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Expected Accuracy when using Non-Calibrated CernoxTM Sensors

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Abstract

Within the ITER-CERN collaboration agreement, task “PROCUREMENT OF CRYOGENIC THERMOMETERS TO MONITOR ITER MAGNETS AND FEEDER TEMPERATURES”, CERN is investigating what would be the expected accuracy when using non-calibrated Cernox™ temperature sensors at 4.2 K.
The cernox™ is a resistive type temperature sensor that is capable of measuring the full temperature range of interest for ITER, it is 4.2 K to 300 K. Non-calibrated cernox™ sensors are delivered with a table listing the resistance at the following temperatures: 4.2 K, 77 K and 300 K.
CERN has deployed several thousands of individually calibrated cernox™ sensors and they are used to compare the manufacturer data at 4.2 K with their individual calibration performed by CERN. Within a sample size of 5’941 sensors, 99.39% of the population is able to provide a measurement within +/-0.1 K at 4.2 well within the requirements at low temperature specified by ITER.

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Introduction

ITER has selected the cernox™ sensors because of their characteristics and performance that have been demonstrated in the CERN LHC machine. These sensors complement a set of optical sensors used to monitor various temperatures on the ITER magnets.

The cernox™ sensors exhibit excellent characteristics in what concern stability when exposed to thermal cycling, radiation effects, long term storage, etc. This sensor was selected for the LHC after qualification mainly for long term stability and robustness against radiation effects in cold conditions. Usually these sensors are individually calibrated and the inherent accuracy can be expected to be below 0.0025 K for 1.8 K and 0.012 K for 20 K (see LHC-Project-Report-321).

The cernox™ sensors have 5 different standard models depending on their temperature range. It shall be noted that for the LHC it was requested to have all the sensors with a narrower range in order to simplify the design of the conditioning electronics. Figure 1 shows the resistance versus temperature characteristics of the various models, it can be seen that the dispersion is relatively important. For instance the model CX-1050 would yield a temperature uncertainty of +/- 5 K at 4.2 K if a single approximation function is used; this is well above the intrinsic uncertainty that can be obtained with cernox™ sensors that are individually calibrated.

In order to avoid series calibrations, individual transfer functions can be constructed mathematically by using both the 3 data points provided by the manufacturer and the CERN database to predict data

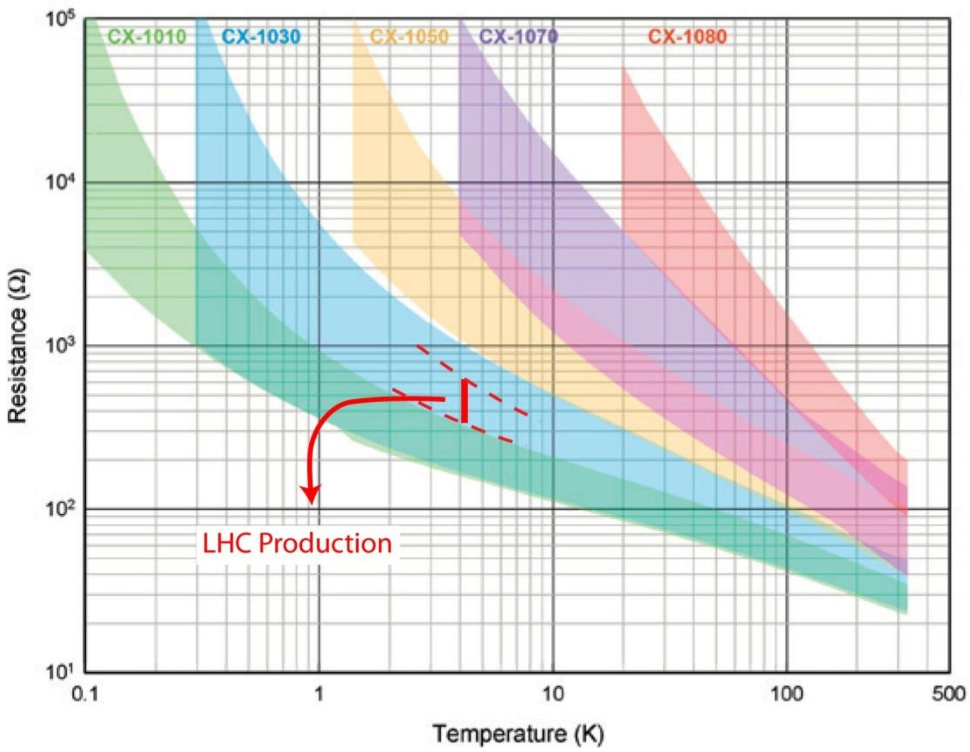

Figure 1: Spread of resistance versus temperature depending on the cernox™ model; the special LHC model is also shown.

Temperature Range [K]	Uncertainty		Annual Drift	
	[K]	[%]	[K/year]	[%/year]
4 to 10	0.2	5 to 2	0.01	0.25 to 0.1
10 to 80	0.3	3 to 0.4	0.01	0.1 to 0.012
80 to 300	0.5	0.6 to 0.17	0.01	0.012 to 0.003

Table 1. ITER requirements on the measurement of temperature.

points in the intermediate temperatures. This would impose that ITER use a cernox™ sensor with the same characteristics as the one selected for the LHC.

ITER Requirements.

Table 1 lists the ITER requirements, as stated in April 2011, for the measurements of temperature. These requirements as listed can only be met by sensors more typically used for metrological tasks, the most difficult parameter is the annual drift in particular for temperatures above 10 K. The compliance with the specifications listed in Table 1 would be indeed a very challenging project.

From a technological point of view, non-calibrated cernox™ can eventually meet the requirements concerning the uncertainty only in the range 4 to 10 K and the associated annual drift in "controlled conditions". It is then assumed that ITER will revise its requirements above 10 K as well as the annual drift for all the range.

Methodology for estimating the error when using non calibrated sensors

To estimate the uncertainty when using non calibrated cernox™, this report uses all the cernox™ sensors that have been delivered, individually calibrated and with its data analyzed and stored in the CERN metrological database. This concern 5'981 cernox™ sensors, most of them delivered for the LHC project. The individual calibration has an uncertainty of about 0.01 K at 4.2 K.

As shown in Figure 1 the cernox™ sensors have a relatively large dispersion in its characteristics. For the LHC, CERN required a tighter tolerance on the dispersion of the resistance values @ 1.8 K. To satisfy this narrower range, Lake Shore delivered CERN with 2 models not available in their commercial catalogue: "XCX-1050-SD-30" or "XCX-1050-SD-108". The conclusions of this document may not be applicable for any type of cernox™ as they may be biased by a special fabrication procedure specifically applied to the CERN order.

To deduce the equivalent error when working with a non-calibrated cernox™, the resistance at 4.2 K is estimated from the calibration data. This estimation selects the 2 closest points around 4.2 K and the resistance is estimated by using a linear interpolation; Figure 2 shows the spread of the two calibration points. By using the 2 calibration points around 4.2 K, the sensitivity (it is the slope of the interpolation: dR/dT) is estimated. The sensitivity is then applied as multiplying factor to the resistance difference between the Lake Shore data and the estimation made by using the linear interpolation; the result is considered as the error that will be done when using non calibrated cernox™ temperature sensors but that do use an individual approximation.

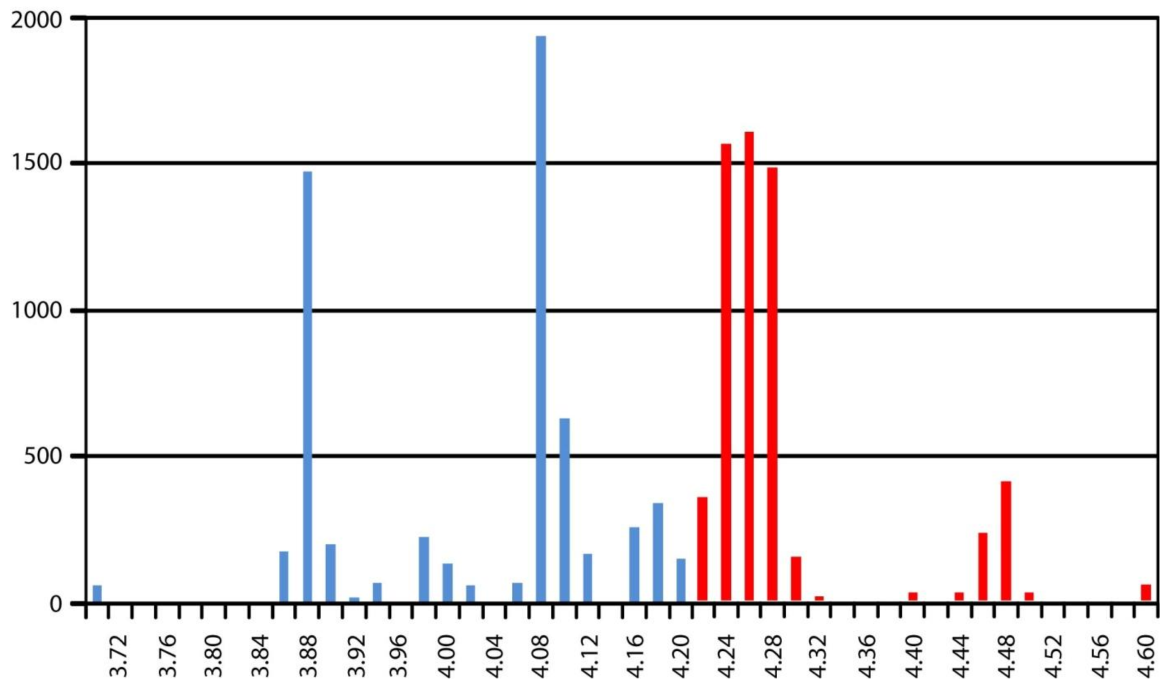

Figure 2. Temperature distribution of the calibration data above (RED) and below (BLUE) 4.2 K. The sum of either of the red or blue histograms is 5981 that correspond to the total number of sensors. Each bin is related to one or more batches of thermometers subjected to a calibration run.

A typical calibration between 300 K and 1.8 K generates about 80 temperature and resistance pairs of values. The calibration temperature values are distributed logarithmically to provide a better match with the characteristics of the cernox™ sensor. The data is clustered in a relatively narrow temperature range and the estimation error shall be less than 0.01 K.

To calculate the error when using off the shelf cernox™sensors some mathematical validation tests are performed. Of the 5981 sensors analyzed, 4 sensors are rejected for the following reasons:

- Two because the calibration data shows a reduction of resistance with a reduction of temperature. This is probably due to a problem with the measurement apparatus.
- Two because of a much higher resistance value than the rest of the population. Their resistance at 4.2 K exceeded 30’000 ohm, for comparison the rest of the sensors had its resistance within the range 2’800 ohm to 6’100 ohm.

After analyzing the data, it is found out that 5’941 cernox™ have an approximation error of 0.1 K or less over a total of 5’977. All these sensors would have been considered valid by checking that the resistance is within an appropriate range at 4.2 K; this yields 99.39% of sensors capable of providing measurement within +/-0.1 K at 4.2 K.

The cernox™ sensor has a resistance that decreases more or less logarithmically when increasing the temperature. From previous experience the typical uncertainty over a wide temperature range (see LHC Project Report 157) can be conservatively estimated to be of the same percentage as the value observed at 4.2 K. That means that 99.39% of the 5’941 cernox™ satisfy the requirement of being able to measure within +/- 0.2 K in the temperature range from 4.2 K to 10 K.

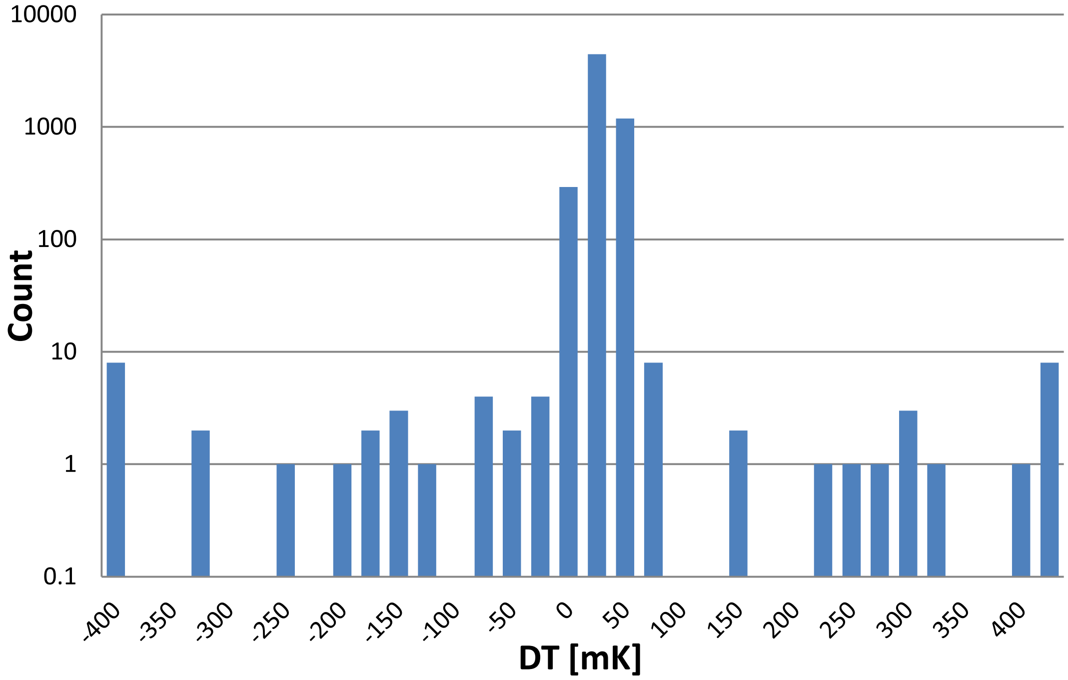

Figure 3. Dispersion of the difference between the measurement that would be done at 4.2 K by using either the manufacturer data or the individual calibration.

For comparison non-conform (non usable) temperature sensors for the LHC (over a total of about 9'600 temperature sensors) represent about 3% for the magnets and less than 1% for the cryogenic distribution line. This is about the same order of magnitude (0.6%) of the sensors that do not satisfy the ITER requirement. The main challenge would be to recognize the cernox™ sensors that are outside the specifications and as for most large scale facilities, this task can only be performed during the commissioning phase.

Figure 3 shows the dispersion of the difference between the value provided by the manufacturer and the one deduced from the individual calibrations; note that a logarithmic scale is used in order to show single thermometers that are out of the ITER requirements that for 4.2 would be +/- 0.1 K. Figure 3 shows that the maximum population occurs at a difference of + 25 mK, indicating a systematic bias between the calibration stations of the manufacturer and of CERN. The detailed numerical data can be found in Annex I.

Conclusion

The ITER specifications may permit to use non calibrated cernox™ on the condition that the ITER requirements stated in Table 1 are completely revised; the main problem is the very tough annual drift as well as the uncertainty requested above 10 K.

If ITER requires a tolerance on the maximum annual drift, it is important to state clearly how it can be determined experimentally. In practice most ageing tests are performed by using some kind of acceleration. As an example for the LHC, the drift was assessed by thermally cycling the sensors for up to 100 cycles between 4.2 K and 300 K, the cycle duration was approximately 7.25 hours.

The ITER requirement concerning the uncertainty on the measurement of temperature, may be met by the cernox™ sensors if it is stated as a percentage of the measured value; a figure of +/- 2.5% is a more realistic value of what non-calibrated units may be able to achieve.

However it would still be recommended to calibrate a percentage of the production. The calibration rigs have a capacity of about 70 sensors and 2 calibration runs will permit to make a statistical check for 14% of the total ITER delivery that requires 950 cernox™ sensors installed.

Finally this document has concerned only the comparison of the CERN and manufacturer data at 4.2 K; later work would require the procedures of constructing approximation functions deduced from the 3 data points; this may add mathematical errors that are outside of the scope of this report.

Annex I: cernox™ temperature error distribution:

The frequency refer to the quantity of cernox™ thermometers that have a temperature difference between the manufacturer and the CERN calibration with a certain temperature range (Bin) in miliKelvin.

Bin	*Frequency*	
-400	8	
-375	0	
-350	0	
-325	2	
-300	0	
-275	0	
-250	1	
-225	0	
-200	1	
-175	2	
-150	3	
-125	1	
-100	0	SPREAD DEFINED FOR ITER: +/- 100mK @ 4.2 K
-75	4	
-50	2	
-25	4	
0	293	
25	4444	
50	1186	
75	8	
100	0	
125	0	
150	2	
175	0	
200	0	
225	1	
250	1	
275	1	
300	3	
325	1	
350	0	
375	0	
400	1	
More	8	
5977	5981.00	