ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

IfU Institute of Environmental Engineering

EMPA Materials Science & Technology

The First Aircraft Engine Certification Measurement of Non-volatile Particulate Matter Emissions

Benjamin Brem[1,2], Lukas Durdina[1,2], Jing Wang[1,2], Theo Rindlisbacher[3], Frithjof Siegerist[4]

[1] Laboratory for Advanced Analytical Technologies, Empa Dübendorf
[2] Institute of Environmental Engineering, ETH Zürich
[3] Swiss Federal Office of Civil Aviation, FOCA, Bern
[4] SR Technics Switzerland Ltd. Zürich, Airport

20th ETH-Conference on Combustion Generated Nanoparticles, June 16, 2016

Current Data on Aircraft Engine Emissions:

ICAO ENGINE EXHAUST EMISSIONS DATA BANK

SUBSONIC ENGINES

ENGINE IDENTIFICATION:		BYPASS RATIO:	5.1
UNIQUE ID NUMBER:		PRESSURE RATIO (π_{oo}):	27.7
ENGINE TYPE:		RATED OUTPUT (F_{oo}) (kN):	117

REGULATORY DATA

CHARACTERISTIC VALUE:	HC	CO	NOx	SMOKE NUMBER
D_p/F_{oo} (g/kN) or SN	3.0	50.6	43.1	14.4
AS % OF ORIGINAL LIMIT	15.4 %	42.9 %	45.2 %	63.4 %
AS % OF CAEP/2 LIMIT (NOx)			56.5 %	
AS % OF CAEP/4 LIMIT (NOx)			68.1 %	
AS % OF CAEP/6 LIMIT (NOx)			77.3 %	
AS % OF CAEP/8 LIMIT (NOx)			91.9 %	

DATA STATUS

- \- PRE-REGULATION
- x CERTIFICATION
- \- REVISED (SEE REMARKS)

TEST ENGINE STATUS

- x NEWLY MANUFACTURED ENGINES
- \- DEDICATED ENGINES TO PRODUCTION STANDARD
- \- OTHER (SEE REMARKS)

EMISSIONS STATUS

- x DATA CORRECTED TO REFERENCE (ANNEX 16 VOLUME II)

CURRENT ENGINE STATUS

(IN PRODUCTION, IN SERVICE UNLESS OTHERWISE NOTED)

- \- OUT OF PRODUCTION
- \- OUT OF SERVICE

MEASURED DATA

MODE	POWER SETTING (%F_{oo})	TIME minutes	FUEL FLOW kg/s	EMISSIONS INDICES (g/kg) HC	CO	NOx	SMOKE NUMBER
TAKE-OFF	100	0.7	1.213	0.02	0.25	21.79	13.1
CLIMB OUT	85	2.2	0.986	0.02	0.16	17.08	9.8
APPROACH	30	4.0	0.331	0.05	3.07	8.93	2.1
IDLE	7	26.0	0.108	1.75	30.94	4.27	2.1
LTO TOTAL FUEL (kg) or EMISSIONS (g)			429	302	5476	4763	-
NUMBER OF ENGINES				3	3	3	3
NUMBER OF TESTS				7	7	7	7
AVERAGE D_p/F_{oo} (g/kN) or AVERAGE SN (MAX)				2.58	46.81	40.71	13.07
SIGMA (D_p/F_{oo} in g/kN, or SN)				0.37	2.6	1.2	4.1
RANGE (D_p/F_{oo} in g/kN, or SN)				2.18 to 2.9	43.8 to 48.7	39.8 to 42.1	8.4 to 16.2

We want to have: Non-volatile PM Mass and Number Data

ICAO ENGINE EXHAUST EMISSIONS DATA BANK

SUBSONIC ENGINES

ENGINE IDENTIFICATION:
UNIQUE ID NUMBER:
ENGINE TYPE:

BYPASS RATIO: 5.1
PRESSURE RATIO (π_{oo}): 27.7
RATED OUTPUT (F_{oo}) (kN): 117

REGULATORY DATA

CHARACTERISTIC VALUE:	HC	CO	NOx	SMOKE NUMBER	nvPM Mass	nvPM Number
D_p/F_{oo} (g/kN) or SN	3.0	50.6	43.1	14.4		
AS % OF ORIGINAL LIMIT	15.4 %	42.9 %	45.2 %	63.4 %		
AS % OF CAEP/2 LIMIT (NOx)			56.5 %			
AS % OF CAEP/4 LIMIT (NOx)			68.1 %			
AS % OF CAEP/6 LIMIT (NOx)			77.3 %			
AS % OF CAEP/8 LIMIT (NOx)			91.9 %			
As % OF CAEP/10			XX.X %		XX.X%	XX.X%

DATA STATUS

- – PRE-REGULATION
- x CERTIFICATION
- – REVISED (SEE REMARKS)

TEST ENGINE STATUS

- x NEWLY MANUFACTURED ENGINES
- – DEDICATED ENGINES TO PRODUCTION STANDARD
- – OTHER (SEE REMARKS)

EMISSIONS STATUS

- x DATA CORRECTED TO REFERENCE (ANNEX 16 VOLUME II)

CURRENT ENGINE STATUS

(IN PRODUCTION, IN SERVICE UNLESS OTHERWISE NOTED)

- – OUT OF PRODUCTION
- – OUT OF SERVICE

MEASURED DATA

MODE	POWER SETTING (%F_{oo})	TIME minutes	FUEL FLOW kg/s	EMISSIONS INDICES (g/kg) HC	CO	NOx	SMOKE NUMBER	nvPM Mass	nvPM Number
TAKE-OFF	100	0.7	1.213	0.02	0.25	21.79	13.1	0.0X	X.XXE14
CLIMB OUT	85	2.2	0.986	0.02	0.16	17.08	9.8	0.0X	X.XXE14
APPROACH	30	4.0	0.331	0.05	3.07	8.93	2.1	–	X.XXE13
IDLE	7	26.0	0.108	1.75	30.94	4.27	2.1	–	X.XXE13
LTO TOTAL FUEL (kg) or EMISSIONS (g)			429	302	5476	4763	–	X.X	X.XXE17
NUMBER OF ENGINES				3	3	3	3	1	1
NUMBER OF TESTS				7	7	7	7	3	3
AVERAGE D_p/F_{oo} (g/kN) or AVERAGE SN (MAX)				2.58	46.81	40.71	13.07	0.XX	X.XXE14
SIGMA (D_p/F_{oo} in g/kN, or SN)				0.37	2.6	1.2	4.1	X	X
RANGE (D_p/F_{oo} in g/kN, or SN)				2.18 to 2.9	43.8 to 48.7	39.8 to 42.1	8.4 to 16.2	X	X

Objective

- Perform a non-volatile PM emissions certification measurement like an engine manufacturer will have to do to comply with the new ICAO standard
- Test the developed certification procedure

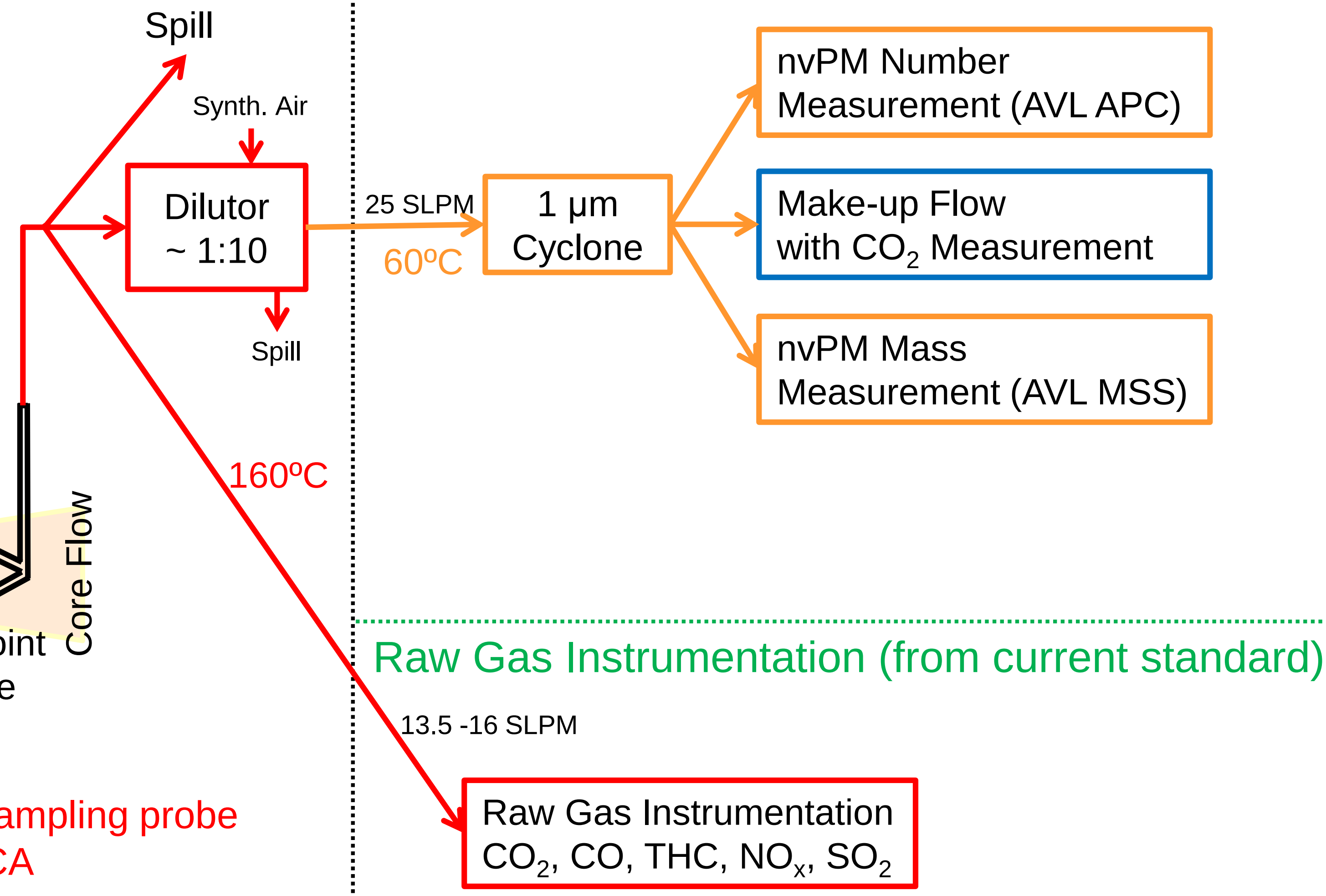
- Relevance
  - Never been attempted before
  - Prove to the industry and regulatory agencies that measurement procedures and technologies are adequate

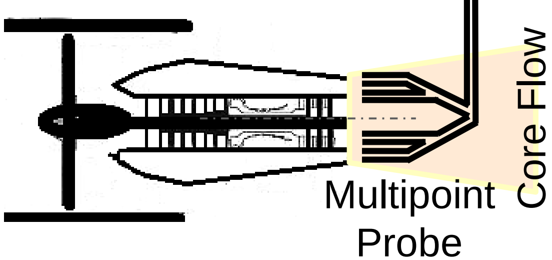
Emission Sampling System at SR Technics

Engine Test Cell

Instrumentation Room

nvPM Instrumentation (new!!)

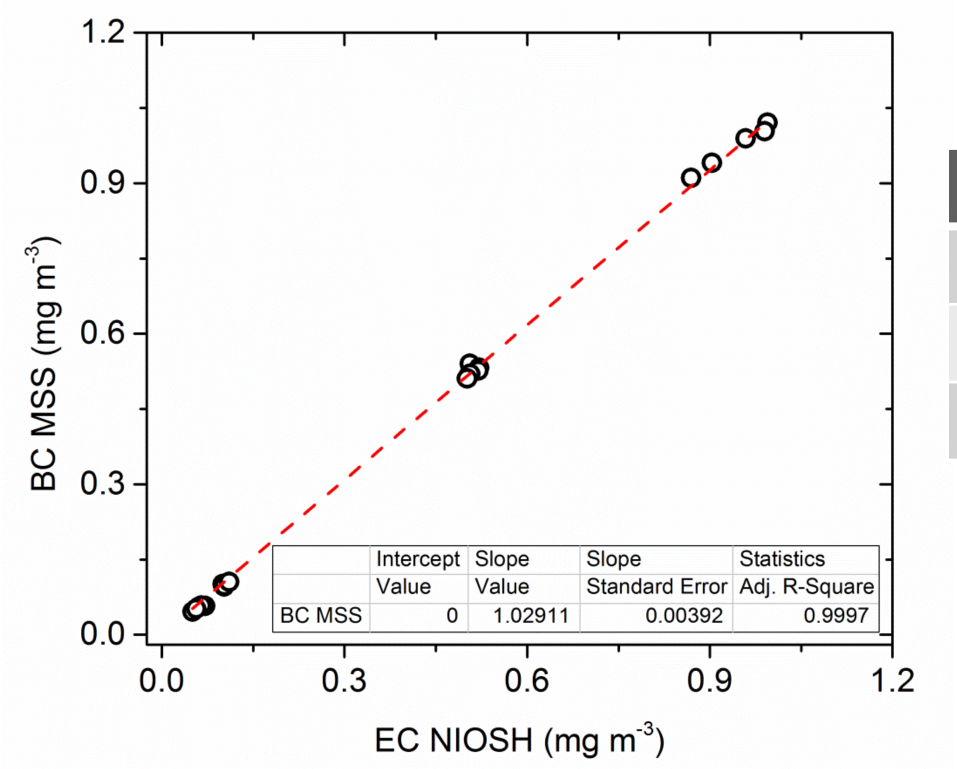




Special multi-orifice sampling probe manufactured by FOCA

Calibration of the nvPM Mass Instrument

- Diffusion flame generated Elemental Carbon (EC) collected on filter considered reference
- Filter EC mass determined with NIOSH 5040 thermal optical transmittance method
- 3 measurements at 100, 250 and 500 µg m^{-3} required for an annual calibration

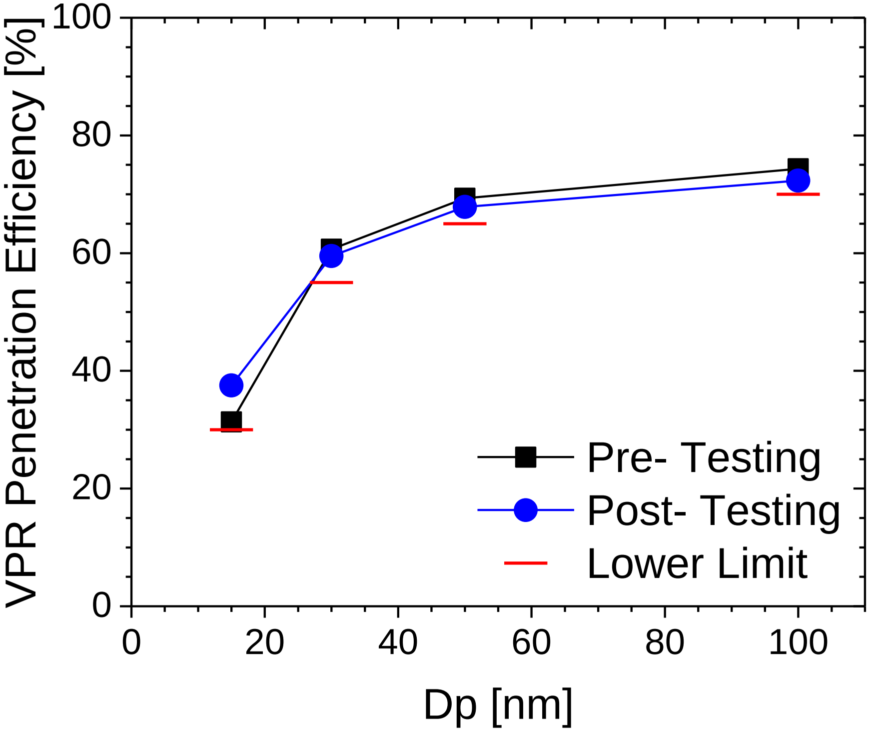


Laboratory	Cal Constant
AVL Graz (commissioning)	0.475
National Research Council Canada	0.462
Empa	0.466

- Method itself robust, but labor intensive and costly
- Ongoing issue: instrument response to different soot types

Calibration of the nvPM Number Instrument (APC)

- Volatile Particle Remover (VPR)
  - Consists of an adjustable primary disk dilutor, a catalytic stripper (350°C), sulfur trap and a secondary dilutor
  - Dilution factor calibration is checked before each engine test
  - Annual calibration of soot particle penetration efficiencies



- Condensation Particle Counter (CPC)
  - Linearity from 2000 cm^{-3} to 10’000 cm^{-3} has to be within ± 10% of the electrometer
  - Counting efficiency for Emery oil:
    - > 50% at 10 nm
    - > 90% at 15 nm

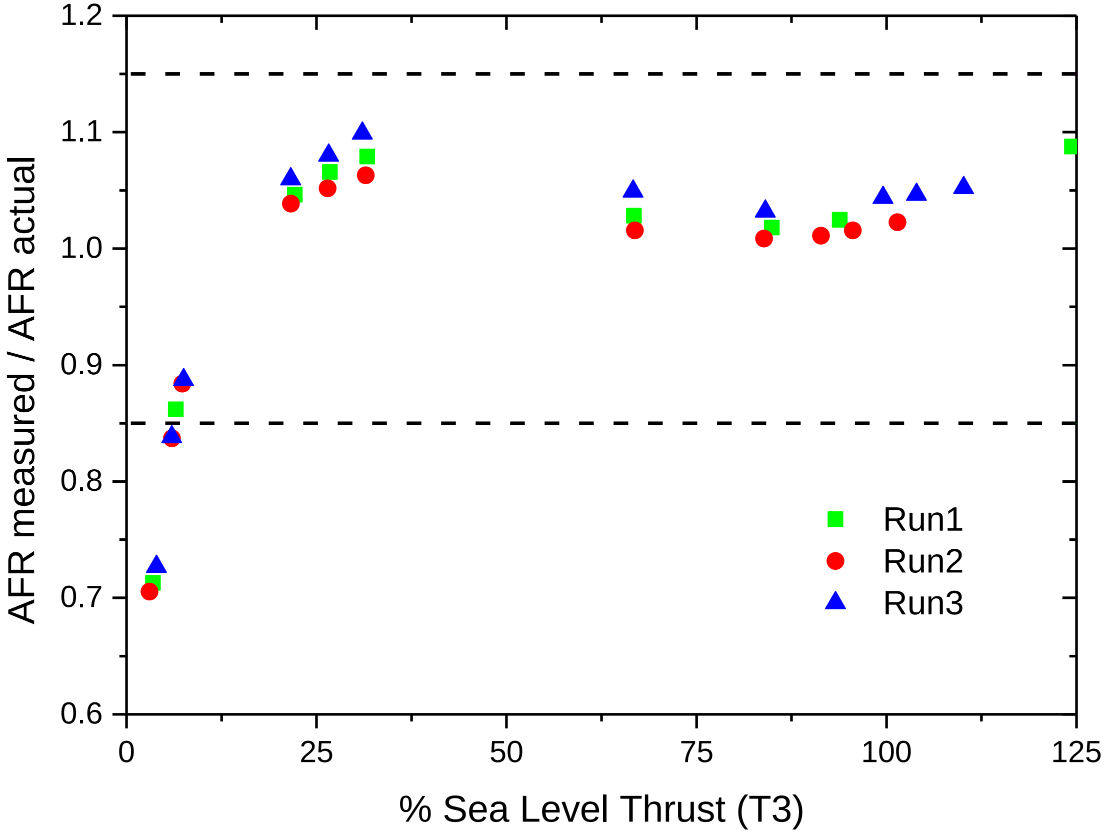
Engine, Test Matrix and Fuel

- Engine
  - In- service, in-production turbofan rented for measurements
  - Certification engine was carefully selected based on performance data
- Test Matrix:
  - Eleven points which covered the entire engine thrust range
  - Chosen to represent the ICAO landing and take-off operations as close as possible:
    - 7% proxy for taxiing
    - 30% proxy for approach
    - 85% proxy for climb-out
    - 100% proxy for take–off
  - Engine is controlled according to combustor inlet temperature for which reference thrust values are known at static sea level conditions (15°C / 1013 mbar)
- Fuel Properties

Parameter	Unit	Average Pre- Post Testing
Net. Heat of Combust.	MJ/kg	43.3
Hydrogen	mass %	13.98
Tot. Aromatics	volume %	17.7
Naphthalenes	volume %	0.75
Sulfur, total	mass %	0.042
H/C ratio	n/m	1.94

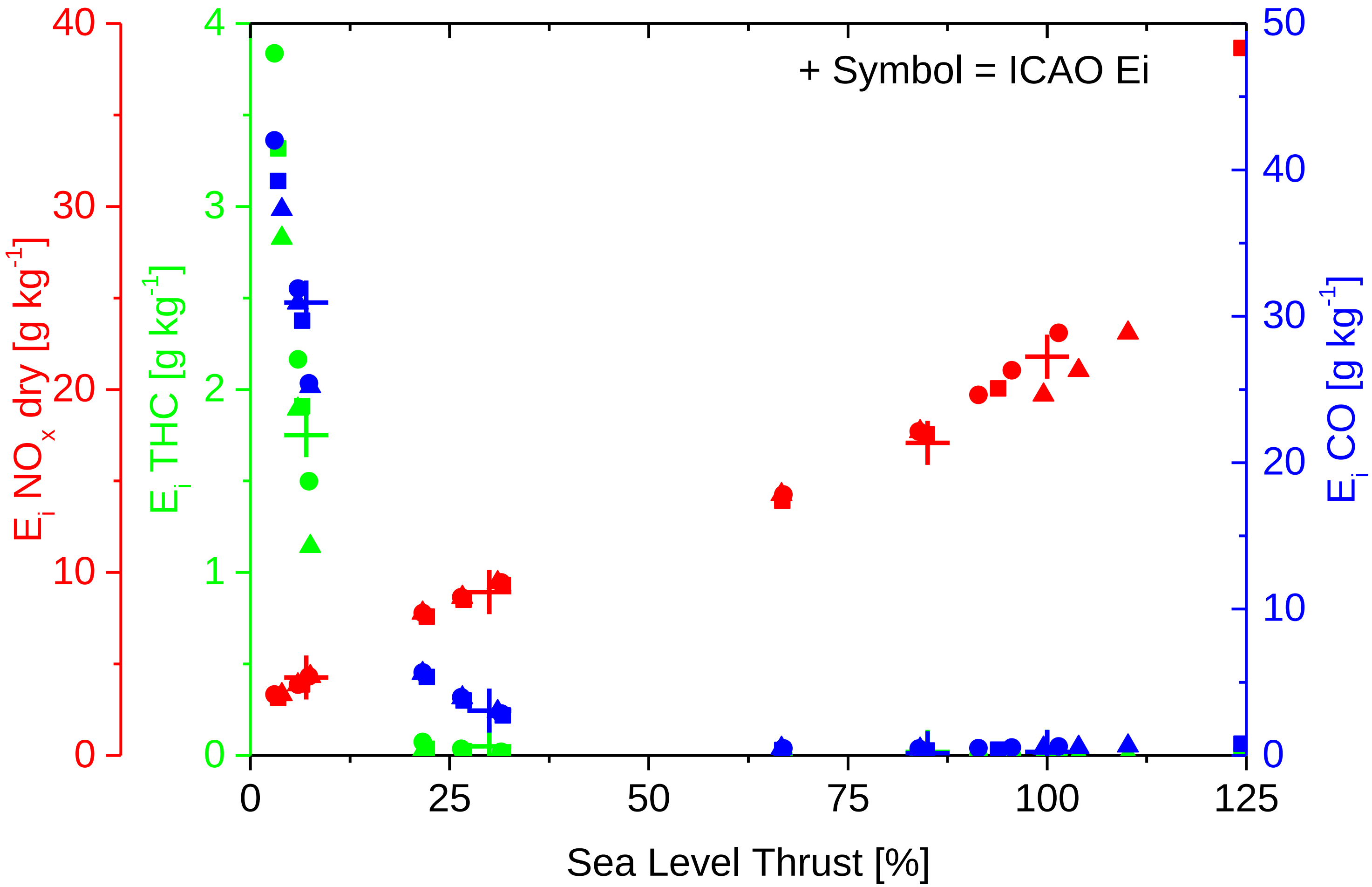
Sampling Representativeness Check

- Air to fuel ratio calculated from emitted gaseous carbon species is compared to engine air to fuel ratio from fuel flow and engine core airflow

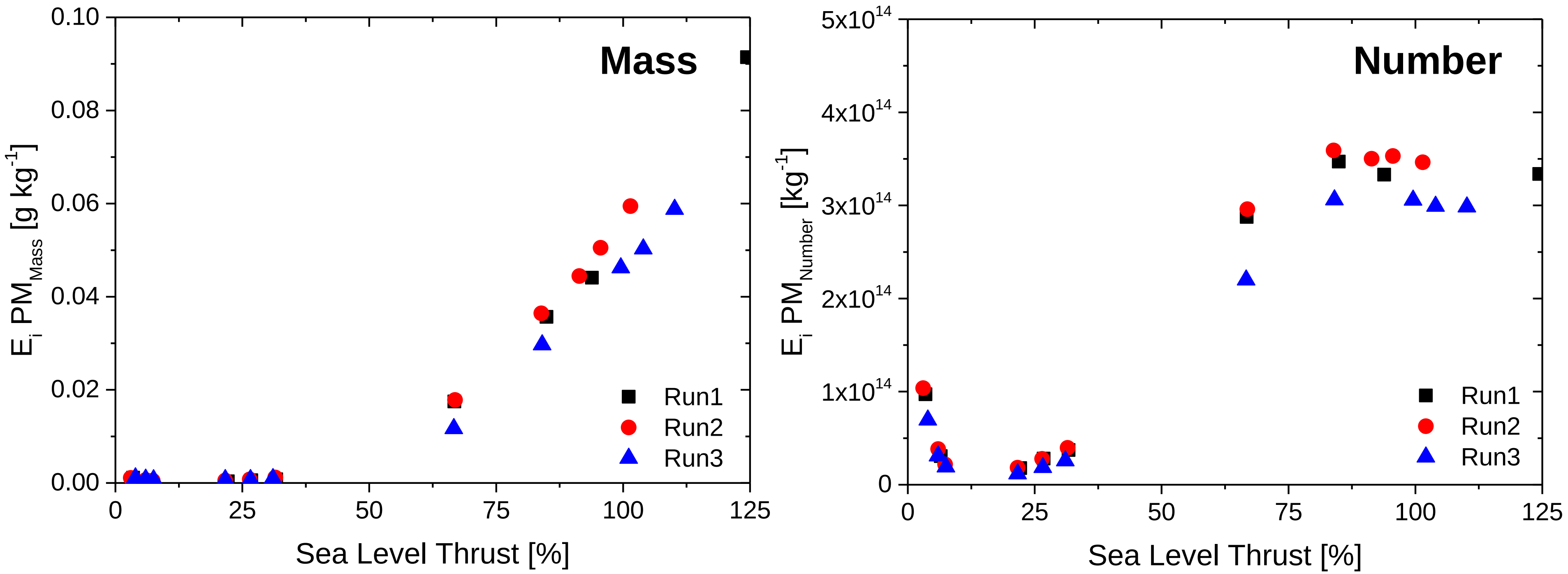


- Representative sampling was achieved for the prescribed thrust points

Comparison of Measured Gaseous Emission Indices with Existing Certification Data from 2006

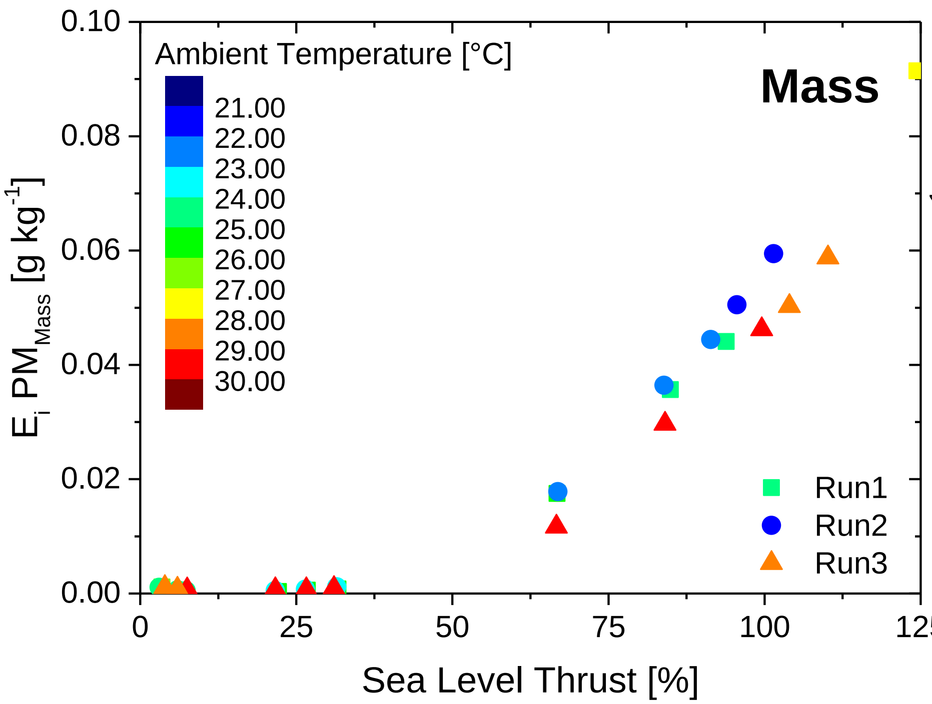


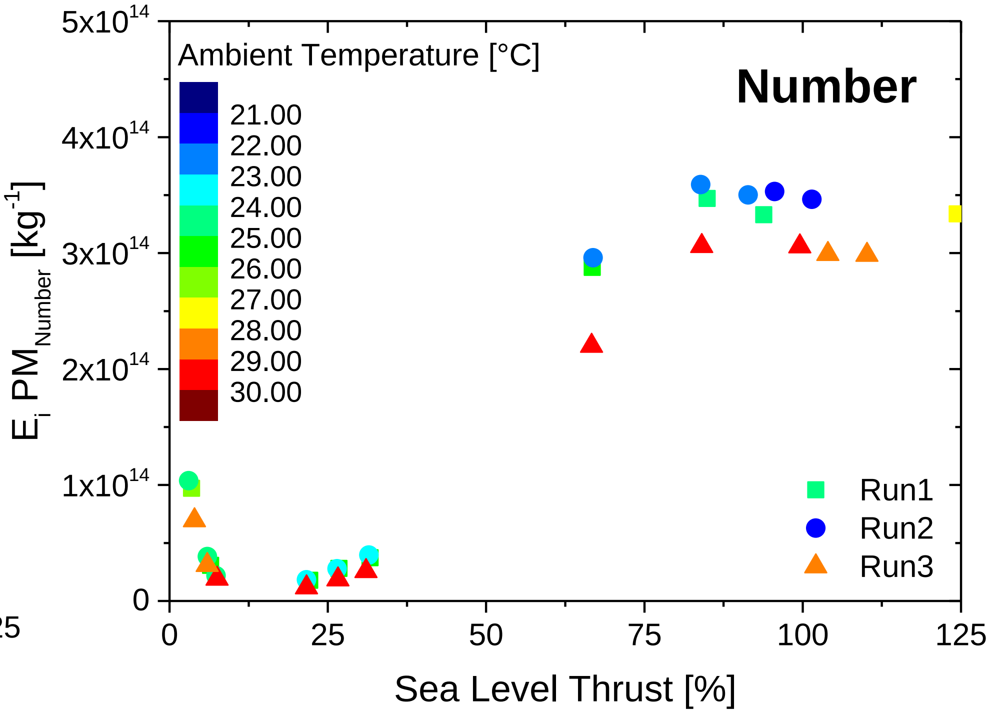
Non-Volatile Particle Emissions



- PM mass at LOD below 50% thrust
- Higher variability in both mass and number than expected

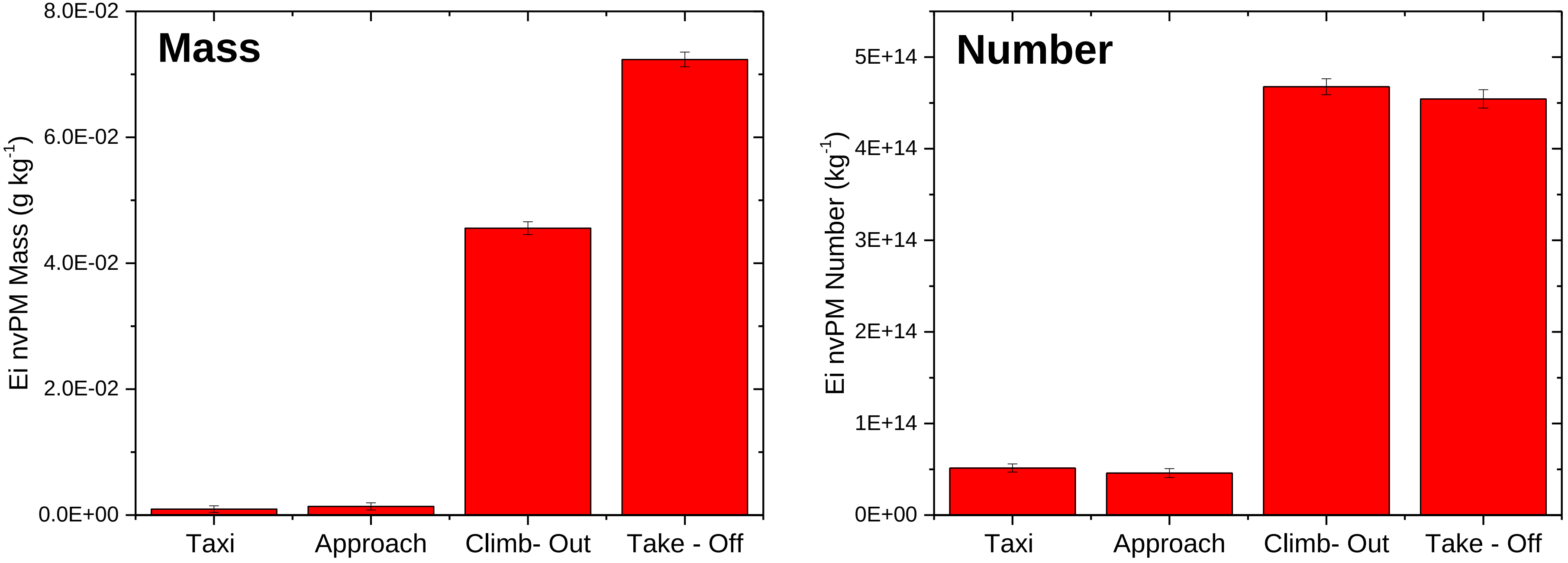
Repeatability: Ambient Temperature Effect





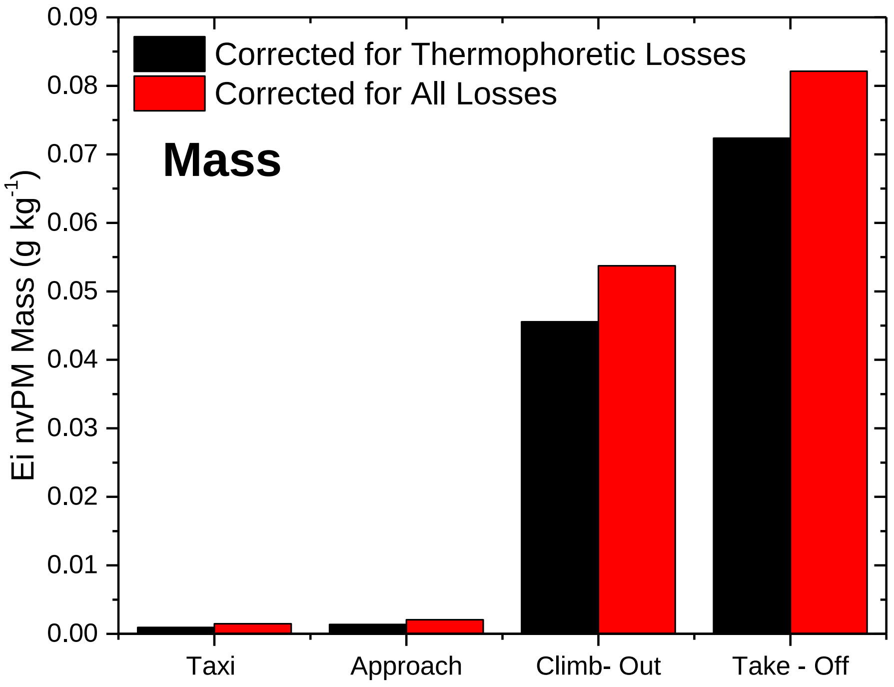
- Higher ambient temperature results in lower nvPM emissions at same combustor temperature and identical measurement condition
- Cause: complex interaction between engine performance and combustor conditions
- Work on semi-empirical corrections that take combustor pressure and temperature into account is ongoing

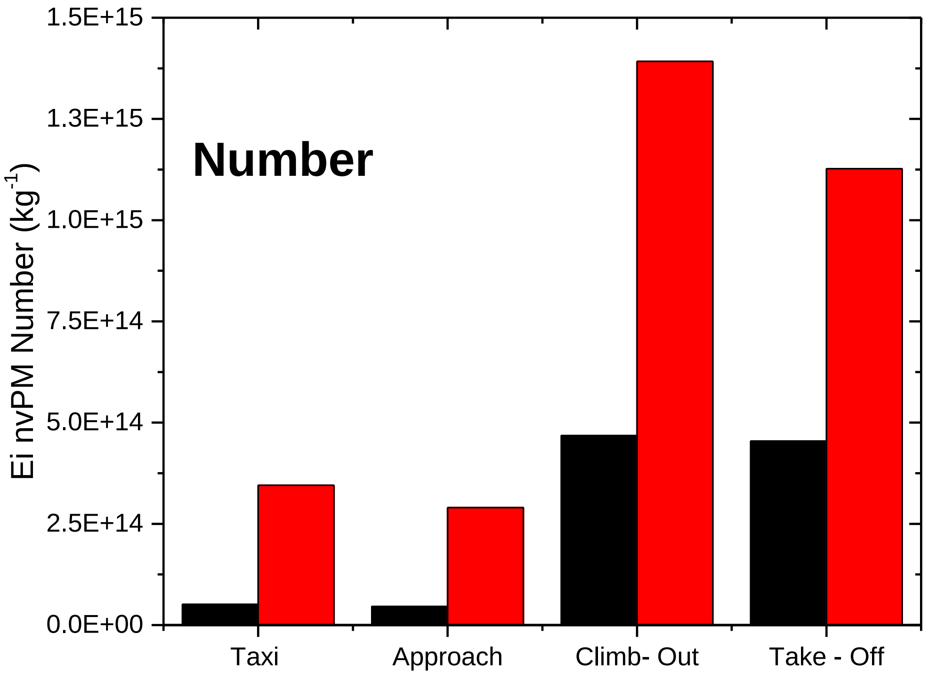
Emission Values for the ICAO Emission Database



- First standardized nvPM data of an aircraft engine
- The reported data include the thermophoretic loss correction in the sampling probe

Same Data including Estimated System Loss Corrections





- System losses are significant in particular for the particle number measurement
- Relevance of this data: Please check Lukas Durdina’s Poster #85!

Conclusions

- The nvPM certification measurement procedure and method have been successfully demonstrated
- Twelve more engine models which will be in production after 2020 have since been measured by engine manufacturers

- In the context of setting stringent regulatory limits in the future:
  - Further improvements of the mass calibration are needed
  - Development of potential corrections for ambient conditions, fuel effects and engine to engine variability are necessary

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

IfU
Institute of
Environmental Engineering

EMPA
Materials Science & Technology

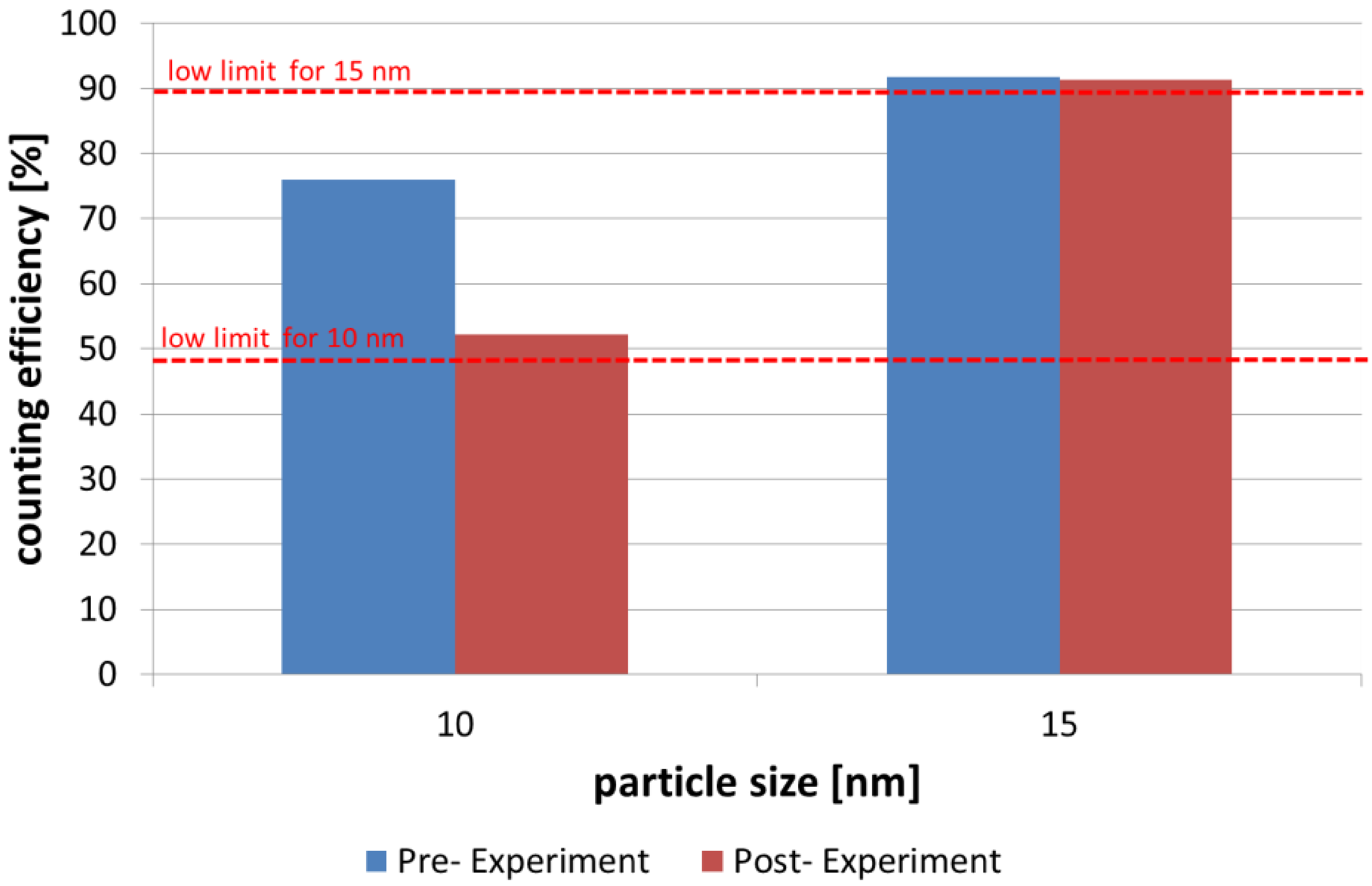
Questions?

Thank you for your attention!

Acknowledgements:

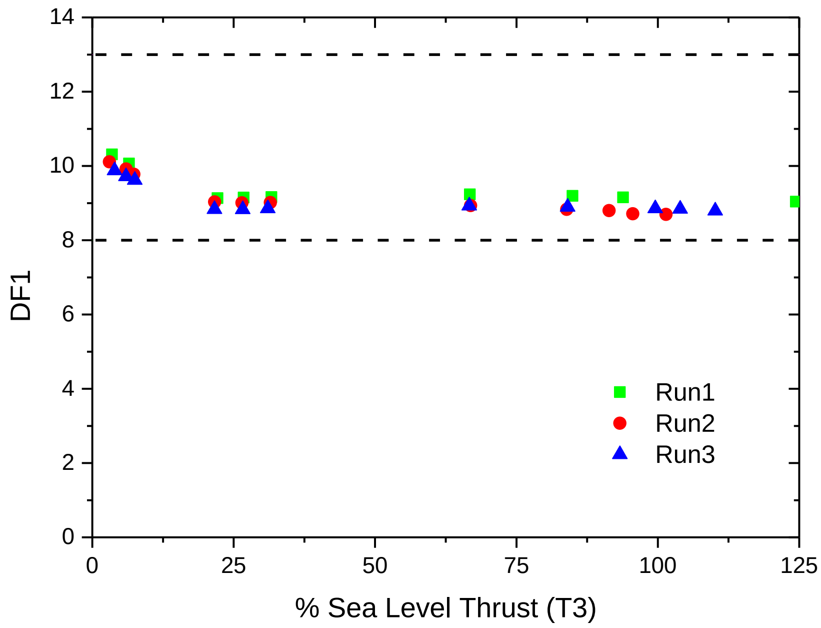
Swiss Federal Office of Civil Aviation, Empa, US Federal Aviation Administration, Transport Canada,European Aviation Safety Agency, Missouri S&T, Cardiff University, NRC Canada, SAE E-31 Committee

Measured CPC Counting Efficiency (Emery Oil)



Required Sampling System Operation Checks

- Cleanliness (Zero) Check
  - Purging the system with pure synthetic air
    - 30 s average mass concentration must be less than 1 µg/m^3
    - 30 s average number concentration must be less than 2.0 particles/cm^3
- Ambient Check
  - Measuring undiluted test cell air for a minimum of three minutes
- Dilution Factor Checks
  - The sampling system dilution factor is monitored in real time with the diluted and undiluted CO_2 measurement
    - Values lie between 8 and 14
  - The VPR dilution is checked offline before testing
    - Values must be within ± 10% of the manufacturer's calibration



Data Processing

- Calculation of emission indices
  - Based on carbon balance

$$EI_{num} = \frac{22.4 \times DF_2 \times nvPM_{num\_STP} \times 10^6}{\left([CO_2]_{dil1} + \frac{1}{DF_1}\left([CO] - [CO_2]_b + [HC]\right)\right)(M_C + \alpha M_H)} \times k_{thermo}$$

  - Thermophoretic particle loss correction factor (k_{thermo})
  - To account for engines with different exhaust gas temperatures

$$k_{thermo} = \left(\frac{T_1 + 273.15}{T_{EGT} + 273.15}\right)^{-0.38}$$

- Other particle loss in the system also must be reported
  - The method uses the measured mass and number concentration as inputs and will be published in the new ICAO Annex 16 Volume II
  - SAE E-31 is working on its further development