SEN6x – Sensor Specification Statement

Understanding the Particulate Matter Specifications of the SEN6x Environmental Sensor Node

Preface

This document explains how to interpret the terminology used in Sensirion particulate matter (PM) sensor specifications. There is currently no universally standardized procedure for PM sensor manufacturers when specifying their sensors, nor a standardized setup for measuring performance. As a result, users often find it difficult to understand and compare the performance parameters of products from different manufacturers. This document aims to clarify the particulate matter specifications of Sensirion's SEN6x environmental sensor node.

Contents

1 Particulate Matter Specifications

1.1 Basic Considerations

Sensirion Particulate Matter (PM) sensors operate as optical particle counters (OPCs) based on laser scattering technology. All OPCs guide ambient, suspended particles to a measurement cell inside the device. The measurement cell consists of a light source (e.g., a laser) and a photodetector. Due to the interaction of particles and light, part of the incoming light is scattered towards the nearby photodetector (see **Figure 1**).

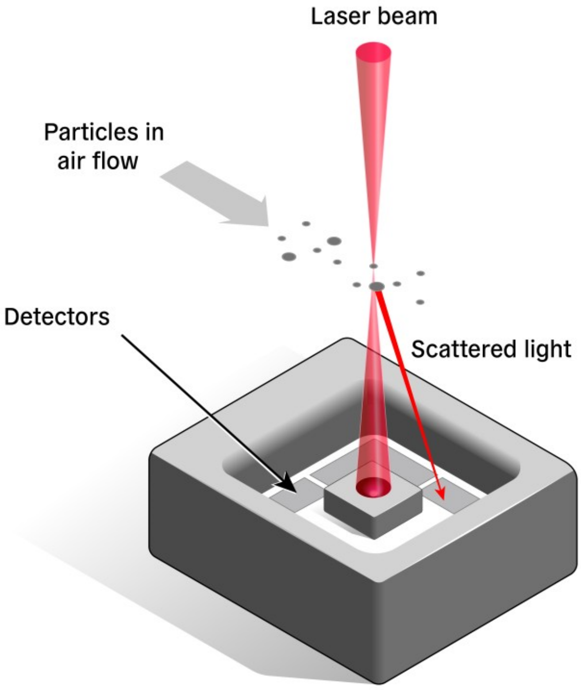

Figure 1. Measurement principle of SPS6x-based particulate matter sensors

The collected signal is then converted into real-time mass concentration values, given in µg/m^3. While most OPCs are comparable in detecting particles, the algorithms that translate the optical signal into mass concentration are a major differentiator among manufacturers. Particle optical properties, such as refractive index and shape, strongly influence this conversion, which is why indirect optical measurements inherently deviate from more accurate gravimetric, weight-based references.

Although this makes optical PM sensors seem like a necessary compromise, it is important to note that µg/m^3 became the standard largely because gravimetric methods existed first. From a health-impact perspective, metrics like particle size distributions or number concentrations would provide more meaningful insight. However, introducing number concentration as a primary metric adds complexity for most applications, as µg/m^3 is widely accepted as the standard. As a result, OPC-based mass concentration remains the most practical and cost-effective solution for commercial products.

To clearly assess the performance of a PM sensor, its specifications must be simplified into a form that can be evaluated using standard equipment. While this simplification inevitably introduces some grey areas that are not fully addressed, a well-defined specification should give the user a reliable tool to understand the sensors and design their own devices accordingly.

1.2 Sensirion PM Sensor Calibration and Reference Equipment

Sensirion PM sensors are calibrated using regularly maintained and aligned high-end reference instruments (e.g., the TSI Optical Particle Sizer Model 3330 or the TSI DustTrak™ DRX 8533), to guarantee the smallest possible batch-to-batch variation. As a result, it is always possible to measure and reproduce the sensor specification values using Sensirion's measurement equipment, and to compare the sensor outputs with the outputs of the reference instruments. However, although the user might employ reference instruments with the same model number and manufacturer as those used by Sensirion to perform numerical comparisons, there may be situations where these instruments show significant output differences among each other. In some cases, these differences may exceed 20% of the measured value. Contributing factors include differing reference instrument configurations, reference drift over time, heavy dust exposure during usage, irregular or missing maintenance, or variations in the recalibration procedures used by different laboratories during regular device maintenance.

The choice of optical reference instruments also influences the apparent output of the PM sensor, as the sensor is calibrated to the selected reference. The SEN6x is adjusted to the output of the TSI DustTrak™ DRX 8533 operated in Ambient Mode. This mode is optimized for indoor environments characterized by relatively light aerosols. In contrast, outdoor and industrial environments often exhibit aerosols with substantially higher densities. Thus, for applications outside the Ambient Mode envelope, Sensirion recommends determining an application-specific correction factor, obtained through external laboratory characterization of the target aerosol, which can then be applied to the SEN6x output.

Thus, to provide the user with a practical and easily reproducible method for verifying Sensirion PM sensor performance independently, *precision* is chosen as the main sensor specification, rather than *accuracy* (more information on both terms in **Section 1.3**.). Nonetheless, each outgoing Sensirion PM sensor is verified for *accuracy* and sorted by performance after calibration using the regularly maintained and aligned reference instruments and aerosols, as specified in the datasheet.

For a simple but thorough understanding, *precision* of PM sensors may be divided into two different contributions: calibration precision and long-term drift. Calibration precision is outlined in **Section 1.3**, while long-term drift is explained in **Section 4**.

1.3 Calibration Precision and Calibration Accuracy

Calibration precision, also referred to as *precision error*, *between-parts variation* or *device-to-device variation* (abbreviated as D2D), is the primary component of the *precision* specification. It provides information on the output deviation of an individual sensor compared to the mean output of a group of sensors, such as a batch, at the time of calibration. Major causes for tolerance in calibration precision are physical variations such as aerosol homogeneity, environmental conditions, repeatability and stability of the calibration reference, and stability of the sensors. Under this definition, the calibration precision is independent of the individual reference characteristic, as long as it delivers repeatable readings.

Sensirion specifies calibration precision in the following way:

Calibration Precision: measured output deviation of an individual sensor against the output mean of a sensor batch at the time of calibration. The product complies with the specification, if the measured deviations are located inside the precision limits (Conditions: 25°C and nominal supply voltage, unless otherwise stated).

In contrast, **calibration accuracy** refers to the measured deviation of an individual sensor's output compared to the output of Sensirion's regularly maintained and aligned reference instruments at the time of calibration.

As mentioned above, it is often not possible to quantitatively compare the sensors output to the output of different high-end reference instruments around the world, as these high-end devices might show considerable output differences among each other if not properly configured and maintained.

1.4 Measuring Calibration Precision

To determine calibration precision, the process begins by randomly selecting multiple SEN6x modules (at least 25) that have not yet been deployed in the field. These modules are then operated simultaneously within a controlled, decaying concentration of KCl (this aerosol was used in the datasheet for the SEN6x), transitioning from high to low levels. Once the aerosol in the test chamber becomes homogeneous and stable, a time-averaged concentration $\overline{MC_i}$ is extracted over a consistent time window for all sensors, within a defined concentration range. To minimize the influence of statistical noise, this averaging period must be at least 150 s long, starting from any point after stabilization. An example of the extraction of the time-averaged concentration value $\overline{MC_i}$ for precision evaluation is shown for one sensor in **Figure 2** and for multiple sensors (e.g. all sensors in the experiment) in **Figure 3**.

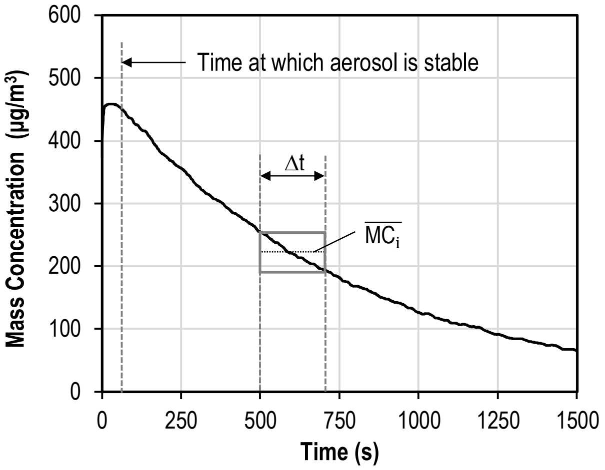

Figure 2. Extraction of the time-averaged mass concentration value ($\overline{MC_i}$) for a Sensirion PM sensor. To filter out the impact of the statistical noise of the measurement, the concentration is averaged over a time period Δt (minimum 150 s).

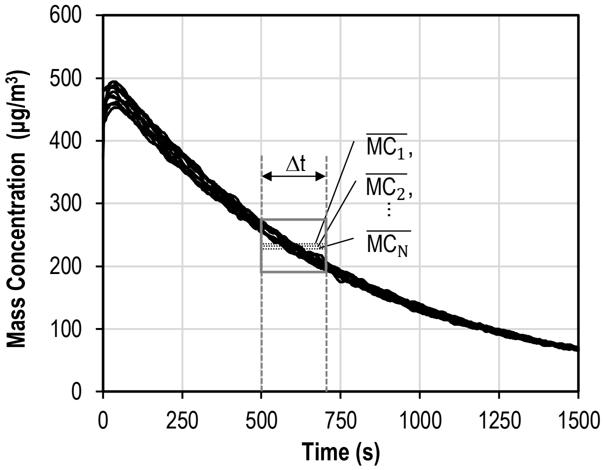

Figure 3. Extraction of the time-averaged mass concentration values ($\overline{MC_i}$) for several sensors. In order to evaluate precision, sensors are individually averaged over the same time period Δt and all $\overline{MC_i}$ values are collected in a distribution.

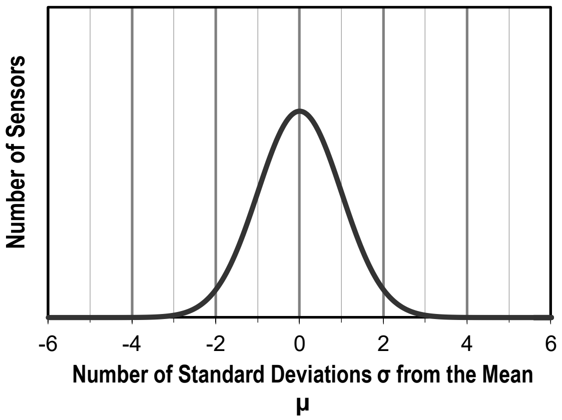

Figure 4. Distribution of time-averaged mass concentration values ($\overline{MC_i}$) for several Sensirion PM sensors around the mean μ. The range μ±2σ (typical deviation) is expected to fall within the precision limits specified in the datasheet, while the maximal deviation observed for any sensor in the experiment should remain within twice those limits.

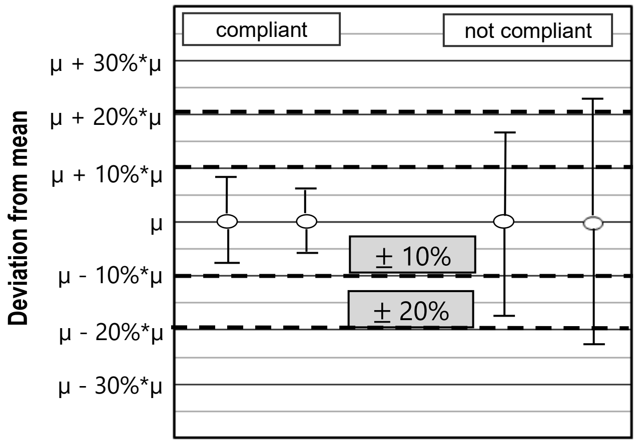

Figure 5. Sensor distribution examples that either comply (left) or do not comply (right) with the precision range specified in the SEN6x datasheet [1]. Open dots indicate mean values μ, while error bars represent the μ±2σ range (typical deviation), which must fall within the datasheet's precision limits (± 10% for 100-1000$\mu g/m^3$) for the sensors in the experiment to be considered compliant. All individual sensors must exhibit deviations of less than ±20% from the mean.

After extracting the time-averaged mass concentration values $\overline{MC_i}$ from each sensor in the experiment, the mean value μ is calculated across all sensors. Based on it, the standard deviation σ is determined. The range μ±2σ (called typical deviation, encompassing approximately 95% of all sensors) defines the experiment's *precision*. The sensors in the experiment are considered compliant if the range μ±2σ falls within the defined precision limits in the datasheet (see **Figure 4** and **Figure 5**). Specifically, the μ±2σ range must be narrower than ±10% of the mean (i.e. μ±0.1*μ) for aerosol concentrations between 100-1000$\mu g/m^3$ or (±(5 μg+5%) for concentrations <100 $\mu g/m^3$ respectively). Additionally, no individual sensor in the experiment may deviate more than ±20% from the mean, which is defined as the maximum deviation for this concentration range.

1.5 Performance of PM4.0 and PM10

One of the limiting aspects of today's laser-based particulate matter sensors is their limited detection rate with respect to the actual sampling volume. While more expensive instruments are often configured to count each particle in the sampling volume, low-cost sensors only capture a much smaller fraction of the aerosol particles (e.g. 3-5%) and therefore heavily rely on statistics and extrapolation. In typical aerosols, the number of particles between 2.5 and 10 μm is very low compared to the number of particles smaller than 2.5μm.

To give an example, at the same mass concentration ($\mu g/m^3$), an artificial aerosol composed of particles having a diameter of 10 μm contains 1000 times fewer particles compared to an aerosol with 1 μm particles, as the weight scales with the volume, which in turn scales with diameter raised to the power of 3. To measure PM10 with the same precision as PM1.0, a low-cost PM sensor would have to integrate over many hours to obtain enough statistics.

Therefore, our advanced algorithm directly derives PM4.0 and PM10 outputs of Sensirion's PM sensors from the measured raw data. Although larger particles can be detected by Sensirion's PM sensors, the integration time needed to produce statistically meaningful data would be excessively long, making direct measurement impractical for most applications.

2 Electrical Specifications

2.1 Supply Voltage

The Supply Voltage (V_{DD}) range is defined with an upper and a lower limit plus a typical value. Any supply voltage in that range may be used for continuous operation. Absolute maximum voltages may be applied for a limited time. The typical value defines the supply voltage at which the sensors are calibrated and at which outgoing quality control is performed.

2.2 Current and Energy Consumption

In operation the sensor draws a certain Supply Current, I_{DD}. This current varies depending on the different modes, e.g., idle and measurement. Furthermore, current consumption varies across sensor samples – the average is specified as the typical value while with minimum and maximum values the upper and lower limit is defined.

3 Acoustic Emission Level

3.1 Basic Considerations

Acoustic emission level provides information on the acoustic sound pressure level (SPL) caused by the sensor. The main sources of acoustic noise for OPCs and PM sensors for the mass-market are the mechanical moving parts, such as the fan, as well as the vibrations of the enclosure of the package. Sensirion high precision manufacturing assembly line ensures high quality packaging, limiting acoustic noise arising from vibration of the sensor enclosure. Regarding the fan, best-of-class components are chosen for Sensirion PM sensors. Additionally, it is important to note that an additional and unwanted external source of acoustic noise may arise from the mechanical coupling between the sensor and the fixations, which can be reduced by a proper mechanical design and assembly [2].

3.2 Acoustic Emission Level

SPL is a logarithmic measure of the effective pressure of a sound relative to a reference value, and it is defined by the formula:

$$\mathrm{L_p}\ [\mathrm{dB}] = 20 \log_{10}\left(\frac{p}{p_0}\right)$$

p is the sound pressure, p_0 represents the reference sound pressure (i.e., 20 µPa), which is often considered as the threshold of human hearing. Note that the lower limit of audibility corresponds to 0 dB. To better reflect human perception of sound, the so-called A-weighting, abbreviated as dB(A), is applied to the measured SPL, which is valid for SPLs up to 55 dB. The SPL is typically characterized according to IEC 61672-1 standard inside an anechoic chamber with very low background noise.

The acoustic emission limits of SEN6x products are specified at 25°C, nominal supply voltage and normal measurement mode, unless otherwise stated.

For this characterization method, an acoustic analyzer Brüel & Kjaer 2250 with calibrated microphone B&K 4189 is operated in an anechoic chamber with a background noise of < 16 dB(A). Each sensor is placed on noise absorbing foam with the fan outlet centered 0.2m below a microphone (see **Figure 6**).

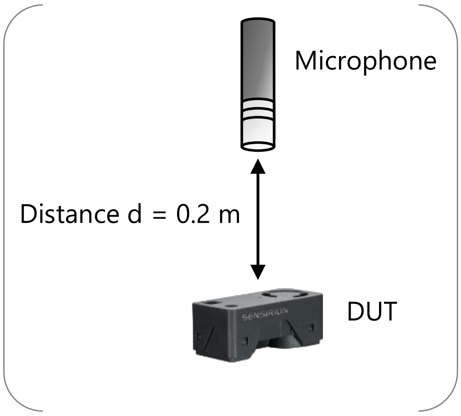

Figure 6. Measurement setup for the acoustic emission level test.

The sound emission of the module is logged every second over a period of 90 s (i.e., 90 data points) with a recording quality of 20 kHz and a resolution of 24 bit.

Fluctuations of the sound pressure are smoothed by using the equivalent continuous sound level LAeq. LAeq is the logarithm of the ratio of a time-mean-square, A-frequency weighted sound pressure for a stated time period (1s for our measurement) to the square of the reference sound pressure (20 µPa).

While the first 70 s of the measurement are used for stabilization (warm-up, stabilizing the fan speed), the successive 20 s (i.e., 20 data points) are taken to calculate the median of the LAeq.

An example of acoustic emission level measurement for a Sensirion PM sensor is shown in . The y-axis shows the LAeq value in dB(A) whereas the x-axis shows the time elapsed from the beginning of the test in seconds.

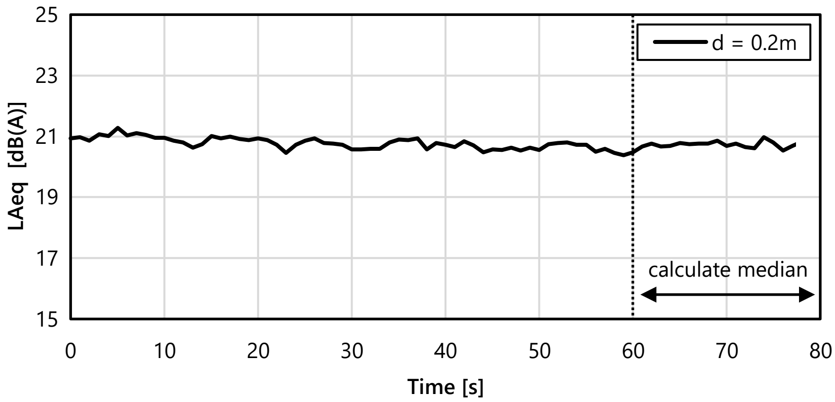

Figure 7: Measurement data for acoustic emission level in dB(A) for the typical SEN6x PM sensor at a distance of 0.2m.

4 Long-Term Drift & Lifetime

4.1 Lifetime definition

According to the SEN6x datasheet, the product lifetime is defined based on mean-time-to-failure (MTTF) calculations. Specifically, MTTF assessments have been performed individually for each subcomponent of the SEN6x. At the module level, a Resistance to Dust (RD) test (see **Section 4.7**), along with all subsequent reliability tests, have been conducted to verify that the long-term drift of the module remains within the specified limits.

4.2 Basic Considerations

Long-term drift applies to precision and acoustic emission level specifications.

Concerning precision, the sensor aging may lead to drift of the measured value compared to initial operation. Such long-term drift may trend upward or downward, and it may even change direction over the course of time. The long-term drift value denotes the change (i.e., the increase) of the precision limits per year.

Concerning acoustic emission level, the sensor aging may lead to drift of the measured level compared to initial operation. Such a long-term drift is usually positive: it moves to the upper side in the course of time, i.e., the sensor acoustic emission level increases. The long-term drift value denotes the drift (i.e., the increase) of the level limit per year.

4.3 Verification of Long-Term Drift

In the case of Sensirion PM sensors, long-term drift is verified by exposing a sample of sensors to several aging tests, as described below.

4.4 Low Temperature Operating Lifetime (LTOL)

LTOL is a thermally activated aging test in which sensors are operated at reduced temperature for a defined test duration (e.g. -10°C, 168 hours) to simulate a much longer lifespan at typical operating conditions (25°C). The test duration for accelerated aging conditions can be calculated following JESD22-A108.

4.5 High Temperature Humidity Bias (THB)

THB is a temperature and humidity activated aging test where sensors are operated at elevated temperature and humidity levels for a defined test duration (e.g., 60°C, 90% RH, 860 hours) to simulate a much longer lifespan. The test duration for accelerated aging conditions can be calculated following JESD22-A101D.

4.6 Temperature Cycling (TC)

TC is a thermo-mechanically activated aging test. Sensors are operated in repeated low and high temperature cycles (e.g. 380 cycles, -10 °C/ +60°C, 30 minutes each) to simulate typical cyclical exposure over lifetime. The typical temperature difference that is being simulated can be calculated following JESD22-A104E.

4.7 Resistance to Dust (RD)

RD is an environmentally activated aging test in which sensors are exposed to a very high PM concentration level in order to simulate dust exposure over lifetime. The test conditions are designed to replicate an indoor PM concentration of approximately 35 µg/m^3 over 10 years. This level corresponds to a rounded-up literature level of average indoor PM concentration during operation in Beijing [3].

5 Bibliography

[1] Sensirion AG, "Datasheet SEN6x," December 2025. [Online]. Available: https://sensirion.com/resource/datasheet/SEN6x

[2] Sensirion AG, "SEN6x – Mechanical Design and Assembly Guidelines," October 2025. [Online]. Available: https://sensirion.com/resource/application_note/SEN6x_mechanical_design_assembly_guidelines

[3] The Beijing News, “PM2.5 Concentration in Beijing-Tianjin-Hebei Region Decreases by 3.4 Percent Year-on-on-Year in 2024,” March 2025. [Online]. Available: https://english.beijing.gov.cn/specials/livablegreenbeijing/livablegreennews/202503/t20250303_4023256.html

6 Revision History

Date	Version	Pages	Changes
January 2026	1.0	all	Initial version

Important Notices

Warning, Personal Injury

Do not use this product as safety or emergency stop devices or in any other application where failure of the product could result in personal injury (including death). Do not use this product for applications other than its intended and authorized use. Before installing, handling, using or servicing this product, please consult the data sheet and application notes. Failure to comply with these instructions could result in death or serious injury.

If the Buyer purchases or uses SENSIRION products for any unintended or unauthorized application, Buyer shall defend, indemnify and hold harmless SENSIRION and its officers, employees, subsidiaries, affiliates and distributors against all claims, costs, damages and expenses, and reasonable attorney fees arising out of, directly or indirectly, any claim of personal injury or death associated with such unintended or unauthorized use, even if SENSIRION is allegedly negligent with respect to the design or the manufacture of the product.

ESD Precautions

The inherent design of this component causes it to be sensitive to electrostatic discharge (ESD). To prevent ESD-induced damage and/or degradation, take customary and statutory ESD precautions when handling this product. See application note "ESD, Latchup and EMC" for more information.

Warranty

SENSIRION solely warrants to the original purchaser of this product for a period of 12 months (one year) from the date of delivery that this product is of the quality, material and workmanship defined in SENSIRION's published specifications of the product. Within such period, if proven to be defective, SENSIRION shall as sole and exclusive remedy, in SENSIRION's discretion, repair this product or send a replacement product, free of charge to the Buyer, provided that:

- notice in writing describing the defects shall be given to SENSIRION within fourteen (14) days after their appearance;
- such defects shall be found, to SENSIRION's reasonable satisfaction, to have arisen from SENSIRION's faulty material or workmanship;
- the defective product shall be returned to SENSIRION's factory at the Buyer's expense; and
- the warranty period for any repaired or replaced product shall be limited to the unexpired portion of the original period.

The Buyer shall at its own expense arrange for any dismantling and reassembly that is necessary to repair or replace the defective product. This warranty does not apply to any product which has not been installed or used within the specifications recommended by SENSIRION. EXCEPT FOR THE WARRANTIES EXPRESSLY SET FORTH HEREIN, SENSIRION MAKES NO WARRANTIES, EITHER EXPRESS OR IMPLIED, WITH RESPECT TO THE PRODUCT. ANY AND ALL WARRANTIES, INCLUDING WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, ARE EXPRESSLY EXCLUDED AND DECLINED.

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SENSIRION reserves the right, without further notice, (i) to change the product specifications and/or the information in this document and (ii) to improve reliability, functions and design of this product.

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