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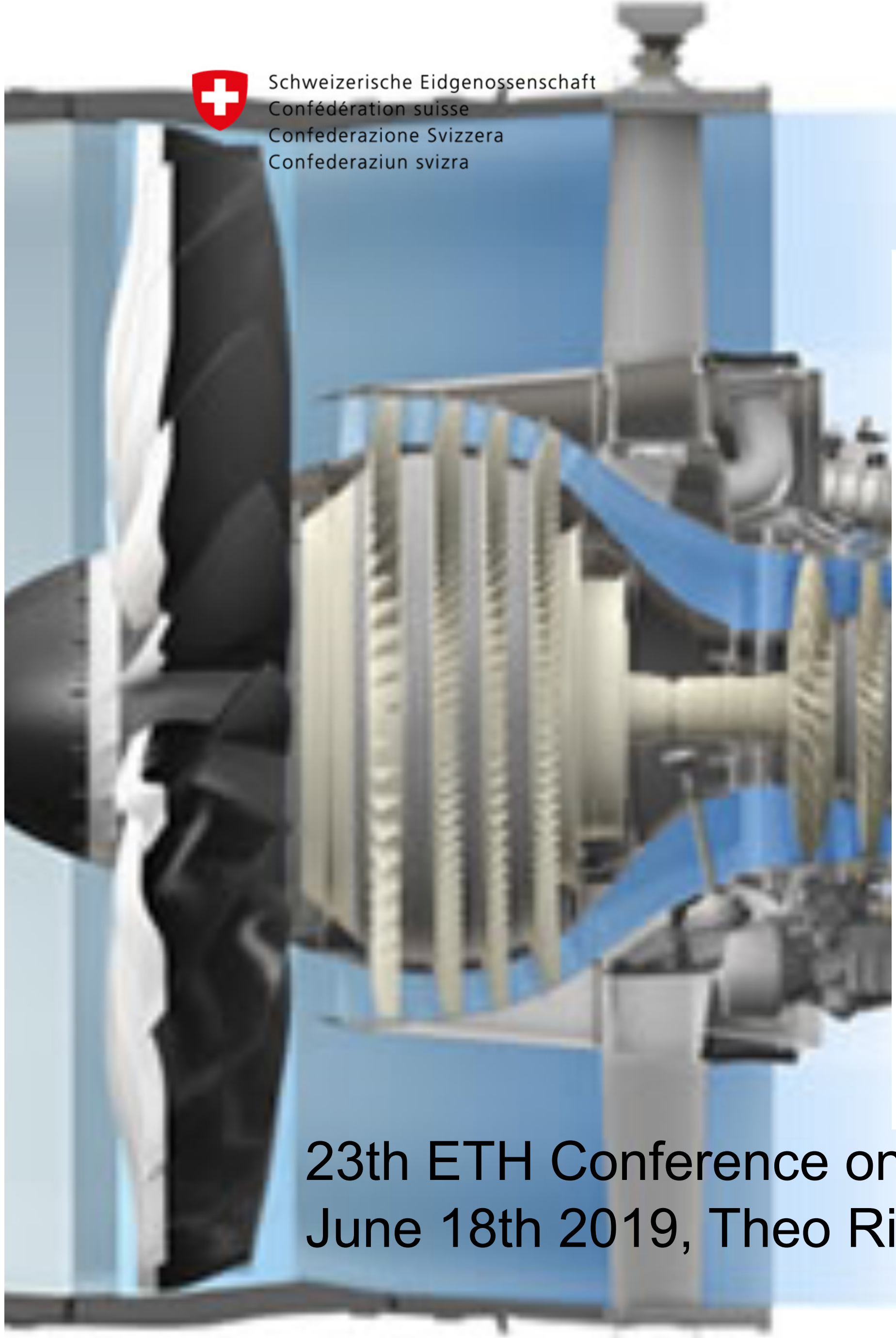
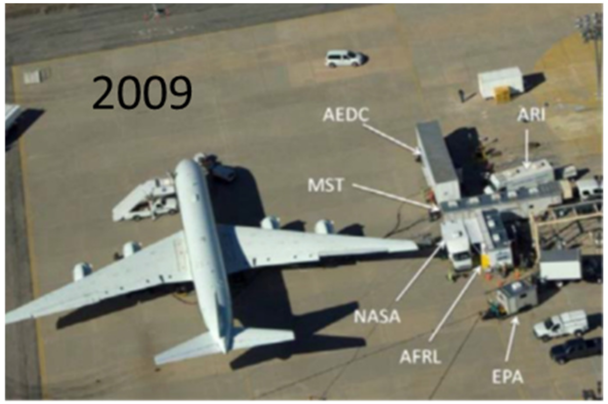


The First Global Regulatory Limits for Aircraft Engine Particle Mass and Number Emissions

23th ETH Conference on Combustion Generated Nanoparticles
June 18th 2019, Theo Rindlisbacher

Background

- Detailed scientific studies were initiated nearly 20 years ago in the United States and Europe to better understand and quantify the characteristics of aircraft gas turbine particle emissions.
- Strong involvement of SAE International aircraft engine emission experts for development of Aerospace Information Report
- In 2008, first proposals for the introduction of an ICAO particulate standard for aircraft engines were made, and subsequently a plan was developed and agreed at the 8th meeting of ICAO Committee on Aviation Environmental Protection (CAEP/8) in 2010.



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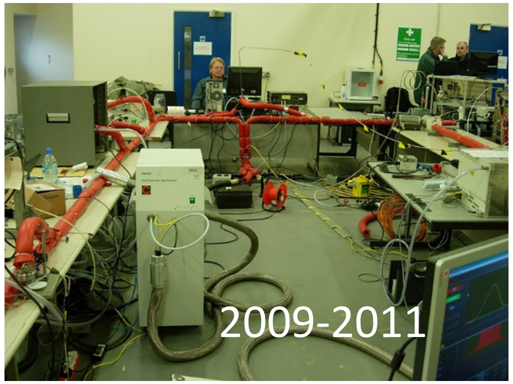
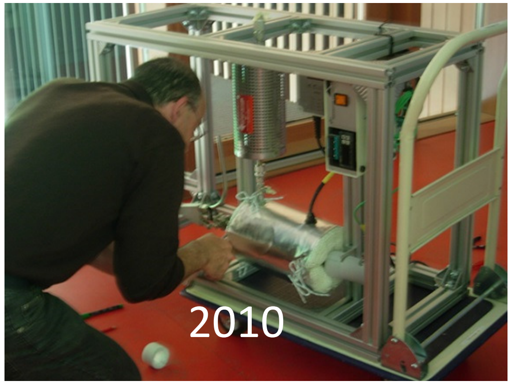
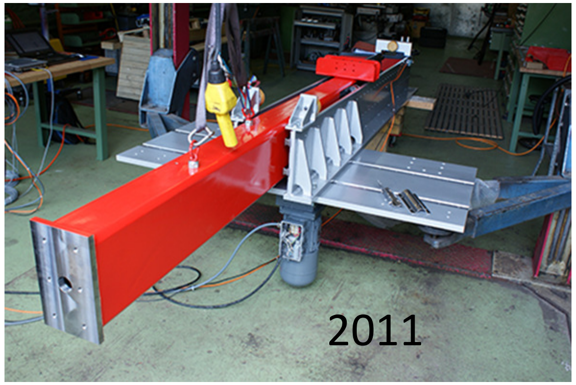
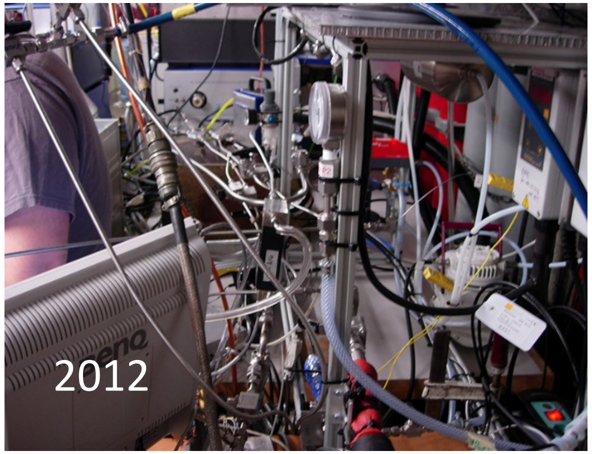






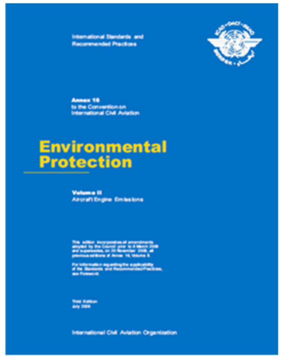
Breakthrough: Use of engine test cell at the maintenance facility of SR Technics, Zurich Airport. FOCA built and installed the system prototype, followed by International measurement campagins. ICAO CAEP agreement on measurement Protocol in spring 2016 → start of globally standardised UFP measurements

Background



2016 – 2018
Testing of 25 new and current in-production engine types according to new ICAO standard measurement protocol (agreed 2016) for development of regulatory limits.
Complex global fleet emission reduction vs cost modelling and technical analysis to propose first limit values for particle mass and particle number in ICAO CAEP.

Aviation introduces the first global UFP standards



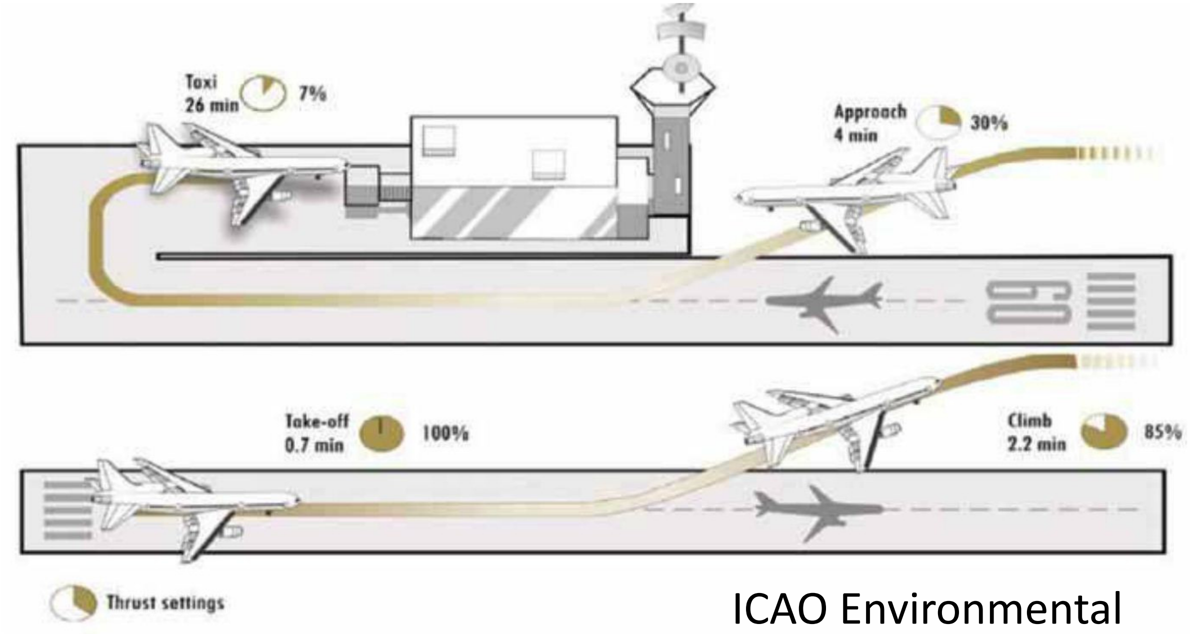
From 1st January 2020, all in-production (larger than small business jet size) will need to be certified according to the new measurement protocol for non-volatile* particle (nvPM) mass and number emissions. With this first standard, the maximum nvPM mass concentration in the exhaust is limited and reporting of nvPM mass and number emissions is mandated.
Published in ICAO Annex 16 Volume II, Chapter 4 and Appendix 7

In February 2019, the ICAO CAEP adopted regulatory limits for nvPM mass and number emissions in the landing and take-off cycle (LTO), both for in-production and new type engines, expected to be applicable globally from 1st January 2023.

* particles, which do not volatilize when heated to 350°C, mostly Black Carbon, Soot

Standard LTO - Cycle

- An engine moves virtually in a standard landing and take-off cycl (LTO cycle).
- The generated emission load (grams of particle emission or number of emitted particles) divided by the maximum rated thrust of the engine must not exceed a regulatory limit value (details on next two slides).



ICAO Environmental Report 2013

Figure 1: *Illustration of ICAO Emissions Certification Procedure for the LTO Cycle.*

Elements of the Metric System

- Four engine modes:
  - Take-off (100% thrust) time t_m = 0.7 minutes = 42 s
  - Climb (85% thrust) time t_m = 2.2 minutes = 132 s
  - Approach (30% thrust) time t_m = 4.0 minutes = 240 s
  - Taxi (7% thrust) time t_m = 26 minutes = 1560 s

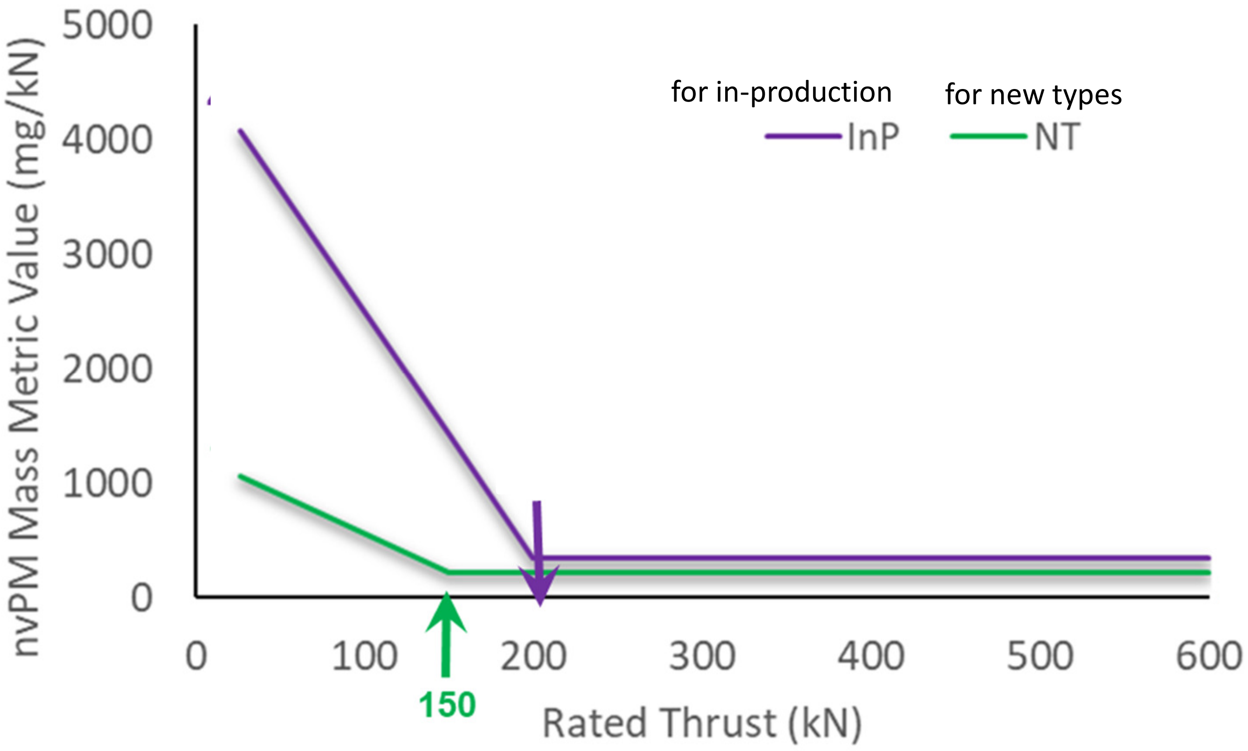
- For each mode the ISA normalised fuel flow W_f (kg/s) and the emission factor EI (mass of particles / kg fuel) or (number of particles / kg fuel) is reported

- Emission of a mode = W_f * EI * t_m
- LTO-Emissions = Sum of the emissions of the four modes
- The LTO-Emissions of an engine are then normalised by the rated thrust F_{oo} of the engine

Final Metric Values

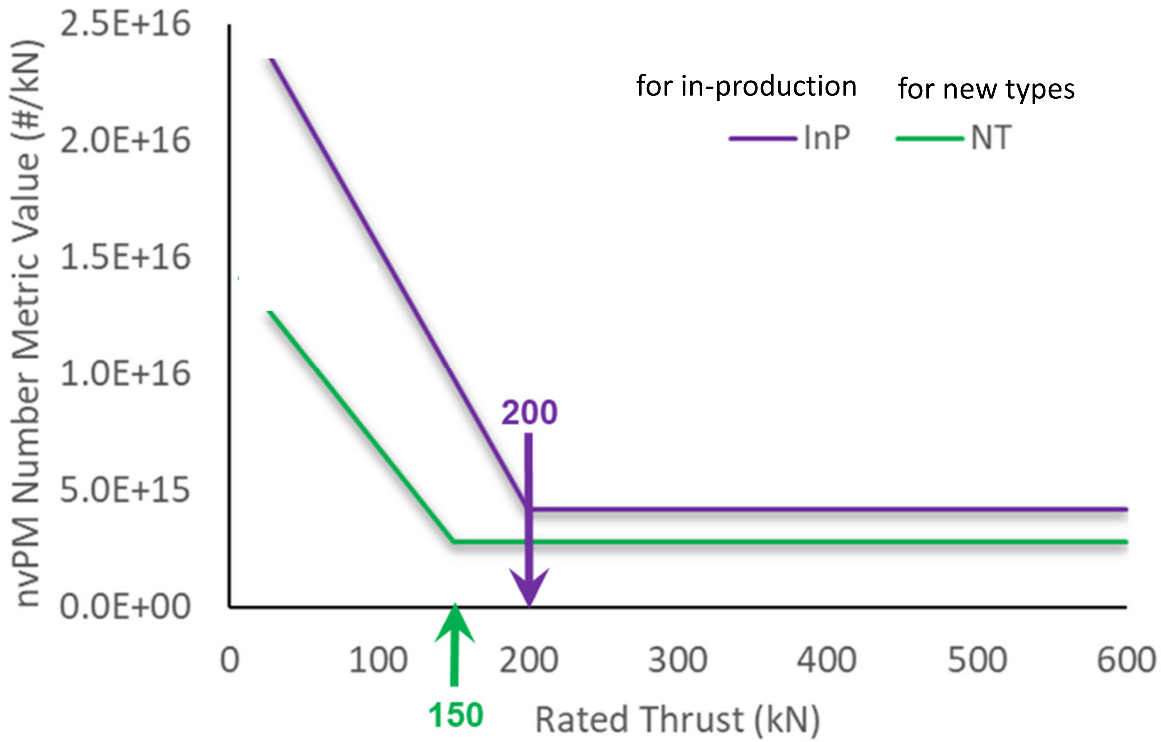
- Mass $$\frac{LTO_{nvpm\_mass}}{F_\infty} = \frac{\sum_{LTO} t_m \times W_f \times EI_{nvpm\_mass}}{F_\infty}$$
- Number $$\frac{LTO_{nvpm\_num}}{F_\infty} = \frac{\sum_{LTO} t_m \times W_f \times EI_{nvpm\_num}}{F_\infty}$$
- EI's are normalized to 13.8%mass fuel hydrogen content and corrected for thermophoretic loss in the collection section
- The metric values (LTO emissions / rated thrust) are adjusted for the number of engines tested to obtain the characteristic metric value for that engine type. (e.g.) one engine serial number tested with a minimum of three curves → measured metric value is increased by 39%
- **The characteristic metric value is the value used to demonstrate compliance to the standard (one for nvPM mass, one for nvPM number)**

CAEP Agreed Regulatory Limits from 1st January 2023



Note: Current in-production engines have not been designed for low nvPM mass emissions.

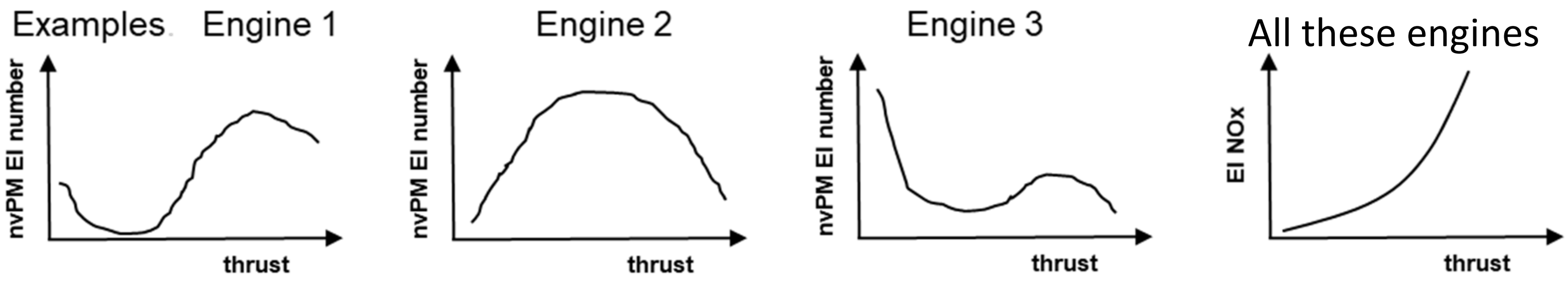
CAEP Agreed Regulatory Limits from 1st January 2023



Note: Current in-production engines have not been designed for low nvPM number emissions.

Special Challenges for Combustion Technology

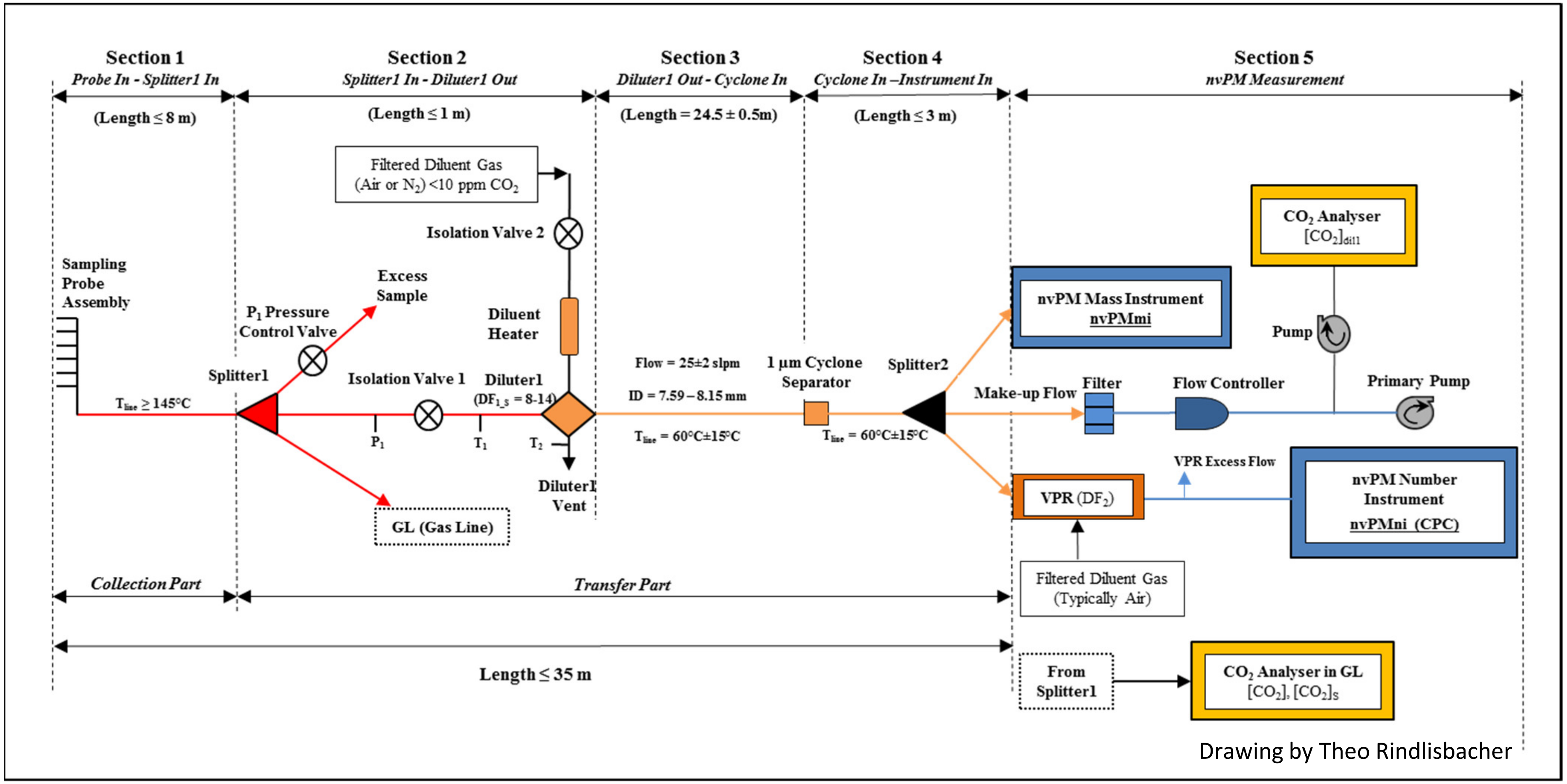
- Especially nvPM number is not well behaved compared to e.g. NOx



- Engine manufacturers are learning to understand this
- Some reduction strategies have trade-offs with other pollutants
- Lean burn combustion technology can address both NOx and nvPM
  (Currently only two engine types in daily aircraft operation worldwide)
- Technologies are not scalable to full range of engine sizes



nvPM Measurement System Overview



Particle Loss Correction

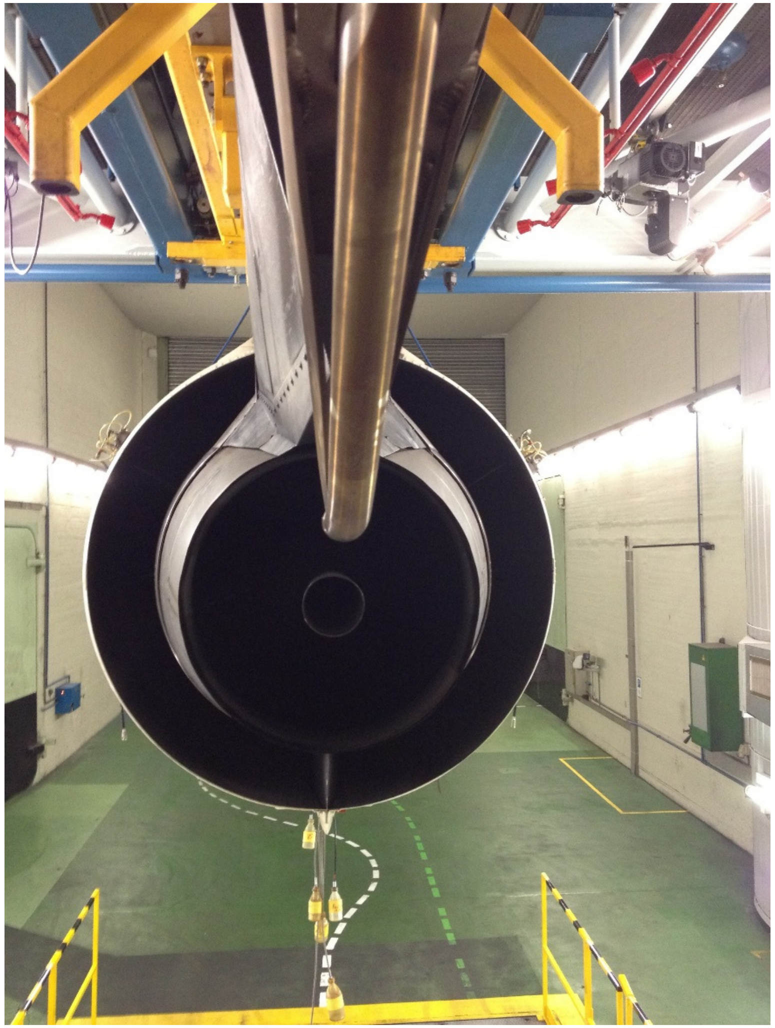
- **Reported emission concentrations respectively emission factors** are **corrected for thermophoretic loss in the collection part** of the sampling system to balance out engine specific differences (from exhaust temperature profile).

- **Overall system particle loss correction factors are provided for modeling of engine exit plane emissions. The methodology is published in ICAO Annex 16 Volume II Part IV and Appendix 8.**
- Part IV: Non-volatile Particulate Matter Assessment for Inventory and Modeling Purposes
- Appendix 8: Procedures for Estimating nvPM System Loss Corrections
- Tools developed by SAE-E31

Outlook

All done in ICAO

- Correction of ambient conditions effects on nvPM emissions (for engine certification)
- Improvement of nvPM correlation for all flight phases (for emissions modelling)
- Better assess technology trade-offs with other pollutants and fuel burn
- Monitor new engine type certification data 2020-2022 and analyse potential increase of 2023 nvPM stringeny levels



Thank You for Your Attention