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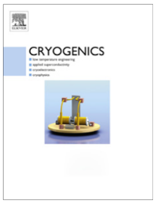

A standardized diode cryogenic temperature sensor for aerospace applications

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ABSTRACT

The model DT-670-SD cryogenic diode temperature sensor, manufactured by Lake Shore Cryotronics, Inc. has been used on numerous aerospace space missions since its introduction nearly 15 years ago. While the sensing element is a diode, it is operated in a non-standard manner when used as a temperature sensor over the 1.4–500 K temperature range. For this reason, the NASA and MIL-type test and performance standards designed to ensure high reliability of diode aerospace parts don't properly define the inspection and test protocol for the DT-670-SD temperature sensor as written. This requires each aerospace application to develop unique test and inspection protocols for the project, typically for a small number of sensors, resulting in expensive sensors with a long lead time. With over 30 years of experience in supplying cryogenic temperature sensors for aerospace applications, Lake Shore has developed screening and qualification inspection and test protocols to provide "commercial off-the-shelf (COTS)" DT-670-SD temperature sensors that should meet the requirements of most high-reliability applications including aerospace. Parts from acceptance and qualified lots will be available at a base sensor level with the ability to specify an interchangeability tolerance, calibration range, mounting adaptor, and/or lead extension for final configuration. This work presents details of this acceptance and qualification inspection and test protocol as well as performance characteristics of the DT-670-SD cryogenic temperature sensors when inspected and tested to this protocol.

1. Introduction

Electronic components intended for use on aerospace missions are subjected to test protocols designed to ensure their reliability under the extreme conditions of launch and space environment. The test protocols are intended to simulate or exceed the expected conditions encountered by the component during the mission. The test protocols and specific test details have been documented for many electrical/electronic component types in NASA, MIL-PRFs, and MIL-STD documents for the purpose of providing a common reference for both NASA and its subcontractors [1–5]. This procedure generally works well, but complications arise when the component type is not addressed in these defined test protocols, as is the case with cryogenic temperature sensors.

This work addresses the development of a standardized aerospace acceptance and qualification test protocol for the Lake Shore Cryotronics, Inc.'s [6] diode temperature sensor (DTS) model DT-670-SD [7] with the end goal of making available a commercial off-the-shelf (COTS) diode temperature sensor suitable for aerospace use.

2. Materials and methods

2.1. Background

Lake Shore Cryotronics, Inc. (Lake Shore) has supplied cryogenic temperature sensors for aerospace applications for over thirty years. During this time frame, however, no standard test protocol from NASA or the Department of Defense has addressed the acceptance or qualification test protocols for these device types. While the most common cryogenic temperature sensors are either resistive or diode in nature, they are operated in a nontraditional manner when used as temperature sensors making the standard resistor or diode test protocols inappropriate for their acceptance and qualification. This lack of a proper test protocol for cryogenic temperature sensors has resulted in turning every procurement into a long and costly endeavor. Customer source inspections require each production lot to be built from beginning and qualification testing completed.

In 2013, Lake Shore worked with NASA and other aerospace contractors to develop a suitable test protocol for the Cernox™ family of cryogenic temperature sensors (CxRTs) to ensure their

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reliability for aerospace use [8]. The test protocol resulting from this collaboration allowed the manufacture of a large production lot of CxRT devices to the specified protocol defining both lot screening and qualification testing. Parts were built and stocked at the base part level while still allowing final configuration (adaptor, lead modification, calibration, etc.) to be specified at time of delivery. This current body of work will lead to development of a similar test protocol for diodes used as cryogenic temperature sensors.

2.2. Sensor selection and properties

Beginning in 2013, a test protocol was first developed for CxRTs because they generally provide superior performance as cryogenic temperature sensors when compared to diodes. CxRT resistance–temperature characteristic can be tailored to maximize performance over various temperature ranges and their high sensitivity allows for sub-millikelvin resolution with absolute temperature uncertainties on the order of tens of millikelvins. CxRTs perform well in magnetic fields, are radiation hard, and typically require less excitation power during measurement. On the other hand, CxRTs are not interchangeable, so they normally require individual calibration, and their wide resistance range typically requires more sophisticated electronics that can scale the current excitation in order to maintain a reasonable signal while avoiding self-heating at colder temperatures or loss of resolution at higher temperatures.

In aerospace applications where stability is important but the absolute temperature accuracy can be relaxed, the model DT-670-SD can provide a cost effective alternative due to their interchangeability to a standard curve and their simpler instrumentation for operation. A discussion of the DT-670-SD properties is given in the following section.

2.3. Model DT-670-SD properties

The DT-600 series die chip is a transistor operated as diode using the base-to-collector p–n junction. The bare die nominally measures 0.406 mm long × 0.432 mm wide × 0.178 mm thick as shown in Fig. 1. The chip is a through-the-body device with a metallized bottom side forming the collector electrical connection and two metallized bond pads on the top side for the emitter and base electrical connections. To provide a robust sensor, the die chips are packaged in Lake Shore's SD package [7]. This package is a flat, hermetically sealed package specially designed for cryogenic thermometry providing a highly efficient thermal connection between internally mounted temperature sensing die chips and the outside world. Construction wise, the package consists of a sapphire base with alumina body and top. All materials are low outgassing and compatible with a 1–500 K temperature range. A top and side view of the SD package with dimensions are shown in Figs. 2 and 3, respectively, while a cutaway side view is shown in Fig. 4. The overall body dimensions are 1.9 mm wide × 3.2 mm long × 1.0 mm high with a small total mass less than 37 mg.

Within the cavity of the package, the DT-600 series die chip is metallurgically bonded to a metallized pad directly on top of the sapphire substrate package base using a gold–silicon eutectic. The metallurgical die attach provides a high mechanical strength interface that far exceeds the minimum die shear strengths required by MIL-STDs for the given die size and die attach area. The DT-600 die chip bottom also serves as the collector electrical connection and the metallized pad to which the die chip is eutectically bonded is connected to an electrical feedthrough that then connects to an external package bond pad. For the connection to the transistor base, a 25 μm diameter gold wire is bonded from base bond pad on the top side of the chip to an internal package bond pad/metallized feedthrough trace which then connects to an external package bond pad. Externally, a flat 0.38 mm wide × 0.1 mm thick × 20 mm long Kovar lead, is brazed to each of the two external package bond pads. The package lid is attached via a gold-tin eutectic solder preform using a commercial sealing oven to form the hermetic seal. The SD package top and bottom are both metallized and the lot date code and serial number scribed into the metallization.

The resulting DT-670-SD sensor can be used over the 1.4–500 K temperature range. In practice, the device is operated at a constant forward current of 10 μA and the output signal is measured as the forward voltage drop, which is a strong function of temperature. The model DT-670-SD temperature sensor's typical voltage and sensitivity response curves are shown in Figs. 5 and 6, respectively. The devices within the series are sufficiently uniform that all devices are interchangeable to a standard response curve. The devices are grouped into tolerance bands ranging from ±0.25 K to

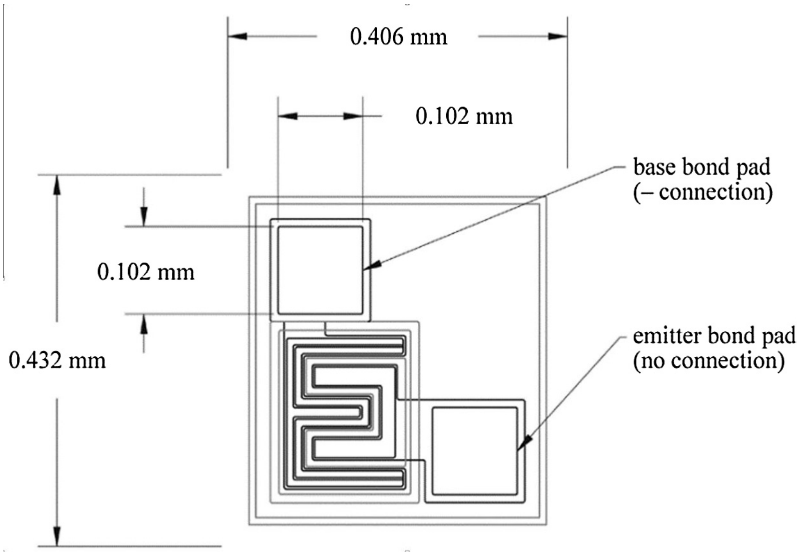

Fig. 1. DT-670 diode temperature bare chip size and dimensions. The die is approximately 0.178 mm thick. Electrical connection is made from the base to the collector on the bottom side of the die chip.

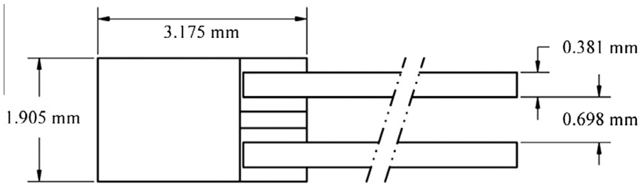

Fig. 2. Top view schematic and dimensions of the model DT-670-SD package.

±1.5% of temperature about the standard curve. The DT-670-SD interchangeability to the standard curve is given in Table 1 for the five commercially available bands, although special tolerances can be specified. With calibration, the absolute temperature uncertainty can be improved to levels ranging from better than ±10 mK at temperatures below 10 K to ±35 mK at room temperature.

The DTS model DT-670-SD has been commercially available from Lake Shore since 2000 [9], and these devices have been used on numerous space missions since that time.

2.4. Model DT-670-SD performance characteristics

Generally speaking, the most important attribute for a cryogenic temperature sensor is stability upon usage, which normally equates to stability upon thermal cycling. However, in aerospace applications these sensors are subjected to additional conditions not normally encountered in laboratory applications. These conditions can include repeated thermal cycling/shocking, mechanical shock/vibration, radiation, and extended operation, among others. The DT-670-SD performance was measured as sensor calibration shift when subjected to treatments chosen to simulate an aerospace application. Electrical measurements were performed in Lake Shore's Quality Control Facility or in their Temperature Calibration Facility. In both facilities all instrumentation is traceable to national standards and the temperature measurements are traceable to the International Temperature Scale of 1990 [10]. In the Quality Control Facility, data was acquired at 4.2 K (open liquid helium bath), 77.35 K (open liquid nitrogen bath) and at 305 K (305 K air oven). In the Calibration Facility, each diode was measured using a 10 μA excitation at approximately 70 temperature points spanning the 1.4–330 K temperature range. Calibration instrumentation included an Agilent model 3458A digital voltmeter, a Keithley model 224 current source, Guildline model 9300 standard resistors from 10 Ω to 1 MΩ in decade steps, an Lake Shore model 340 temperature controller, and a Keithley model 702 switching mainframe with model 7067 low-thermal EMF scanner cards. Resulting uncertainties ranged from better than ±10 mK to about ±35 mK.

3. Theory

3.1. Screening test protocol

In aerospace applications, screening tests are component-specific tests that are performed on 100% of a production lot in order to fail nonconforming parts and induce infant mortality with the assumption that the remaining parts possess higher reliability. The development of a screening test protocol begins with identifying relevant treatments and tests that are likely good predictors of the reliability for the component. For the present work, development of a screening test protocol started with identifying the most similar component contained in NASA or MIL standard, keeping in mind that the DT-670-SD, while a transistor, is operated as a cryogenic temperature sensor and not as a semiconductor component. Within defined test standards, the closest match was a cryogenic thermistor with a screening protocol contained within the NASA Goddard Space Flight Center's document EEE-INST-002, "Instructions for EEE Parts Selection, Screening, Qualification, and Derating" [1]. However, due to the semiconductor nature of the component, certain tests contained within the MIL-PRF-19500 document were deemed important and also incorporated. These selections were validated by comparing them to the numerous aerospace orders that Lake Shore has completed for the model DT-670-SD and its predecessors, models DT-470-SD and DT-500. With regard to both standards, tests that were inappropriate for the present usage were eliminated and additional tests added as needed. For example, the thermistor section, T1, of NASA's EEE-INST-002 incorporates the visual inspection, electrical characteristics, and the critical thermal cycling test, but this standard clearly refers to a glass or epoxy encapsulated sensing element absent an internal cavity and internal die attach and wire bonds. The MIL-PRF-19500 tests incorporated the burn-in and high temperature reverse bias tests. To address the cavity nature of the DT-670-SD, additional tests were added including a particle impact noise detection (PIND) test, fine and gross leak hermeticity tests, a constant acceleration test, and an X-ray inspection. To verify internal construction, in-process destructive wire pull, die shear, and cross-sectioning steps were also incorporated.

After developing the preliminary screening test protocol above, a number of aerospace customers' orders for DT-670-SDs were reviewed to identify any commonly requested tests that were overlooked. Some tests were added and other test parameters were slightly modified with the end goal of developing a widely accepted test protocol that allows for building and inventorying large screened lots of devices. The final 100% screening test protocol for DT-670-SDs is given in Table 2.

Following testing, the screened inventory of off-the-shelf parts will be stored at the DT-670-SD level, which is the base part level. Final configuration, including lead extension length and material, adapter, tolerance band, and calibration can be specified at time of order, yielding a screened DT-670-SD DTS part with approximately 1 month delivery.

3.2. Qualification test protocol

Unlike lot screening testing that is intended to verify that parts meet a specified level of workmanship, lot qualification testing is designed to verify that parts will meet the required design, performance, and reliability criteria for the intended application, and these tests normally address the expected mechanical, electrical, and environmental conditions that would be encountered for that application. Both the thermistor section of document EEE-INST-002 and the MIL-PRF-19500 were also used as starting points for developing a qualification test protocol for DT-670-SDs. As with

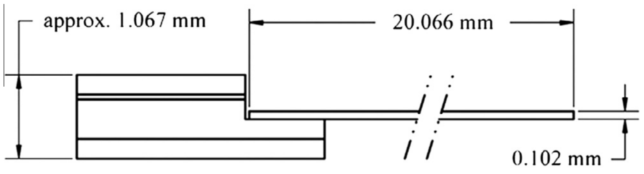

Fig. 3. Side view schematic and dimensions of the model DT-670-SD package.

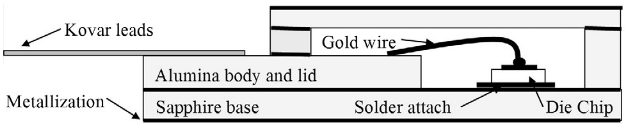

Fig. 4. Cut away side view of the DT-670-SD-SD package.

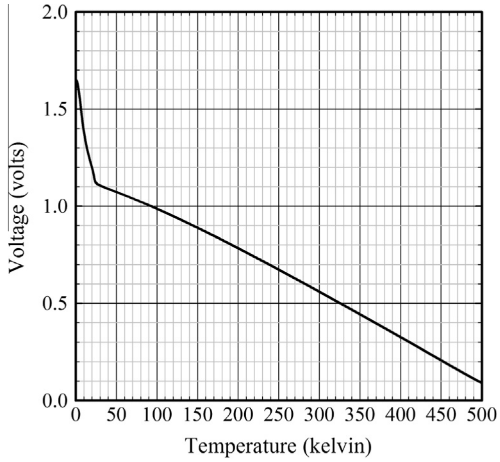

Fig. 5. Typical voltage response for a model DT-670-SD diode temperature sensor.

the screening test protocol, tests were eliminated if not applicable and others were added to address the thermometry usage of the device. Modifications were also made as the test protocol was compared against previous aerospace orders for device.

For the case of a cryogenic temperature sensor the qualifications tests are broken into subgroups that verify physical/mechanical design, package materials, thermometry performance, and long term reliability performance. Since this work is performed without oversight from NASA or other aerospace contractor, an additional independent Destructive Physical Analysis (DPA) was added. DPA tests are performed both to verify internal design, materials, construction, and workmanship, and to monitor processes. For the model DT-670-SD, the qualification tests are divided into 7 subgroups as outlined in Table 3. Summarizing this table, physical/material tests include physical dimension, solderability, and outgassing. Mechanical design is verified through thermal shock, mechanical shock, and vibration testing. Thermometry performance is verified through thermal shock testing. Finally, long term reliability is verified through accelerated life and high temperature life testing. Test details are given in Table 3.

While the off-the-shelf devices will be available with configurable lead extensions, adapter, tolerance band, and calibration, qualification testing will be performed using the standard DT-670-SD package shown in Figs. 2 and 3.

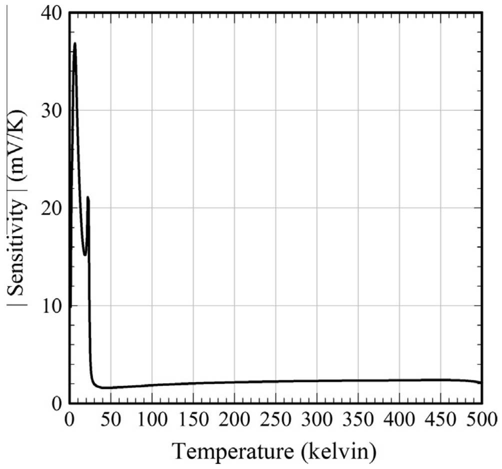

Fig. 6. Typical sensitivity (absolute value) as a function of temperature for a model DT-670-SD temperature sensor.

4. Results

4.1. Qualification test results

Performance results are presented below for each test condition as appropriate. A majority of the data were obtained from either a DT-670-SD aerospace order completed during the 2013–2014 time frame, additional DT-670-SDs devices tested in parallel with that or another aerospace order, or from dedicated special testing on DT-670-SD groups. Measurements were performed in Lake Shore's Quality Control Facility at temperatures of 4.2 K (liquid helium bath), 77.35 K (liquid nitrogen bath), and 305 K (air oven), with measurement uncertainties of ±36 mK, ±86 mK, and ±72 mK, respectively. In some cases below, similar test results with full calibrations from 1.4 K to 325 K are included to provide supplemental information.

Physical and mechanical design features of the SD package are tested in Subgroup 1 (supplier-performed physical dimensions and solderability), Subgroup 2 (independent test lab-performed DPA), which was performed as a precursor to the aerospace order, and Subgroup 3 (outgassing) after the devices complete 100% screening per Table 2. These tests yield only pass/fail results with regard to physical dimensions, solderability, visual inspection, packaging attributes (hermeticity, X-ray inspection, particle impact noise detection, residual gas analysis, and prohibited materials analysis) and mechanical robustness (wire pull and die shear tests). No electrical measurements were performed during completion of these subgroup tests.

Subgroup 4 tested the stability of 6 model DT-670-SD sensors after 25 thermal shocks from 400 K into a liquid helium bath (nominally 4.2 K). Average group offsets and their standard deviation at 4.2 K, 77.35 K, and 305 K are presented in Table 4. Following the post-thermal shock electrical measurements, hermeticity tests, wire pull tests, and die shear tests were performed to confirm package robustness with all devices passing. In a similar test, 3 devices were thermally shocked 100 times from flowing room temperature air into liquid nitrogen (nominally 77.35 K). Calibration over the 1.4–325 K temperature range was performed both pre- and post-thermal shocking. The stability for all three devices over the entire 1.4–325 K temperature range was better than ±15 mK. These results are shown in Fig. 7.

Subgroups 5 and 6 establish long-term reliability through accelerated testing. Subgroup 5 is performed as an accelerated life test per MIL-STD-750, Method 1027, using an ambient temperature of 473 K ± 10 K for 1000 h with a forward excitation of 10 μA. Twelve devices tested in the referenced aerospace order showed average offsets and standard deviations as listed in Table 5. Subgroup 6 was performed as high temperature life test (non-operational) per MIL-STD-750, Method 1032, using an ambient temperature of 473 K ± 10 K for 340 h. Six devices were tested in the reference aerospace order and there average offsets and standard deviations are given in Table 6. Supplemental data from a separate aerospace order is shown in Fig. 8 for a group of 5 DT-670-SDs completing a 1000 h life test at 473 K with 10 μA excitation and subsequently recalibrated over the 1.4–325 K temperature range.

Table 1
Tolerance bands for the model DT-670-SD.

Band	Tolerance to standard curve at temperature		
	2–100 K	100–305 K	305–500 K
Band A	±0.25 K	±0.5 K	±0.5 K
Band A1	±0.25 K	±1.5% of temp.	±1.5% of temp.
Band B	±0.5 K	±0.5 K	±0.33% of temp.
Band B1	±0.5 K	±1.5% of temp.	±1.5% of temp.
Band C	±1 K	±1 K	±0.5% of temp.

Table 2
100% Screening test sequence for DT-670-SD diode thermometers.

Step	Inspection/test	Standard	Method and conditions
1	SEM of bare die	MIL-STD-750	Method 2077
2	Die visual	MIL-STD-750	Method 2073
3	Internal visual pre-cap	MIL-STD-750	Method 2072
4	In-process bond pull test	MIL-STD-750	Method 2037, Condition D
5	In-process die shear test	MIL-STD-750	Method 2017
6	In-process cross section	IPC-TM-650	
7	Stabilization bake	Lake Shore procedure	475 K, 8 h minimum
8	Temperature cycling (liquid to air)	MIL-STD-750	Method 1051, 77–305 K, 20 times
9	Temperature cycling (liquid to air)	MIL-STD-750	Method 1051, 4.2–305 K, 20 times
10	Initial electrical measurements	Lake Shore procedure	Data at 4.2 K, 77 K, and 305 K
11	Serialization	Lake Shore procedure	
12	Constant acceleration	MIL-STD-750	Method 2006
13	Particle impact noise detection	MIL-STD-750	Method 2052, Condition A
14	Fine hermetic seal	MIL-STD-750	Method 1071, Condition G or H
15	Gross hermetic seal	MIL-STD-750	Method 1071, Condition C, G2, or K
16	Radiography	MIL-STD-750	Method 2076, film or digital X-ray allowed
17	Interim electrical measurements	Lake Shore procedure	Data at 4.2 K, 77 K, and 305 K
18	Interim parameter drift	Lake Shore procedure	Drift calculation for 4.2 K, 77 K, and 305 K measurements
19	HTRB	MIL-STD-750	Method 1038, Condition A, 32 V, 48 h, $T_A = 130 \pm 5$ °C
20	Interim electrical measurements	Lake Shore procedure	Data at 4.2 K, 77 K, and 305 K
21	Interim parameter drift	Lake Shore procedure	Drift calculation for 4.2 K, 77 K, and 305 K measurements
22	PDA calculation		Level 1 < 5%, Level 2 < 10%
23	Burn-in	MIL-STD-750	Method 1038, Condition A, 10 μA, 240 h, $T_A = 130 \pm 5$ °C.
24	Final electrical measurements	Lake Shore procedure	Data at 4.2 K, 77 K, and 305 K
25	Interim parameter drift	Lake Shore procedure	Drift calculation for 4.2 K, 77 K, and 305 K measurements
26	PDA		Level 1 < 5%, Level 2 < 10%
27	Overall parameter drift	Lake Shore procedure	Drift calculation for 4.2 K, 77 K, and 305 K measurements
28	External visual	MIL-STD-750	Method 2071

In Subgroup 7, devices were subjected to mechanical shock and vibration to verify the robustness of the DT-670-SD assembly. Six devices underwent vibration testing per MIL-STD-202, Method 214, Condition H, and mechanical shock testing per MIL-STD-883, Method 2002, Condition B (1500 G). The average temperature offsets and standard deviations are listed in Table 7. Note that all average offsets are below the uncertainty in the measurement, indicating no effect due to the mechanical treatments. These devices completed hermeticity testing, wire pull, and die shear tests with all devices passing. As supplemental data, during completion of a separate aerospace order a group of 5 devices were subjected to vibration per MIL-STD-202, Method 214, Condition H, and mechanical shock per MIL-STD-883, Method 2002, Condition B. The results are shown in Fig. 9 and indicate that the mechanical testing-induced calibration offsets are less than ±50 mK over the 1.4–325 K temperature range and better than ±20 mK for temperatures above 20 K.

4.2. Supporting DT-670-SD test results

When possible, additional testing relevant to aerospace applications has been performed to further determine performance specifications for the model DT-670-SD. The first of these tests measured the stability of four model DT-670-SDs when continuously operated in an open liquid nitrogen bath (nominally 77.35 K) for a period of 420 days. A traceable platinum thermometer mounted on the same copper calibration block was used to correct the data for fluctuations in bath temperature due to fluctuations in atmospheric pressure. Device measurements were performed using a Lake Shore model 336 temperature controller. The corrected data are presented in Fig. 10 and show a low temperature stability of better than ±20 mK for all four test samples.

In a second test, a group of 12 DT-670-SDs were subjected to accelerated thermal shocking with 1000 thermal shocks from room temperature into liquid nitrogen (nominally 77.35 K) [11]. Recalibrations from 1.4 K to 325 K were performed after 20, 40, 60, 100, 250, 500, and 1000 thermal shocks. A summary of the results showing average offset of the group after 20, 100, 250, 500 and 1000 thermal shocks is presented in Fig. 11. These data show long term stability upon extended thermal shocking better than −20 mK to +45 mK across the 1.4–325 K temperature range.

Sensors for a specific aerospace mission are often purchased years in advance of their actual launch. During this time, they may be stored at room temperature in original packaging or installed on a larger component that is stored at room temperature. A third additional test measured the effect of room temperature storage on DTSs that had been stored at room temperature [12]. A group of 23 model DT-670-SDs were recalibrated following a 110 month storage period at room temperature. No special storage precautions were taken other than the sensors being stored in their original box. The group average calibration shifts from the original calibration are shown in Fig. 12 with the data showing a group average calibration shift of less than 75 mK in the 4–20 K temperature range and less than 35 mK over the 20–325 K temperature range. The standard deviation of all devices was less than 30 mK over this entire range.

A third test measured the radiation hardness of model DT-670-SDs [13]. These devices are small signal transistors and their inherent design does make them susceptible to radiation-induced calibration offsets. A group of 23 DT-670-SDs were irradiated to various levels ranging from 10 Gy to 10,000 Gy using a cesium-137 gamma source. Irradiation was performed at room temperature at a dose rate of approximately 0.007 Gy/s. Data are presented in Fig. 13 for total dose levels of 100 Gy, 300 Gy, and 1000 Gy. As seen in this figure, significant offsets in excess of 1 K are observed at higher temperatures when the total dose exceeds 100 Gy. The offsets reduce with temperature and become sub-kelvin below 50 K for all irradiation levels.

As a side note, X-ray radiography inspection is commonly specified for these devices when they are to be used on aerospace missions. The traditional X-ray radiography inspection uses a photographic film. For small devices such as the DT-670-SD, the subsequent inspection requires the use of a microscope to examine the X-ray image. It is far more convenient to take advantage of

Table 3
Qualification test sequence for DT-670-SD thermometers.

Sub group	Inspection test	Standard	Test method, conditions, and requirements
1 (5 parts)	Screening per Table 1		Table 1
	Physical dimensions	MIL-STD-750	Method 2055
	Solderability	MIL-STD-750	Method 2026
2 (5 parts)	Screening per Table 1		Table 1
	Independent DPA (external test lab)	MIL-STD-1580	Requirement 21, Table 1
3 (6 parts)	Screening per Table 1		Table 1
	Outgassing	ASTM E595	
4 (5 parts)	Screening per Table 1		Table 1
	Electrical measurements	Lake Shore procedure	Data at 4.2 K, 77 K, and 305 K
	Thermal shock (liquid to air)	MIL-STD-750	Method 1056, 4.2–400 K, 25 times
	Electrical measurements	Lake Shore procedure	Data at 4.2 K, 77 K, and 305 K
	Parameter drift	Lake Shore procedure	Drift calculation for 4.2 K, 77 K, and 305 K measurements
	Fine and gross hermetic seal	MIL-STD-750	Fine—Condition G or H, Gross—Condition C, G2 or K
	De-cap internal visual	MIL-STD-750	Method 2075
	Post cap bond integrity	MIL-STD-750	Method 2037, Condition D
	Post-cap die shear strength	MIL-STD-750	Method 2017
5 (5 parts)	Screening per Table 1		Table 1
	Electrical measurements	Lake Shore procedure	Data at 4.2 K, 77 K, and 305 K
	Accelerated steady-state operation life	MIL-STD-750	Method 1027, 1000 h, 10 μA forward excitation, $T_A = 200 \pm 10$ °C
	Electrical measurements	Lake Shore procedure	Data at 4.2 K, 77 K, and 305 K
	Parameter drift	Lake Shore procedure	Drift calculation for 4.2 K, 77 K, and 305 K measurements
	Post cap bond integrity	MIL-STD-750	Method 2037
6 (5 parts)	Screening per Table 1		Table 1
	Electrical measurements	Lake Shore procedure	Data at 4.2 K, 77 K, and 305 K
	High temperature life (non-operating)	MIL-STD-750	Method 1032, 340 h, $T_{STG}(\max) = 200$ °C
	Electrical measurements	Lake Shore procedure	Data at 4.2 K, 77 K, and 305 K
	Parameter drift	Lake Shore procedure	Drift calculation for 4.2 K, 77 K, and 305 K measurements
7 (10 parts)	Screening per Table 1		Table 1
	Electrical measurements	Lake Shore procedure	Data at 4.2 K, 77 K, and 305 K
	Vibration	MIL-STD-202	Method 214, Condition H
	Mechanical shock	MIL-STD-883	Method 2002, Condition B
	Electrical measurements	Lake Shore procedure	Data at 4.2 K, 77 K, and 305 K
	Fine and gross hermetic seal	MIL-STD-750	Fine—Condition G or H, Gross—Condition C or K
	Post cap bond integrity	MIL-STD-750	Method 2037
	Post-cap die shear strength	MIL-STD-750	Method 2017

Table 4
Measured temperature offsets for 6 DT-670-SDs following 25 thermal shocks from 400 K to 4.2 K.

Temperature (K)	Average offset (mK)	Standard deviation (mK)
4.2	−0.78	25.45
77.35	6.95	24.56
305	−102.38	95.18

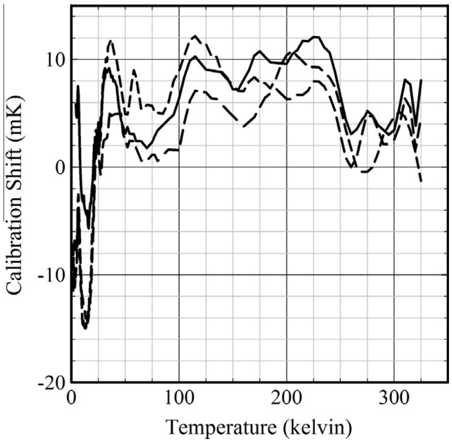

Fig. 7. Calibration offset for 3 model DT-670-SDs following 100 thermal shocks from room temperature to 77 K and one month stability monitoring.

Table 5
Measured temperature offsets for 12 DT-670-SDs following an accelerated life test per MIL-STD-750, Method 1027, with an ambient temperature of 473 K ± 10 K for 1000 h with a forward excitation of 10 μA.

Temperature (K)	Average offset (mK)	Standard deviation (mK)
4.2	−258.1	10.7
77.35	302.8	28.7
305	233.0	50.7

Table 6
Measured temperature offsets for 6 DT-670-SDs following a high temperature life test per MIL-STD-750, Method 1032, using an ambient temperature of 473 K ± 10 K for 340 h.

Temperature (K)	Average offset (mK)	Standard deviation (mK)
4.2	80.6	7.6
77.35	−218.7	21.3
305	−282.8	104.4

digital X-ray inspection, which can provide a digital photographic image. During a recent aerospace order for DT-670-SDs, it was discovered that the standard technique for measuring dose rate from a digital X-ray machine can vastly underestimate the actual dose rate when the device being inspected is small and requires locating it closer to the X-ray source for proper magnification. In this case, the estimated 2.5 Gy/min in reality was closer to 250 Gy/min based

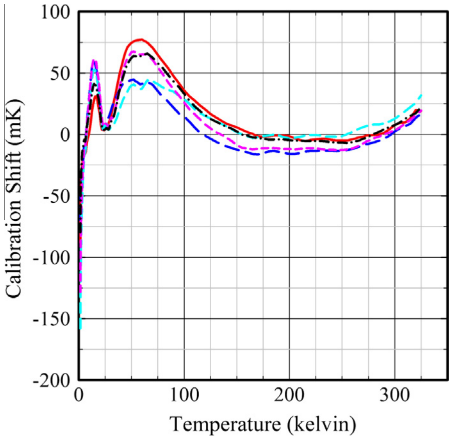

Fig. 8. Calibration offsets for 5 model DT-670-SDs following a 1000 h life test performed at 473 K with 10 μA excitation.

Table 7
Measured temperature offsets for 6 DT-670-SDs following vibration testing per MIL-STD-202, Method 214, Condition H, and mechanical shock testing per MIL-STD-883, Method 2002, Condition B.

Temperature (K)	Average offset (mK)	Standard deviation (mK)
4.2	15.2	2.6
77.35	8.2	26.6
305	−10.6	31.2

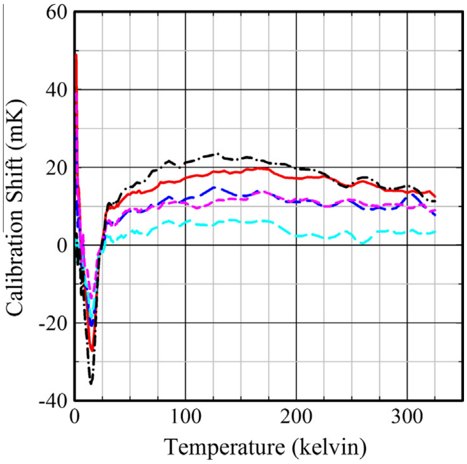

Fig. 9. Calibration offset for 5 model DT-670-SD temperature sensors following vibration and mechanical shock testing.

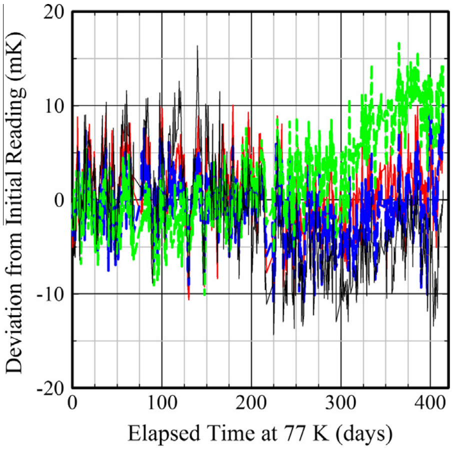

Fig. 10. Stability of 4 model DT-670-SDs monitored in liquid nitrogen (nominally 77.35 K) for 415 days. A traceable platinum thermometer was used to correct for temperature variations due to fluctuations in ambient atmospheric pressure.

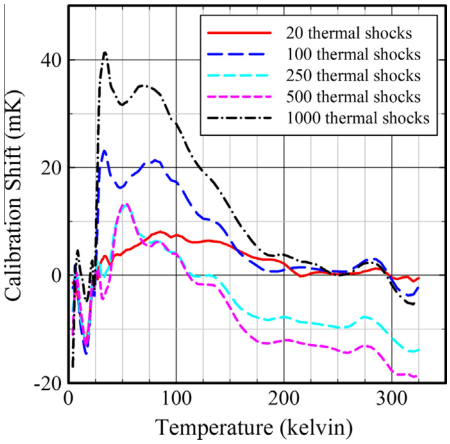

Fig. 11. Average offset of 12 DT-670-SDs after 20, 100, 250, 500, and 1000 thermal shocks from room temperature into liquid nitrogen.

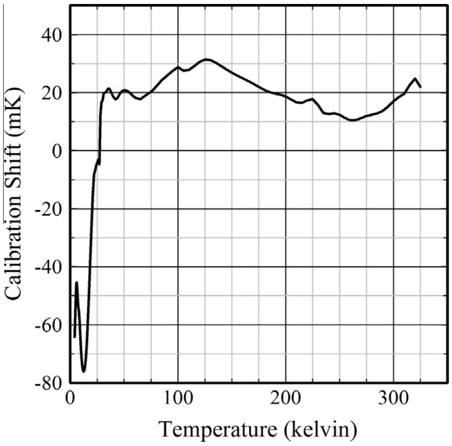

Fig. 12. The group average calibration shift from the original calibration for 23 DT-670-SD stored at room temperature after a time period of 110 months (9.17 years).

on comparisons to previous DT-670-SD irradiation tests where dosimetry was performed during irradiation. This indicates that either a film X-ray radiography should be performed for the DT-670-SD or that a digital X-ray be taken with minimum exposure and the image inspected as opposed to real time inspection. This discovery will have ramifications for digital X-ray inspection of other devices that are not radiation tolerant.

The last test measured the susceptibility of the DT-670-SD to electrostatic discharge (ESD) damage. Sample devices were tested for ESD vulnerability using a Human Body Model (HBM) per TIA/EIA FOTP-129 [14]. Samples were tested with three ESD pulses in either the forward or the reverse direction. The testing was performed at an ambient temperature of 25 °C with device measurements taken prior to the first discharge and subsequent to completion at each ESD level. The testing showed the DT-670-SD diode temperature sensor to be susceptible to ESD damage at the 1500–1750 V level with the calibration shift increasing with higher ESD level. Between 1000 V and 1500 V, low level damage was observed. At these levels the damage is permanent and the devices

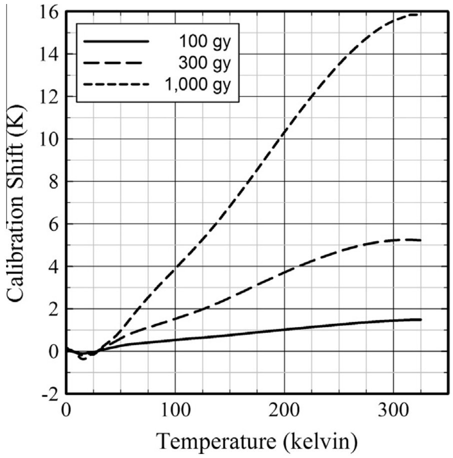

Fig. 13. Typical DT-670-SD radiation-induced calibration offsets after exposure to 100 Gy, 300 Gy, and 1000 Gy gamma radiation from a cesium 137 source.

are stable with regard to time and thermal shocking. The model DT-670-SD is considered HBM ESD Component Classification Level Class 1C. [15]

5. Discussion

The end goal of this work is to develop a screening and qualification test protocol plan for the DT-670-SD that is widely accepted to aerospace contractors. Adoption of this plan would allow the production and inventory of large production lots of the devices resulting in the availability of an aerospace screened, off-the-shelf diode temperature sensor. Collaborative work with NASA began in 2013 with the development of a test protocol for CxRTs resulting in the pending release of a NASA GSFC S-311-P-837 part specification. A similar approach will continue with the DT-670-SD to develop and release a separate S-311 part number, allowing the off-the-shelf parts manufactured to this test protocol to be available through reference to the NASA S-311 part number specification. Final configuration of lead extensions, adapter, tolerance band, and/or calibration would still result in part availability within approximately one month instead of the 30–50 weeks currently required for aerospace orders. The economy of scale and decreased delivery time will yield cost savings to both the manufacturer and the aerospace community.

Standardization of this test protocol will be beneficial in the majority of aerospace applications, but in the cases where it does not meet the requirements then either (1) additional testing can be performed on devices manufactured to this specification in order to meet the requirements, or (2) a unique production lot can be screened and qualified to the customer's specific source control document as is the current process.

6. Conclusions

Availability of cryogenic temperature sensors for aerospace applications has been limited due the absence of a recognized screening and qualification test protocol. Lake Shore has previously addressed this issue by working with NASA and its subcontractors to develop an accepted protocol for CxRTs, and the current work addresses a similar protocol for the cryogenic DTS model DT-670-SD. This test protocol is based upon NASA and MIL defined test plans for similar components as well as requirements from previous Lake Shore customer aerospace orders for DTSs over the past 30 years. Modifications have been added to address the thermometer usage and unique physical packaging of the device. TD-670-SD devices have been manufactured and tested to the proposed test protocol with performance data demonstrating high reliability and stability with regard to extended thermal shocking and mechanical shock/vibration with offsets of less than ±16, ±9, and ±105 mK at test temperatures of 4.2 K, 77.35 K, 305 K, respectively. Under both accelerated and high temperature life tests, average treatment-induced offsets less than ±305 mK at all test temperatures of 4.2 K, 77.35 K, and 305 K.

Supplemental performance data from testing performed over the lifetime of the DT-670-SDs show (1) low temperature stability of better than ±25 mK over 420 days at 77.35 K, (2) excellent average stability over 1000 thermal shocks from room temperature to 77.35 K of better than ±45 mK over the 1.4–325 K temperature range, (3) room temperature storage stability over 110 months of ±75 mK from 1.4 K to 20 K and ±35 mK from 20 K to 325 K, (4) radiation induced offsets above 20 K of about +0.5% of temperature for a total dose of 100 Gy, +1.8% of temperature for a total dose of 300 Gy, and +5.3% of temperature for a total dose of 1000 Gy and radiation induced offsets of less than −500 mK for all doses up to 1000 Gy exposure.

Adoption of the DT-670-SD screening and qualification test protocols proposed within this work will allow the manufacture and inventory of aerospace qualified, commercial off-the-shelf diode temperature sensors with greatly reduced delivery times and reduced cost.

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