Non-Volatile Particulate Matter Mass and Number Emission Indices of Aircraft Gas Turbine Sources

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Particulate matter (PM) emissions from aircraft gas turbines are a concern for human health, environmental pollution and climate change. Expected future regulations on emissions require a reliable determination and understanding of PM emission factors under variable engine and environmental conditions.

This work presents preliminary results of non-volatile PM mass and number emission indices (mass or number PM emitted per mass fuel burned) for aircraft gas turbine sources obtained with measurements at the engine test cell at SR Technics, Zürich Kloten. Such measurements are challenging due to the high temperature (up to 800°C) and pressure conditions in the turbine exhaust. Figure 1 provides a simplified overview of the sampling system operated for these measurements.

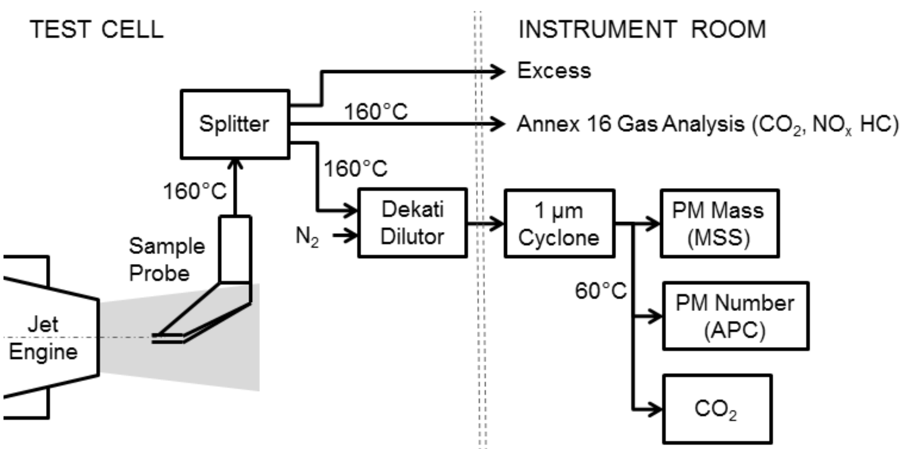

Figure 1 Simplified schematic of the aircraft gas turbine PM sampling system installed at SR Technics

PM laden exhaust was continuously sampled by a single point sampling probe at the engine exit plane. The aerosol sampled was then diluted with dry nitrogen by a factor of eight to ten and transported via temperature controlled lines to minimize condensation, particle agglomeration, and gas-to-particle conversion. Non-volatile PM mass was determined with a micro soot sensor (MSS, Model 483, AVL Inc.) based on the photoacoustic detection principle. In parallel to the MSS, an AVL particle counter (APC) and a CO_2 analyzer (Model 410i, Thermo Inc.) provided PM number and CO_2 concentrations emitted. The CO_2 concentration emitted was used in the PM mass and number emission indices calculation according to e.g. Lobo et al. (2007).

Mass and number emission indices as a function of engine power from three aircraft gas turbine sources categorized according to their technology are shown in Figure 2. The "Late 80s" and "90s" engine technologies included in Figure 2 are two single annular combustor turbofans with maximum thrust levels of 250 and 108 kN, respectively. The "Late 90s" engine technology corresponds to a double annular combustor turbofan designed for low NO_x emissions with a maximum thrust of 120 kN.

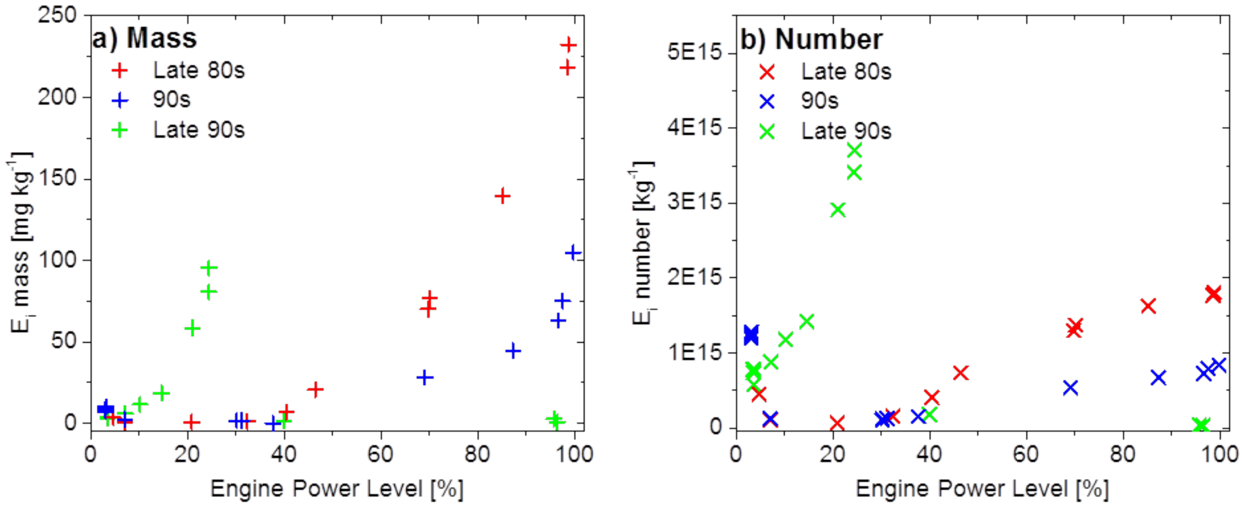

Figure 2 PM mass emission indices (a) and PM number emission indices (b) for three different engine technologies as a function of engine thrust level

The Late 80s and 90s engine technologies had increasing emission indices in mass and number with increasing engine thrusts, except at low power levels below 5%. Furthermore, both engines had a higher mass than number index increase with increasing power, indicating bigger particle sizes present at higher thrust levels. Analysis of this phenomenon with a scanning mobility analyzer for the 7 and 98% power levels of the 90s engine confirmed an increase in the count median diameter and geometric standard deviation from 24 to 50 nm and from 1.51 to 1.67, respectively.

The late 90s low NO_x combustor design equipped with a staged double annular combustor provided unique PM emission characteristics: higher emission indices (up to 110 mg kg^{-1}) at thrust levels below 25% and emission indices near the detection limit of the instrumentation (< 5 mg kg^{-1}) at higher thrusts. At low power levels this engine technology also had the highest observed number emission index (3.7 x 10^{15} kg^{-1}) of all three engine technologies tested.

Acknowledgements:

We thank Theo Rindlisbacher, (Swiss Federal Office of Civil Aviation, FOCA) and Frithjof Siegerist (SR Technics) for their help, guidance and support.

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References:

Lobo, P.; Hagen, D. E.; Whitefield, P. D.; Alofs, D. J. (2007), Physical characterization of aerosol emissions from a commercial gas turbine engine, *J. Propul. Power*, *23*, 919– 929

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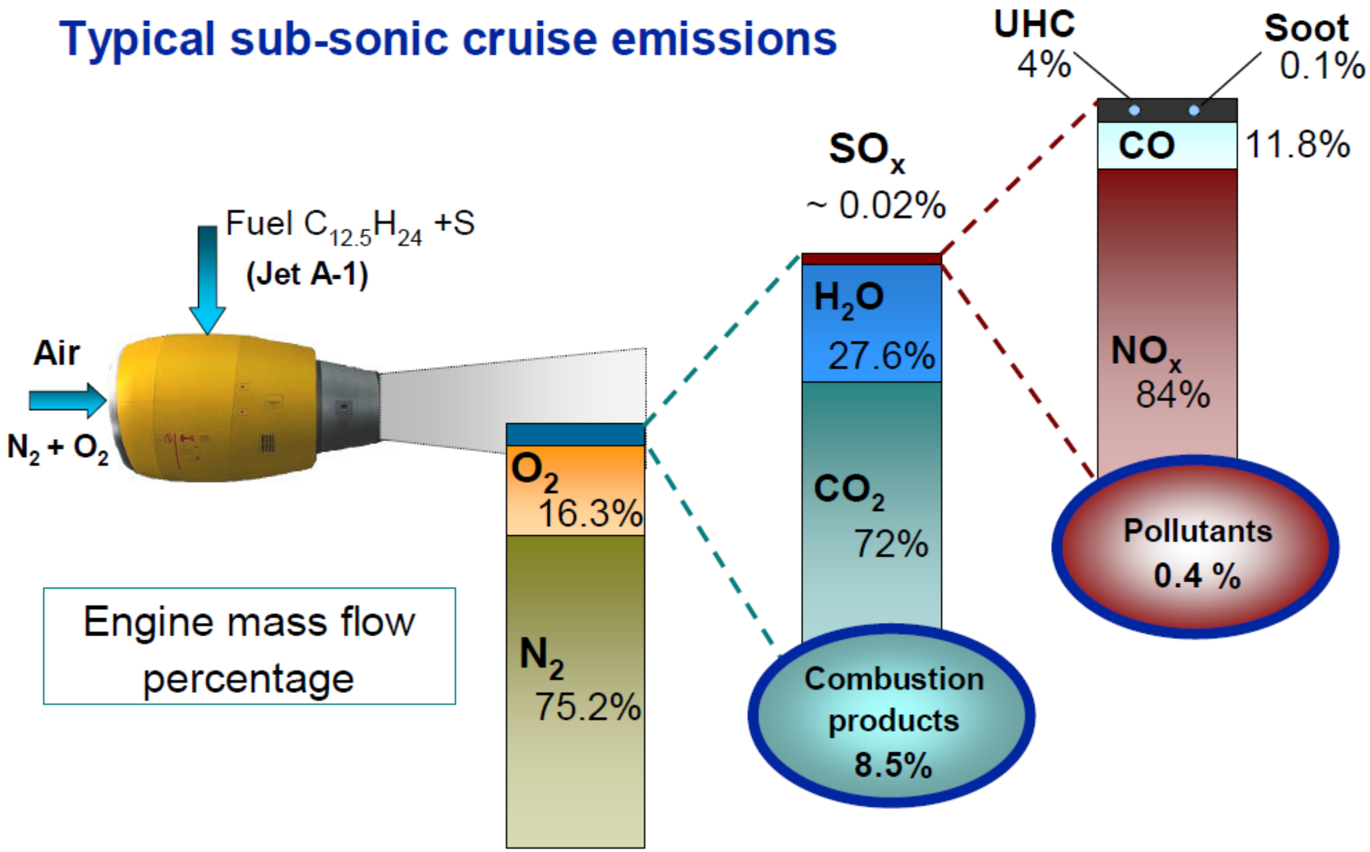
Soot PM, a Small Fraction of Modern Aircraft Exhaust



- Soot PM affects human health, visibility and climate
- Estimated contribution of aviation to global BC emission mass: < 1%
- Emissions occur in sensitive regions of the atmosphere

Image source: T. Doerr (Rolls-Royce), Introduction to Gas Turbine Combustion, VKI Lecture Series 2012

Aircraft PM Emission Standards - Quo Vadis?

- Smoke Number (Current Standard)
  - Introduced by the International Civil Aviation Organization (ICAO) in 1981 to reduce “smoke”
  - Metric for plume opacity (light attenuation of collected soot PM on filter)
  - Not an intrinsic PM characterization parameter
  - Current and new engine technologies have negligible smoke numbers

- PM emission standard for non-volatile mass and number expected in 2016
  - Empa is operating a draft-standard compliant system at SR Technics in Zürich Kloten designed by the Swiss Federal Office of Civil Aviation (FOCA)

Photo Credit: Boeing Photo

Photo Credit: Boeing Photo

Project Objectives

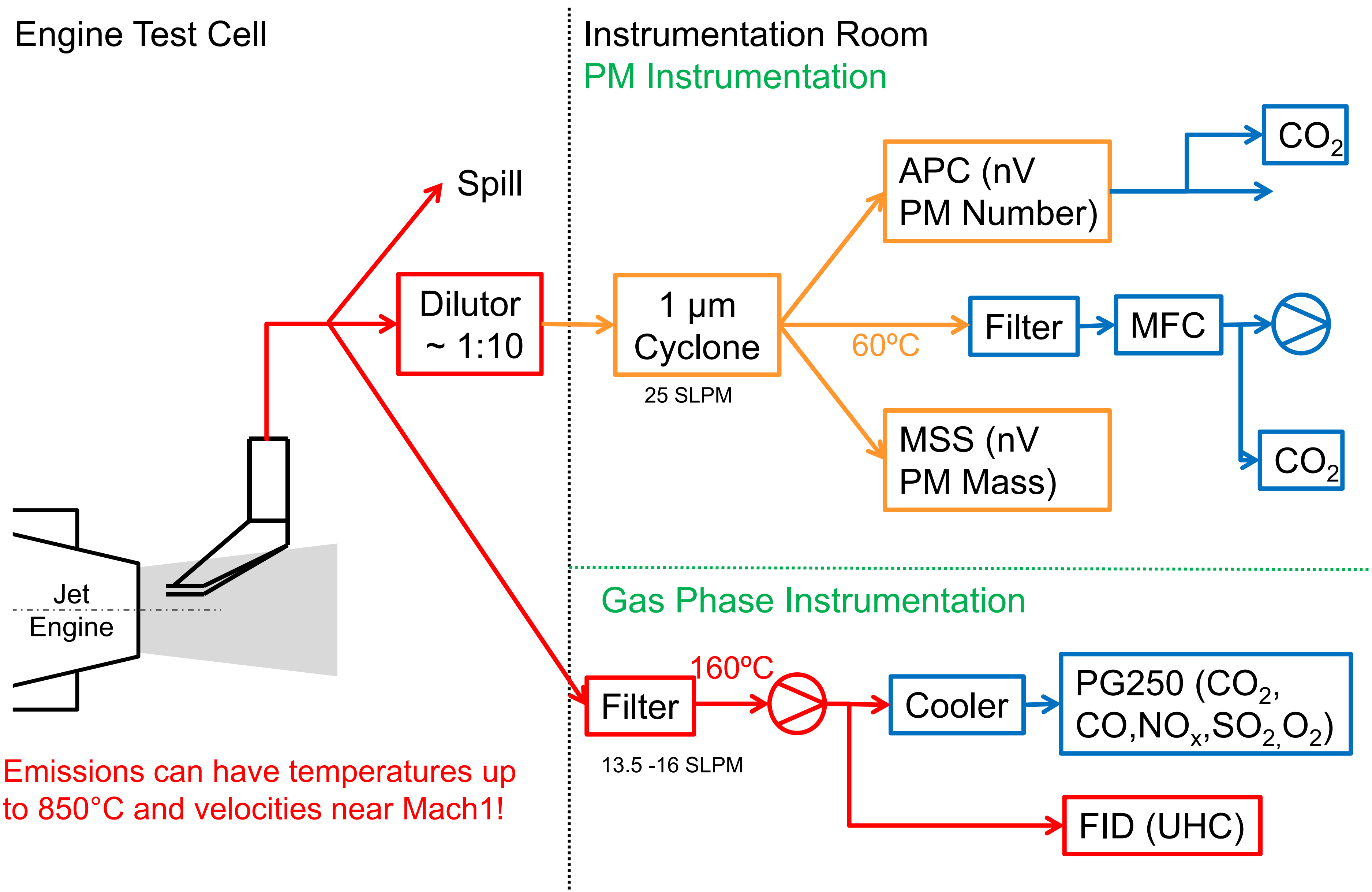
PM Measurement Standardization (FOCA, SAE-E31 and EMPA)

- Development of a sampling system for the representative measurement of non-volatile PM number and mass in aircraft gas turbine exhaust
  - Selection of suitable measurement technologies
  - Calibration and certification
  - Intercomparison with other sampling systems

PM Emission Characterization (EMPA, PSI and ETH)

- Effects of:
  - Engine type
  - Thrust level
  - Fuel composition
  - Ambient conditions
- Chemical and physical properties
- SOA formation potential
- Climate relevant properties

Sampling System Overview



Emissions can have temperatures up to 850°C and velocities near Mach1!

Engine Sources Characterized

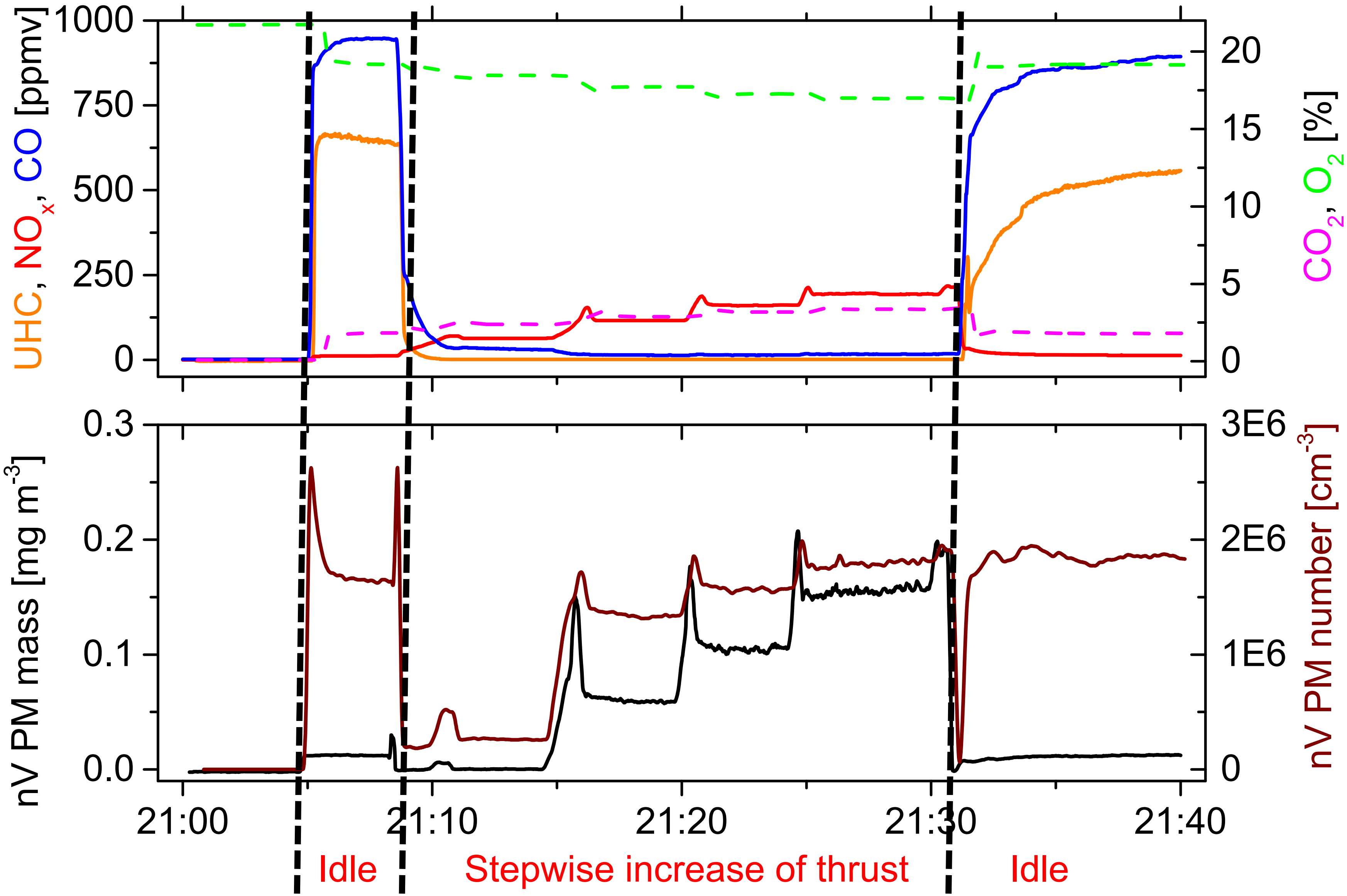
Type	**Late 80s**	**90s**	**90s Staged Combustor**
Maximum Thrust [kN]	250	108	120
By-pass ratio	4.7	5.2	5.9
Combustor type	Single annular	Single annular	Double annular
Comment		One of the most common engines	Designed for low NO_x emissions

Jet A1 Fuel Composition (PM Related Parameter)

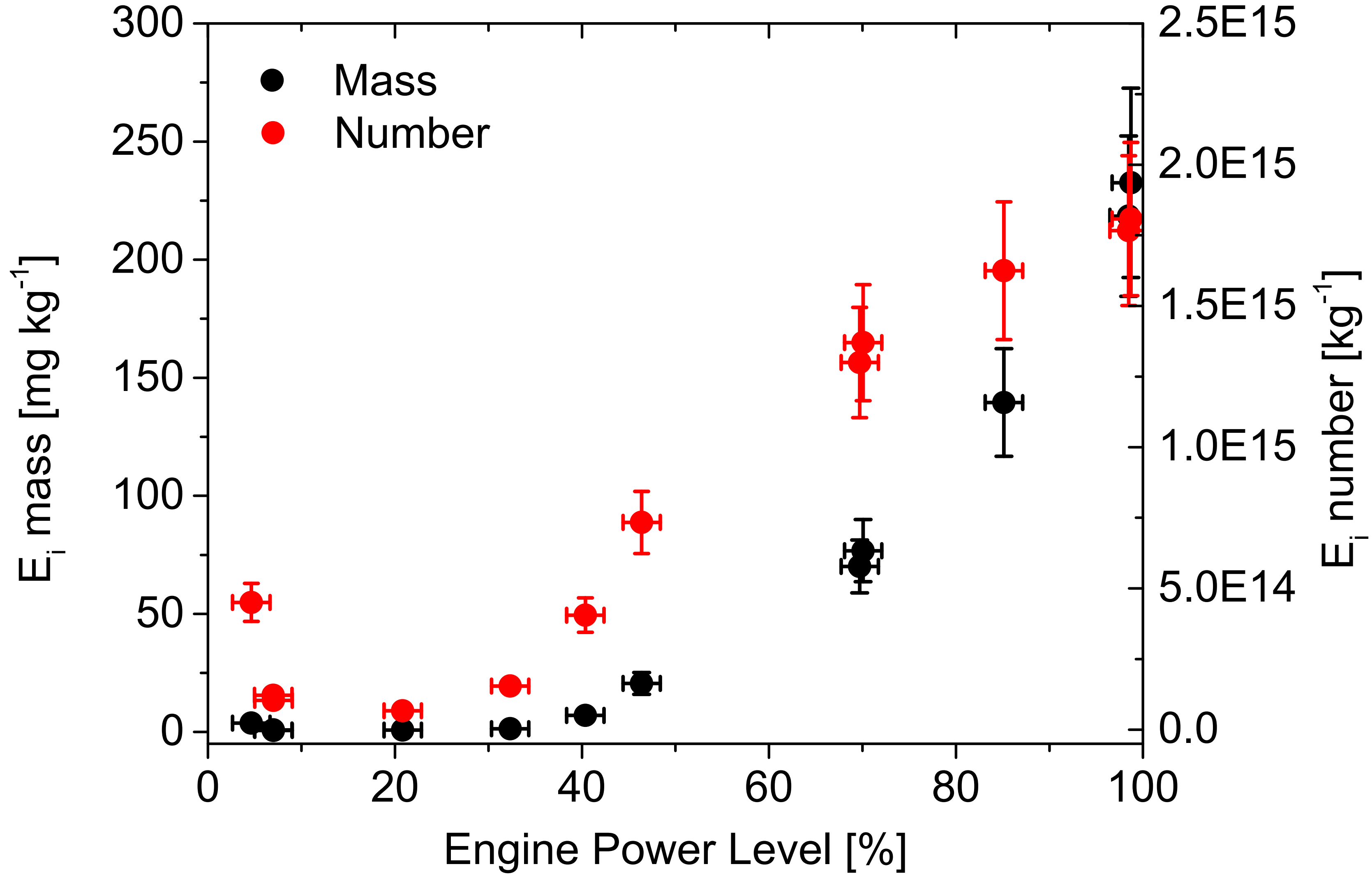
(Measured ranges of 4 samples)

Specific energy, net [MJ kg^{-1}]	**Aromatics [$\%_v$]**	**Naphthalenes [$\%_v$]**	**Sulfur [ppm_m]**
43.2	17.8 – 18.4	0.78 – 1.11	600 - 660

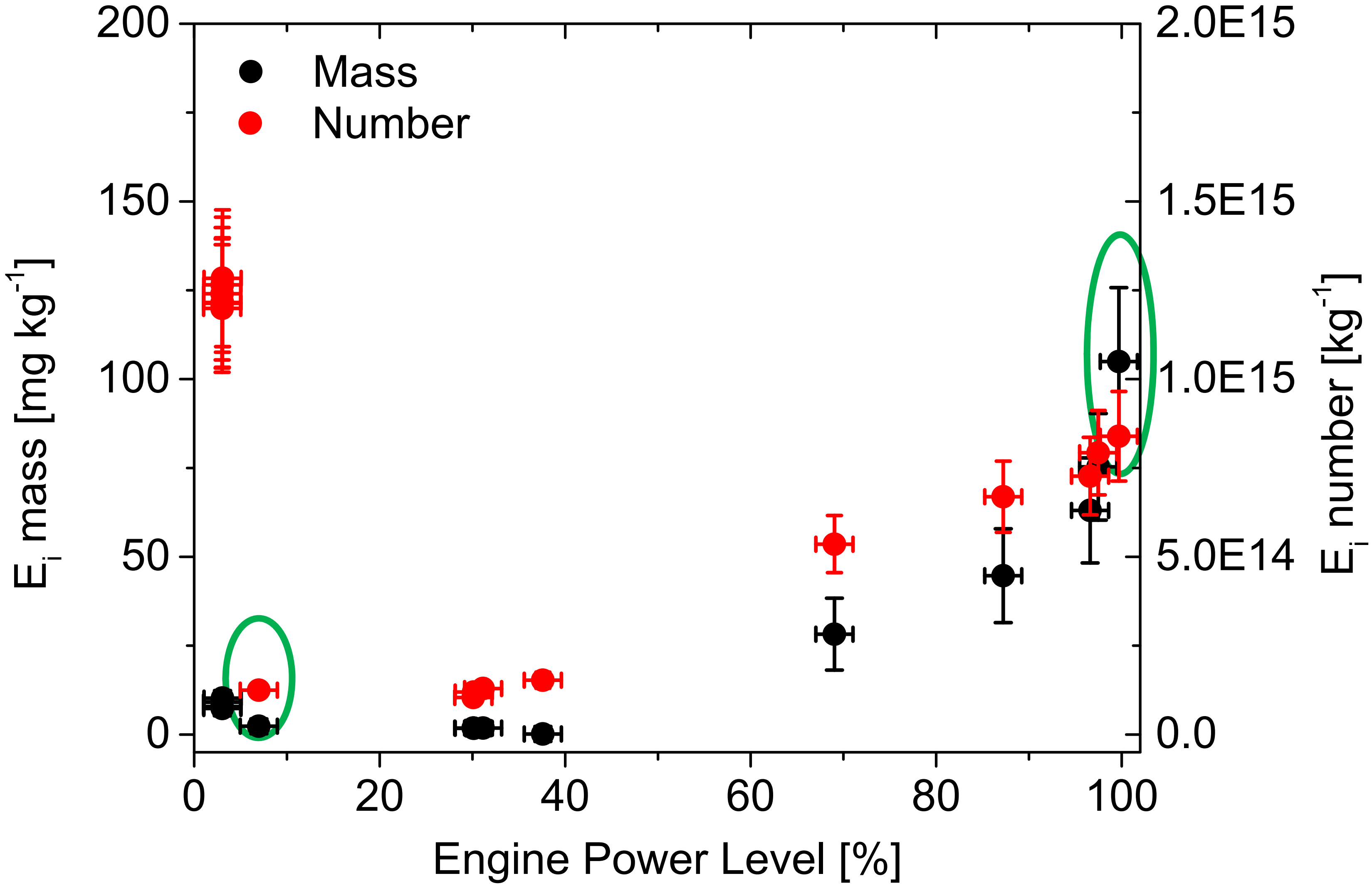
Raw Data Example of a 90s Source



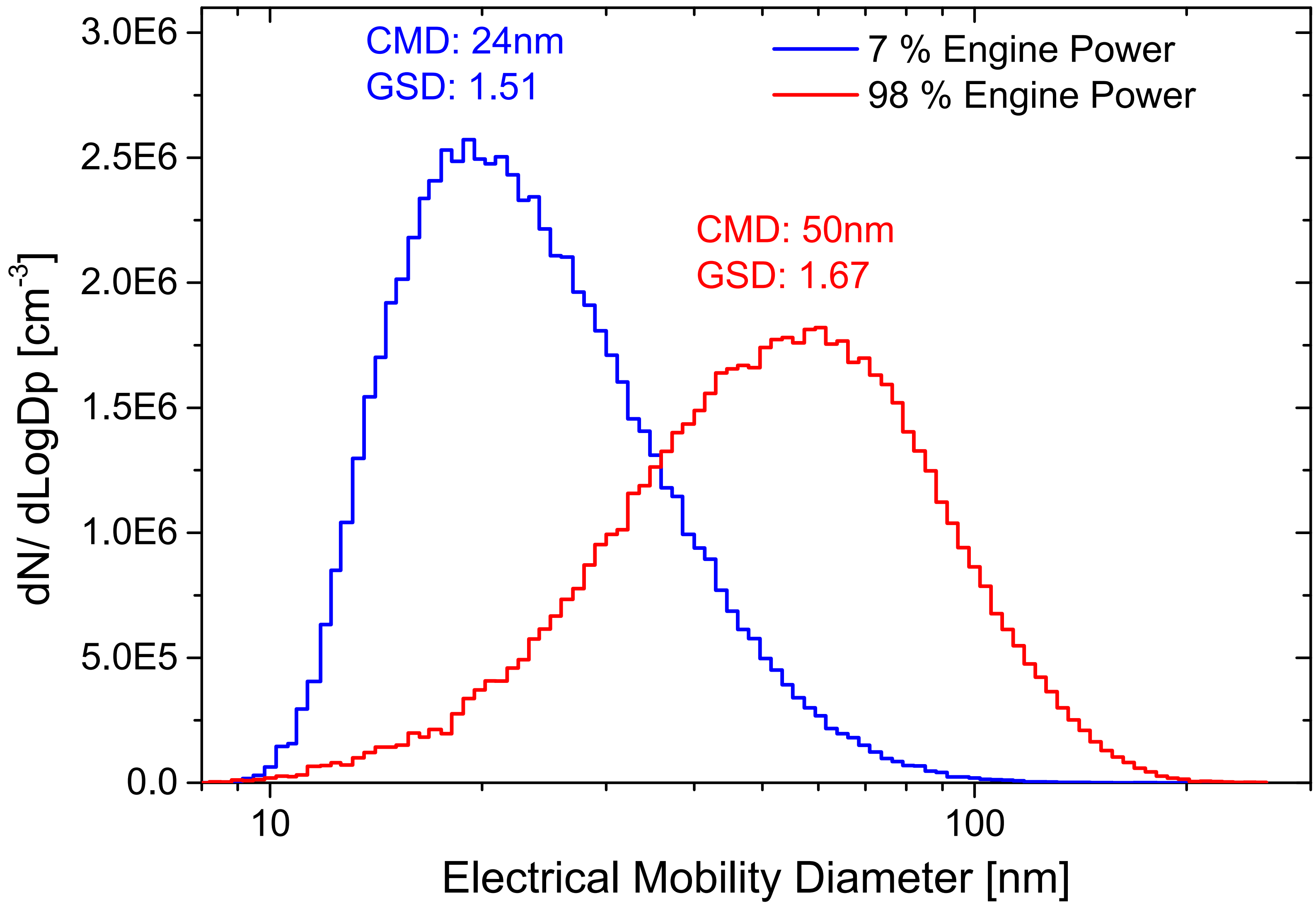
Emission Indices (Late 80s Engine Source)



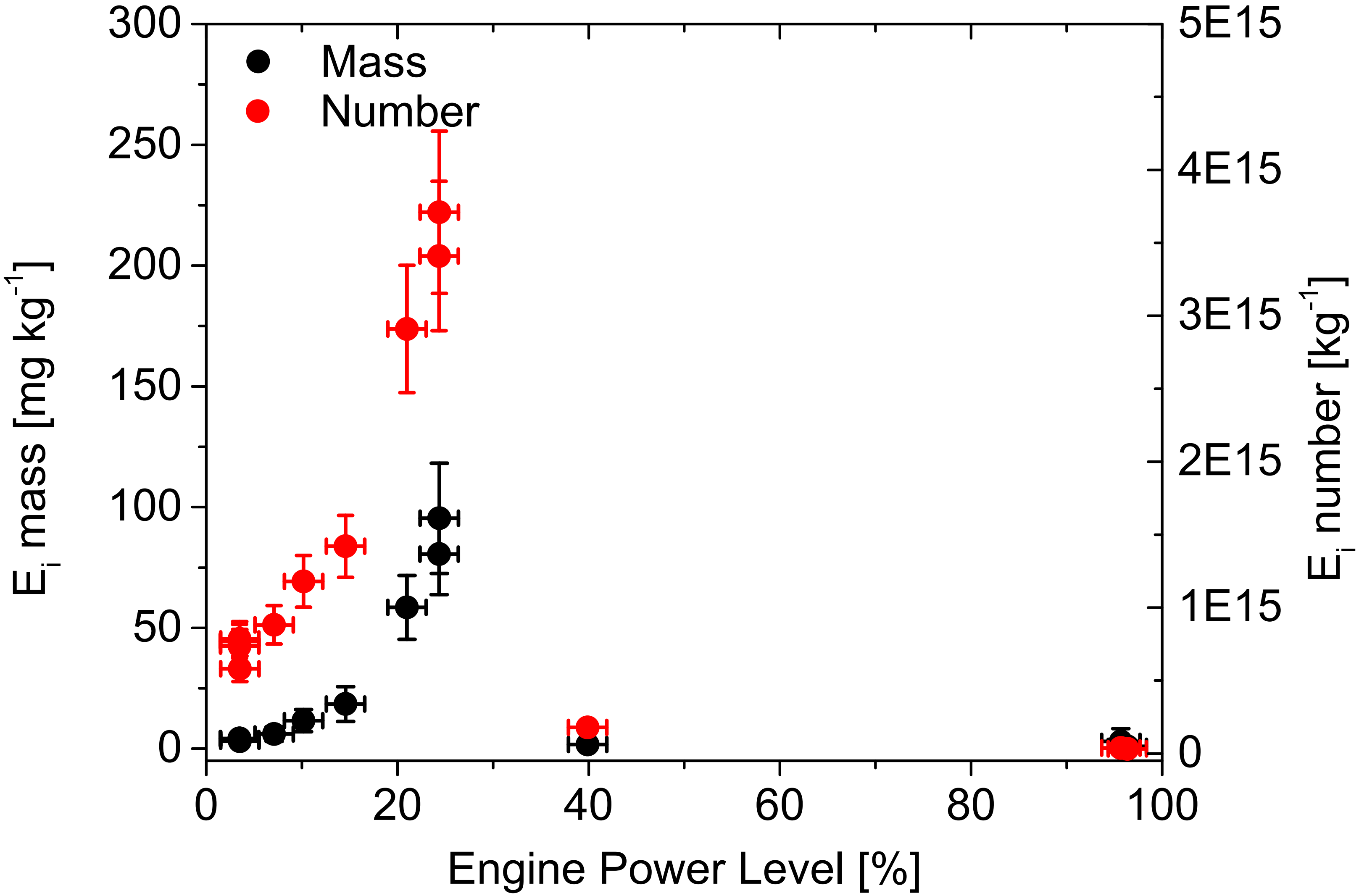
Emission Indices (90s Engine Source)



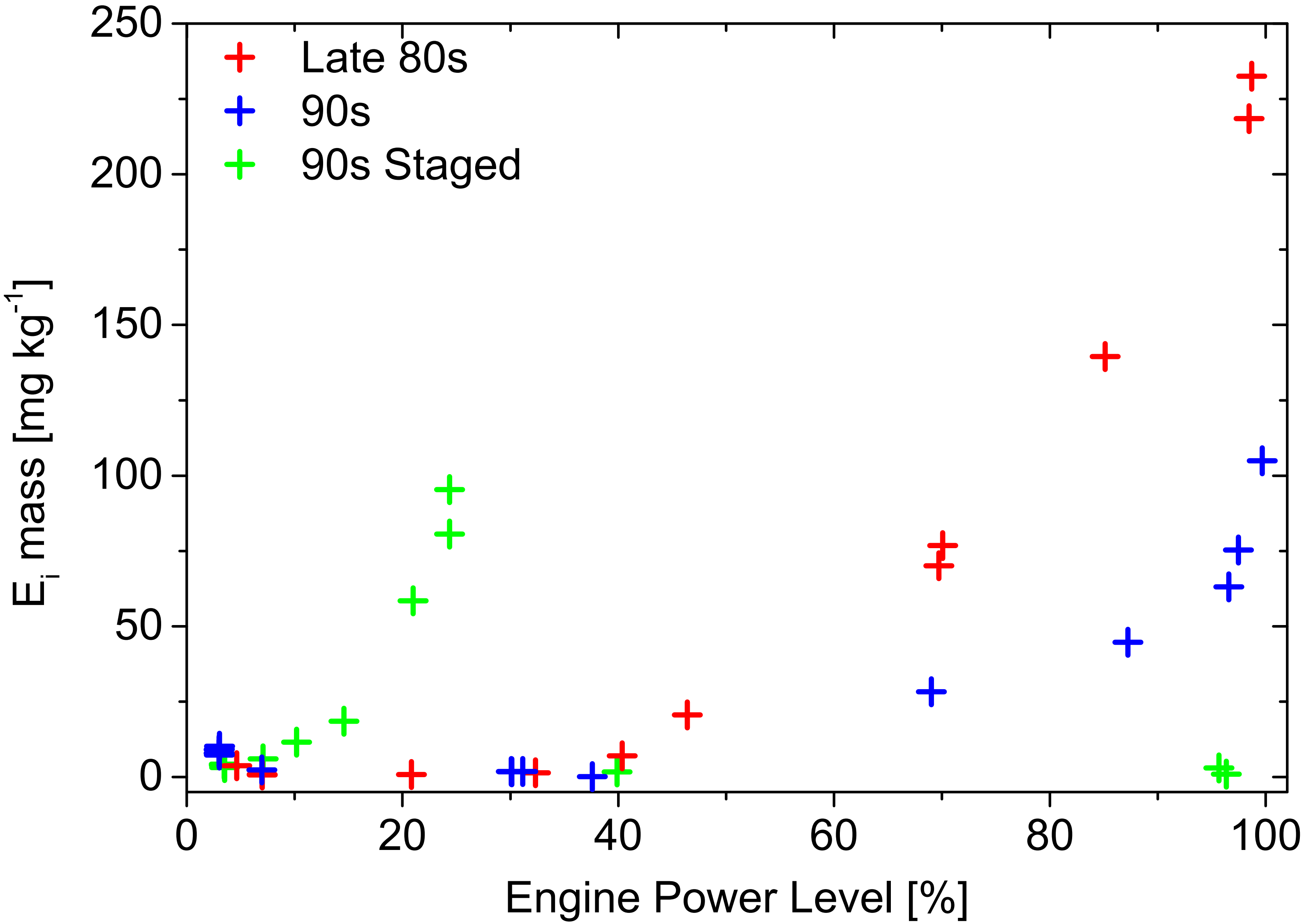
Observed Change in PSD (90s Engine Source)



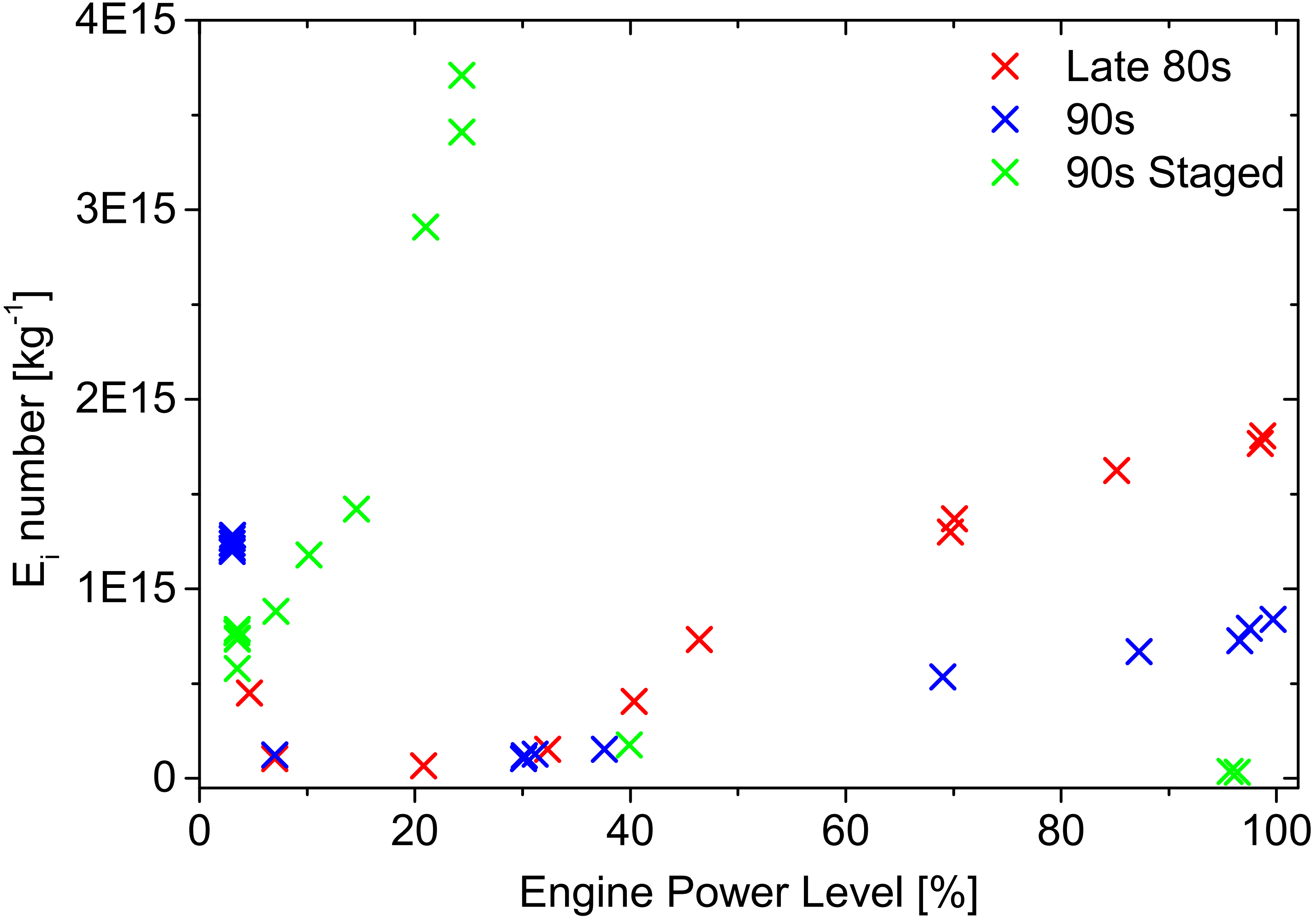
Emission Indices (90s Staged Combustor)



Comparison of Engine Sources (PM mass)



Comparison of Engine Sources (PM number)



Summary and Conclusions

- A new aircraft gas turbine PM standard is in the works
- Empa operates a draft-standard compliant sampling system at SR Technics in Zürich Kloten
- Except at idle, nV PM mass and nV PM number increase with engine power for traditional single annular combustor technologies. PM mass increases more rapidly than the number → Particle distribution shifts to larger sizes
- The staged double annular combustor design from the late 90s has unique emission profiles with high nV PM mass and numbers at engine powers < 25% and low emissions for engine powers > 25%
- Improvements in combustor designs have significantly reduced PM mass emissions at all thrust levels, but effects on nV PM number at low engine power merit further research

Acknowledgements

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Questions?

Thank you for your attention!