YRKESHÖGSKOLAN NOVIA

Evaluation of Measurement Uncertainties in SDAQ Sensor Calibration

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Abstract

This thesis focuses on determining the measurement uncertainty of SDAQ sensors, which are used in Wärtsilä's engine laboratory for standard measurements. To achieve this, Type A and Type B evaluations are applied according to the guidelines in the Guide to the Expression of Uncertainty in Measurement (GUM). The study aims to identify the factors affecting measurement accuracy and establish a reliable method for estimating uncertainty.

An SDAQ sensor is defined in this study as a unit consisting of an SDAQ device and a connected sensor. To obtain an accurate estimation of the measurement uncertainty, both a Type A and Type B evaluation of the SDAQ sensor were conducted, where the results were combined. Since no manufacturer specifications for the uncertainty of the SDAQ device were available, a separate Type A evaluation of the SDAQ device alone was performed. This uncertainty was then incorporated into the Type B evaluation of the SDAQ sensor.

The calibration was carried out using an automated calibration rig developed by Wärtsilä and was performed with high-precision instruments. Data was collected from 15 calibration certificates for each of the 20 standard sensor types, with multiple measurement points per certificate. The standard uncertainty was determined by combining statistical analysis (Type A) and manufacturer specifications (Type B), ensuring a comprehensive evaluation. This study presents a method for quantifying the uncertainty of SDAQ sensors, enabling more reliable measurements in the engine laboratory.

Language: English
Key Words: calibration, measurement uncertainty, standard uncertainty, metrology.

EXAMENSARBETE

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Abstrakt

Detta examensarbete handlar om bestämning av mätosäkerheten för SDAQ-givare, som används i Wärtsiläs motorlaboratorium för standardmätningar. För att uppnå detta tillämpas Typ A- och Typ B-utvärdering enligt riktlinjerna i Guide to the Expression of Uncertainty in Measurement (GUM). Studien fokuserar på att identifiera de faktorer som påverkar mätnoggrannheten och skapa en tillförlitlig metod för att uppskatta osäkerhet.

En SDAQ-givare definieras i denna studie som en enhet bestående av en SDAQ och en ansluten givare. För att få en noggrann uppskattning av mätosäkerheten genomfördes både en Typ A- och Typ B-utvärdering av SDAQ-givaren, där resultaten kombinerades. Eftersom ingen specifikation för SDAQ-enhetens osäkerhet fanns tillgänglig från tillverkaren, utfördes en separat Typ A-utvärdering av enbart SDAQ-enheten. Denna osäkerhet inkluderades sedan i Typ B-utvärderingen av SDAQ-givaren.

Kalibreringen genomfördes med en automatiserad kalibreringsrigg utvecklad av Wärtsilä och utfördes med högprecisionsinstrument. Data samlades in från 15 kalibreringscertifikat för varje av de 20 standardgivartyperna, med flera mätpunkter per certifikat. Standardosäkerheten beräknades genom att kombinera statistisk analys (Typ A) och tillverkarens specifikationer (Typ B), vilket säkerställde en heltäckande utvärdering.

Studien presenterar en metod för att kvantifiera osäkerheten hos SDAQ-givare, vilket möjliggör mer tillförlitliga mätningar i motorlaboratoriet.

Språk: Engelska
Nyckelord: kalibrering, mätosäkerhet, standardosäkerhet, metrologi.

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2 List of Abbreviations

mA	Milliampere
ISO	International Organization for Standardization
FS	Full Scale
CTR3000	Calibration and Testing Rig 3000
CPC6050	Pneumatic Pressure Controller and Calibrator
CAN	Controller Area Network
USB	Universal Serial Bus
TC	Thermocouple
STH	Sustainable Technology Hub
SDAQ	Single purpose Digital Acquisition System
RTD	Resistance Temperature Detector
PT100	Platinum 100
PRT	Platinum Resistance Thermometer
µA	Microampere
mV	Millivolt
mbar	Millibar
MC6	Multifunction Calibrator 6
RSS	Root sum of squares

3 Introduction

Accurate measurement is essential in industrial applications, where sensors play a crucial role in monitoring and controlling processes. In Wärtsilä's engine laboratory, SDAQ sensors are used for standard laboratory measurements, mainly for pressure and temperature monitoring. However, all measurements contain some level of uncertainty, which can affect the reliability of data and, ultimately, the performance of the test results.

To ensure accuracy, calibration is performed once a year using an automated calibration rig developed by Wärtsilä. However, determining the exact measurement uncertainty is a complex process that requires systematic evaluation. This thesis investigates how measurement uncertainty in SDAQ sensor calibration can be quantified using Type A and Type B methods, as defined in the Guide to the Expression of Uncertainty in Measurement (GUM).

The main objective of this study is to establish a robust methodology for estimating measurement uncertainty in sensor calibration, combining statistical analysis with manufacturer specifications.

3.1 Company description

Wärtsilä is a global technology company specializing in marine and energy solutions, with a strong focus on sustainability and energy efficiency. Founded in 1834 in Finland, the company operates in over 200 locations across 79 countries, employing approximately 17,500 people worldwide. [1]

In the marine industry, Wärtsilä provides propulsion systems, engines, propellers, and digital solutions to optimize fuel consumption and reduce emissions. In the energy sector, the company develops power plants and energy storage solutions to support the transition to renewable energy. [1]

In Vaasa, Finland, Wärtsilä operates the Sustainable Technology Hub (STH), which includes the Engine Laboratory and Fuel Laboratory. These facilities are used for testing next-generation fuels, such as hydrogen, ammonia, and methanol, playing a crucial role in the development of future sustainable energy systems [2]. The Fuel Laboratory conducts in-depth analyses of fuel quality, chemical composition, and thermal stability to ensure compatibility with Wärtsilä's engines [3].

With a strong commitment to carbon neutrality and fossil-free energy, Wärtsilä actively invests in research and innovation to develop sustainable solutions for both the marine and energy sectors [1].

4 Purpose

The purpose of this thesis is to evaluate and quantify the measurement uncertainties in SDAQ sensor calibration. By applying Type A and Type B uncertainty evaluation methods as defined in the Guide to the Expression of Uncertainty in Measurement (GUM), the study aims to establish a systematic approach for determining measurement uncertainty.

5 SDAQ sensors

SDAQ is a product manufactured by Icraft Oy for Wärtsilä, designed to function as an A/D converter for analog sensors in laboratory use. An analog sensor is connected to the SDAQ device, which performs an analog-to-digital (A/D) conversion on the analog signal from the sensor and transmits the data using the CAN bus protocol. Different SDAQ models exist depending on the type of sensor output being used.

SDAQ devices support a range of analog input types, including thermocouples, resistance temperature detectors (RTDs), voltage, and current signals. The A/D conversion is performed using a 24-bit resolution analog-to-digital converter, ensuring high precision in measurement. The sampling rate varies between models, with typical values such as 10 Hz for thermocouple measurements. The specific model used depends on the sensor type, with variants supporting ±2 VDC and ±100 VDC voltage inputs, ±40 mADC current inputs, and different thermocouple types (e.g., K-type: -200 to 1372 °C, PT100/PT1000: -200 to 850 °C).

In the engine laboratory, SDAQ sensors are primarily used for measuring pressure and temperature in various engine components, such as receivers, turbochargers, lube oil systems, fuel systems, cooling water, and more. The use of high-resolution A/D conversion enables precise data collection, which is crucial for performance monitoring and diagnostics.

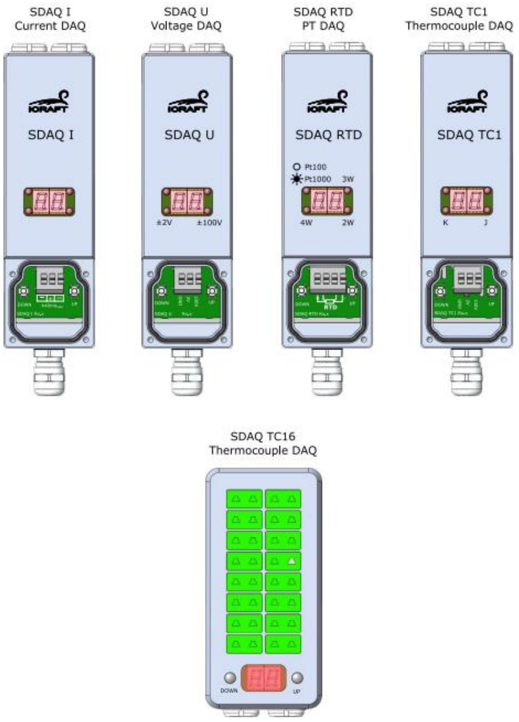


Figure 1 SDAQ types

The data bus serves both as a communication channel and a power supply for devices on the network. The nominal bus voltage is +24 VDC, and the power supply is electrically isolated from the sensor housing to prevent interference. Beneath the LEMO connector, a white plastic insulator ensures proper isolation and must not be short-circuited to the sensor housing. To maintain a stable connection, the CAN master side should be linked to the local ground potential.

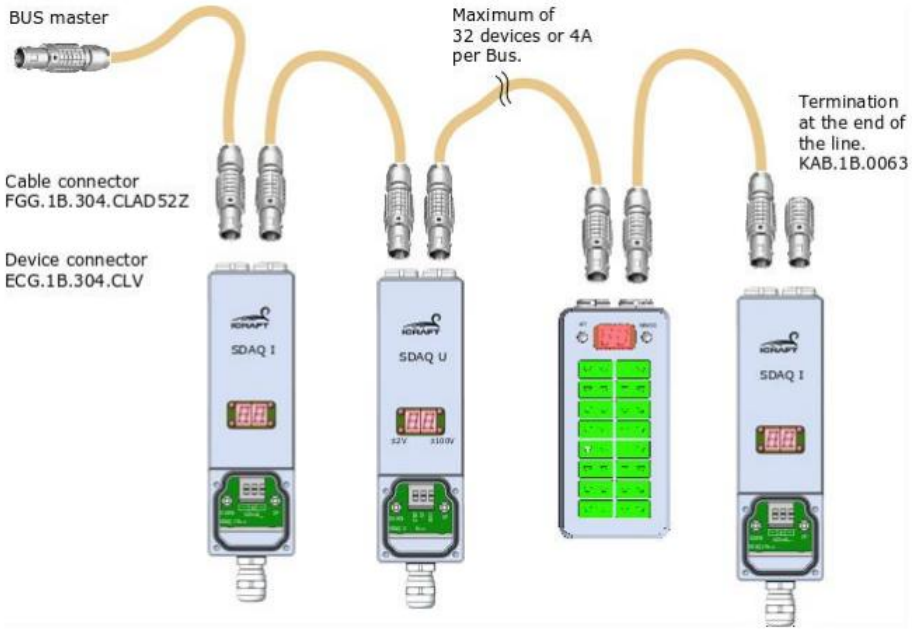


Figure 2 Data Bus Connection

6 Measuring instruments used in calibration

6.1 Wika CPC6050

The WIKA CPC6050 is a high-precision pneumatic pressure controller and calibrator, used for pressure calibration in the engine laboratory. The CPC6050 is very accurate, typically within ±0.01% of reading, making it suitable for precision calibration work. It can operate across a wide pressure range, from as low as -1 bar to as high as 210 bars, enabling versatile use for different calibration requirements. The device offers quick control of pressure, with fast settling times that minimize calibration time. It includes a user-friendly touchscreen interface, making it easier to navigate settings, configure calibration sequences, and monitor live pressure data. It supports both fully automatic and manual pressure control, offering flexibility based on the application and user's needs. The CPC6050 has integrated data logging capabilities and supports multiple communication interfaces (USB, RS-232, Ethernet) for remote control, data transfer, and integration into automated calibration systems such as the SDAQ calibration program. [4]

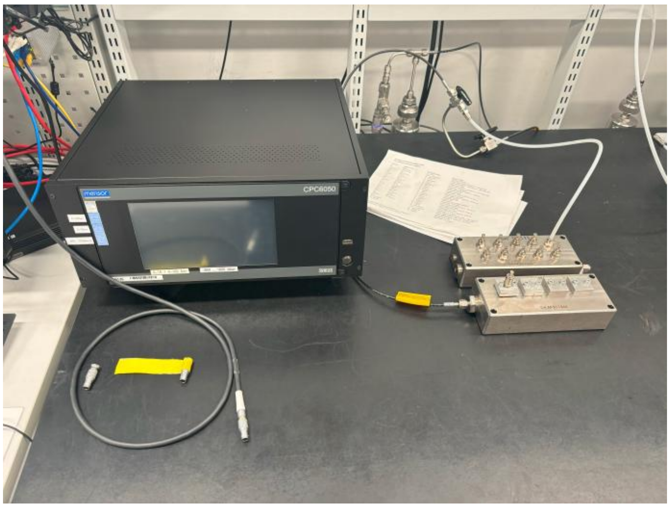
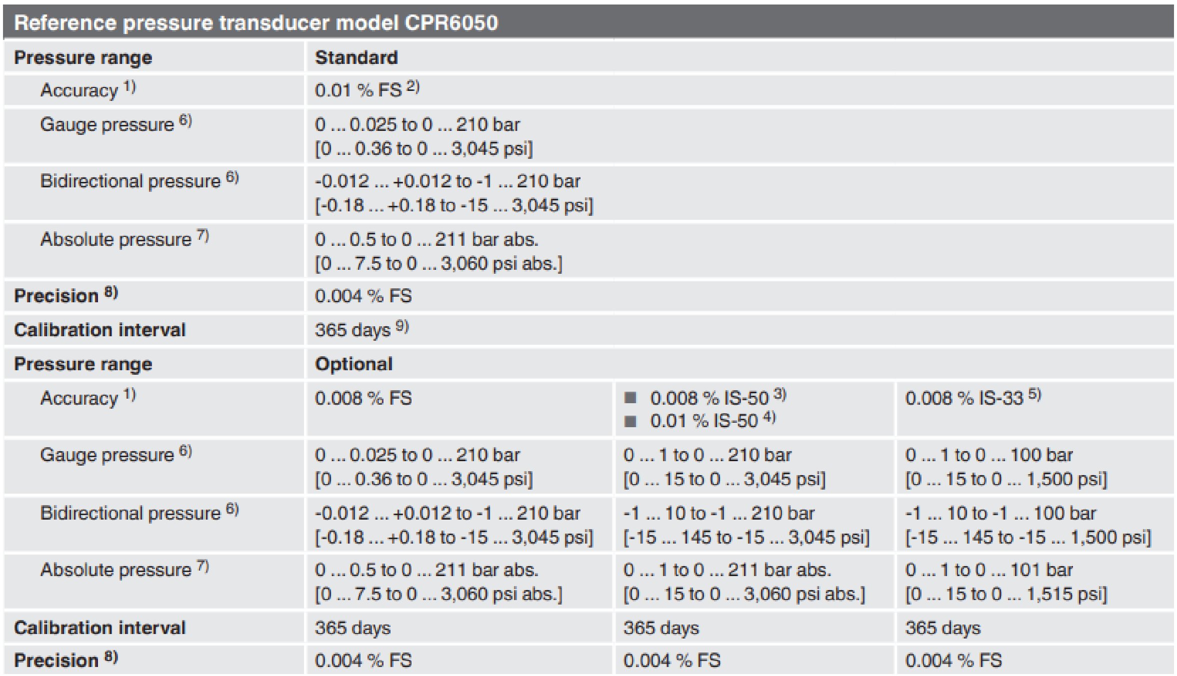


Figure 3 WIKA CPC6050



Reference pressure transducer model CPR6050			
Pressure range	**Standard**		
Accuracy [1]	0.01 % FS [2]		
Gauge pressure [6]	0 ... 0.025 to 0 ... 210 bar [0 ... 0.36 to 0 ... 3,045 psi]		
Bidirectional pressure [6]	-0.012 ... +0.012 to -1 ... 210 bar [-0.18 ... +0.18 to -15 ... 3,045 psi]		
Absolute pressure [7]	0 ... 0.5 to 0 ... 211 bar abs. [0 ... 7.5 to 0 ... 3,060 psi abs.]		
Precision [8]	0.004 % FS		
Calibration interval	365 days [9]		
Pressure range	**Optional**		
Accuracy [1]	0.008 % FS	■ 0.008 % IS-50 [3] ■ 0.01 % IS-50 [4]	0.008 % IS-33 [5]
Gauge pressure [6]	0 ... 0.025 to 0 ... 210 bar [0 ... 0.36 to 0 ... 3,045 psi]	0 ... 1 to 0 ... 210 bar [0 ... 15 to 0 ... 3,045 psi]	0 ... 1 to 0 ... 100 bar [0 ... 15 to 0 ... 1,500 psi]
Bidirectional pressure [6]	-0.012 ... +0.012 to -1 ... 210 bar [-0.18 ... +0.18 to -15 ... 3,045 psi]	-1 ... 10 to -1 ... 210 bar [-15 ... 145 to -15 ... 3,045 psi]	-1 ... 10 to -1 ... 100 bar [-15 ... 145 to -15 ... 1,500 psi]
Absolute pressure [7]	0 ... 0.5 to 0 ... 211 bar abs. [0 ... 7.5 to 0 ... 3,060 psi abs.]	0 ... 1 to 0 ... 211 bar abs. [0 ... 15 to 0 ... 3,060 psi abs.]	0 ... 1 to 0 ... 101 bar [0 ... 15 to 0 ... 1,515 psi]
Calibration interval	365 days	365 days	365 days
Precision [8]	0.004 % FS	0.004 % FS	0.004 % FS

Figure 4 WIKA 6050 Datasheet

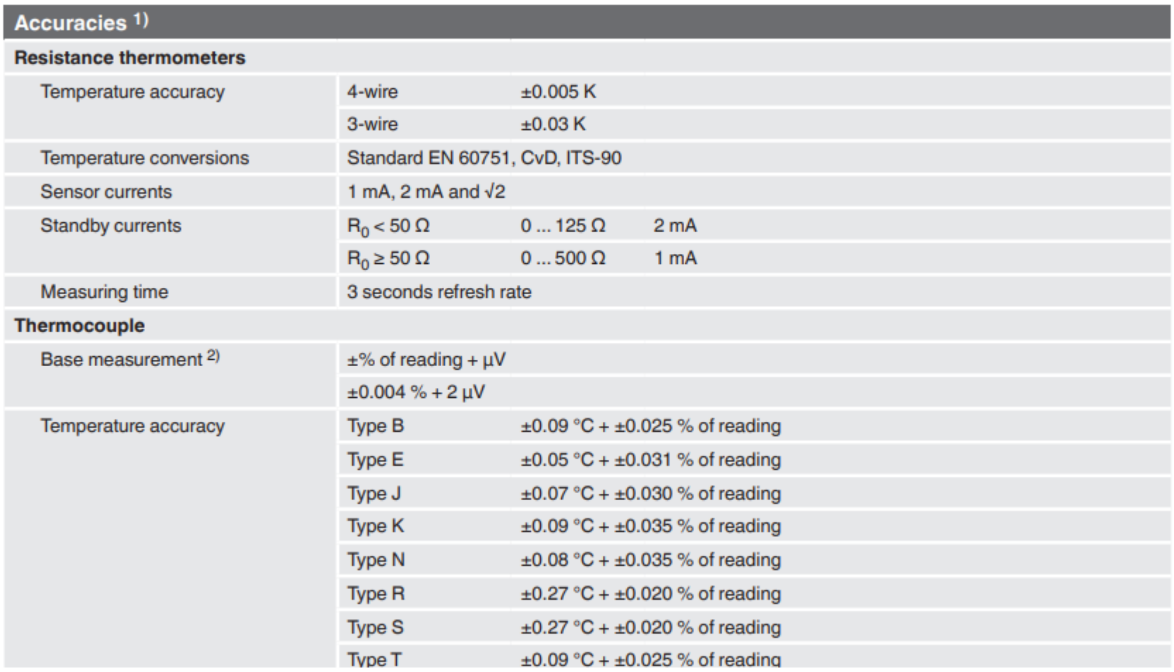
6.2 Wika CTR3000

Wika CTR3000 is a high-precision temperature calibrator used for RTD, thermocouple, and thermistor sensor calibration. It supports multiple thermocouple types, including K-type and T-type, as well as 2-, 3-, and 4-wire RTD configurations. The device performs resistance (Ω), voltage (mV), and temperature (K/°C) measurements with high accuracy, ensuring compatibility with both standard and custom probe configurations.

The system offers multi-range resistance measurements, allowing accurate calibration of RTDs such as PT100 and PT1000. It achieves an accuracy of ±0.006 Ω for 0–400 Ω RTDs, which corresponds to approximately ±0.016 °C for PT100 sensors. With a resolution down to 0.0001 K, it provides exceptional precision.

Additionally, CTR3000 includes real-time data logging and connectivity via USB, RS-232, and Ethernet, making it an excellent choice for laboratories and industries requiring strict calibration standards [5].

Figure 5 WIKA CTR3000

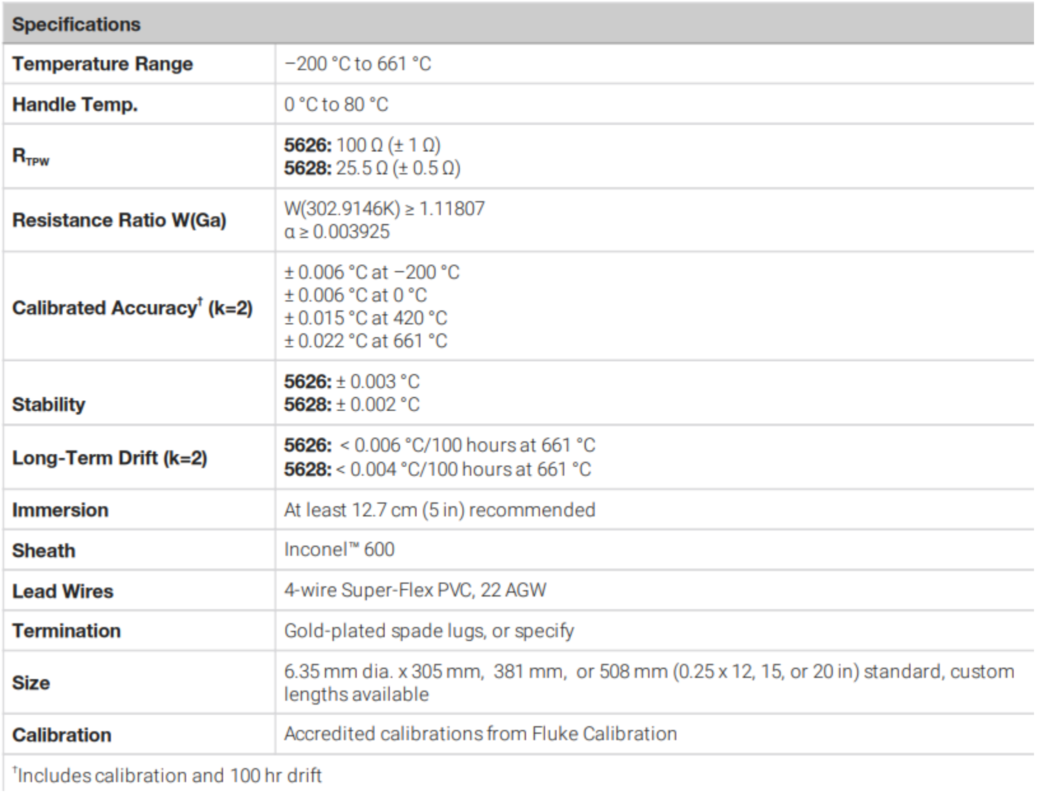


Accuracies 1)			
Resistance thermometers			
Temperature accuracy	4-wire	±0.005 K	
	3-wire	±0.03 K	
Temperature conversions	Standard EN 60751, CvD, ITS-90		
Sensor currents	1 mA, 2 mA and √2		
Standby currents	$R_0 < 50\ \Omega$	0 ... 125 Ω	2 mA
	$R_0 \geq 50\ \Omega$	0 ... 500 Ω	1 mA
Measuring time	3 seconds refresh rate		
Thermocouple			
Base measurement 2)	±% of reading + µV		
	±0.004 % + 2 µV		
Temperature accuracy	Type B	±0.09 °C + ±0.025 % of reading	
	Type E	±0.05 °C + ±0.031 % of reading	
	Type J	±0.07 °C + ±0.030 % of reading	
	Type K	±0.09 °C + ±0.035 % of reading	
	Type N	±0.08 °C + ±0.035 % of reading	
	Type R	±0.27 °C + ±0.020 % of reading	
	Type S	±0.27 °C + ±0.020 % of reading	
	Type T	±0.09 °C + ±0.025 % of reading	

Figure 6 WIKA CTR3000 Datasheet [5]

6.2.1 Fluke 5628 Secondary Standard PRT

The Fluke 5628 is a Secondary Standard Platinum Resistance Thermometer (PRT) designed for high-precision temperature calibration in environments where temperatures exceed 420 °C, up to a maximum of 660 °C. It is ideal for use with block calibrators, furnaces, and high-temperature applications, making it a reliable reference for industrial and laboratory settings. Ensures compliance with international temperature calibration standards. [6]



Specifications	
Temperature Range	−200 °C to 661 °C
Handle Temp.	0 °C to 80 °C
R_{TPW}	**5626:** 100 Ω (± 1 Ω) **5628:** 25.5 Ω (± 0.5 Ω)
Resistance Ratio W(Ga)	W(302.9146K) ≥ 1.11807 α ≥ 0.003925
Calibrated Accuracy† (k=2)	± 0.006 °C at −200 °C ± 0.006 °C at 0 °C ± 0.015 °C at 420 °C ± 0.022 °C at 661 °C
Stability	**5626:** ± 0.003 °C **5628:** ± 0.002 °C
Long-Term Drift (k=2)	**5626:** < 0.006 °C/100 hours at 661 °C **5628:** < 0.004 °C/100 hours at 661 °C
Immersion	At least 12.7 cm (5 in) recommended
Sheath	Inconel™ 600
Lead Wires	4-wire Super-Flex PVC, 22 AGW
Termination	Gold-plated spade lugs, or specify
Size	6.35 mm dia. x 305 mm, 381 mm, or 508 mm (0.25 x 12, 15, or 20 in) standard, custom lengths available
Calibration	Accredited calibrations from Fluke Calibration

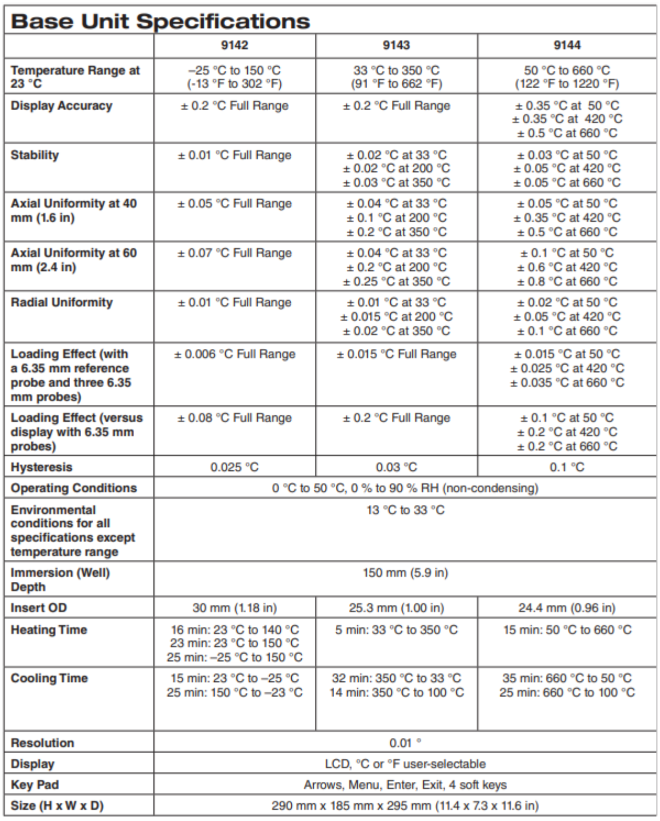
†Includes calibration and 100 hr drift

Figure 7 Fluke 5628 Datasheet [6]

6.3 Fluke 9144

The fluke 9144 is the calibrator for thermocouples, within the range of 50 °C to 600 °C. The device offers excellent temperature stability, often cited around ±0.005 °C to ±0.02 °C, which is crucial for calibration purposes. [7]

Figure 8 Fluke 9144



Base Unit Specifications

	9142	9143	9144
Temperature Range at 23 °C	–25 °C to 150 °C (-13 °F to 302 °F)	33 °C to 350 °C (91 °F to 662 °F)	50 °C to 660 °C (122 °F to 1220 °F)
Display Accuracy	± 0.2 °C Full Range	± 0.2 °C Full Range	± 0.35 °C at 50 °C ± 0.35 °C at 420 °C ± 0.5 °C at 660 °C
Stability	± 0.01 °C Full Range	± 0.02 °C at 33 °C ± 0.02 °C at 200 °C ± 0.03 °C at 350 °C	± 0.03 °C at 50 °C ± 0.05 °C at 420 °C ± 0.05 °C at 660 °C
Axial Uniformity at 40 mm (1.6 in)	± 0.05 °C Full Range	± 0.04 °C at 33 °C ± 0.1 °C at 200 °C ± 0.2 °C at 350 °C	± 0.05 °C at 50 °C ± 0.35 °C at 420 °C ± 0.5 °C at 660 °C
Axial Uniformity at 60 mm (2.4 in)	± 0.07 °C Full Range	± 0.04 °C at 33 °C ± 0.2 °C at 200 °C ± 0.25 °C at 350 °C	± 0.1 °C at 50 °C ± 0.6 °C at 420 °C ± 0.8 °C at 660 °C
Radial Uniformity	± 0.01 °C Full Range	± 0.01 °C at 33 °C ± 0.015 °C at 200 °C ± 0.02 °C at 350 °C	± 0.02 °C at 50 °C ± 0.05 °C at 420 °C ± 0.1 °C at 660 °C
Loading Effect (with a 6.35 mm reference probe and three 6.35 mm probes)	± 0.006 °C Full Range	± 0.015 °C Full Range	± 0.015 °C at 50 °C ± 0.025 °C at 420 °C ± 0.035 °C at 660 °C
Loading Effect (versus display with 6.35 mm probes)	± 0.08 °C Full Range	± 0.2 °C Full Range	± 0.1 °C at 50 °C ± 0.2 °C at 420 °C ± 0.2 °C at 660 °C
Hysteresis	0.025 °C	0.03 °C	0.1 °C
Operating Conditions	0 °C to 50 °C, 0 % to 90 % RH (non-condensing)		
Environmental conditions for all specifications except temperature range	13 °C to 33 °C		
Immersion (Well) Depth	150 mm (5.9 in)		
Insert OD	30 mm (1.18 in)	25.3 mm (1.00 in)	24.4 mm (0.96 in)
Heating Time	16 min: 23 °C to 140 °C 23 min: 23 °C to 150 °C 25 min: –25 °C to 150 °C	5 min: 33 °C to 350 °C	15 min: 50 °C to 660 °C
Cooling Time	15 min: 23 °C to –25 °C 25 min: 150 °C to –23 °C	32 min: 350 °C to 33 °C 14 min: 350 °C to 100 °C	35 min: 660 °C to 50 °C 25 min: 660 °C to 100 °C
Resolution	0.01 °		
Display	LCD, °C or °F user-selectable		
Key Pad	Arrows, Menu, Enter, Exit, 4 soft keys		
Size (H x W x D)	290 mm x 185 mm x 295 mm (11.4 x 7.3 x 11.6 in)		

Figure 9 Fluke 9144 Datasheet [7]

6.4 Fluke 7109A

Fluke 7109A is the calibrator used in the laboratory for PT-100 calibration. It has a temperature range of -25 °C to 140 °C and a display accuracy of ±0,1 °C. This high accuracy ensures a 4:1 Test Uncertainty Ratio (TUR), making it suitable for critical applications like pharmaceutical and biotechnology environments where sanitary sensors and RTDs need calibration.

The bath accommodates up to four tri-clamp sanitary sensors simultaneously, optimizing calibration throughput and reducing downtime. Its stainless-steel casing resists harsh sterilizing chemicals, making it ideal for cleanroom use. The portable design allows easy transportation across facilities, and it includes NVLAP-accredited calibration as standard, ensuring traceability and compliance with stringent quality requirements. [8]

Figure 10 Fluke 7109A

6.5 Beamex MC6

The Beamex MC6 is a high-precision multifunctional field calibrator designed for industrial calibration applications. It supports pressure, temperature, and electrical signal calibration, making it a versatile tool for various industries.

Its multifunctionality allows it to operate as a meter, calibrator, documenting calibrator, data logger, and fieldbus communicator, reducing the need for multiple devices in the field. With high accuracy and user-friendly operation, the MC6 is a widely used instrument for calibration tasks. For pressure measurements, it provides an accuracy of ± (0.005% of full scale + 0.0125%) of the measured value. When measuring temperature, the accuracy is ±0.011 °C, ensuring reliable calibration results. For current measurements, the accuracy is specified as ± (0.75 µA + 0.0075% of the measured value), allowing for precise electrical signal calibration [9].

7 Theory

7.1 Calibration

Calibration is the process of checking and adjusting a measurement instrument’s accuracy to ensure it consistently delivers precise and dependable results, it’s often done once a year. This involves comparing the instrument’s readings to a known reference or standard, adjusting if necessary to align with the correct values. Calibration is essential in fields like laboratories, engineering, and manufacturing, where precise measurements are critical for quality and reliability. The calibrator is typically 4 times more accurate than the measurement device. [10]

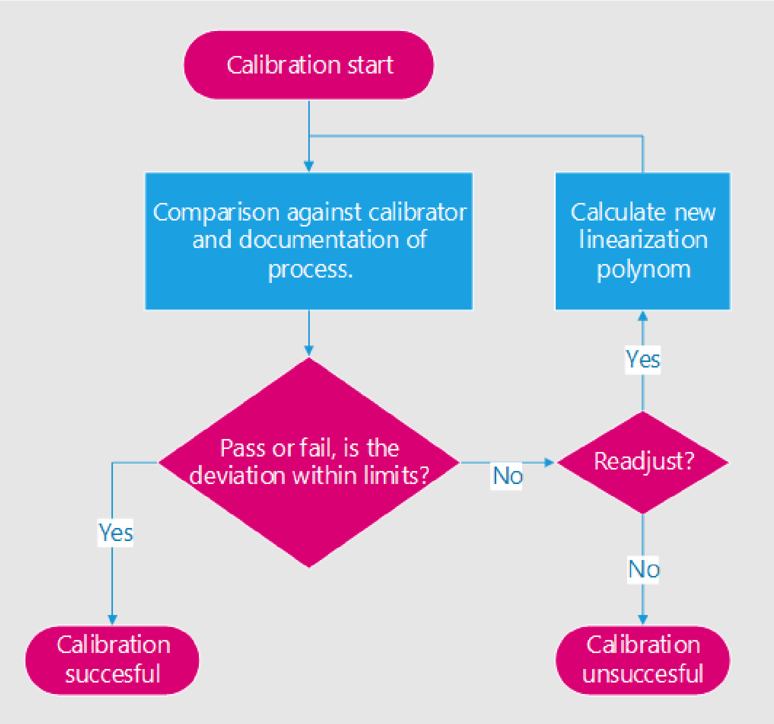


Figure 11 Calibration procedure

7.2 Type A evaluation of standard uncertainty

This method can be used when specifications and other documentation are unavailable. It provides a practical approach to estimating uncertainty solely based on repeated measurements, making it particularly useful when Type B information is not accessible. Type A evaluation of standard uncertainty involves using statistical analysis of repeated, independent measurements to determine the uncertainty associated with a quantity. The general guideline for the repetition is 4 to 10 times. When the measurements have been made, the estimated standard uncertainty can be calculated [11].

7.3 Type B evaluation of standard uncertainty

When measurement uncertainty cannot be determined through repeated observations, a Type B evaluation provides an alternative approach. This method relies on scientific judgment and careful consideration of all available data regarding the possible variability of the measured quantity. Type B evaluations are particularly valuable when Type A evaluations are limited by a small number of observations.

A Type B evaluation starts by identifying all potential sources of uncertainty. These may include manufacturer specifications, calibration certificates, reference data from handbooks, and environmental factors like temperature and humidity. Each source provides important insights into factors that influence measurement accuracy.

Once the sources of uncertainty are identified, numerical values must be assigned to them. For example, a calibration certificate may specify an uncertainty of ±0.1 °C, while the manufacturer's specifications might indicate an accuracy of ±0.2 °C. If uncertainty is given with a coverage factor (e.g., $k = 2$), the standard uncertainty is obtained by dividing the given value by the multiplier.

To incorporate these uncertainty values into a meaningful model, an appropriate probability distribution is selected based on the nature of the data. A rectangular distribution is used when all values within a range are equally probable, whereas a triangular distribution is applied when central values are more likely. If uncertainty is provided as a standard deviation, a normal distribution is typically assumed.

Once the probability distribution is determined, the standard uncertainty for each source is calculated. A rectangular distribution is divided by √3, a triangular distribution by √6, and a normal distribution by the specified coverage factor.

When multiple sources of uncertainty exist, they are combined using the root sum of squares (RSS) method. This calculates a single standard uncertainty that accounts for total variability from all sources [11].

For example, consider a temperature sensor with a manufacturer-specified accuracy of ±0.2 °C and a calibration certificate specifying an uncertainty of ±0.1 °C with k = 2. The standard uncertainties would be calculated as follows:

From the manufacturers’ specifications:

$$u(x_1) = \frac{0{,}2}{\sqrt{3}} = 0{,}115\ ^{\circ}\mathrm{C}$$

From the calibration certificate:

$$u(x_2) = \frac{0{,}1}{2} = 0{,}05\ ^{\circ}\mathrm{C}$$

The combined uncertainty:

$$u_c = \sqrt{(0{,}115)^2 + (0{,}05)^2} = 0.125\ ^{\circ}\mathrm{C}$$

7.4 Standard deviation and Standard uncertainty

Standard deviation is a statistical measure that describes the dispersion of a set of values around the mean. It quantifies the precision of repeated measurements and indicates how much individual data points deviate from the average [11]. The empirical standard deviation for a set of n measurements is calculated as follows:

$$s = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}}$$

A lower standard deviation indicates that the measurements are closely grouped around the mean, whereas a higher standard deviation suggests greater variation [12]. However, standard deviation alone does not provide information about the uncertainty of the measurement result. This is where standard uncertainty becomes relevant.

Standard uncertainty is a measure of the uncertainty in a measurement expressed as a standard deviation. Unlike standard deviation, which describes the spread of a dataset, standard uncertainty quantifies the confidence in a measurement result [11]. It is derived from the standard deviation as follows:

$$u = \frac{s}{\sqrt{n}}$$

This relationship shows that increasing the number of measurements reduces the standard uncertainty, as the mean estimate becomes more precise.

In uncertainty analysis, confidence levels are often expressed in terms of multiples of the standard deviation. This follows the principles of a normal distribution, where data is symmetrically distributed around the mean. The coverage factors $k = 1$, $k = 2$, $k = 3$ correspond to different confidence intervals, indicating the probability that a measured value falls within a certain range of the true value [13].

- **k=1 (68% confidence level):** Approximately 68.3% of all measurements fall within one standard deviation from the mean. This is the standard uncertainty as defined in the GUM framework.

- **k=2 (95% confidence level):** Around 95.4% of all measurements lie within two standard deviations (±2σ). This is the most commonly used coverage factor for expanded uncertainty providing a balance between accuracy and practicality.

- **k=3 (99.7% confidence level):** Nearly 99.7% of all measurements are contained within three standard deviations (±3σ). This provides a highly conservative estimate of uncertainty, used in applications requiring very high confidence.

The standard deviation and corresponding confidence levels can be visualized using a normal distribution curve (Figure 12).

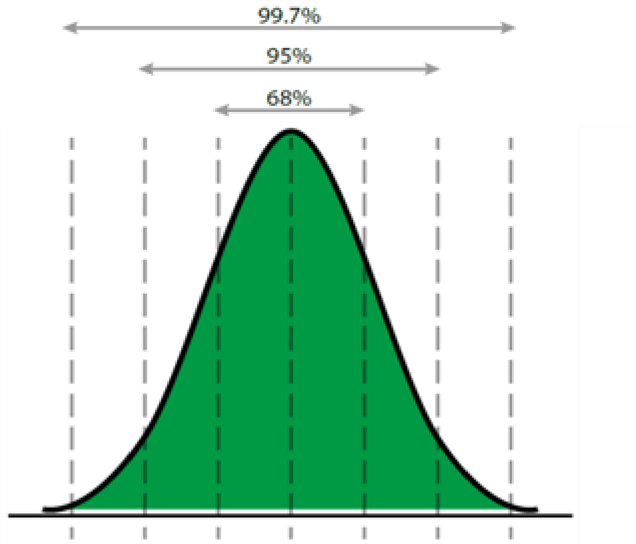


Figure 12, Normal distribution [14]

7.5 Guide to the expression of uncertainty in measurement

The Guide to the Expression of Uncertainty in Measurement (GUM) is an internationally recognized framework for evaluating and reporting measurement uncertainty. It provides a structured methodology for quantifying uncertainty using statistical and non-statistical methods. The GUM ensures consistency and reliability in uncertainty estimation across different fields.

GUM is widely used in calibration laboratories, industrial measurement processes, scientific research, and regulatory compliance. It is particularly important in metrology, where precise and standardized uncertainty evaluation is crucial. The guide is published by the Joint Committee for Guides in Metrology (JCGM) and is based on principles from ISO standards, making it a de facto standard for uncertainty analysis worldwide [11].

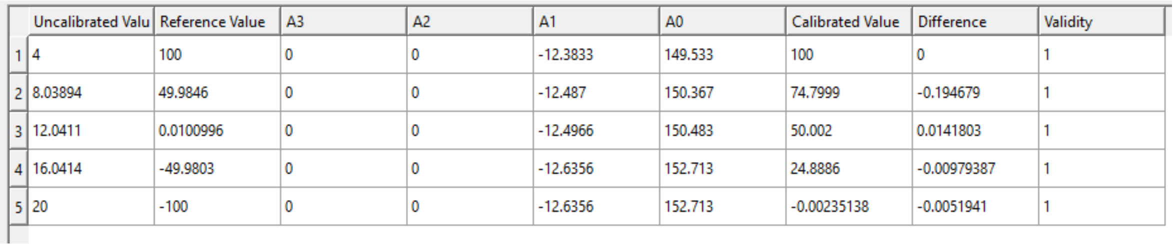
8 Calibration of SDAQ sensors

To calculate measurement uncertainties using the Type A method, data was collected by calibrating the sensors multiple times. For each sensor type, 15 calibration certificates were gathered, each containing several measurement points. According to the GUM an accurate estimation of measurement uncertainty requires repeating measurements 4 to 10 times. From these certificates, multiple measurement points were obtained, with each point repeated 15 times using three identical sensors and SDAQs.

The calibration process typically follows these steps: the calibration rig provides specific procedures based on the sensor type being calibrated. Once the correct procedure is selected, calibration begins. Upon completion, the system indicates whether the sensor has passed or failed. If the sensor passes, the calibration rig generates a calibration certificate in Excel format. If the sensor fails, a new interpolation must be calculated, and the calibration repeated (Figure 11).

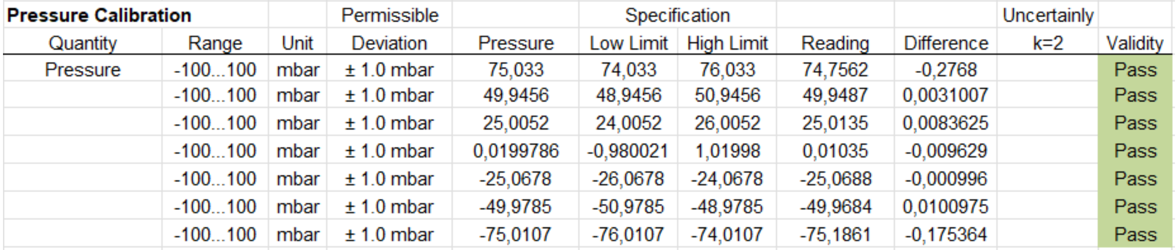
When calibrating a new SDAQ-I sensor, a polynomial is calculated after the initial calibration to ensure accurate output values and correct units. Once the polynomial is determined, the updated values are added to the sensor's calibration table shown in Figure 13. To improve the estimation of measurement uncertainty, additional data is collected by calibrating not only at the original polynomial points but also between them as shown in the calibration certificate (Figure 14). This approach helps identify potential errors between the polynomial points.

This procedure was only applied to the current-measuring SDAQ-I sensors to adhere to the standard procedure for using the calibration rig. For other types of SDAQ sensors, interpolation calculations are unnecessary if the sensor passes the calibration process.



	Uncalibrated Valu	Reference Value	A3	A2	A1	A0	Calibrated Value	Difference	Validity
1	4	100	0	0	-12.3833	149.533	100	0	1
2	8.03894	49.9846	0	0	-12.487	150.367	74.7999	-0.194679	1
3	12.0411	0.0100996	0	0	-12.4966	150.483	50.002	0.0141803	1
4	16.0414	-49.9803	0	0	-12.6356	152.713	24.8886	-0.00979387	1
5	20	-100	0	0	-12.6356	152.713	-0.00235138	-0.0051941	1

Figure 13 Sensor Calibration table



Pressure Calibration			Permissible		Specification				Uncertainly	
Quantity	Range	Unit	Deviation	Pressure	Low Limit	High Limit	Reading	Difference	k=2	Validity
Pressure	-100...100	mbar	± 1.0 mbar	75,033	74,033	76,033	74,7562	-0,2768		Pass
	-100...100	mbar	± 1.0 mbar	49,9456	48,9456	50,9456	49,9487	0,0031007		Pass
	-100...100	mbar	± 1.0 mbar	25,0052	24,0052	26,0052	25,0135	0,0083625		Pass
	-100...100	mbar	± 1.0 mbar	0,0199786	-0,980021	1,01998	0,01035	-0,009629		Pass
	-100...100	mbar	± 1.0 mbar	-25,0678	-26,0678	-24,0678	-25,0688	-0,000996		Pass
	-100...100	mbar	± 1.0 mbar	-49,9785	-50,9785	-48,9785	-49,9684	0,0100975		Pass
	-100...100	mbar	± 1.0 mbar	-75,0107	-76,0107	-74,0107	-75,1861	-0,175364		Pass

Figure 14 Calibration Certificate

9 Determination of Standard Uncertainty

When the calibrations were completed and all calibration certificates were organized into folders, each standard sensor received a folder containing 15 calibration certificates. At this point, it was time for data processing. Since there were a total of 300 calibration certificates distributed across 20 folders, it was decided to create a macro in Excel.

This macro first prompts the user to select the folder from which they want to import data. Once the folder is selected, the data import begins. The macro imports the SDAQ serial number, the Value, which represents the measured value of the reference sensor, the Reading, which is the measured value of the sensor being calibrated, and the Error. Then, it also names the worksheet after the selected folder.

As intended, the Type A uncertainty calculations were presented in a way that allows for easy identification of the measurement points where uncertainty is highest across different standard sensors. To achieve this, a macro was made that rounds the Value to the nearest integer while ensuring that Reading is adjusted by the same amount in the same direction, preserving the original Error.

For example, if Value = 4.8 and Reading = 5.2, the macro rounds Value to 5 and adjusts Reading to 5.4, maintaining the original Error. This approach made the presentation of the results much easier to interpret.

9.1 Type A Uncertainty Evaluation

In this section, the Type A evaluation of measurement uncertainty is presented. The analysis is based on repeated measurements at different temperature setpoints, allowing for an assessment of the variability in the measured values. For each predefined value, multiple measurements were taken to calculate the following statistical parameters:

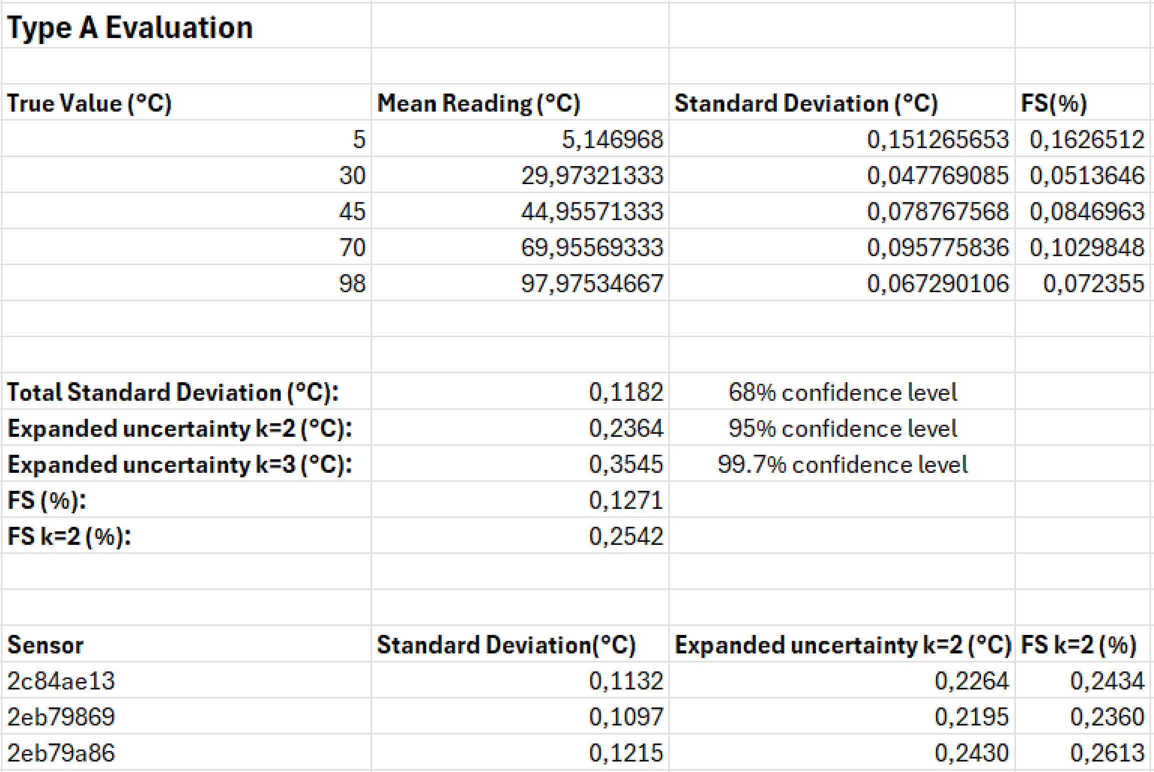
- **Mean reading:** The average value of the recorded measurements at each temperature point.

- **Standard deviation:** The spread of the measured values around the mean, representing the measurement uncertainty at each measurement point.

- **Full-Scale Percentage:** The standard deviation expressed as a percentage of the full-scale range of the sensor.

The total standard deviation of the measurement process was computed based on all measurement points, which serve as a general representation of the Type A uncertainty across different measurement points. To estimate the expanded uncertainty, coverage factors of k=2 and k=3 were applied, corresponding to confidence levels of 95% and 99.7%.

To further investigate measurement variability, an analysis was performed for individual sensors. The standard deviation was calculated for each sensor across all temperature points, and the expanded uncertainty at k=2 was determined. This analysis also serves to identify whether a specific sensor exhibits greater variation than expected. If a sensor shows significantly higher deviations compared to others, the reliability of its measurements may be questioned, and the uncertainty estimation should be interpreted with caution.



Type A Evaluation

True Value (°C)	Mean Reading (°C)	Standard Deviation (°C)	FS(%)
5	5,146968	0,151265653	0,1626512
30	29,97321333	0,047769085	0,0513646
45	44,95571333	0,078767568	0,0846963
70	69,95569333	0,095775836	0,1029848
98	97,97534667	0,067290106	0,072355

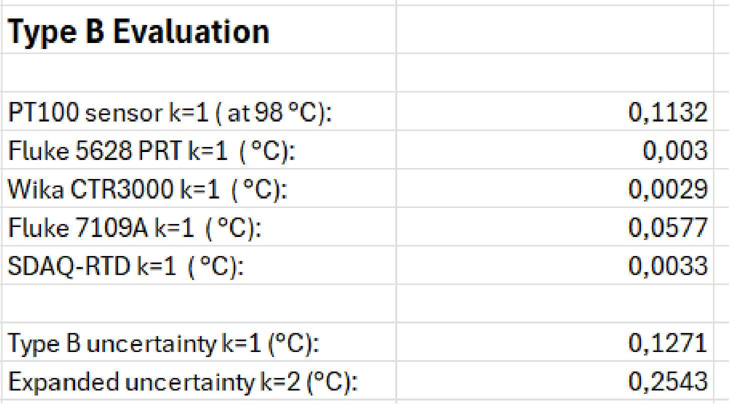
Total Standard Deviation (°C):	0,1182	68% confidence level
Expanded uncertainty k=2 (°C):	0,2364	95% confidence level
Expanded uncertainty k=3 (°C):	0,3545	99.7% confidence level
FS (%):	0,1271	
FS k=2 (%):	0,2542	

Sensor	Standard Deviation(°C)	Expanded uncertainty k=2 (°C)	FS k=2 (%)
2c84ae13	0,1132	0,2264	0,2434
2eb79869	0,1097	0,2195	0,2360
2eb79a86	0,1215	0,2430	0,2613

Figure 15, Type A evaluation for PT100 65mm

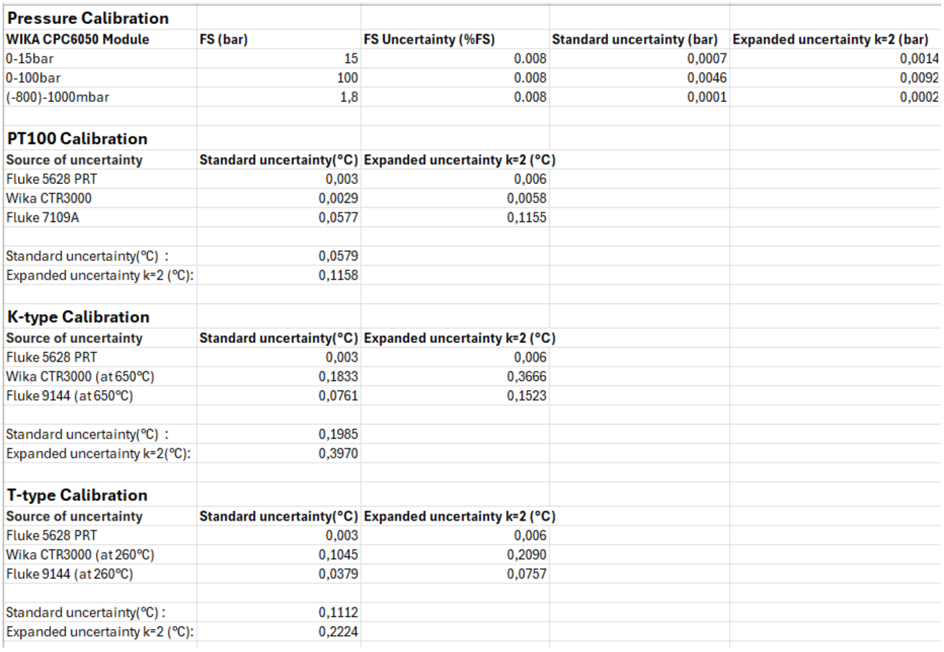
9.2 Type B Uncertainty Evaluation

The uncertainty components from various reference instruments and sensors were considered. Each component’s uncertainty was taken with a coverage factor of k=1 corresponding to a 68% confidence level. To begin the calculation of Type B uncertainty for each sensor type, I first needed to determine the uncertainty of all measuring instruments used in the calibration process. The measuring instruments varies depending on the type of sensor being calibrated. In the data sheets, the uncertainty was often presented in a different unit than the sensor's measurement unit, such as FS%. Therefore, I had to convert the values to the desired unit before proceeding with the calculations. The standard uncertainty was calculated using the RSS method. Calculations for PT100 65mm shown in Figure 16.



Type B Evaluation	
PT100 sensor k=1 (at 98 °C):	0,1132
Fluke 5628 PRT k=1 (°C):	0,003
Wika CTR3000 k=1 (°C):	0,0029
Fluke 7109A k=1 (°C):	0,0577
SDAQ-RTD k=1 (°C):	0,0033
Type B uncertainty k=1 (°C):	0,1271
Expanded uncertainty k=2 (°C):	0,2543

Figure 16, Type B evaluation for PT100 65mm



Pressure Calibration

WIKA CPC6050 Module	FS (bar)	FS Uncertainty (%FS)	Standard uncertainty (bar)	Expanded uncertainty k=2 (bar)
0-15bar	15	0.008	0,0007	0,0014
0-100bar	100	0.008	0,0046	0,0092
(-800)-1000mbar	1,8	0.008	0,0001	0,0002

PT100 Calibration

Source of uncertainty	Standard uncertainty(°C)	Expanded uncertainty k=2 (°C)
Fluke 5628 PRT	0,003	0,006
Wika CTR3000	0,0029	0,0058
Fluke 7109A	0,0577	0,1155
Standard uncertainty(℃) :	0,0579	
Expanded uncertainty k=2 (℃):	0,1158	

K-type Calibration

Source of uncertainty	Standard uncertainty(°C)	Expanded uncertainty k=2 (°C)
Fluke 5628 PRT	0,003	0,006
Wika CTR3000 (at 650℃)	0,1833	0,3666
Fluke 9144 (at 650℃)	0,0761	0,1523
Standard uncertainty(℃) :	0,1985	
Expanded uncertainty k=2(℃):	0,3970	

T-type Calibration

Source of uncertainty	Standard uncertainty(°C)	Expanded uncertainty k=2 (°C)
Fluke 5628 PRT	0,003	0,006
Wika CTR3000 (at 260℃)	0,1045	0,2090
Fluke 9144 (at 260℃)	0,0379	0,0757
Standard uncertainty(℃) :	0,1112	
Expanded uncertainty k=2 (℃):	0,2224	

Figure 17, Sources of uncertainty

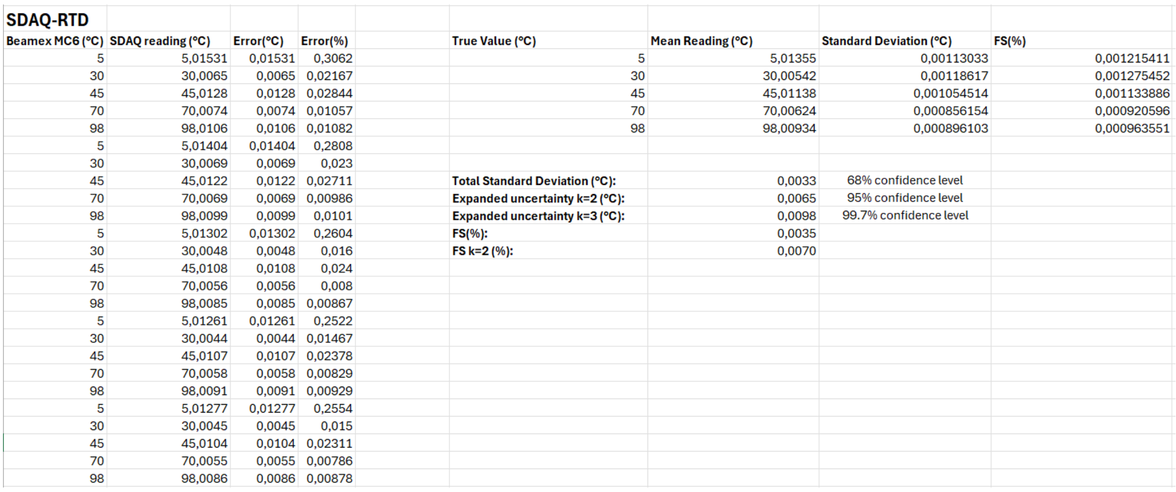
9.2.1 SDAQ uncertainty

Since the SDAQ module is responsible for the A/D conversion of the sensor signal, it is also a source of uncertainty in the Type B evaluation. However, no manufacturer specifications for uncertainty were available, only noise data, which was calculated to be so small that it could be neglected.

Due to the lack of uncertainty specifications, it was chosen to apply a Type A evaluation, as it is specifically designed for this purpose, estimating uncertainty based on statistical analysis of repeated measurements.

This was done by simulating sensor signals using the Beamex MC6 field calibrator, which is capable of outputting simulated PT100 signals, TC signals, and mA signals. The calibrator was connected to the SDAQ input where the sensor is normally connected. A manual calibration was performed, with the calibrator acting as both the reference sensor and the sensor itself.

This test was conducted on a single SDAQ unit for the RTD, TC1, and I types. Five calibration sequences were performed, each with five different measurement points, resulting in a total of 25 measurement points per SDAQ.



SDAQ-RTD

Beamex MC6 (°C)	SDAQ reading (°C)	Error(°C)	Error(%)
5	5,01531	0,01531	0,3062
30	30,0065	0,0065	0,02167
45	45,0128	0,0128	0,02844
70	70,0074	0,0074	0,01057
98	98,0106	0,0106	0,01082
5	5,01404	0,01404	0,2808
30	30,0069	0,0069	0,023
45	45,0122	0,0122	0,02711
70	70,0069	0,0069	0,00986
98	98,0099	0,0099	0,0101
5	5,01302	0,01302	0,2604
30	30,0048	0,0048	0,016
45	45,0108	0,0108	0,024
70	70,0056	0,0056	0,008
98	98,0085	0,0085	0,00867
5	5,01261	0,01261	0,2522
30	30,0044	0,0044	0,01467
45	45,0107	0,0107	0,02378
70	70,0058	0,0058	0,00829
98	98,0091	0,0091	0,00929
5	5,01277	0,01277	0,2554
30	30,0045	0,0045	0,015
45	45,0104	0,0104	0,02311
70	70,0055	0,0055	0,00786
98	98,0086	0,0086	0,00878

True Value (°C)	Mean Reading (°C)	Standard Deviation (°C)	FS(%)
5	5,01355	0,00113033	0,001215411
30	30,00542	0,00118617	0,001275452
45	45,01138	0,001054514	0,001133886
70	70,00624	0,000856154	0,000920596
98	98,00934	0,000896103	0,000963551

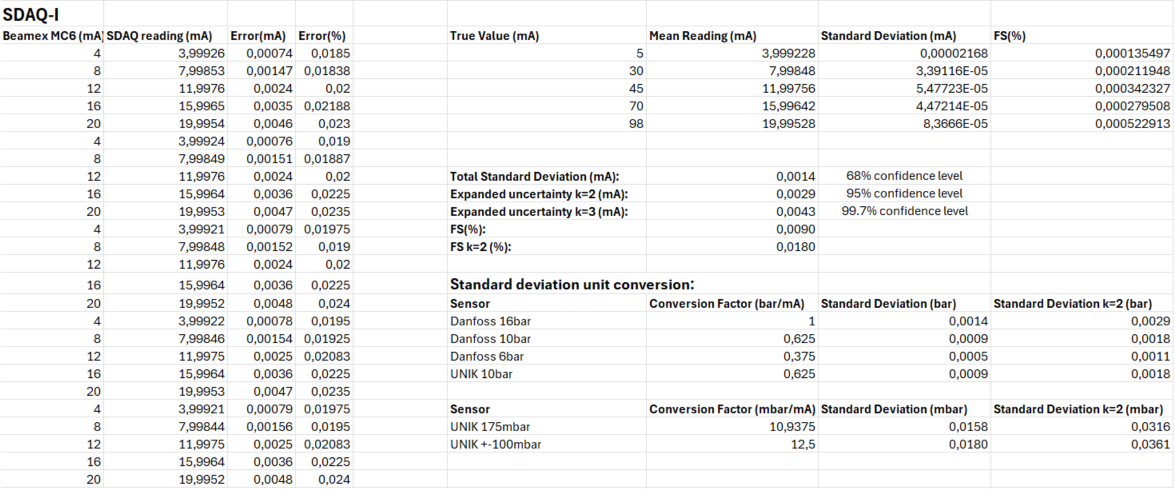
Total Standard Deviation (°C):	0,0033	68% confidence level
Expanded uncertainty k=2 (°C):	0,0065	95% confidence level
Expanded uncertainty k=3 (°C):	0,0098	99.7% confidence level
FS(%):	0,0035	
FS k=2 (%):	0,0070	

Figure 18, Evaluation of SDAQ-RTD uncertainty

When combining uncertainties using the RSS method in Type B evaluation, all uncertainties must be expressed in the same unit. While SDAQ RTD and TC1 use degrees Celsius as their measurement unit, SDAQ-I do not.

SDAQ-I measures in milliamps (mA) and only displays values in mbar or bar after interpolation. In this test, SDAQ-I measured in mA, which had to be converted to the appropriate unit depending on the sensor being used.

The uncertainty was first calculated in mA and then converted to the correct unit and value to ensure consistency. This was necessary due to different sensors having different scaling factors.



SDAQ-I

Beamex MC6 (mA)	SDAQ reading (mA)	Error(mA)	Error(%)
4	3,99926	0,00074	0,0185
8	7,99853	0,00147	0,01838
12	11,9976	0,0024	0,02
16	15,9965	0,0035	0,02188
20	19,9954	0,0046	0,023
4	3,99924	0,00076	0,019
8	7,99849	0,00151	0,01887
12	11,9976	0,0024	0,02
16	15,9964	0,0036	0,0225
20	19,9953	0,0047	0,0235
4	3,99921	0,00079	0,01975
8	7,99848	0,00152	0,019
12	11,9976	0,0024	0,02
16	15,9964	0,0036	0,0225
20	19,9952	0,0048	0,024
4	3,99922	0,00078	0,0195
8	7,99846	0,00154	0,01925
12	11,9975	0,0025	0,02083
16	15,9964	0,0036	0,0225
20	19,9953	0,0047	0,0235
4	3,99921	0,00079	0,01975
8	7,99844	0,00156	0,0195
12	11,9975	0,0025	0,02083
16	15,9964	0,0036	0,0225
20	19,9952	0,0048	0,024

True Value (mA)	Mean Reading (mA)	Standard Deviation (mA)	FS(%)
5	3,999228	0,00002168	0,000135497
30	7,99848	3,39116E-05	0,000211948
45	11,99756	5,47723E-05	0,000342327
70	15,99642	4,47214E-05	0,000279508
98	19,99528	8,3666E-05	0,000522913

Total Standard Deviation (mA):	0,0014	68% confidence level
Expanded uncertainty k=2 (mA):	0,0029	95% confidence level
Expanded uncertainty k=3 (mA):	0,0043	99.7% confidence level
FS(%):	0,0090	
FS k=2 (%):	0,0180	

Standard deviation unit conversion:

Sensor	Conversion Factor (bar/mA)	Standard Deviation (bar)	Standard Deviation k=2 (bar)
Danfoss 16bar	1	0,0014	0,0029
Danfoss 10bar	0,625	0,0009	0,0018
Danfoss 6bar	0,375	0,0005	0,0011
UNIK 10bar	0,625	0,0009	0,0018

Sensor	Conversion Factor (mbar/mA)	Standard Deviation (mbar)	Standard Deviation k=2 (mbar)
UNIK 175mbar	10,9375	0,0158	0,0316
UNIK +-100mbar	12,5	0,0180	0,0361

Figure 19, Evaluation of SDAQ-I uncertainty

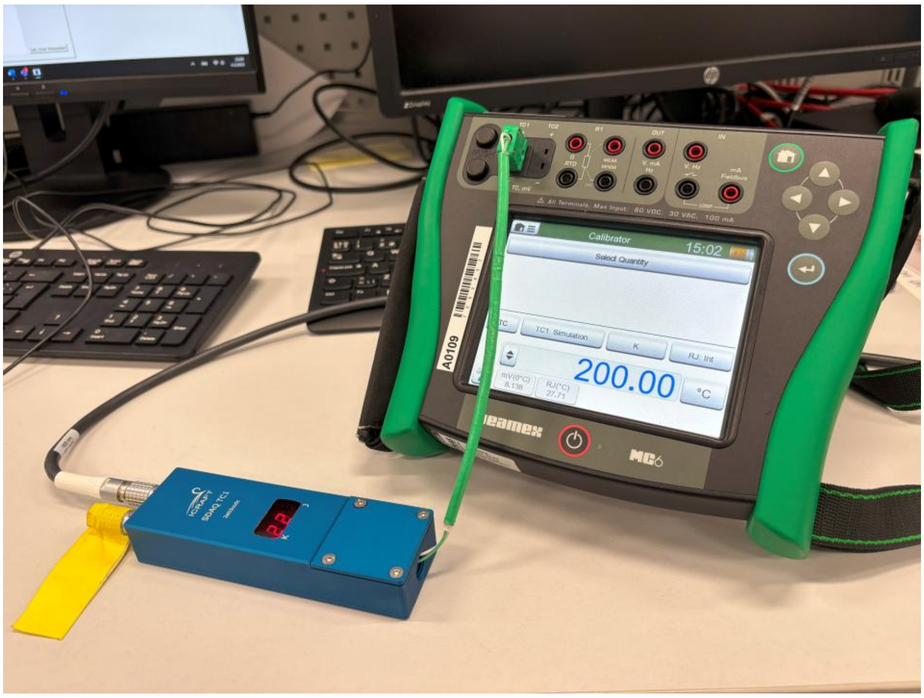


Figure 20, MC6 calibrator connected to SDAQ-TC1

10 Findings and Issues

Just because the calibration rig is automatic doesn't mean human error can't cause mistakes and measurement errors. Always double-check that values look reasonable to avoid ending up with an approved calibration certificate when the sensor isn't showing the correct readings.

This chapter will go over the observations and possible mistakes that can happen when using the calibration rig.

When the sensors are connected to the calibration rig's CAN interface, each sensor must be assigned a unique "ID" that is displayed on the SDAQ screen. Although rare, for an unknown reason there are instances where the ID is not assigned correctly. Two SDAQs can end up with the same ID as shown in Figure 21 SDAQ with same ID, resulting in identical measurements, which are not accurate. The ID is adjustable on the calibration rig. Later, it was discovered that it’s also possible to change the ID manually on the SDAQ by pressing down and holding the UP button for approximately 2 seconds, when the ID starts blinking, it indicates that you can adjust it. Use the UP button to increase the value or the DOWN button to decrease it.

Figure 21 SDAQ with same ID

When calibrating pressure sensors, it is always important to check for leaks. The leak test feature available in the Wika CPC6050 was used for this purpose, shown in Figure 23. Leaks are usually more common in hoses and connections to the sensor, but occasionally, quality issues from the manufacturer can occur that also the sensor itself leaks. During the calibration, it was noticed that the pressure was dropping slightly too quickly, and it turned out that the sensor itself was leaking as shown in Figure 22.

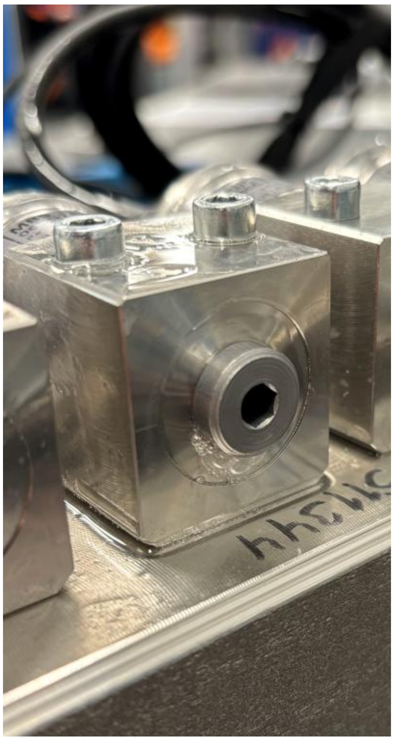


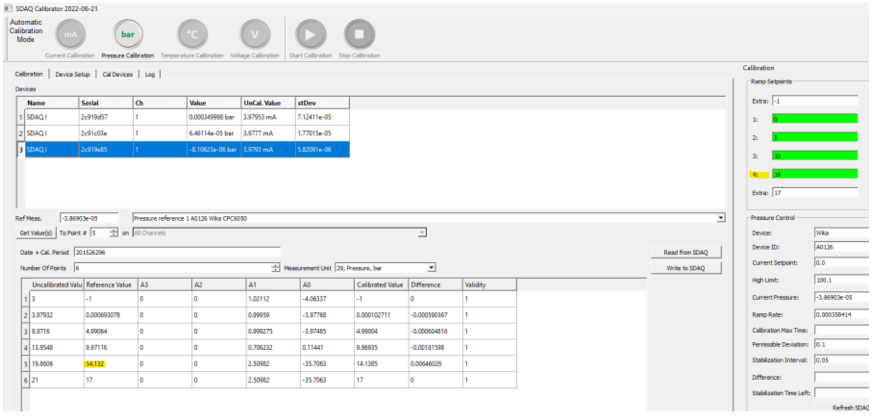
Figure 22 Leaking Pressure Sensor

Channel:A 0.0000 .. 15.0000 bar

Initial 0.500
Final 0.500
Delta 0.000
0.0000 bar
Setpoint 0.500 bar
Dwell Delay 30.0 Sec
Dwell Time 0.0 Sec
Delta 0.001 bar
Status Pass

Figure 23 Wika CPC6050 Leak Test

When calibrating 16-bar pressure sensors, it is important to set the range on the Wika CPC6050 to 0–100 bar. If this step is skipped, the following issue can occur: the calibrator outputs 16 bars, but the reference sensor reads it as approximately 14 bars. This discrepancy causes the SDAQ's polynomial calculation to be incorrect during the first calibration. Despite this, the calibration rig may still accept the sensor. As a result, you could end up with a sensor that passes calibration but does not provide accurate readings, unless you catch the issue yourself.



	Name	Serial	Ch	Value	UnCal. Value	stDev
1	SDAQ I	2c919d57	1	0.000349998 bar	3.97953 mA	7.12411e-05
2	SDAQ I	2c91c03e	1	6.46114e-05 bar	3.9777 mA	1.77015e-05
3	SDAQ I	2c919e85	1	-8.10623e-06 bar	3.9793 mA	5.82091e-06

Ref Meas. -3.86903e-05
Pressure reference 1 A0126 Wika CPC6050
To Point # 5 on All Channels
Date + Cal. Period 201526296
Number Of Points 6
Measurement Unit 29, Pressure, bar

	Uncalibrated Valu	Reference Value	A3	A2	A1	A0	Calibrated Value	Difference	Validity
1	3	-1	0	0	1.02112	-4.06337	-1	0	1
2	3.97932	0.000693078	0	0	0.99959	-3.97768	0.000102711	-0.000590367	1
3	8.9716	4.99064	0	0	0.999275	-3.97485	4.99004	-0.000604816	1
4	13.9548	9.97116	0	0	0.706232	0.11441	9.96935	-0.00181598	1
5	19.8606	14.132	0	0	2.50982	-35.7063	14.1385	0.00646026	1
6	21	17	0	0	2.50982	-35.7063	17	0	1

Extra: -1
1: 0
2: 5
3: 10
4: 16
Extra: 17

Device: Wika
Device ID: A0126
Current Setpoint: 0.0
High Limit: 100.1
Current Pressure: -3.86903e-05
Ramp Rate: 0.000358414
Calibration Max Time:
Permissible Deviation: 0.1
Stabilization Interval: 0.05
Difference:
Stabilization Time Left:

Figure 24 Incorrect polynomial calculation

11 Results

The expanded uncertainty, with a coverage factor of k=2, was determined for each sensor, corresponding to a 95% confidence interval. Among the tested sensors, PT100 sensors exhibited the lowest expanded uncertainty, consistently remaining below 0.35°C. This confirms their high stability and reliability for temperature measurements. In contrast, K-type thermocouple sensors showed significantly higher uncertainties, exceeding 3.0°C. This outcome aligns with expectations, as thermocouples are known to be more sensitive to external influences such as cold junction compensation errors, and their inherently larger measurement range.

For pressure sensors, the expanded uncertainty varied depending on the pressure range. The lowest uncertainty, 0.0067°C, was observed in high-pressure measurements, whereas lower-pressure sensors showed uncertainties up to 0.3144°C. This suggests that sensor range and sensitivity play a crucial role in determining measurement uncertainty. Additionally, since pressure sensors rely on a current signal (mA) that is later converted to pressure values, some degree of interpolation error may contribute to the observed variations.

The results highlight the influence of different measurement principles on uncertainty. Resistance-based sensors, such as PT100, exhibit more stable readings, whereas voltage-based thermocouples and current-based pressure sensors introduce additional variability due to their inherent measurement properties.

Sensor	Sensor manufacturer	Sensor type	SDAQ type	Expanded Uncertainty k=2
PT100 65x6mm, 3m cable	Pentronic	PT100	SDAQ-RTD	0,3472
PT100 90x6mm, 3m cable	Pentronic	PT100	SDAQ-RTD	0,2582
PT100 140x6mm, 3m cable	Pentronic	PT100	SDAQ-RTD	0,2838
PT100 190x6mm, 3m cable	Pentronic	PT100	SDAQ-RTD	0,2628
PT100 225x6mm, 3m cable	Pentronic	PT100	SDAQ-RTD	0,2627
PT100 275x6mm, 3m cable	Pentronic	PT100	SDAQ-RTD	0,2652
PT100 325x6mm, 3m cable	Pentronic	PT100	SDAQ-RTD	0,2641
TC Type-K 190x6mm, 3m cable	Pentronic	Thermocouple	SDAQ-TC	3,3938
TC Type-K 225x6mm, 3m cable	Pentronic	Thermocouple	SDAQ-TC1	3,0324
TC Type-K 275x6mm, 3m cable	Pentronic	Thermocouple	SDAQ-TC1	3,142
TC Type-K 325x6mm, 3m cable	Pentronic	Thermocouple	SDAQ-TC1	3,2064
TC Type-T 140x6mm, 3m cable	Pentronic	Thermocouple	SDAQ-TC1	1,2269
TC Type-T 325x6mm, 3m cable	Pentronic	Thermocouple	SDAQ-TC1	1,2602
TC Type-K 250x6mm, 12m cable	Pentronic	Thermocouple	SDAQ-TC1	3,231
GE PTX5022, +-100mBar g	GE	Pressure sensor	SDAQ-I	0,3144
GE PTX5022, 0-10 Bar g	GE	Pressure sensor	SDAQ-I	0,0067
GE PTX5022, 0-175mBar dif	GE	Pressure sensor	SDAQ-I	0,2246
6 bar 6m cable - absolute pressure	Danfoss	Pressure sensor	SDAQ-I	0,286
10 bar 3m cable - relative	Danfoss	Pressure sensor	SDAQ-I	0,1155
16 bar 3m cable - relative	Danfoss	Pressure sensor	SDAQ-I	0,1851

12 Conclusions

A large amount of new data has been collected during this thesis, and with further research in the field, even more data could be obtained.

The Type A evaluation for the SDAQ unit has been conducted in a controlled calibration environment at room temperature. However, since these sensors are primarily used in engine cells, it would be beneficial to investigate their performance under real operating conditions, such as higher ambient temperatures (e.g., 40 °C). One approach could be to use the Beamex MC6 for sensor signal simulation while placing the SDAQ unit in an oven to evaluate its response.

Further studies could explore additional methods for simulating sensors installed on an engine, including dynamic load variations or vibration testing to better replicate real-world conditions. Additionally, sensor drift over time could be analyzed through long-term stability tests under cyclic temperature changes. These investigations would provide a more comprehensive understanding of the sensor's reliability and accuracy in demanding environments.

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