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INFLUENCE OF THERMAL CYCLING ON CRYOGENIC THERMOMETERS

Ch. Balle, J. Casas, J.M. Rieubland, A. Suraci, F. Togny and N. Vauthier

Abstract

The stringent requirements on temperature control of the superconducting magnets for the Large Hadron Collider (LHC), impose that the cryogenic temperature sensors meet compelling demands such as long-term stability, radiation hardness, readout accuracy better than 5 mK at 1.8 K and compatibility with industrial control equipment.

This paper presents the results concerning long-term stability of resistance temperature sensors submitted to cryogenic thermal cycles. For this task a simple test facility has been designed, constructed and put into operation for cycling simultaneously 115 cryogenic thermometers between 300 K and 4.2 K. A thermal cycle is set to last 71/4 hours: 3 hours for either cooling down or warming up the sensors and 1 respectively 1/4 hour at steady temperature conditions at each end of the temperature cycle. A Programmable Logic Controller (PLC) drives automatically this operation by reading 2 thermometers and actuating on 3 valves and 1 heater. The first thermal cycle was accomplished in a temperature calibration facility and all the thermometers were recalibrated again after 10, 25 and 50 cycles. Care is taken in order not to expose the sensing elements to moisture that can reputedly affect the performance of some of the sensors under investigation. The temperature sensors included Allen-Bradley® and TVO® carbon resistors, Cernox™, thin-film germanium, thin-film and wire-wound Rh-Fe sensors.

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Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

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LHC Division, CERN
1211 Geneva 23, Switzerland

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The stringent requirements on temperature control of the superconducting magnets for the Large Hadron Collider (LHC), impose that the cryogenic temperature sensors meet compelling demands such as long-term stability, radiation hardness, readout accuracy better than 5 mK at 1.8 K and compatibility with industrial control equipment.

This paper presents the results concerning long-term stability of resistance temperature sensors submitted to cryogenic thermal cycles. For this task a simple test facility has been designed, constructed and put into operation for cycling simultaneously 115 cryogenic thermometers between 300 K and 4.2 K. A thermal cycle is set to last $7^1/_4$ hours: 3 hours for either cooling down or warming up the sensors and 1 respectively 1/4 hour at steady temperature conditions at each end of the temperature cycle. A Programmable Logic Controller (PLC) drives automatically this operation by reading 2 thermometers and actuating on 3 valves and 1 heater. The first thermal cycle was accomplished in a temperature calibration facility and all the thermometers were recalibrated again after 10, 25 and 50 cycles. Care is taken in order not to expose the sensing elements to moisture that can reputedly affect the performance of some of the sensors under investigation. The temperature sensors included Allen-Bradley® and TVO® carbon resistors, Cernox™, thin-film germanium, thin-film and wire-wound Rh-Fe sensors.

INTRODUCTION

Within the framework of various tests and developments of a cryogenic thermometer[1-4] for the LHC, the long-term stability of the temperature characteristics in correlation with thermal cycles had to be evaluated for the various LHC prototype temperature sensors (RhFe thin film and wire-wound, Allen-Bradley®, TVO® and Cernox™). In the past much work has been published concerning either the long-term or thermal cycling stability of cryogenic temperature sensors[5-10]. Data is missing for some of the sensors under investigation and also it is often unreliable or at least difficult to interpret. For instance many contradictory reports concerning the performance of Allen-Bradley® temperature sensors exist, it is possible to find many recipes[9-10] to improve their characteristics by encapsulation techniques, sudden thermal cycles, exposure to high temperature, etc. To further complicate this situation it is worth pointing out that Allen-Bradley® resistors were produced for the electronic industry and their characteristics from a cryogenic point of view may change from year to year. Allen-Bradley® thermometer is

Table 1. LHC-conditions

Items	Value
Expected LHC-lifetime	20 year
LHC-Temperature Range	1.8…300 K
Cooling-speed	60 K/day
Warming-speed	40 K/day
Cool-down and Warm-up	1/year
300 – 1.8 K thermal cycles	20/lifetime

Table 2. LHC cryogenic thermometer needs

Temperature Range/K	Accuracy [mK]	Quantity
1.6…2.2	10	2418
2.2…4.0	20	2550
4.0…6.0	30	4061
6.0…25	1000	3603
25…300	5000	3603

still a LHC prototype even though the fabrication of these sensors was ceased in 1997; CERN still holds a stock large enough for satisfying the LHC requirements.

The measurement of temperature is critical for the proper operation of the LHC and it was then decided to investigate the stability of LHC prototype temperature sensors when subjected to thermal cycles between 4.2 and 300 K. It is important to note that such cycles are relatively slow and the temperature sensors are never exposed to humidity. The maximum cooling rate is given by the test of individual magnets. The main parameters for such a test are dictated by the relevant LHC-specifications that are shown in Tables 1 and 2. The accuracy budget is defined by the LHC process constraints and it is arbitrarily divided in equal parts between the uncertainties related to the sensing element and the conditioning electronics.

TEST

A total number of 100 thermal cycles between 300 K and 4.2 K will be attained by the end of summer 1999. The number of cycles is higher than the specifications of the LHC machine, which represents a safety margin for taking into account uncertainties due to the relatively small number of sensors under test and to the variability of sensor fabrication. For simplicity no monitoring of the thermometers is done when using the cycling cryostat. The thermometers are calibrated at CERN's main calibration facility during the first thermal cycle and then on cycles 10, 25, 50 and 100. This calibration facility has been described elsewhere[4].

Thermal cycling setup

To simulate the above-mentioned conditions, a simple cycling facility has been built. Apart from thermometers many other cryogenic devices can be installed for investigating ageing processes provoked by thermal cycling without exposure to humidity or air.

Cryostat. The main part is the cylindrical helium chamber made of copper (Figure 2). which is located inside a cryostat under vacuum (Figure 1) and equipped with:

- three baskets (ø 5 cm x 11 cm) to carry up to 120 thermometers,
- an ISO-KF flange to open and close the chamber for manipulating the baskets. Leak tightness is provided by an indium gasket,
- a tube inside the chamber fixed on the centre of the ISO-KF flange, used to guide the baskets,
- two control thermometers TT4 and TT5 measuring two different locations inside the chamber,
- an electrical connector on the ISO-KF flange to connect the two control thermometers,
- the exchange gas flow controlled by inlet and outlet tubes,
- an external cooling loop to cool down the chamber,
- an external electrical heater EH6 to warm up the chamber,
- an external thermal radiation screen which is cooled down by the outlet from the liquid helium transfer line,
- liquid helium from a 500 l storage dewar, forced through the transfer line.

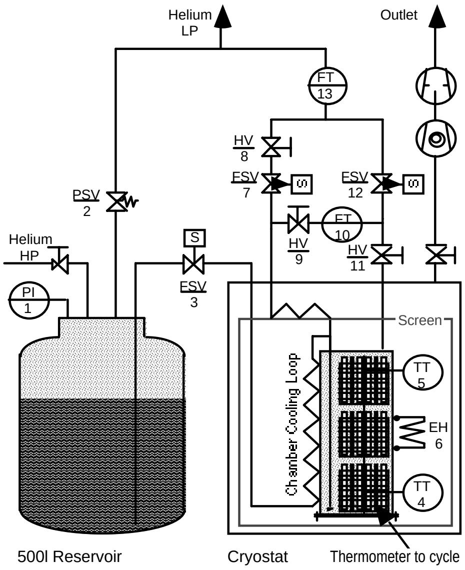


Figure 1. Piping & instrumentation diagram

Figure 2. Loading of the helium chamber

Instrumentation. This cycling facility is intended to run without operator intervention. Thus instrumentation and the relevant control should be simple and robust. A Programmable Logic Controller (PLC) takes care of all automatic procedures and stops the cycling after a given number of cycles. The instrumentation controlled by the PLC is:

- FSV3, a switching valve controlling the transfer of LHe into the cryostat,
- Control thermometers TT4 and TT5 (Allen-Bradley® type). The supply of a proper excitation current and the 4-20 mA output signal is ensured by signal conditioners,
- EH6, an electrical heater from Minco® with a power of 30 Watt,
- FSV7 and FSV12, two solenoid valves.

Before starting the automatic procedure it is necessary to adapt the manual valves to the thermal load of the devices under test. The following equipment is used:

- HV7, HV9, HV11, three precision needle hand-valves from Hoke® for adjusting in combination with FSV7 and FSV12 the cooling speed,
- FT10 and FT13, two flow meters 0 to 2.2 m^3/h and 0 to 15 m^3/h as a help for the operator when adjusting the precision needle hand-valves,
- the pumping group, to establish a vacuum better then 10^{-6} mbar.

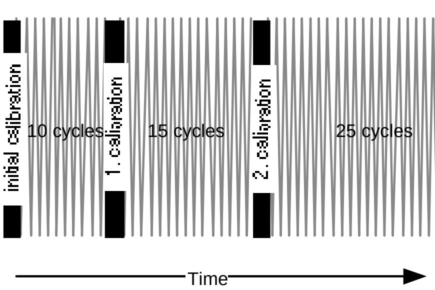
For diagnostics a 32-channel paper recorder monitors all electrical signals from thermometers, heaters and valves positioners.

Functional principle. Via an operator interface the duration of the 4.2 and 300 K plateaus and the total number of thermal cycles to perform is entered into the PLC. One thermal cycle is composed of four successive phases (Figure 4). Table 3 shows the setup for this experiment when cycling 120 thermometers. The main heat capacity is stored in the copper used for lodging the sensors, its approximate total weight is about 0.95 kg.

Table 3. Setup for cycling 120 thermometers

Actuator/Sensor	300 K to 20 K	20 K to 4.2 K	4.2 K to 300 K
FSV3	open	open	closed
FSV7	open	closed	open
FSV12	closed	open	open
EH6	0	0	30 W
FT10	0.7 m^3/h	3.0 m^3/h	0

FT13	0	0.8 m³/h	0



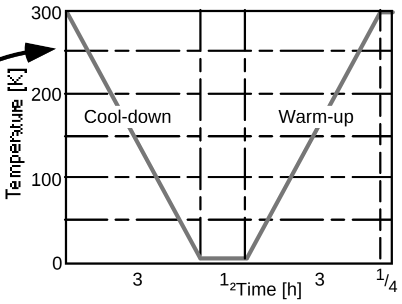


Figure 3. Operation

Figure 4. Definition of one thermal cycle

Procedure

Load. The facility was loaded with the following resistance thermometers:

15 x CRT	(Carbon Resistance Thermometer) from Allen-Bradley®, USA, Model 100 Ohm, 1/8 Watt
4 x CRT	from Allen-Bradley®, USA, Model 100 Ohm, 1/8 Watt, placed inside a copper canister and sealed with Stycast®, by CNRS-IPN, France
16 x CRT	from TVO®, Russia
15 x CX	(Cernox™) from Lake Shore®, USA, Model CX-1050-SD

Adjustment. The hand-valves were adjusted to obtain a cooling and warming speed of approximately 100 K/h. The plateaus at 4.2 K and 300 K were set to 75 minutes (Figure 4). Those parameters are imposed to some extent by the aim of completing 100 thermal cycles plus 5 long calibrations, within a time span of one year.

Operation. Figure 3 shows how the calibration procedures are interleaved within the thermal cycles. Arbitrarily it was assumed that the most significant changes in the sensor characteristics would occur during the first cycles, which explains why 0, 10, 25, and 50 cycles are chosen as calibration cycles. Common sense and previous experience with other sensing elements led us to tentatively perform the tests in this manner. In principle when an element drifts, it either drifts indefinitely or it may reach a stable status after a certain number of thermal cycles.

Results

The drift •T of the T-R-characteristic of each thermometer was calculated after 10, 25 and 50 cycles as follows:

- generation of an individual calibration function T(R) for each thermometer by fitting the initial calibration points obtained during the first thermal cycle,
- application of this calibration function T(R) on the later calibrations,
- elimination of the mathematical approximation error by subtracting the difference of the temperature reference between the cycle under investigation and the initial calibration:

$$\bullet T_n = (T(R_n) - T(R_0)) - (Tref_0 - Tref_n) \qquad (1)$$

Table 4 shows the numerical results of the variation of the sensors characteristics after 10, 25 and 50 thermal cycles. Due to the higher sensitivity at low temperatures all the sensors show good results at liquid helium temperatures and most of the population complies with the LHC specifications listed in Table 2. It should be noted however that some Allen-Bradley® sensors below 2.2 K exceed the uncertainty of 5 mK as shown in Figure 5. At 20 K it is possible to see that the spread in the uncertainty is lower for sensors with higher sensitivity, this explains the better performance of Cernox™ when compared with TVO®, and TVO® when compared with Allen-Bradley®. This difference is the more obvious the higher the temperature.

Concerning the Allen-Bradley® it is worth to note that no difference in quality can be observed between the off-the-shelf and the copper-canister encapsulated sensors. Also one of the encapsulated samples was damaged by the thermal cycles after about 25 cycles. Their sensitivity above 100 K is very poor and this type of sensor is typically used with a Platinum sensor for measuring the higher temperatures. According to the published literature we would have expected a much worse degradation for Allen-Bradley®. Actually with some selection procedure, Allen-Bradley® temperature sensors are from the thermal cycling point of view within the LHC specifications. At present, selection rules by performing thermal cycles and measuring data at room temperature only are being investigated but so far without success. The mean average temperature difference above 20 K seems to reach a stable value for Cernox™. This could be an indication that this sensor benefits from being exposed to 25 thermal cycles before use. When delivered Cernox™ are accompanied by a low temperature test sheet implying that they have been cycled at least once before delivery. For TVO® and Allen-Bradley® no such stabilization behaviour is observed.

Table 4. Numeric results

		Calibration 1 after 10 cycles		Calibration 2 after 10+15 cycles		Calibration 3 after 10+15+25 cycles	
T [K]	Sensor Name	$^{2}\overline{T}_{1}$ [mK]	σT_1 [mK]	$^{2}\overline{T}_{2}$ [mK]	σT_2 [mK]	$^{2}\overline{T}_{3}$ [mK]	σT_3 [mK]
1.8	CX	-0.7882	0.5535	0.5037	0.6802	-0.6513	0.4330
	TVO	-0.0455	0.6606	0.3939	1.0351	-0.3835	1.2027
	AB	2.7427	2.0045	3.3095	2.8231	-1.9148	4.2703
2	CX	-0.8491	0.4570	0.9300	0.5250	-0.7064	0.3422
	TVO	0.0978	0.6431	0.6417	1.1550	-0.5706	1.3620
	AB	3.0962	2.2987	3.9094	3.2699	-2.5211	4.9080
3	CX	-1.0763	0.3334	0.2618	0.3449	-0.8783	0.2863
	TVO	-0.4328	1.2796	-0.4419	1.9982	-1.1056	2.3854
	AB	7.6528	4.1628	7.2454	5.9068	-3.4715	8.6093
4.7	CX	1.7374	2.0156	-2.9928	2.1274	-5.2280	2.0487
	TVO	0.7607	2.1165	-1.5941	3.9934	-2.2640	4.3788
	AB	17.3037	8.3450	13.5193	12.7921	-8.3744	17.5300
20	CX	3.0921	2.4428	-2.2611	2.5180	-1.3179	2.5545
	TVO	-1.3065	18.2370	-14.8668	31.5075	-20.3284	36.2329
	AB	207.4665	110.8418	139.2465	206.5669	-246.6199	421.5318
50	CX	4.7892	5.0310	-14.1263	5.1998	-14.9530	5.2845
	TVO	-13.7263	57.6131	-74.9515	93.2377	-93.4202	108.2195
	AB	811.1598	499.0036	483.8471	951.0693	-1327.8682	2471.7225
80	CX	9.1676	6.9240	-20.7874	7.3440	-25.6557	7.3030
	AB	1388.3302	969.4480	798.4592	1825.3065	-2768.8821	5457.5423
	TVO	-12.7281	83.8031	-116.6825	140.3333	-150.2212	154.0933
180	CX	13.0871	13.5885	-43.7546	13.4965	-53.3914	13.2617
	TVO	96.4536	215.0169	-149.6401	216.1717	-191.2922	262.8603
270	CX	-28.2666	18.5580	-105.6869	16.2912	-120.5796	18.4223
	TVO	-110.2638	157.1709	-485.0942	133.4017	-635.3769	124.2295

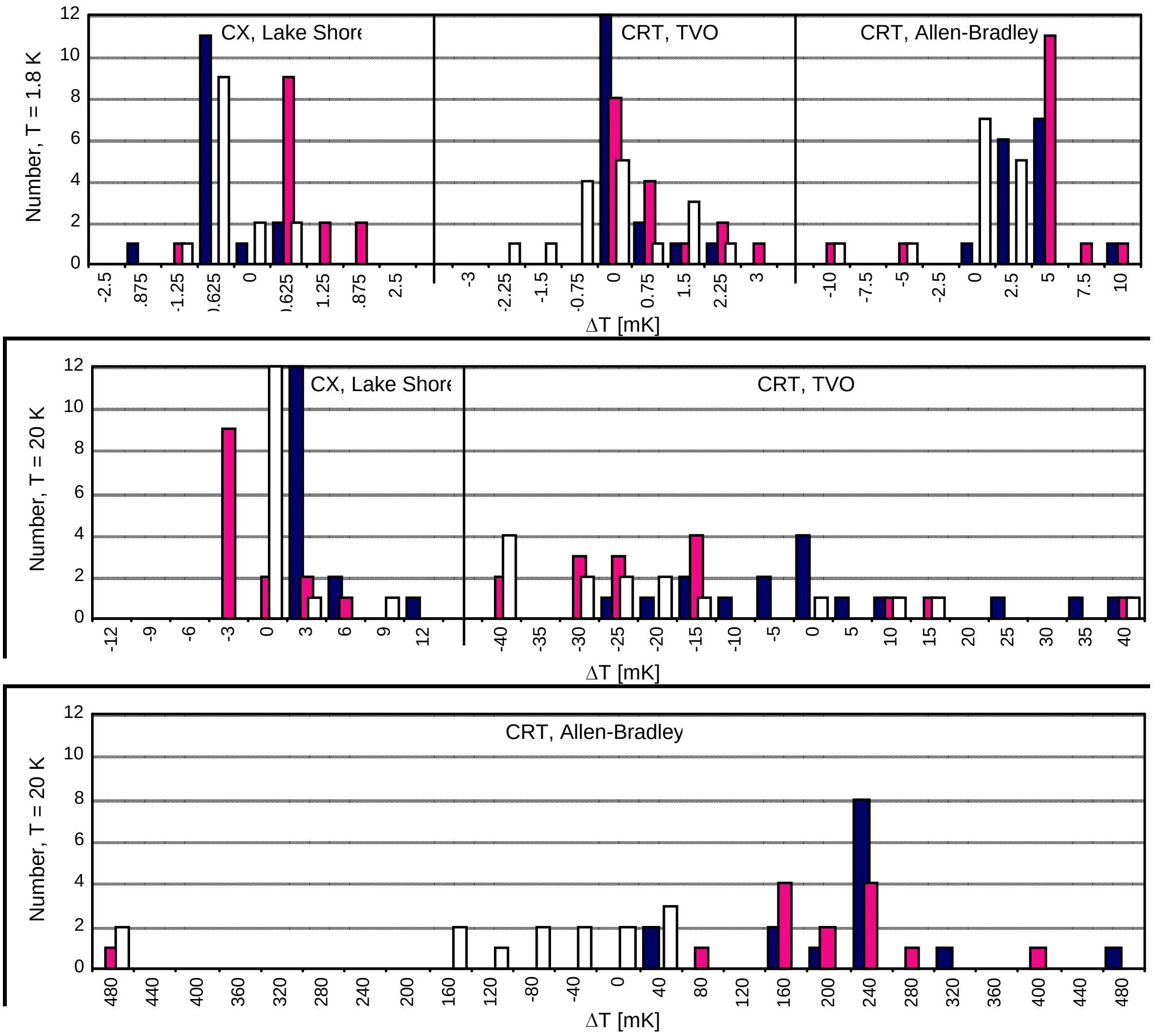


Figure 5. Distribution curves at 1.8 K and 20 K for different temperature sensors after 10 (black), 25 (grey) and 50 (white) thermal cycles (keep in mind the different •T-scales).

CONCLUSION

A simple and robust, automatic cycling facility has been designed, commissioned and operated. The first results of the thermal cycled cryogenic thermometers clearly show that sensors with higher sensitivity across the temperature operating range have a much better reproducibility of their characteristics. Below 4 K all sensors presented behave similarly but for temperatures above 20 K, Cernox™ has much better stability against thermal cycles. However, Allen-Bradley®, Cernox™ and TVO® satisfy the LHC specifications.

One of the aims of this test was to identify selection rules for the Allen-Bradley®. No correlation in performance has been found between stability at low temperatures and variations of resistance at room temperature, encapsulation, etc. From our results it is clear that it is extremely difficult to improve the performance of off-the-shelf Allen-Bradley® resistors by some simple recipe.

The experimental data suggest that Cernox™ characteristics are improved if they are previously exposed to at least 25 thermal cycles.

RhFe wire-wound and thin-film temperature sensors have also been investigated although more work is still required for analysing their results. The main difficulty is the poor sensitivity of this type of temperature sensors below 20 K, which is up to one order of magnitude lower than Allen-Bradley®.

We intend to complete 100 thermal cycles by the third quarter of 1999 and later we will also investigate other types of temperature sensors like germanium (bulk and thin-film), diodes, etc. Although not considered for equipping the LHC ring, these other sensors may find potential applications in other components of the complex cryogenic system for CERN's accelerators and detectors.

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