ATLAS ITk Electronics Specification
Component or Facility Name:
ITk Environmental Monitoring System: Temperature

Version: V 1.0

Abstract

The document describes the temperature monitoring within the scope of the ITk environmental monitoring project. The specifications are mainly driven by the technical requirements of the cooling system. Actually different options of temperature sensors are evaluated. An experimental test bench for different temperature sensors is described and preliminary results to validate the functionality of this system are shown. Concerning the final readout system, we foresee to use ATLAS standard DCS components.

Revision History			
Rev. No.	***Proposed Date*** ***Approved Date***	***Description of Changes*** *(Include section numbers or page numbers if appropriate)*	***Proposed By: author*** ***Approved By: reviewer***
1.0	P: 23/01/2019 A: date		P: David Florez, Sussane Kersten A: name

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1 Conventions and Glossary

DCS: Detector Control System

ELMB: Embedded Local Monitor Board

NTC: Negative thermal coefficient

RTD: Resistance temperature detectors

2 Related Documents

- ATLAS ITK monitoring temperature sensors for cooling system (EDMS 2044113)
- "ATLAS ITK monitoring temperature sensors for cooling system", P. Lopez Macia et al., November 2018.Online: https://edms.cern.ch/document/2044113/1
- "Developments towards ELMB replacement document" - Kamil Nicpon, AUW April 2018
- Cernox™ Resistance Temperature Sensors for High Energy Physics Applications, S. Scott Courts, Lake Shore Cryotronics. Online: https://www.lakeshore.com/Documents/CernoxForHighEnergy.pdf
- Cypress application note AN66477. Online_ http://www.cypress.com/file/45091/download
- https://twiki.cern.ch/twiki/bin/viewauth/Atlas/PixelDCSElmb
- http://www.mosaic-industries.com/embedded-systems/microcontroller-projects/temperature-measurement/thermocouple/type-k-calibration-table#type-k-calibration-equation

3 Description of Component or Facility

This documents describes the selection process for the temperature sensors to be installed in the different parts of ITK volume with the following purposes:

- Cooling system debugging
- Bake-out process monitoring
- Historical record
- Real time monitoring

In Table 3.1 and 3.2 the number of sensors at the different positions are summarized.

Table 3.1: number of sensors on the cooling pipes

Sub-detector	Number of cooling loops	Local support type	Minimum amount of temperature sensors
Strip End Cap (SEC)	384	Petal	264
Strip Barrel (SBR)	392	Stave	288
Pixel End Cap (PEC)	112	Half ring	132
Pixel Outer Barrel (POB)	158	Longeron, half ring	248
Pixel Inner System (PXI)	96	Stave, L0-L1 coupled ring, L0 intermediate ring, L1 ring	108
Total	1142		1040

Table 3.2: number of sensors in the atmosphere etc.

Detector volume	Number of sensors
strip (barrel + EC)	(96 + 80) 176
pixel	ca 250
outer service volume	108
total	ca 530

Sensors selection criteria

Given the amount of sensors to be installed in the ITK upgrade, the reduction of wiring is a priority, stated by the different teams. A two wire readout of the sensors must be possible, this has some impact on the required sensitivity [ohm/K] of the sensor. If possible a further reduction of services might be implemented, e.g. by a common return for a group of sensors or a remote bias network. In these cases e.g. 8 sensors would require 9 lines instead of 16. Specially for the sensors, where the required precision is not that demanding, these options will be further investigated.

Technical requirements of temperature range, accuracy, precision and robustness have been discussed and defined. These are detailed in section 9.

Regarding the sensors mounting, three different cases are considered: the installation on the cooling pipes, mounting on PCBs, or direct connection to the readout wires. The sensors packages, well adapted for these scenarios, are selected.

Currently NTC thermistors are the first option of sensor, together with a two wire signal conditioning circuit consisting of a resistive voltage divider, installed on a PCB expansion board connected to a data acquisition system (DCS or an intermediary interface). The resistors used for signal conditioning must offer high precision and high stability with temperature.

4 Interfaces

The temperature sensors interface to other components listed in Table 4.1. The temperature sensors will be part of a voltage divider and must be powered by a stable reference voltage. The voltage across the temperature sensor is measured by an ADC. This ADC must be part of ELMB2 or any other DCS readout unit. Figure 4.1 gives an example as it was built for ATLAS pixel and ID. There is no electrical contact to other circuits of the pixel or strip detector.

Table 4.1: Components which Interface to this Component

Name of Component	Name of Component Specification
voltage divider and stable reference voltage	This circuit can be part of the DCS, the ELMB, or a separate circuit performing the required functions
ATLAS standard DCS component	baseline: ELMB2

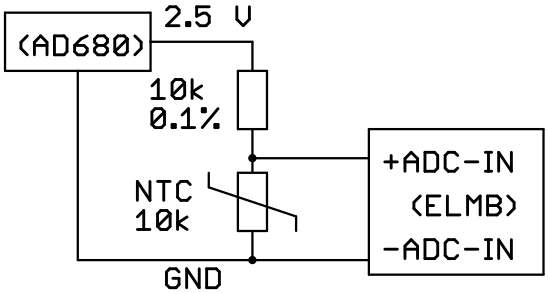

Figure 4.1: two wire readout of temperature sensor (used in ATLAS pixel)

5 Physical Description

Two main technologies are candidates to be used: NTC thermistor and Platinum RTD. The mounting method depends on the position and package of the sensor. A film type sensor, e.g. Semitec NTC 103JT thermistor (Table 5.1), could be installed in direct contact with the cooling pipes, The use of Kapton ® tape or epoxy resin to attach the sensor to the cooling pipe surface is expected (a procedure is proposed by Bart Verlaat). In the case of the PCBs temperature monitoring (detectors), an SMD chip package is the simplest solution.

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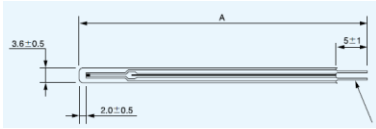
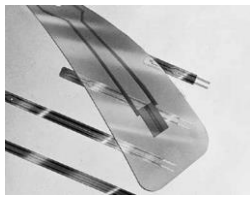
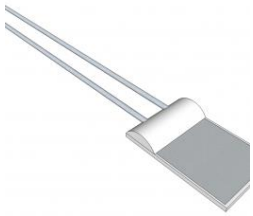
Table 5.1. Option of temperature sensors

Reference	***Type***	***Dimensions***	***Use***	
Semitec 103JT	NTC Thermistor	 A=25 mm	Cooling pipes	
Semitec 103KT NCP18X103F03RB	NTC Thermistor	0805 SMD Package	PCB	
IST- AG P10K.520.6W.B.010.D	PT10000	5.0 x 2.0 x 1.05 mm (L x W x H)	Multi	
MINCO Point Sensitive RTDs: S17624PSYT120A	PT10000	0.20 x 0.60 x 0.08" (5 x 15 x 2 mm)	Multi	

6 Manufacturer

In Table 6.1 the manufacturers of the components proposed for the temperature monitoring are listed.

Table 6.1. Temperature monitoring components

Component	*Manufacturer or technology*
Temperature sensors	NTC Thermistor: Semitec, Murata manufacturing. RTD: Heraeus, Littelfuse, MINCO, IST-AG
Signal conditioning	Vishay PSF Resistors: 2012 Metal Film Resistors, High Precision, High Stability, Surface Mount. 0.01%, 5 ppm/C For NTC / PT10000 sensors R1 is a 10 kΩ resistor.

Connectors - wires	To be defined later. It is strongly preferred to find a common (across the sub-systems) solution for connectors and cables.

7 Power

Table 7.1: Power Requirements

Name	Max/Nom/Min V or I Supplied	Nom/Max I for Voltage Source	Max/Min V for Current Source	Other Requirements
Vcc	3.3 V – 5 V	8.6 µA - 430 µA		Voltage level defined by the maximum power dissipation of the sensor and the ELMB2 system

8 Input/Output

Table 8.1: Input and Output Signals

Name	In, Out or I/O	Type of Signal or Max/Min	Input or Output Impedance	Description
Vtemp NTC	OUT	Vcc=3.3 V →0.47 / 3.21 V Vcc=5 V →0.71 / 4.87 V	Zout=1-10 kΩ	Voltage divider output, proportional to monitored temperature
Vtemp PT10000	OUT	Vcc=3.3 V →1.47 / 1.89 V Vcc=5 V →2.23 / 2.87 V	Zout=4-6 kΩ	

9 Detailed Functional Description and Specification

Next, the temperature sensors and their readout system are described.

9.1. Temperature sensors

Initial requirements of temperature range and measurement accuracy for the temperature sensors are defined in EDMS Nb. 2044113 (under revision). The requirements for the most demanding cases are presented. In general the most demanding volume in terms of performance of the temperature monitoring system is the cooling pipe.

Accuracy

This requirement has been established to at least 1 °C in the whole temperature range.

The sensors resistance tolerance and stability over the years is directly related to the temperature measurement accuracy. Also the sensors cable resistance impact the incertitude of the measurement (Other factors impacting this accuracy related to the readout system are described in 9.2)

For the cable resistance parameter, the worst case impact is estimated over the following assumptions:

- Temperature coefficient of Cu 4 x 10-3 /K
- Maximum cable length: 15m Cu cable AWG 30, with resistance of 9.6 **Ω** at room temperature (both directions)
- Change of cable resistance
  - -60°C to 0°C: 2304 m**Ω**
  - 0°C to +20°C: 768 m**Ω**
  - Overall -60°C to 20°C: 3 **Ω**

Accordingly, the impact of cable resistance versus the sensitivity for different sensors is presented in Table 9.1. From these estimations the use of 10 kΩ impedance (0°C) sensors is prioritized.

Table 9.1. Cable resistance impact

Sensors	***Sensitivity [Ω/K]***	***Impact of 3 Ω cable shift [K]***
Pt 1000	4	0,75
Pt 10000	40	0,075

NTC 10 kΩ	-25°C → -24°C	5507	0,0005
NTC 10 kΩ	+25°C → +26°C	378	0,008
NTC 10 kΩ	-60°C → -59°C	71e3	0,00004

Temperature range

Different points of view regarding the temperature range the sensors should cover have been exposed by the teams. For this document, an extended normal operating range is defined as -50 °C to + 80 °C. The calibration and evaluation of the sensors is performed for this range. However, sensors with an operating range from -80 °C to +250 °C will be selected if the required performance for the extended normal operating range is not compromised.

Resolution

For the defined operating range, a minimum 0.5 °C resolution is expected. This performance could be obtained using NTC (10 kΩ) or PT10000 together with a 16 bits ADC resolution as explained below.

9.2. Readout system

To reduce development efforts and the long-term maintenance, it is planned to use ATLAS standard monitoring units, provided they are available in time and cover the needs of the system. As ELMB2 is the only actually available ATLAS monitoring unit and it covers the requirements, it is taken as baseline for the moment.

ADC

For the -50 °C – 80 °C range, a 16 bits resolution of an ideal ADC allows to obtain a temperature resolution of:

- 2.39×10^{-3} °C, for NTC 10kΩ thermistor
- 15.4×10^{-3} °C, for PT10000

This performance is in coherence with the temperature resolution required and provides enough margin to compensate the noise impact (effective resolution). Further computations to predict effective resolution and accuracy impact of the ADC must be done on the basis of the ELMB2 ADC specifications. As reference, in Fig. 9.1 the specifications of a high-precision 16 bit ADC are presented.

Parameter	Condition	PSoC 3
Maximum resolution		20 bits
Offset error	Buffered, 16-bit mode, 25 °C	±0.1 mV
Gain error	Range = ±1.024 V, buffered, buffer gain = 1, 16-bit mode, 25 °C	±0.2 %
Differential nonlinearity	Range = ±1.024 V, unbuffered, 16-bit mode	±1 LSB
Integral nonlinearity	Range = ±1.024 V, unbuffered, 16-bit mode	±2 LSB
Common-mode rejection ratio	Range = ±1.024 V, buffered, buffer gain = 1, 16-bit mode	85 dB
Power-supply rejection ratio	Range = ±1.024 V, buffered, buffer gain = 1, 16-bit mode	90 dB

Fig. 9.1. Cypress Delta-Sigma ADC specifications [Cypres AN84783]

The expected voltage range of the ADC input voltage (V_t) is presented in Table 9.2 for different cases of voltage supply (10 kΩ resistor voltage divider):

Table 9.2. ADC input

	Vcc (V)	*Vt_min(V)*	*Vt_max (V)*
NTC (10 kΩ)	3,3	4,72E-01	3,21E+00
	5	7,15E-01	4,87E+00
PT10000	3,3	1,47E+00	1,89E+00
	5	2,23E+00	2,87E+00

The temperature measurement accuracy can be improved by the use of a ratio-metric ADC reading, which implies the use of an additional ADC channel to monitor the sensor signal conditioning voltage supply. Additionally, a differential ADC can help to reject ground disturbances. The need for these features has not been yet determined.

Finally, the temperature computation algorithm employed also has an impact in the accuracy of the obtained data. The proposed models are:

- Steinhart-Hart equation, for NTC
- Look up table or third degree polynomial approximation, for PT10000

Signal conditioning

The first option of signal conditioning consists of a resistor voltage divider (Section 4) with two-wire reading. A specific board, external to the ELMB2, will contain the signal conditioning circuits.

The minimum required precision of the sensors network components, to make possible an accuracy of 1°C are:

- Voltage supply: 0.1%
- Voltage divider resistor: 0.01%
- Cable resistance: < 3Ω

- NTC / PT10000 resistance: 0.5%

Additionally the circuit includes a first order low pass filter (components to be selected) for noise reduction. The proposed updating period is between 5 – 10 s.

9.1 First Function

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9.2 Second Functional Interface

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9.3 Programming Model

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10 Radiation Tolerance and Other Special Requirements

The temperature sensors must withstand:

- Radiation: 500 Mrad
- Magnetic field: 2 T

Readout system: located at PP2 (Patch Panel 2)

- Radiation: 0.01 Mrad

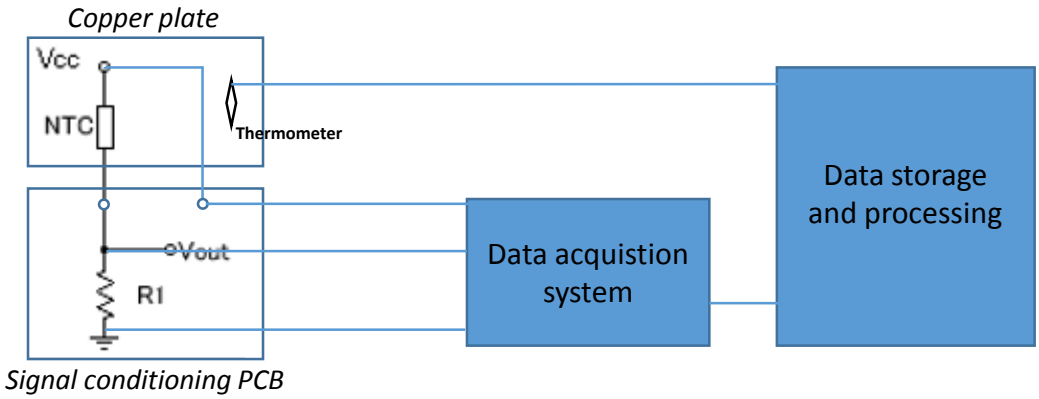
11 Testing, Validation and Commissioning

An experimental test bench was designed to evaluate the performance and to calibrate different temperature sensors. Additionally a simulation tool was used to predict accuracy.

Experimental test bench

The main components of the bench are (Fig. 11.1 and Table 11.1):

- Temperature sensors under test
- Data acquisition system: A development kit specially conceived for analog applications and featuring a 20 bit Delta-Sigma differential ADC is selected. A signal conditioning circuit must be connected externally (Fig. 3.1).
- Iso-thermal surface.
- Data storage unit.
- Reference thermometer.
- Cryogenic chamber.



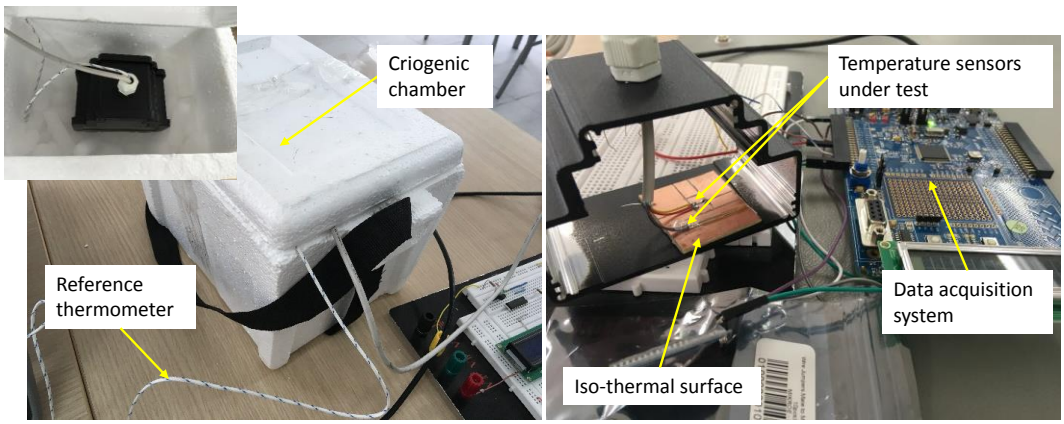


Fig. 11.1. Test setup

This experimental bench was commissioned using the NTC thermistors described in section 5: a film type sensor intended for the cooling pipes and an SMD chip for the detectors PCB.

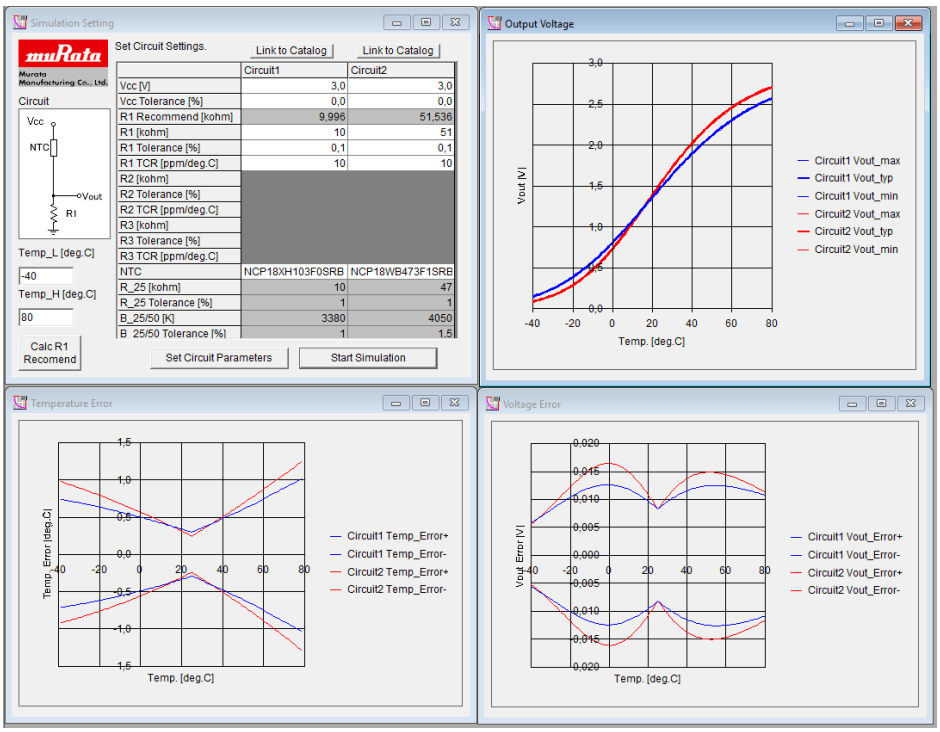
Table 11.1. Validation - Calibration bench specifications

Component	*Manufacturer or technology*
Data acquisition system	CYPRESS PSOC 3 development kit
Iso-thermal surface	FR4 type PCB
Data storage unit	PC connected through serial communication (RS-232) to the data acquisition system and to the reference thermometer.
Reference thermometer	Generic K-type thermocouple and digital multimeter Rigol DM3058E

Cryogenic chamber	EPS foam box with 1 kg of carbonic ice

Thermistor temperature sensing simulation

A simulation free license software (https://www.murata.com/en-eu/tool/download/thermistor/download) from Murata company was used to predict the error using an NTC thermistor with the simple two wire connection conditioning circuit (Fig. 11.1).



	Circuit1	Circuit2
Vcc [V]	3,0	3,0
Vcc Tolerance [%]	0,0	0,0
R1 Recommend [kohm]	9,996	51,536
R1 [kohm]	10	51
R1 Tolerance [%]	0,1	0,1
R1 TCR [ppm/deg.C]	10	10
R2 [kohm]		
R2 Tolerance [%]		
R2 TCR [ppm/deg.C]		
R3 [kohm]		
R3 Tolerance [%]		
R3 TCR [ppm/deg.C]		
NTC	NCP18XH103F0SRB	NCP18WB473F1SRB
R_25 [kohm]	10	47
R_25 Tolerance [%]	1	1
B_25/50 [K]	3380	4050
B_25/50 Tolerance [%]	1	1,5

Fig. 11.1

From this result, in the -40°C – 80 °C range, a maximum expected error of up 1.2 ° C is expected. This error is a consequence of the theoretical tolerances of the components (1%) and assumes that the sensor is not calibrated. Better results should be obtained with more precise sensors and with one-by-one sensor calibration.

Preliminary results

A pilot experiment was developed with the only purpose of demonstrate the operability of the test setup, including data transmission and storage.

A copper plate coupled to a K-type thermocouple thermometer and an NTC-103JT thermistor was placed into the carbonic ice chamber. The temperature was registered during approximately 3 hours.

A sub-range polynomial approximation (http://www.mosaic-industries.com/embedded-systems/microcontroller-projects/temperature-measurement/thermocouple/type-k-calibration-

table#type-k-calibration-equation) is used to calculate temperature from the K-type voltage measurement.

For the NTC-103JT thermistor (SEMITEC), the Steinhart-Hart equation is used (https://twiki.cern.ch/twiki/bin/viewauth/Atlas/PixelDCSElmb) to calculate temperature in the PSOC3 data acquisition system. The equation coefficients are calculated by an algorithm running in the same data acquisition system using three points of the sensor resistance-temperature specification. These three values are manually introduced as algorithm inputs. Also, the algorithm performs a temperature offset correction based on the reference thermometer reading.

Fig. 11.1 and Fig. 11.2 are examples of how the test setup presents the measurement results. Fig. 11.1 shows the comparison between the temperature readout of the reference thermometer and an NTC sensor under test is presented. Fig. 11.2 presents the difference between the two sensors measurement. In this pilot the large differences are explained by the difference in the sensors time constants and an a non-uniformity in the surface temperature.

Following experiments will be performed using calibrated high precision sensors described in Table 11.1. RTD 1KOHM with 0.06% of resistance tolerance (Littlefuse PPG102A6) and with faster response, to compare with the K-type thermocouple result.

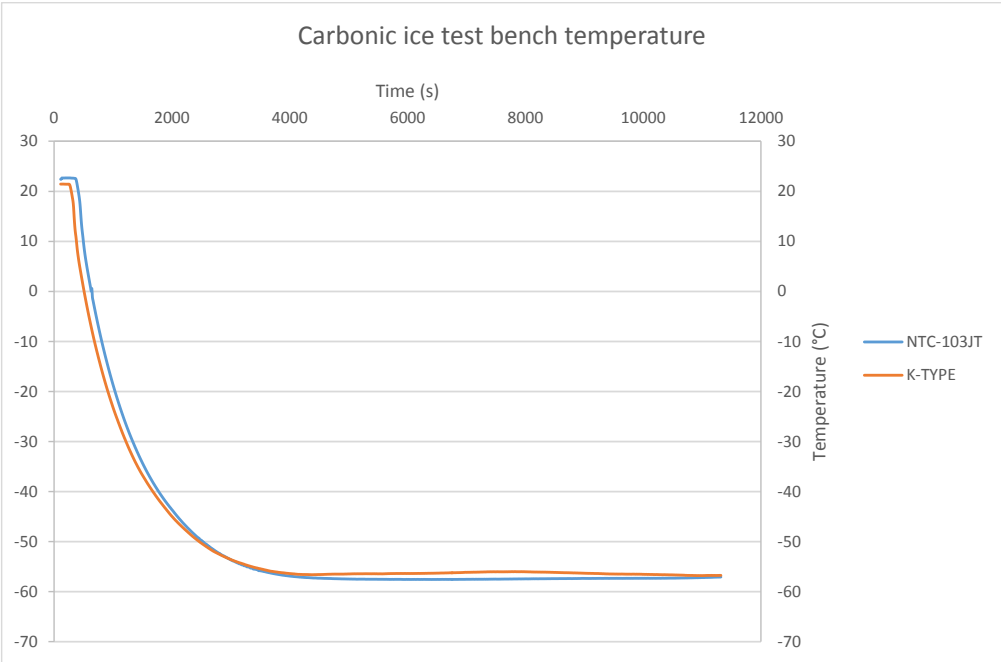


Fig. 11.2. Temperature evolution of the copper plate immersed in the carbonic ice chamber.

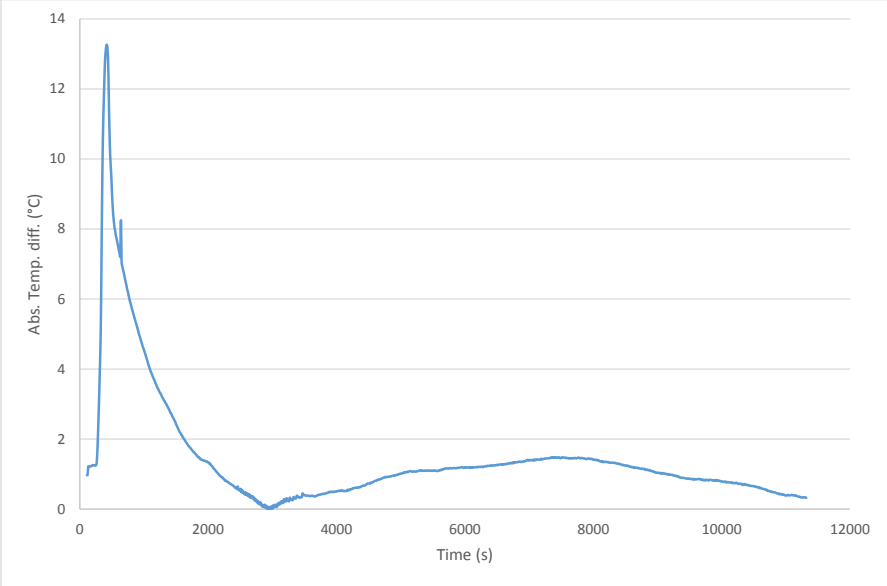
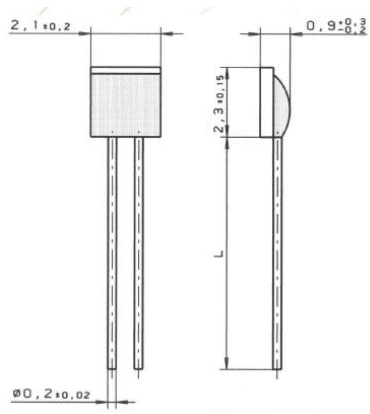


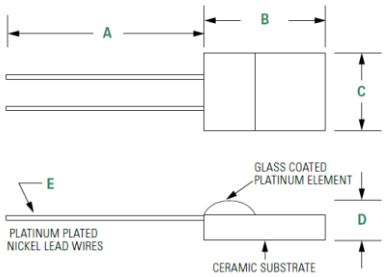
Fig. 11.3. Difference between the NTC sensor and reference thermometer measurements.

The test has demonstrated operability of the calibration system to perform measurement comparisons between the reference thermometer and the studied sensors in the -50 – 25°C range.

The accuracy of the reference thermometer and the K thermocouple is guaranteed by certified calibration of the instrument. Additionally the high precision RTD sensors described in Table 11.1 will be calibrated to provide and additional point of comparison.

Table 11.1. RTD Sensors for reference thermometer

Reference	***Type***	***Dimensions***	***Use***	***Range / Accur.***	
Heraeus 32208571	Platinum RTD		Cooling pipe / PCB	-70°C ~ 500°C / ±0.3°C	

Littelfuse PPG102A1	Platinum RTD	 A=0.2”/B=0.118”/C=0.079”	Cooling pipe / PCB	-50 – 500 °C / 0.15 °C	

12 Reliability Matters

12.1 Consequences of Failures

Describe the consequences to the detector of a failure of one unit of this component, e.g. x% of the sub-detector channels will be lost, or one stave or petal could overheat causing delamination of its component parts. The severity of the consequences will determine the level of reliability required and the level to be validated by QA and QC procedures defined in sections 12.4 and 12.5.

12.2 Prior Knowledge of Expected Reliability

Based upon industry experience, collaboration experience or personal experience, give an estimate of the reliability of this component.

12.3 Measures Proposed to Insure Reliability of Component and/or System

Include such measures as conservative design techniques (give specific examples), redundancy and possibilities to replace failed part. . If failed part could be replaced, estimate the difficulty and time involved for installing replacements,

12.4 Quality Assurance to Validate Reliability of Design and Construction or Manufacturing Techniques

Describe what stress tests will be applied during the development period to validate the reliability of this component. Give a brief outline of any appropriate reliability theory being used. These tests could involve destructive tests.

It is not required to complete this section prior to the first specification review but it must be completed prior to the PDR. It is strongly recommended that these plans be reviewed and approved prior to the actual PDR to avoid the possibility of failing the PDR and thus delaying the fabrication or construction of the prototype parts,

12.5 Quality Control to Validate Reliability Specifications during Production

Describe what stress tests will be applied during production, possibly on a sampling basis, to validate the reliability of production units. These could likely be destructive tests. Specify the required sampling percentage of production units.

It is not required to complete this section prior to the first specification review but it must be completed prior to the FDR. It is strongly recommended that these plans be reviewed and approved prior to the actual FDR to avoid the possibility of failing the FDR and thus delaying the fabrication or construction of the pre-production parts,

13 References

If there are any references pertaining to the development of this component, list them here.