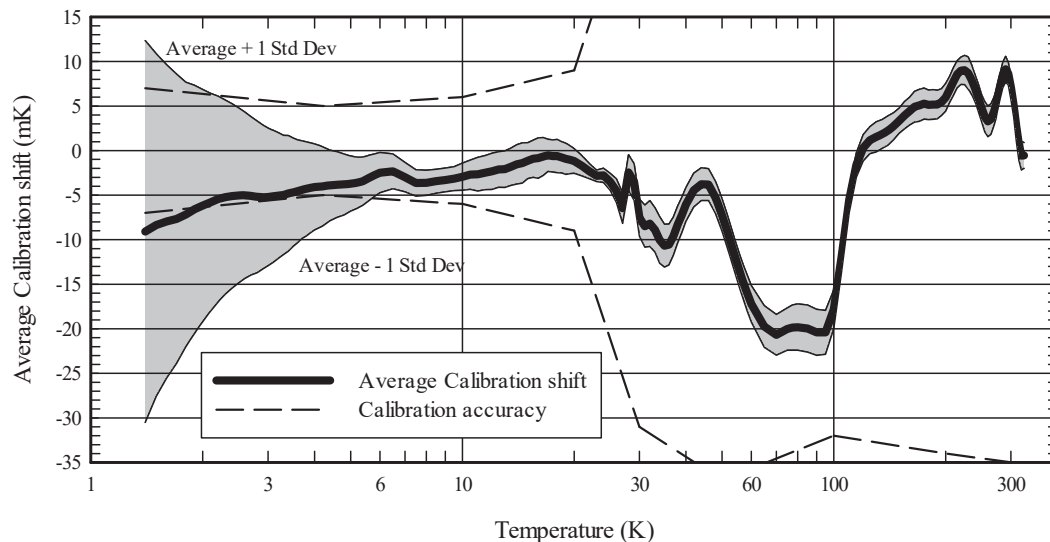


Figure 9. Effects of the of the random vibration and shock test on 20 DTS model DT-670-SDs. The shaded area indicates one standard deviation on either side of the average calibration offset.

CxRT model CX-1050-SDs showed no measurable effects when subjected to the drop test and either random vibration or mechanical shock.

CxRT model CX-1050-AAs showed a slight tendency toward higher resistance/negative calibration shift after the drop test, but only at the level of the calibration uncertainty. A few of these devices did, however, show offsets above the calibration uncertainty when subjected to random vibration or shock with random vibration resulting in higher offsets. The offsets are attributed to small increases in resistance resulting from the deformations of the gold leads connecting the Cernox die chip to the phosphor bronze electrical feedthrough leads.

DTS model DT-670-SDs showed no measurable effects after mechanical testing, although scatter due to non-repeatable mounting and subsequent self-heating was observed at temperatures below 10 K. Overall, the devices packaged in the flat, hermetic –SD package performed better than a comparable sensor packaged in a gold plated copper can.

Future work will examine other temperature sensor types as well as whether the order of the testing affects the final results.

References

- [1] Lake Shore Cryotronics, Inc., 575 McCorkle Blvd., Westerville, OH, 43082, USA.
- [2] Lake Shore Cryotronics Temperature Product Catalog or manufacturer's website: www.lakeshore.com.
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- [6] DfR Solutions, 9000 Virginia Manor Rd Suite 290 Beltsville, MD 20705, USA.