Literature Review:

Key Insights from Hammer et al. (2022) on Standardizing Aerosol Generation and CPC Calibration with the °Silver Particle Generator (SPG)

APPLICATION NOTE 027-24

Introduction

Aerosol generation plays a fundamental role in various fields, including environmental monitoring, emissions testing, and instrument calibration. However, achieving reproducibility, stability, and precision in aerosol production has long been a challenge, particularly with traditional methods such as combustion sources or tube furnaces, which often introduce variability and complexity (Chen et al., 2011). To address these issues, we have developed a user-friendly aerosol generator that operates at the push of a button, providing a stable and controlled source of silver particles with minimal effort.

This **Application Note provides a concise summary of the key findings from the detailed scientific characterization of the first generation °Silver Particle Generator (SPG), as published by Hammer et al. (2022).** The SPG was developed to offer a stable and thermally resistant silver aerosol source that meets the requirements of international standards and regulatory frameworks. Its significance is particularly evident in the context of **ISO 27891:2015**, the international standard for the calibration of Condensation Particle Counters (CPCs), and the tightening European emissions regulations, which lower the particle number (PN) emissions threshold from **23 nm to 10 nm**.

For a comprehensive scientific analysis of the SPG's aerosol properties and performance, readers are encouraged to refer to the original publication by Hammer et al. (2022). This study marks the first time that the SPG was analyzed and characterized at the national metrological institute METAS[1]

Notably, this characterization at a metrological institute was a first, and the primary distinction between the first-generation SPG and the current version lies solely in internal design modifications. Before delving into the characterization of the SPG and its performance, it is essential to outline the core specifications that enable its high precision in aerosol generation.

Specifications of the SPG
The SPG is designed to meet the demanding requirements of both research and industrial applications, offering advanced control over aerosol production. Here are the key specifications:

- **Short Warm-Up Time**: The SPG requires less than 15 minutes for warm-up.
- **Wide Particle Size Range**: It generates aerosol particles with diameters from 2 nm to 200 nm (300 nm for high temperature version).
- **High Concentrations**: The SPG achieves concentrations exceeding 1 x 10^7 p/cc.
- **Stable and Reproducible number concentration**: The SPG maintains a number concentration stability within ±1% over a period of 14 hours and a stability with switching on and off over a period of 1 week below 15%.
- **Stable and Reproducible size distribution**: The SPG maintains a size distribution stability within ±1% over a period of 14 hours and a stability with on and off over a period of 1 week below 10%.
- **The GMD** @ 1000°C is 15 nm and @ 1100 °C it is 55 nm (in carrier gas: air).
- **The GSD** @ 1000°C is 1.15[2] and @ 1100 °C it is 1.4 (in carrier gas: air).
- **Remote Monitoring**: Data can be logged remotely via USB or LAN.
- **One-Touch Presets**: Quick-select size modes with customizable settings. 2 factory settings and one free programmable custom setting.
- **Wide range Material Compatibility**: The SPG allows the generation of particles from various materials such as Tetracontane, any salts (combinations of Li^+, Na^+, K^+ and F^-, Cl^-, Br^-, J^-), various metals such as Ag (as long as you can evaporate the metal below 1100°C).
- **Gas Compatibility**: It operates with nitrogen (N_2) or compressed air or any other gas you may wish to use during the evaporation and condensation process.
- **Sintering capability**: Optional sintering stage for spherical particle production.
- **Residence Chamber**: Optional residence chamber to grow the particles.
- **Dilution**: Optional dilution to decrease number concentration.
- **Wide range of flows**: Accurate flow control via high precision flow controller between 0.1 to 15 L/min flow.

1. Fundamentals of the °Silver Particle Generator (SPG)

The SPG is a vertical tube furnace that vaporizes high-purity silver (99.99%) to form aerosol particles. The silver vapor is transported by a carrier gas (typically nitrogen or air) and condenses into particles. These particles are ideal for calibration due to their stability and

[1] https://www.metas.ch/metas/de/home.html
[2] *According to **Hinds (1982)**, aerosols with a **geometric standard deviation (GSD) smaller than 1.2** are classified as **monodisperse**. Hinds, W. (1982). Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles. John Wiley & Sons, Inc.*

reproducibility, which align with the standards set by **ISO 27891:2015** and **ISO 15900:2020**. The latter defines the procedures for particle size distribution measurement using DMAs (Hammer et al., 2022).

1.1 Modes of Operation

The SPG has two preset operation modes and one custom setting.

- **Mode 1 @ 1000 °C**: produces particles smaller than 10 nm, primarily spherical, particularly when N_2 is used as the carrier gas (see Figure 10).
- **Mode 2 @ 1100 °C:** generates larger particles (over 10 nm), which can be reshaped into uniformly spherical particles via sintering at 400°C, especially when nitrogen is used as the carrier gas.
- **Custom** to allow your own preset for size and number concentration.

The SPG can produce high aerosol number densities (up to 1×10^7 particles/cm³), making it ideal for applications that demand high precision in aerosol generation, such as vehicle emissions testing, which must comply with **EN 16976:2024** standards for air quality monitoring (Giechaskiel et al., 2020).

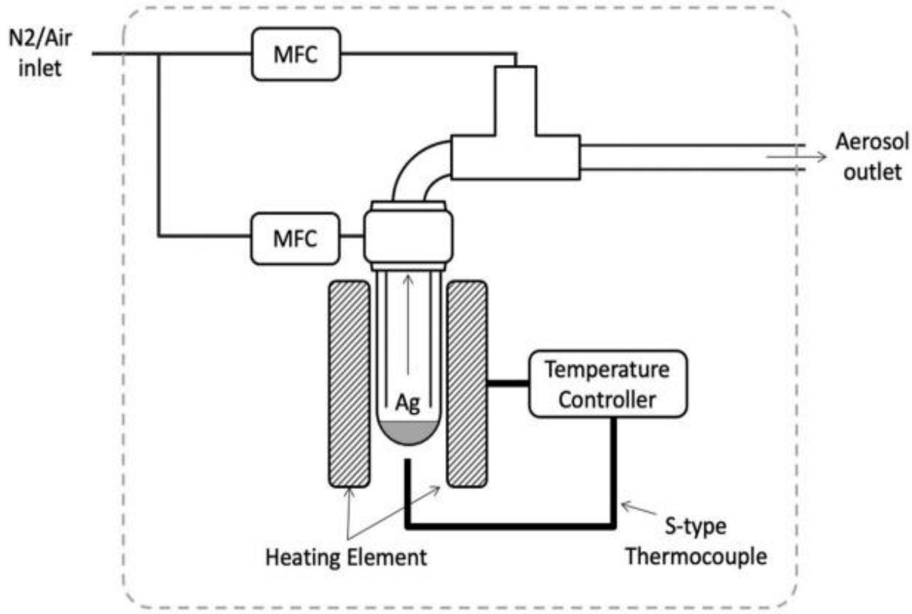

*Figure 1 : Schematic diagram of the °**Silver Particle Generator** (SPG) system, illustrating the key components involved in aerosol generation. Pressurized nitrogen or air is used as a carrier gas, while mass flow controllers (MFCs) regulate the flow through the system. The silver particles are generated by heating high-purity silver in a vertical tube furnace and condensing the vapor into aerosol particles, controlled by a PID temperature controller (Hammer et al., 2022).*

2. Aerosol Properties and Stability

The SPG was developed to address the key challenges associated with traditional aerosol generation methods, such as inconsistency, limited reproducibility, and difficulties in producing stable particle sizes. Below, we examine its performance regarding aerosol stability and control over aerosol density through dilution.

2.1 Stability of Generated Aerosols

The stability of the aerosols generated by the SPG is a critical factor, particularly for its application in calibrating instruments like CPCs and DMAs. The SPG can produce highly stable aerosols with consistent particle sizes over extended periods, which ensures reliable and reproducible calibration results.

In a series of tests, the SPG demonstrated exceptional stability in aerosol generation over continuous operation, with the geometric mean mobility diameter (GMD) showing minimal variation. During tests spanning several hours, the GMD for Mode 1 aerosols showed a variance of less than 1.3%, which is a key indicator of the SPG's ability to maintain precise control over the size distribution of generated particles.

For example, across multiple tests conducted over three consecutive days, the following GMD values were recorded:

- **Mode 1**: Produced aerosols with a GMD of 5.48 nm ± 0.73 nm.
- **Mode 2**: With nitrogen and sintering applied, the aerosols exhibited a GMD of 8.10 nm ± 0.15 nm.

These results highlight the SPG's reliability in producing consistent particle sizes over time. This high degree of stability ensures that aerosol instruments like CPCs and DMAs can be calibrated with confidence, as the SPG minimizes errors caused by fluctuations in particle size.

Additionally, the SPG's day-to-day stability is equally impressive. Over several days of testing, the GMD showed minimal variability, ensuring that the device consistently produces aerosols within the desired size range, regardless of operational duration or environmental condition.

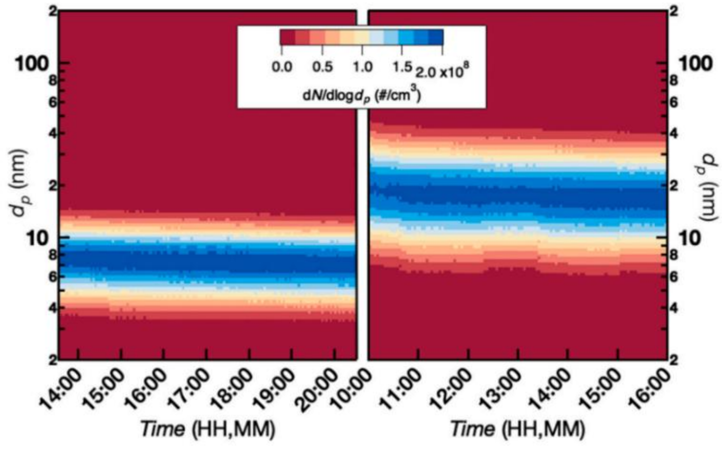

Figure 2 Long-term stability test of Mode 1 and Mode 2 aerosols over a 6-hour period. The variance in GMD remained below 1.3%, indicating strong stability during prolonged operation (Hammer et al., 2022).

The SPG's performance across consecutive days also showed consistent aerosol generation, with minimal variance in particle size. This stability makes it an optimal tool for ensuring that measurements for CPC and DMA calibrations remain accurate and repeatable.

2.2 Dilution Control and Aerosol Density

The °**Silver Particle Generator (SPG)** offers precise control over aerosol density and particle size through its internal dilution feature. Dilution plays a crucial role in managing particle coagulation, which can affect both the size and stability of the generated aerosols. By adjusting the internal dilution ratio, the SPG can produce smaller, more stable particles, which are ideal for calibration tasks requiring high precision.

For instance, in **Mode 1**, the particle size decreased from 7.38 nm at a dilution ratio of 1 (DR1) to 5.2 nm at a dilution ratio of 6 (DR6). Similarly, in **Mode 2**, the GMD decreased from 16.25 nm at DR1 to 11.5 nm at DR6. This ability to fine-tune the aerosol's size and density through dilution makes the SPG highly adaptable for a wide range of calibration needs, including those specified in ISO 15900 (Determination of particle size distribution – Differential mobility analysis of aerosols) and ISO 27891 (Aerosol particle number concentration – Calibration of condensation particle counters (CPCs)).

The relationship between the internal dilution ratio and aerosol density is particularly important for controlling coagulation. Higher dilution ratios reduce coagulation, resulting in more monodisperse particles, which is critical for calibrating particle measurement devices. The SPG's design allows for precise manipulation of the dilution ratio, ensuring that the generated aerosols remain stable and reproducible over time.

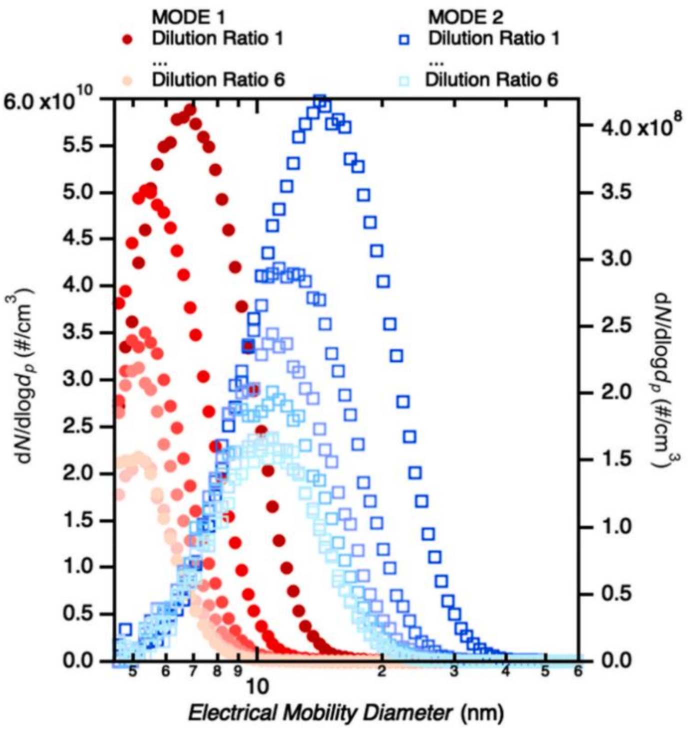

Figure 3 *The effect of internal dilution on aerosol size distribution in both Mode 1 (<10 nm) and Mode 2 (>10 nm). As the dilution ratio increases, the particle size decreases, leading to more stable and monodisperse aerosols. The mobility size distributions for Mode 1 and Mode 2 aerosols at different internal dilution ratios (DR1 to DR6). The particle size decreases with increasing dilution ratio, and the data is corrected for external dilution factors but not for changes in CPC counting efficiency for particles smaller than 15 nm. The final GMD for each mode is shown along with the uncertainties derived from at least three independent measurements (Hammer et al., 2022).*

Key Insights from Figure 3:

1. **Mode 1 Results (Small Particles, <10 nm):**
   - In **Mode 1**, the SPG generates particles with a GMD of **7.38 nm ± 0.12 nm** at a dilution ratio (DR1), which means no internal dilution.
   - When the dilution ratio is increased to DR6, the GMD decreases to **5.2 nm ± 0.01 nm**. This reduction is primarily due to the reduction in particle coagulation at higher dilution ratios, which leads to smaller and more stable particles.
2. **Mode 2 Results (Larger Particles, >10 nm):**
   - In **Mode 2**, the GMD starts at **16.25 nm ± 0.05 nm** at DR1 and decreases to **11.5 nm ± 0.04 nm** at DR6. Like Mode 1, this decrease is also attributed to reduced particle coagulation as dilution increases.
   - **Aerosol Density**: The corresponding aerosol density (dN/dlogdp) in Mode 1 is **6.10×10^{10} particles/cm³** at DR1 and decreases as the dilution increases. In Mode 2, the aerosol density is **4.18×10^{8} particles/cm³** at DR1.

Figure 4 provides a detailed visualization of the GMD as a function of the internal dilution ratio for both **Mode 1** and **Mode 2**. The GMD is an important measure of aerosol monodispersity, with lower values indicating a more uniform particle size distribution. As shown in the figure, the GMD decreases as the internal dilution ratio increases, particularly in **Mode 1**, where it drops below 1.2 for higher dilution ratios. As the dilution ratio increases, the particle size decreases.

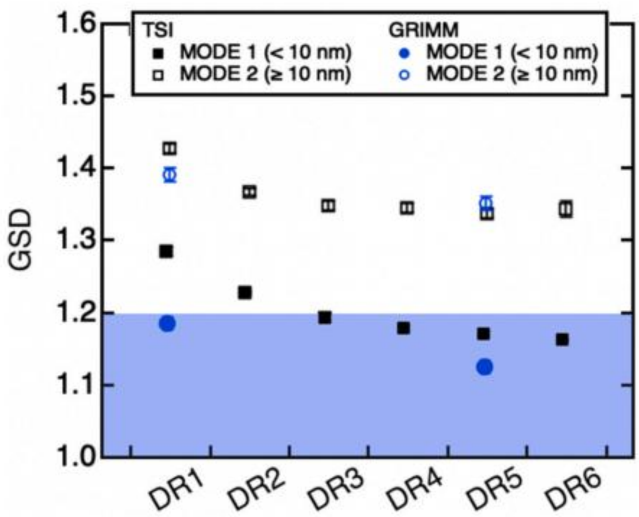

*Figure 4 The GMD as a function of the internal dilution ratio (DR) for both **Mode 1** and **Mode 2**. The particle size distributions were measured using two SMPS systems: TSI (DMA 3085 + CPC 3776) and GRIMM (M-DMA and CPC 5.403). The light blue region represents the threshold for monodisperse aerosols according to Hinds (1982) (Hammer et al., 2022).*

For example, in **Mode 1**, the GMD decreases from 7.38 nm at dilution ratio 1 (DR1) to 5.2 nm at dilution ratio 6 (DR6). Similarly, in **Mode 2**, the GMD decreases from 16.25 nm at DR1 to 11.5 nm at DR6.

The figure also compares results from two different Scanning Mobility Particle Sizer (SMPS) systems (TSI and GRIMM), which both confirm that higher dilution ratios lead to more monodisperse aerosols. This trend is less pronounced in **Mode 2**, but the GMD values remain within acceptable limits for calibration purposes. Aerosols with GMD below 1.2 are considered monodisperse, making them ideal for use in calibration tasks[3].

2.3 Aerosol Properties

The SPG's ability to produce monodisperse particles across a range of sizes is another key feature that enhances its suitability for instrument calibration. The aerosols generated by the SPG are thermally stable and non-volatile, which makes them ideal for use in calibration scenarios where high accuracy and consistency are required.

- **Mode 1** typically produces smaller, spherical particles . These particles are particularly useful for calibrating instruments that require sub-10 nm particle sizes.

- **Mode 2** generates larger particles, which can be reshaped into uniform spherical forms through sintering[4] at 800°C[4]. This is particularly useful for applications that demand highly uniform particle shapes, such as those used in vehicle emissions testing or environmental monitoring.

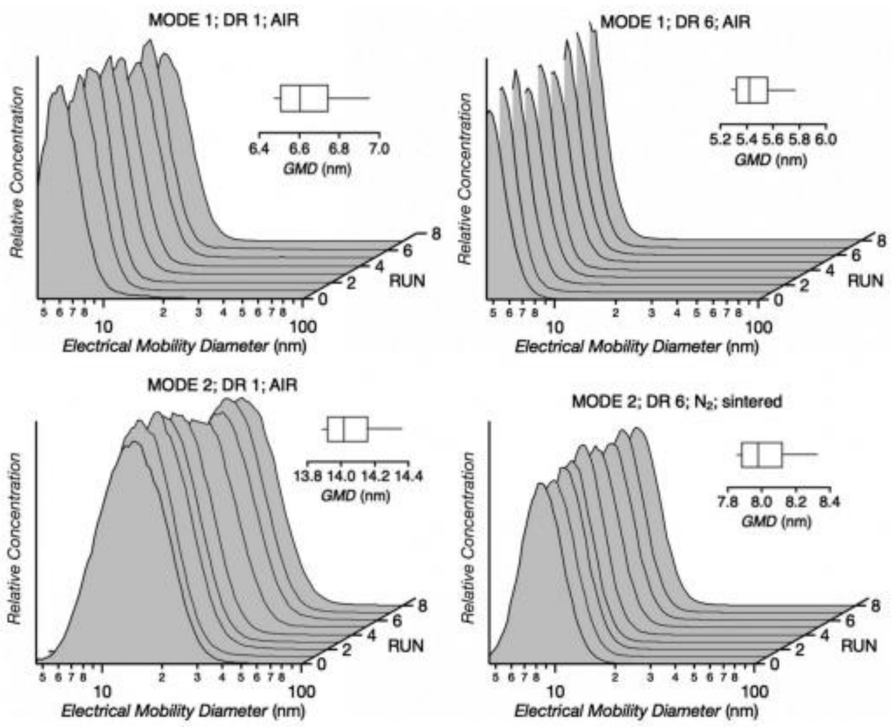

Figure 5 The box plots highlight the stability of the aerosol size distribution produced by the SPG over time. For Mode 1, using air and a dilution ratio of DR6, the median GMD is centered at approximately 5.48 nm with minimal variability. For Mode 2, the median GMD increases to around 13.99 nm when air is used and to 8.10 nm when nitrogen (N_2) and sintering at 800°C are applied. The plot shows the 50th percentile as the center of each box, with the 25th and 75th percentiles forming the edges. Whiskers indicate the 10th and 90th percentiles, showcasing the reproducibility of the particle size (Hammer et al., 2022).

[3] Based on Hinds (1982)*, aerosols with GSD smaller than 1.2 can be categorized as monodisperse. Hinds, W. (1982). Book "Aerosol technology: Properties, behavior, and measurement of airborne particles". John Wiley & Sons, Inc.
[4] Current sintering processes are performed at 400°C, as recommended by Ku. et al. (2006). For further details, see *Application Note 030-24: Transformation of Silver Agglomerates through Sintering*, available at https://catalytic-instruments.com/silver-particle-generator-spg/.

The flexibility of the SPG allows operators to adjust the particle size and shape depending on the application, making it a versatile tool for various fields, including aerosol science, emissions control, and air quality monitoring.

This data confirms that the **°Silver Particle Generator** provides a reliable and repeatable source of stable silver aerosols, with consistent size distributions across multiple experimental runs. Its ability to ensure reproducibility in GMD under varying operating conditions makes the SPG particularly well-suited for calibration tasks in aerosol measurement, where high precision and consistency are essential.

3. Calibration of Aerosol Measurement Instruments

3.1 CPC Calibration with Silver Particles as Test Aerosol and Calibration Methodology

Condensation Particle Counters are widely used to measure particle concentrations in air quality monitoring and emissions testing. Accurate CPC calibration is essential for ensuring compliance with regulatory standards, and the SPG offers an optimal aerosol source for this purpose.

The SPG is widely used for calibrating CPCs, following the strict guidelines set by **ISO 27891:2015**, which ensures traceable calibration of particle counting instruments. CPC calibration was conducted by comparing the counting efficiencies of three CPCs (TSI 3775, TSI 3752, and GRIMM 5.412) with those of a Faraday Cup Aerosol Electrometer (FCAE). The results confirmed that the SPG-generated silver aerosols are an ideal source for CPC calibration, yielding reliable counting efficiencies that are consistent with the d50 cut-off values[5] of each device (Hammer et al 2022).

Setup: The aerosol stream generated by the SPG was divided using a four-way splitter, allowing simultaneous measurements by three CPCs (TSI 3775, TSI 3752, and

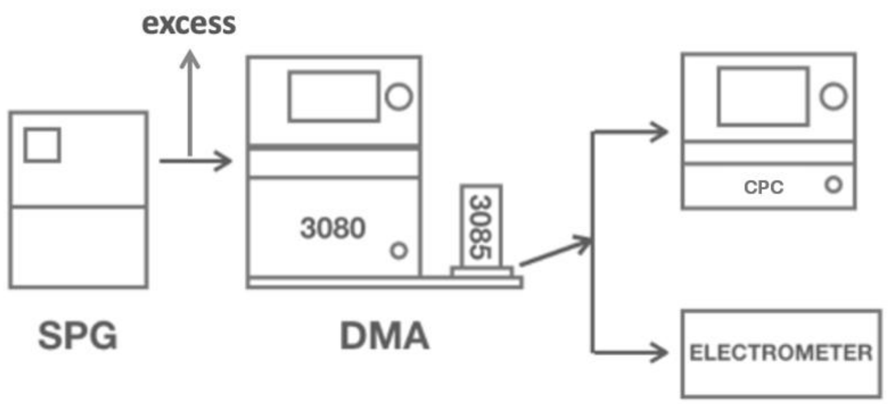

Figure 6 Simplified representation of the calibration of a CPC using a reference instrument, in this case, an electrometer (FCAE).

[5] **The D50 cut-off value** refers to the particle diameter at which a measurement instrument detects **50% of the actual particle concentration** due to its counting efficiency curve. This threshold is commonly used in the calibration of CPCs to define their lower detection limit (ISO 27891:2015).

GRIMM 5412) and the FCAE. The **nano-DMA** (TSI 3085) was used to control the aerosol size distribution in the range of 3 to 15 nm (Hammer et al 2022).

CPC calibration was conducted according to the **ISO 27891** standard, which specifies the procedures for aerosol particle number concentration calibration. The SPG-generated silver aerosols were size-selected using a **DMA**, and the CPCs were calibrated by comparing their counting efficiencies against a **FCAE.**

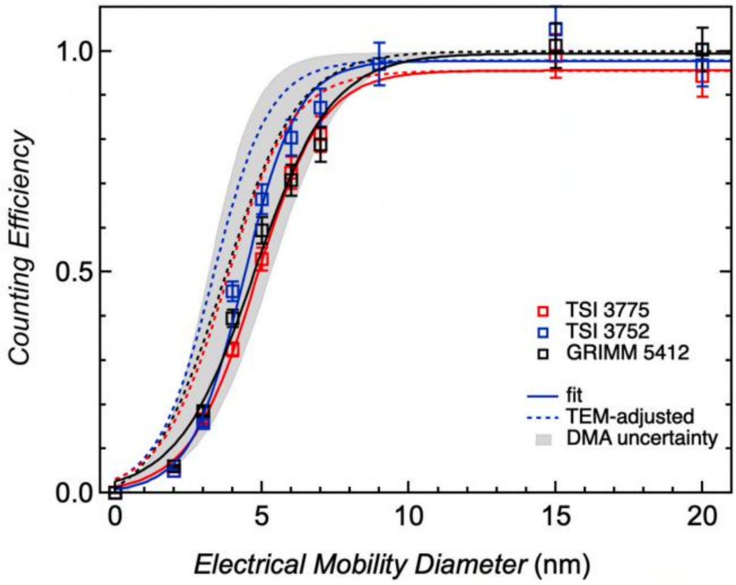

Figure 7 This figure presents the counting efficiency curves of three CPCs (TSI 3775, TSI 3752, and GRIMM 5.412) against the reference FCAE, according to the calibration methodology described in ISO 27891:2015. The efficiency curves were plotted as a function of particle mobility diameter, with the d50 cut-off values determined through a sigmoidal fit (Hammer et al., 2022).

The **CPC counting efficiency** was measured as a function of particle diameter, and the **d50 cut-off** was determined for each CPC:

- **TSI 3775**: 4.65 nm
- **TSI 3752**: 4.24 nm
- **GRIMM 5.412**: 4.14 nm.

These d50 values are consistent with the nominal cut-off values for these devices, confirming the SPG's suitability for CPC calibration (Hammer et al 2022).

3.1.3 Effect of Sintering on Calibration Accuracy

When the SPG operates in **Mode 2**, the particles tend to form aggregates, which can impact CPC calibration. To ensure consistent, spherical particles, sintering is applied at 800°C, reshaping the aggregates into a more uniform form.

Figure 7 presents three TEM images of silver particles produced in Mode 2 under different conditions:

(a) Particles generated with air as the carrier gas, showing non-spherical shapes.

(b) Particles generated with nitrogen as the carrier gas, showing improved but still non-uniform shapes.

(c) Particles subjected to sintering at 800 °C[6] in nitrogen, which reshapes them into uniformly spherical forms, critical for calibration accuracy (Hammer et al., 2022).

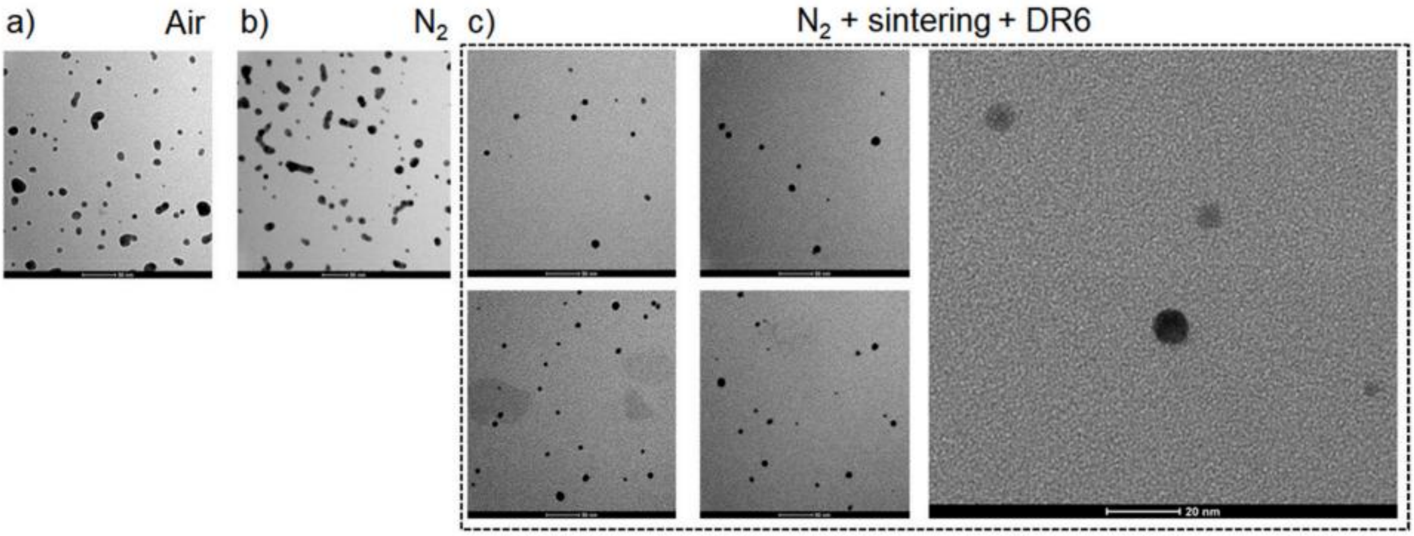

Figure 8 TEM images of silver particles before and after sintering, illustrating the transformation into spherical particles (Hammer et al., 2022).

Sintering Impact: The sintering process significantly improved the calibration accuracy by producing uniformly spherical particles. Aggregated particles showed a wider spread in counting efficiency, which was reduced after sintering (Hammer et al 2022).

3.1. Influence of Carrier Gas and Dilution

The SPG allows flexibility in choosing the carrier gas (air or nitrogen) and controlling the dilution ratio, which can significantly impact particle generation and subsequent calibration accuracy. The use of nitrogen as the carrier gas prevents silver oxide formation, which could otherwise skew the results by altering the particle surface properties.

- **Nitrogen vs. Air**: In Mode 1 (sub-10 nm particles), nitrogen was shown to produce smaller, more uniform particles, enhancing the precision of CPC calibration at low sizes. In Mode 2, nitrogen combined with sintering produced consistently spherical particles, reducing the overall uncertainty in counting efficiency (Hammer et al 2022).

Carrier/dilution gas	Sintering at 800 °C	Dilution ratio	GMD_{mob} (nm)	GSD_{mob} (−)	*Total aerosol density* (cm^{-3})
Air	No	1	13.43 ± 0.05	1.45 ± 0.00	$7.32 \times 10^8 \pm 4.61 \times 10^6$
Nitrogen	No	1	10.35 ± 0.02	1.36 ± 0.00	$5.41 \times 10^8 \pm 3.19 \times 10^7$
Nitrogen	Yes	1	11.88 ± 0.14	1.34 ± 0.00	$3.11 \times 10^8 \pm 2.03 \times 10^6$
Nitrogen	Yes	6	8.75 ± 0.08	1.28 ± 0.00	$9.20 \times 10^7 \pm 5.72 \times 10^5$

Figure 9 Effect of nitrogen as carrier gas and additional sintering at 800 °C on the aerosol size distribution of Mode 2 (>10 nm) using an internal dilution ratio (DR) of 1 and 6 and low aerosol flow mode (0.3 l/min) at CPC 3076 (Hammer et al., 2022).

[6] We recommend sintering at 400 °C, as advised by Ku et al. (2006). For more information, please refer to Application Note 030-24: **Transformation of Silver Agglomerates through Sintering**, available at https://catalytic-instruments.com/silver-particle-generator-spg/.

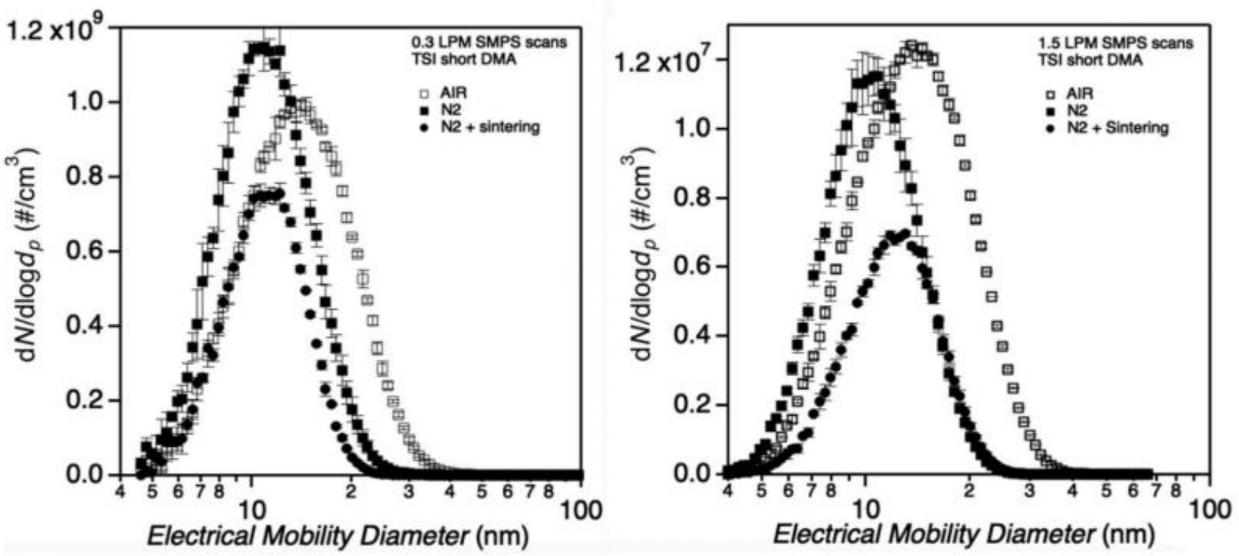

Figure 10 Influence of carrier gas (air vs. nitrogen) and sintering on CPC calibration. Nitrogen produced more uniform particles, leading to better calibration consistency (Hammer et al., 2022).

Summary

The **°Silver Particle Generator (SPG)** has been developed as a reliable and stable aerosol source with a small footprint, addressing challenges in traditional generation methods. Initially characterized at Metas, it is now implemented in multiple metrological institutes for research, calibration, and regulatory applications, continuously evolving to meet new demands.

This Application Note summarizes key insights from Hammer et al. (2022), highlighting the SPG's role in standardizing aerosol generation by producing monodisperse silver aerosols with high stability. It aligns with international standards such as ISO 27891:2015 for CPC calibration and ISO 15900:2020 for Differential Mobility Analyser, ensuring traceable and reproducible measurements in various applications.

With its ability to generate stable aerosols across different operational modes, the **°Silver Particle Generator** has become an essential tool in emissions testing, environmental monitoring, and instrument calibration. Ongoing improvements further enhance its performance and adaptability.

As the SPG continues to be adopted by leading institutions, it remains a valuable tool for precise and reliable aerosol generation. For the latest updates, advancements, and technical insights, visit https://catalytic-instruments.com/silver-particle-generator-spg/.

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Giechaskiel, B., Lahde, T., Suarez-Bertoa, R., Valverde, V., & Clairotte, M. (2020). Particle Number (PN) Emissions Limits and Measurement Procedures in the European Union. *Aerosol Science and Technology*, 54(9), 1009-1022.