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Procedures for the Sampling and Measurement of Particle Size Distributions from Aircraft Turbine Engines

RATIONALE

This SAE Aerospace Information Report (AIR) provides guidelines and multiple possible options for performing particle size measurements in ARP6320B nonvolatile Particulate Matter (nvPM) systems in parallel with nvPM mass and number measurements. It outlines several state-of-the-art methods for measuring aircraft engine exhaust nvPM Particle Size Distributions (PSDs) and discusses some of the uncertainties associated with different measurement techniques, calibration practices, and sampling location and conditioning. The goal of this information report is to advance the nvPM particle size measurement process for aircraft turbine engines.

While aircraft engine PSDs provide useful engineering information for evaluating combustion technologies, their primary benefit may be in improving system loss correction. Accurate system loss correction is essential for estimating engine-exit concentrations, enabling comparisons across engine technologies, supporting environmental monitoring, and becoming increasingly important as modern engine technologies and sustainable aviation fuels produce smaller nvPM. Using a measured PSD can significantly reduce uncertainty in estimating size-dependent system loss correction factors (k_{SL_num} and k_{SL_mass}) compared to the current ARP6481A methodology. Based on the available data, the ARP6481A methodology can underestimate system loss correction factors by as much as 67% compared to methods using measured PSD due mostly to uncertainties inherent to the measured nvPM number and mass. In contrast, k_{SL_num} and k_{SL_mass} derived from measured PSD have been shown to exhibit a variability $\leq 10\%$, influenced by the method, particle size instrument type, or model used. AIR6504A describes methodologies for using measured PSD to calculate system loss correction factors and includes a calculation tool.

This AIR also explores the applicability of using PSD measurements to derive nvPM number and mass emissions.

A summary of currently available PSD measurement technologies and instrument-specific recommendations is provided in [Section 10](#) and [Table 1](#).

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1. SCOPE

This document, expanding upon AIR6037A, provides technical specifications and operational protocols for instruments commonly used to measure aircraft engine nonvolatile Particulate Matter (nvPM) Particle Size Distributions (PSDs). For each instrument type, its functionality, calibration, uncertainties, and known limitations are discussed to support the development of procedures that help ARP6320B nvPM system operators reliably determine PSDs. Practical setup considerations, such as sample conditioning and instrument positioning, are highlighted, together with guidelines for maintenance, data correction, and quality control to minimize measurement uncertainty.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (U.S. and Canada only) or +1 724-776-4970 (outside U.S. and Canada), www.sae.org.

AIR6037A	Aircraft Exhaust Nonvolatile Particle Matter Measurement Method Development
AIR6504A	Procedure for the Calculation of Non-Volatile Particulate Matter Sampling and Measurement System Penetration Functions and System Loss Correction Factors
ARP6320B	Procedure for the Continuous Sampling and Measurement of Nonvolatile Particulate Matter Emissions from Aircraft Turbine Engines
ARP6481A	Procedure for the Calculation of Non-Volatile Particulate Matter Sampling and Measurement System Losses and System Loss Correction Factors

2.1.2 Other Publications

- 2.1.2.1 Durdina, L., Durand, E., Edebeli, J., Spirig, C., Brem, B.T., Elser, M., Siegerist, F., Johnson, M., Sevcenco, Y.A., and Crayford, A.P. (2024). Characterizing and Predicting nvPM Size Distributions for Aviation Emission Inventories and Environmental Impact. *Environmental Science & Technology*, 58, 10548-10557. <https://doi.org/10.1021/acs.est.4c02538>.
- 2.1.2.2 Durand, E., Durdina, L., Smallwood, G., Johnson, M., Spirig, C., Edebeli, J., Roth, M., Brem, B., Sevcenco, Y., and Crayford, A. (2023). Correction for particle loss in a regulatory aviation nvPM emissions system using measured particle size. *Journal of Aerosol Science*, 169, 106140. <https://doi.org/10.1016/j.jaerosci.2023.106140>.
- 2.1.2.3 Hinds, W.C. (1998). *Aerosol Technology: Properties Behavior, and Measurement of Airborne Particles*. Wiley-Interscience.
- 2.1.2.4 Baron, P., Willeke, K., and Kulkarni, P. (2011). *Aerosol Measurement, Principles, Techniques, and Applications* (Third ed.). John Wiley and Sons.
- 2.1.2.5 Durdina, L., Brem, B.T., Elser, M., Schönenberger, D., Siegerist, F., and Anet, J.G. (2021). Reduction of Nonvolatile Particulate Matter Emissions of a Commercial Turbofan Engine at the Ground Level from the Use of a Sustainable Aviation Fuel Blend. *Environmental Science & Technology*, 55, 14576-14585. <https://doi.org/10.1021/acs.est.1c04744>.

- 2.1.2.6 Lobo, P., Christie, S., Khandelwal, B., Blakey, S., and Raper, D. (2015). Evaluation of Non-Volatile PM Emissions Characteristics of an Aircraft Auxiliary Power Unit with Varying Alternative Jet Fuel Blend Ratios. *Energy & Fuels*, 29, 151016011415009. <https://doi.org/10.1021/acs.energyfuels.5b01758>.
- 2.1.2.7 Durand, E., Lobo, P., Crayford, A., Sevcenco, Y., and Christie, S. (2021). Impact of fuel hydrogen content on non-volatile particulate matter emitted from an aircraft auxiliary power unit measured with standardised reference systems. *Fuel*, 287, 119637. <https://doi.org/10.1016/j.fuel.2020.119637>.
- 2.1.2.8 Delhay, D., Ouf, F.-X., Ferry, D., Ortega, I.K., Penanhoat, O., Peillon, S., Salm, F., Vancassel, X., Focsa, C., Irimiea, C., Harivel, N., Perez, B., Quinton, E., Yon, J., and Gaffie, D. (2017). The MERMOSE project: Characterization of particulate matter emissions of a commercial aircraft engine. *Journal of Aerosol Science*, 105, 48-63. <https://doi.org/10.1016/j.jaerosci.2016.11.018>.
- 2.1.2.9 Giannelli, R., Stevens, J., Kinsey, J.S., Kittelson, D., Zelenyuk, A., Howard, R., Forde, M., Hoffman, B., Leggett, C., Maeroff, B., Bies, N., Swanson, J., Suski, K., Payne, G., Manin, J., Frazee, R., Onasch, T.B., Freedman, A., Khalek, I., Badshah, H., Preece, D., Premnath, V., and Agnew, S. (2024). Evaluation of methods for characterizing the fine particulate matter emissions from aircraft and other diffusion flame combustion aerosol sources. *Journal of Aerosol Science*, 178, 106352. <https://doi.org/10.1016/j.jaerosci.2024.106352>.
- 2.1.2.10 Crayford, A., Durand, E., Delhay, D., Durdina, L., Ortega, I.K., and Williams, P. (2022). RAPTOR Work Package 4: PM Measurements Deliverables Report. <https://doi.org/10.5281/zenodo.7385796>.
- 2.1.2.11 Owen, B., Lim, L., Christie, S., Johnson, M., Crayford, A., Matthes, S., Eirenschmalz, L., Righi, M., Muller, M., Terrenoire, M., and Janicke, U. (2023). AVIATOR - D7: A Synthesis of the Measurement and Technical Evidence in a Form Suitable for a Regulatory Policy Context. <https://aviatorproject.eu/wp-content/uploads/2023/12/AVIATOR-WP7-DEL-023-PU-v1.1-FINAL-D7.27.3.pdf>.
- 2.1.2.12 TSI Inc., 2019. Aerosol Instrument Manager® Software For Scanning Mobility Particle Sizer™ (SMPS™) Spectrometers, User manual.
- 2.1.2.13 Grimm Aerosol Technik, G. and Co. K. (2023). Manual for CPC Model 5420 (rev 1.0).
- 2.1.2.14 Wiedensohler, A., Wiesner, A., Weinhold, K., Birmili, W., Hermann, M., Merkel, M., Müller, T., Pfeifer, S., Schmidt, A., Tuch, T., Velarde, F., Quincey, P., Seeger, S., and Nowak, A. (2018). Mobility particle size spectrometers: Calibration procedures and measurement uncertainties. *Aerosol Science and Technology*, 52, 146-164. <https://doi.org/10.1080/02786826.2017.1387229>.
- 2.1.2.15 Wang, S.C. and Flagan, R.C. (1990). Scanning Electrical Mobility Spectrometer. *Aerosol Science and Technology*, 13, 230-240. <https://doi.org/10.1080/02786829008959441>.
- 2.1.2.16 ISO 15900:2020. Determination of particle size distribution - Differential electrical mobility analysis for aerosol particles. <https://www.iso.org/standard/67600.html>.
- 2.1.2.17 Collins, D.R., Cocker, D.R., Flagan, R.C., and Seinfeld, J.H. (2004). The Scanning DMA Transfer Function. *Aerosol Science and Technology*, 38, 833-850. <https://doi.org/10.1080/027868290503082>.
- 2.1.2.18 Biskos, G., Reavell, K., and Collings, N. (2005). Description and Theoretical Analysis of a Differential Mobility Spectrometer. *Aerosol Science and Technology*, 39, 527-541. <https://doi.org/10.1080/027868291004832>.
- 2.1.2.19 Hagen, D.E., Lobo, P., Whitefield, P.D., Trueblood, M.B., Alofs, D.J., and Schmid, O. (2009). Performance Evaluation of a Fast Mobility-Based Particle Spectrometer for Aircraft Exhaust. *Journal of Propulsion and Power*, 25, 628-634. <https://doi.org/10.2514/1.37654>.
- 2.1.2.20 Saari, S., Arffman, A., Harra, J., Rönkkö, T., and Keskinen, J. (2018). Performance evaluation of the HR-ELPI + inversion. *Aerosol Science and Technology*, 52, 1037-1047. <https://doi.org/10.1080/02786826.2018.1500679>.
- 2.1.2.21 ISO 27891:2015. Aerosol particle number concentration - Calibration of condensation particle counters. <https://www.iso.org/standard/44414.html>.

- 2.1.2.22 DIN CEN/TS 17434 - Ambient air - Determination of the particle number size distribution of atmospheric aerosol using a Mobility Particle Size Spectrometer (MPSS). German version CEN/TS 17434:2020.
- 2.1.2.23 Cambustion Application Note (2007). Calibration of DMS Series Fast Particle Spectrometers. https://www.tesscorn-aerofluid.com/wp-content/uploads/2020/11/dms_calibrationv3.pdf.
- 2.1.2.24 Awasthi, A., Wu, B.-S., Liu, C.-N., Chen, C.-W., Uang, S.-N., and Tsai, C.-J. (2013). The Effect of Nanoparticle Morphology on the Measurement Accuracy of Mobility Particle Sizers. *MAPAN*, 28, 205-215. <https://doi.org/10.1007/s12647-013-0068-7>.
- 2.1.2.25 Wang, X., Grose, M.A., Avenido, A., Stolzenburg, M.R., Caldow, R., Osmondson, B.L., Chow, J.C., and Watson, J.G. (2016). Improvement of Engine Exhaust Particle Sizer (EEPS) size distribution measurement - I. Algorithm and applications to compact-shape particles. *Journal of Aerosol Science*, 92, 95-108. <https://doi.org/10.1016/j.jaerosci.2015.11.002>.
- 2.1.2.26 Wang, X., Grose, M.A., Caldow, R., Osmondson, B.L., Swanson, J.J., Chow, J.C., Watson, J.G., Kittelson, D.B., Li, Y., Xue, J., Jung, H., and Hu, S. (2016). Improvement of Engine Exhaust Particle Sizer (EEPS) size distribution measurement - II. Engine exhaust particles. *Journal of Aerosol Science*, 92, 83-94. <https://doi.org/10.1016/j.jaerosci.2015.11.003>.
- 2.1.2.27 Xue, J., Li, Y., Wang, X., Durbin, T.D., Johnson, K.C., Karavalakis, G., Asa-Awuku, A., Villela, M., Quiros, D., Hu, S., Huai, T., Ayala, A., and Jung, H.S. (2015). Comparison of Vehicle Exhaust Particle Size Distributions Measured by SMPS and EEPS During Steady-State Conditions. *Aerosol Science and Technology*, 49, 984-996. <https://doi.org/10.1080/02786826.2015.1088146>.
- 2.1.2.28 Giechaskiel, B., Cresnoverh, M., Jörgl, H., and Bergmann, A. (2010). Calibration and accuracy of a particle number measurement system. *Measurement Science and Technology*, 21, 045102. <https://doi.org/10.1088/0957-0233/21/4/045102>.
- 2.1.2.29 Wang, X. and Horn, H.-G. (2012). TSI application note EECPC-001: Flow rate correction for the model 3790 engine exhaust condensation particle counter (EEPC). https://tsi.com/getmedia/5c391661-ba43-48cd-b745-5aa6edfee538/EECPC-001_Flow_Rate_Correction?ext=.pdf.
- 2.1.2.30 Mamakos, A., Ntziachristos, L., and Samaras, Z. (2008). Differential Mobility Analyser Transfer Functions in Scanning Mode. *Journal of Aerosol Science*, 39(3), 227-243. <https://doi.org/10.1016/j.jaerosci.2007.11.005>.
- 2.1.2.31 Gopalakrishnan, R., McMurtry, P.H., and Hogan Jr., C.J. (2015). The Bipolar Diffusion Charging of Nanoparticles: A Review and Development of Approaches for Non-Spherical Particles. *Aerosol Science and Technology*, 49(12), 1181-1194. <https://doi.org/10.1080/02786826.2015.1109053>.
- 2.1.2.32 Kittelson, D.B., Swanson, J., Aldridge, M., Giannelli, R.A., Kinsey, J.S., Stevens, J.A., Liscinsky, D.S., Hagen, D., Leggett, C., Stephens, K., Hoffman, B., Howard, R., Frazee, R.W., Silvis, W., McArthur, T., Lobo, P., Achterberg, S., Trueblood, M., Thomson, K., Wolff, L., Cerully, K., Onasch, T., Miake-Lye, R., Freedman, A., Bachalo, W., and Payne, G. (2022). Experimental Verification of Principal Losses in a Regulatory Particulate Matter Emissions Sampling System for Aircraft Turbine Engines. *Aerosol Science and Technology*, 56(1), 63-74. <https://doi.org/10.1080/02786826.2021.1971152>.
- 2.1.2.33 Symonds, J.P.R., Reavell, K. St.J., Olfert, J.S., Campbell, B.W., and Swift, S.J. (2007). Diesel Soot Mass Calculation in Real-Time with a Differential Mobility Spectrometer. *Journal of Aerosol Science*, 38(1), 52-68. <https://doi.org/10.1016/j.jaerosci.2006.10.001>.
- 2.1.2.34 Asbach, C., Kaminski, H., Lamboy, Y., Schneiderwind, U., Fierz, M., and Todea, A.M. (2016). Silicone Sampling Tubes Can Cause Drastic Artifacts in Measurements with Aerosol Instrumentation Based on Unipolar Diffusion Charging. *Aerosol Science and Technology*, 50(12), 1375-1384. <https://doi.org/10.1080/02786826.2016.1241858>.

- 2.1.2.35 Kumar, P., Fennell, P., Symonds, J., and Britter, R. (2008). Treatment of Losses of Ultrafine Aerosol Particles in Long Sampling Tubes during Ambient Measurements. *Atmospheric Environment*, 42(38), 8819-8826. <https://doi.org/10.1016/j.atmosenv.2008.09.003>.
- 2.1.2.36 Kim, J.H., Mulholland, G.W., Kukuck, S.R., and Pui, D.Y.H. (2005). Slip Correction Measurements of Certified PSL Nanoparticles Using a Nanometer Differential Mobility Analyzer (Nano-DMA) for Knudsen Number From 0.5 to 83. *J. Res. Natl. Inst. Stand. Technol.*, 110(1), 31-54. <https://doi.org/10.6028/jres.110.005>.
- 2.1.2.37 Kittelson, D., Khalek, I., McDonald, J., Stevens, J., and Giannelli, R. (2022). Particle Emissions from Mobile Sources: Discussion of Ultrafine Particle Emissions and Definition. *Journal of Aerosol Science*, 159, 105881. <https://doi.org/10.1016/j.jaerosci.2021.105881>.
- 2.1.2.38 Amanatidis, S., Maricq, M.M., Ntziachristos, L., and Samaras, Z. (2016). Measuring Number, Mass, and Size of Exhaust Particles with Diffusion Chargers: The Dual Pegasor Particle Sensor. *Journal of Aerosol Science*, 92 (Supplement C), 1-15. <https://doi.org/10.1016/j.jaerosci.2015.10.005>.
- 2.1.2.39 Durand, E., Crayford, A.P., Johnson, M., and Williams, P. (2025). SAMPLE IV SC.02 Deliverable 3 Report - Improving nvPM Sampling and Measurement System Uncertainties. <https://www.easa.europa.eu/en/downloads/141733/en>.
- 2.1.2.40 Johnson, M., Crayford, A.P., Durand, E., Williams, P., Durdina, L., and Smallwood, G.J. (2024). SAMPLE IV SC.02 Deliverable 1 report - Potential Improvements to Current ICAO nvPM Sampling and Measurement System. <https://www.easa.europa.eu/en/downloads/140629/en>.
- 2.1.2.41 Corbin, J.C., Schripp, T., Anderson, B.E., Smallwood, G.J., LeClercq, P., Crosbie, E.C., Achterberg, S., Whitefield, P.D., Miake-Lye, R.C., Yu, Z., Freedman, A., Trueblood, M., Satterfield, D., Liu, W., Oßwald, P., Robinson, C., Shook, M.A., Moore, R.H., and Lobo, P. (2022). Aircraft-Engine Particulate Matter Emissions from Conventional and Sustainable Aviation Fuel Combustion: Comparison of Measurement Techniques for Mass, Number, and Size. *Atmospheric Measurement Techniques*, 15(10), 3223-3242. <https://doi.org/10.5194/amt-15-3223-2022>.
- 2.1.2.42 Johnson, T.J., Nishida, R.T., Irwin, M., Symonds, J.P.R., Olfert, J.S., and Boies, A.M. (2020). Measuring the Bipolar Charge Distribution of Nanoparticles: Review of Methodologies and Development Using the Aerodynamic Aerosol Classifier. *Journal of Aerosol Science*, 143, 105526. <https://doi.org/10.1016/j.jaerosci.2020.105526>.
- 2.1.2.43 TSI, Measuring Nanoparticle Size Distributions in Real-Time: Key Factors for Accuracy - Application Note SMPS-003. <https://tsi.com/getmedia/952fc58b-ec23-4f18-86e4-58d23636e56d/SMPS-003appnote?ext=.pdf>.
- 2.1.2.44 Liu, Z.G., Vasys, V.N., Dettmann, M.E., Schauer, J.J., Kittelson, D.B., and Swanson, J. (2009). Comparison of Strategies for the Measurement of Mass Emissions from Diesel Engines Emitting Ultra-Low Levels of Particulate Matter. *Aerosol Science and Technology*, 43(11), 1142-1152. <https://doi.org/10.1080/02786820903219035>.
- 2.1.2.45 Durdina, L., Brem, B.T., Abegglen, M., Lobo, P., Rindlisbacher, T., Thomson, K.A., Smallwood, G.J., Hagen, D.E., Sierau, B., and Wang, J. (2014). Determination of PM Mass Emissions from an Aircraft Turbine Engine Using Particle Effective Density. *Atmospheric Environment*, 99, 500-507. <https://doi.org/10.1016/j.atmosenv.2014.10.018>.
- 2.1.2.46 ELPI®+ User Manual (Ver 1.6).
- 2.1.2.47 Saari, S., Arffman, A., Harra, J., Rönkkö, T., and Keskinen, J. (2018). Performance Evaluation of the HR-ELPI + Inversion. *Aerosol Science and Technology*, 52(9), 1037-1047. <https://doi.org/10.1080/02786826.2018.1500679>.
- 2.1.2.48 Lidstone-Lane, F. (2025). *Particle Transport and Losses when Sampling Aircraft Gas Turbine Combustion Engine nvPM Emissions* [Doctoral dissertation, University of Manchester]. https://pure.manchester.ac.uk/ws/portalfiles/portal/360317789/FULL_TEXT.PDF.

- 2.1.2.49 Corbin, J.C., Smallwood, G.J., Leroux, I.D., Norooz Oliaee, J., Liu, F., Sipkens, T.A., Green, R.G., Murnaghan, N.F., Koukoulas, T., and Lobo, P. (2021). Systematic Experimental Comparison of Particle Filtration Efficiency Test Methods for Commercial Respirators and Face Masks. *Sci Rep*, 11(1), 21979. <https://doi.org/10.1038/s41598-021-01265-8>.
- 2.1.2.50 ISO 19996:2024. Charge conditioning of aerosol particles for particle characterization and the generation of calibration and test aerosols. <https://www.iso.org/standard/73974.html>.
- 2.1.2.51 EN 16976:2024. Ambient air - Determination of the particle number concentration of atmospheric aerosol. <https://standards.iteh.ai/catalog/standards/cen/ab8b1143-a1d3-481b-b268-38a3b1da18b7/en-16976-2024>.
- 2.1.2.52 Bau, S., Bémer, D., Gripari, F., Appert-Collin, J.-C., and Thomas, D. (2014). Determining the Effective Density of Airborne Nanoparticles Using Multiple Charging Correction in a Tandem DMA/ELPI Setup. *J Nanopart Res*, 16(10), 2629. <https://doi.org/10.1007/s11051-014-2629-2>.
- 2.1.2.53 Perraud, V., Smith, J.N., and Olfert, J. (2023). High-Accuracy Effective Density Measurements of Sodium Methanesulfonate and Aminium Chloride Nanoparticles Using a Particulate Calibration Standard. *Aerosol Science and Technology*, 57(4), 355-366. <https://doi.org/10.1080/02786826.2023.2176739>.
- 2.1.2.54 Johnson, T.J., Symonds, J.P.R., and Olfert, J.S. (2013). Mass-Mobility Measurements Using a Centrifugal Particle Mass Analyzer and Differential Mobility Spectrometer. *Aerosol Science and Technology*, 47(11), 1215-1225. <https://doi.org/10.1080/02786826.2013.830692>.
- 2.1.2.55 Williamson, C., Kupc, A., Wilson, J., Gesler, D.W., Reeves, J.M., Erdesz, F., McLaughlin, R., and Brock, C.A. (2018). Fast Time Response Measurements of Particle Size Distributions in the 3-60 nm Size Range with the Nucleation Mode Aerosol Size Spectrometer. *Atmospheric Measurement Techniques*, 11(6), 3491-3509. <https://doi.org/10.5194/amt-11-3491-2018>.
- 2.1.2.56 Kidd, C., Perraud, V., and Finlayson-Pitts, B.J. (2014). Surfactant-Free Latex Spheres for Size Calibration of Mobility Particle Sizers in Atmospheric Aerosol Applications. *Atmospheric Environment*, 82, 56-59. <https://doi.org/10.1016/j.atmosenv.2013.09.056>.
- 2.1.2.57 TSI Inc. Updated Inversion Matrices For Engine Exhaust Particle Sizer™ (EEPS™) Spectrometer Model 3090 - Application Note EEPS-005 (A4), 2015.
- 2.1.2.58 Stratmann, F., Kauffeldt, T., Hummes, D., and Fissan, H. (1997). Differential Electrical Mobility Analysis: A Theoretical Study. *Aerosol Science and Technology*, 26(4), 368-383. <https://doi.org/10.1080/02786829708965437>.
- 2.1.2.59 TSI Inc. Correcting For Humidity Effects On TSI® General Purpose Flowmeters - Application Note Flow-001.
- 2.1.2.60 Cambustion Ltd. DMS500 User Manual (V4.26), 2022.
- 2.1.2.61 Trivanovic, U. and Pratsinis, S.E. (2024). Opinion: Eliminating Aircraft Soot Emissions. *Aerosol Research*, 2(2), 207-223. <https://doi.org/10.5194/ar-2-207-2024>.
- 2.1.2.62 Crayford, A. and Johnson, M. (2012). SAMPLE III SC.02 - Studying, Sampling and Measuring of Aircraft Particulate Emission. <https://www.easa.europa.eu/document-library/research-reports/easa2010fc10-sc02>.

2.2 Definitions

AERODYNAMIC PARTICLE DIAMETER: The diameter of an equivalent sphere of unit density (1.0 g/cm³) with the same settling velocity as the particle in question; also referred to as aerodynamic diameter.

AIRCRAFT GAS TURBINE ENGINE: Any gas turbine engine used for aircraft propulsion or for power generation on an aircraft, including those commonly called turbojet, turbofan, turboprop, or turboshaft type engines, or auxiliary power units.

CATALYTIC STRIPPER (CS): A heated catalytic device that removes volatile species of an aerosol through oxidation.

ELECTRICAL MOBILITY DIAMETER: The diameter of an equivalent sphere with the same electrical mobility as the particle in question; also referred to as mobility diameter.

NONVOLATILE PARTICULATE MATTER (nvPM): Emitted particles that exist at gas turbine engine exhaust nozzle exit plane that do not volatilize when heated to 623.15 K (350 °C).

PARTICLE LOSS: The loss of particles during transport through the sampling system due to various deposition mechanisms, some of which are size-dependent.

PARTICLE SIZE DISTRIBUTION (PSD): The probability density function, list of values, or mathematical function that expresses the PM (number, mass, surface area, or volume) concentration according to size. Engine exhaust is composed of nanoparticles that are typically measured in terms of their electrical mobility.

STANDARD GAS VOLUME (STP): The volume of gas at 273.15 K (0 °C) and 101.325 kPa (1 atm).

VOLATILE PARTICLES: Particles formed from condensable gases after the exhaust has been cooled to below engine exit temperatures (e.g., sulfuric acid particles); combustion exhaust material that volatilizes at ≤ 623.15 K (350 °C).

2.3 Symbols, Acronyms, and Terminology

CML	carboxylated modified polystyrene latex
CPC	condensation particle counter; referred to as CNC in AIR6037A
CPMA	centrifugal particle mass analyzer, manufactured by Cambustion
DEHS	di-ethyl-hexyl sebacate
DES	di-ethyl sebacate
DMA	differential mobility analyzer; also referred to as differential electrical mobility classifier (DEMC) in ISO documentation
DMS500	differential mobility spectrometer, manufactured by Cambustion
DOS	di-octyl sebacate
d_a	aerodynamic diameter
d_m	electrical mobility diameter
D_{mc}	count mean diameter of an nvPM size distribution, also commonly known as CMD in the literature, in nanometers (nm)
D_{mg}	geometric mean diameter of an nvPM size distribution, also commonly known as GMD in the literature, in nanometers (nm)
D_p	nvPM particle diameter - refers to the electrical mobility diameter (d_m) except for the cyclone separator, where the particle diameter is the aerodynamic diameter (d_a) - in nanometers (nm)
EENEP	engine exhaust nozzle exit plane
EEPS	engine exhaust particle sizer, manufactured by TSI
EUR	European
EI	emission index, emissions unit per kilogram of fuel

El _{mass}	particle mass emission index, grams per kilogram of fuel
El _{num}	particle number emission index, particles per kilogram of fuel
FCE	Faraday cup electrometer
σ_g	geometric standard deviation; also commonly known as GSD in the literature
IPSD	integrated particle size distribution
ISO	International Organization for Standardization
k _{SL_{mass}}	El _{mass} correction factor for system losses excluding sampling probe inlet to Splitter1 thermophoretic loss correction for particle diameters greater than or equal to 10 nm
k _{SL_{num}}	El _{num} correction factor for system losses excluding sampling probe inlet to Splitter1 thermophoretic loss correction for particle diameters greater than or equal to 10 nm
LOD	limit of detection
NARS	North American reference system
NIST	National Institute of Standards and Technology
nvPM	nonvolatile particulate matter
OEM	original equipment manufacturer
PAO	poly-alpha-olefin oil
PM	particulate matter
PSD	particle size distribution
PSL	polystyrene latex
RQL	rich-quench-lean
SAF	sustainable aviation fuel
SMPS	Scanning Mobility Particle Sizer (TSI trade name); also referred to as differential mobility analyzer system (DMAS) in ISO documentation and as mobility particle size spectrometer (MPSS) in CEN (European Committee for Standardization) documentation
TEM	transmission electron microscopy
UFP	ultrafine particle

2.4 Units

atm	1 standard atmosphere, 101325 Pa
cm	centimeter (10 ⁻² m)
g	gram
Hz	Hertz (1 per second)

K	Kelvin
kPa	kilopascal (10^3 Pa)
lpm	liters per minute
m	meter
nm	nanometer (10^{-9} m)
Pa	Pascal
s	second
slpm	standard liters per minute; volumetric flow at STP condition
STP	standard temperature 273.15 K and pressure 1 atm (101.325 kPa)
μm	micrometer (10^{-6} m)

3. INTRODUCTION

Aircraft gas turbine engines typically produce nvPM in the range of 10 to 50 nm geometric mean diameter (D_{mg}) at the engine exhaust nozzle exit plane (EENEP) (see 2.1.2.1). Within the nvPM sampling and measurement system defined in ARP6320B, significant size-dependent particle losses occur. To address this, an analytical tool for quantifying the size-dependent losses has been developed, as reported in AIR6504A and ARP6481A. This analytical method uses the measured nvPM number-to-mass ratio along with several assumptions to estimate a PSD at the EENEP and determine the correction factors needed to account for particle loss. However, this approach has been found to lead to large uncertainties (see 2.1.2.2).

While aircraft engine PSDs provide useful engineering information for evaluating combustion technologies, their primary benefit may be in improving system loss correction. Accurate system loss correction is essential for estimating engine-exit concentrations, enabling comparisons across engine technologies, supporting environmental monitoring, and becoming increasingly important as modern engine technologies and sustainable aviation fuels produce smaller nvPM. Using a measured PSD can significantly reduce uncertainty in estimating size-dependent system loss correction factors ($k_{\text{SL_num}}$ and $k_{\text{SL_mass}}$) compared to the current ARP6481A methodology. Based on the available data, the ARP6481A methodology can underestimate system loss correction factors by as much as 67% compared to methods using measured PSD due mostly to uncertainties inherent to the measured nvPM number and mass. In contrast, $k_{\text{SL_num}}$ and $k_{\text{SL_mass}}$ derived from measured PSD have been shown to exhibit a variability $\leq 10\%$, influenced by the method, particle size instrument type, or model used. AIR6504A describes methodologies for using measured PSD to calculate system loss correction factors and includes a calculation tool. This AIR also explores the applicability of using PSD measurements to derive nvPM number and mass emissions.

Particle size instruments typically output PSDs as discrete spectra of $dN/d\log D_p$, from which the D_{mg} , geometric standard deviation (σ_g), and total number concentration are derived (see 2.1.2.3 and 2.1.2.4). Historically, PSDs from aircraft gas turbines have been measured using differential electrical mobility analyzers, which report particle size in terms of electrical mobility (see 2.1.2.5 through 2.1.2.9). There are two main types of mobility-based size analyzers: (a) scanning mobility-type instruments utilizing a differential mobility analyzer (DMA) that scans through a range of mobility sizes with particles directly counted using either a condensation particle counter (CPC) or a Faraday cup electrometer (FCE) and (b) real-time mobility spectrometers that use parallel electrometer detectors to simultaneously derive concentrations at each size bin across the measurement range.

Scanning mobility-type analyzers used on aircraft engine emissions research include the TSI Scanning Mobility Particle Sizer (SMPS™), Grimm SMPS+C and SMPS+E, Brechtel SEMS, Airmodus MPSS, etc. A TSI SMPS (Model 3938) has been used in the Swiss ARP6320B nvPM reference system over the past decade in various configurations.

During aircraft engine testing, rapid measurements are required once stable (average of at least 30 individual data measurements at 1 Hz) in accordance with ARP6320B. Thus, real-time mobility spectrometers are typically used for measuring aircraft engine combustion exhaust. These include the Combustion Differential Mobility Spectrometer (DMS500) and the TSI Engine Exhaust Particle Sizer Spectrometer (EEPS Model 3090). The DMS500 has been used in aircraft emissions testing since the early 2000s, and its latest version is part of the European (EUR) and North American (NARS) nvPM reference systems, while the EEPS has been tested in more recent research campaigns (see 2.1.2.9, 2.1.2.10, and 2.1.2.62). Some engine OEMs have used SMPS-type instruments, DMS500, and EEPS during their nvPM engine emission tests.

In addition to electrical mobility-based analyzers, real-time instruments based on electrical impaction that measure PSD in terms of aerodynamic diameter are also available and have been used in aircraft engine exhaust PM research (e.g., Dekati ELPI+) (see 2.1.2.11). However, the experience with these instruments for aircraft engine nvPM emissions testing is more limited. Electrical impaction-based particle sizers classify and collect particles by size using a cascade impactor while simultaneously measuring the electrical current carried by charged particles at each stage to infer real-time size distributions.

This document outlines the current knowledge and practices for performing a particle size measurement within an ARP6320B nvPM sampling and measurement system. The material is primarily based on emissions testing and research work performed using the Swiss, EUR, and NARS nvPM sampling and measurement reference systems, on information from particle size instrument manufacturers and metrology groups, and draws upon and expands information in AIR6037A. It is intended to guide nvPM system operators who have implemented, or plan to implement, particle size measurement in their aircraft engine sampling and measurement systems. Information on current and future applications, as well as actions needed to support standardized nvPM size measurement, is also included.

A summary of currently available technologies and instrument-specific recommendations is provided in [Section 10](#) and [Table 1](#).

4. OVERVIEW OF PARTICLE SIZE MEASUREMENT METHODOLOGY

This section details the functionalities, operation, and currently known uncertainties of commonly used particle size instruments for aircraft gas turbines nvPM measurements. The instruments included are scanning particle sizers (SMPS-type instruments) and real-time particle sizers (DMS500, EEPS, ELPI+).

4.1 Description of Particle Size Instruments

4.1.1 Electrical Mobility-Based Instruments

4.1.1.1 Scanning Mobility-Type Instruments

A scanning mobility particle sizer (SMPS) consists of (see 2.1.2.12 and 2.1.2.13):

- An optional impactor at the inlet to protect the SMPS-type instrument from larger particles above the measurement range and to measure the flow rate (the pressure drop across the impactor is proportional to the square of the flow rate).
- An aerosol neutralizer, also referred to as bipolar charge conditioner, to charge particles to a known state according to Fuch's charging theory (see 2.1.2.50), with two options:
 - A radioactive neutralizer containing a radioactive source (e.g., Kr-85, Ni-63, Am-241, Po-210) with a half-life ranging from several months to several years. These sources emit ionizing radiation continuously and cannot be switched off, so they typically require handling and transport permits depending on the country of use.
 - A soft X-ray neutralizer with a lifetime of typically thousands of hours of operation, although degradation can occur within that lifetime (see 2.1.2.14). X-rays are generated in a vacuum tube when accelerated electrons strike a metal anode, producing ionizing radiation that can be switched on or off electrically.