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

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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 ($p_a$): | 27.7 |
| ENGINE TYPE: | RATED OUTPUT ($P_{o2}$) (kW): | 117 |

**REGULATORY DATA**

<table>
<thead>
<tr>
<th>CHARACTERISTIC VALUE:</th>
<th>HC</th>
<th>CO</th>
<th>NOX</th>
<th>SMOKE NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_0/F_{O2}$ (g/kN) or SN</td>
<td>3.0</td>
<td>50.6</td>
<td>43.1</td>
<td>14.4</td>
</tr>
<tr>
<td>AS % OF ORIGINAL LIMIT</td>
<td>15.4 %</td>
<td>42.9 %</td>
<td>45.2 %</td>
<td>63.4 %</td>
</tr>
<tr>
<td>AS % OF CAEP/2 LIMIT (NOx)</td>
<td>56.5 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS % OF CAEP/4 LIMIT (NOx)</td>
<td>68.1 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS % OF CAEP/6 LIMIT (NOx)</td>
<td>77.3 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS % OF CAEP/8 LIMIT (NOx)</td>
<td>91.5 %</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DATA STATUS**

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

**TEST ENGINE STATUS**

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

**EMISSIONS STATUS**

- 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**

<table>
<thead>
<tr>
<th>MODE</th>
<th>POWER SETTING ($P_{o2}$)</th>
<th>TIME (minutes)</th>
<th>FUEL FLOW (kg/s)</th>
<th>EMISSIONS INDICES (g/kg)</th>
<th>HC</th>
<th>CO</th>
<th>NOX</th>
<th>SMOKE NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAKE-OFF</td>
<td>100</td>
<td>0.7</td>
<td>1.213</td>
<td>0.02</td>
<td>0.25</td>
<td>21.75</td>
<td>13.1</td>
<td></td>
</tr>
<tr>
<td>CLIMB OUT</td>
<td>48</td>
<td>2.2</td>
<td>0.996</td>
<td>0.02</td>
<td>0.16</td>
<td>17.09</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>APPROACH</td>
<td>30</td>
<td>4.0</td>
<td>0.331</td>
<td>0.05</td>
<td>0.07</td>
<td>8.93</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>IDLE</td>
<td>7</td>
<td>26.0</td>
<td>0.108</td>
<td>1.75</td>
<td>30.94</td>
<td>4.27</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>LTO TOTAL FUEL (kg) or EMISSIONS (g)</td>
<td>429</td>
<td>302</td>
<td>5476</td>
<td>4763</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NUMBER OF ENGINES</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NUMBER OF TESTS</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVERAGE $L_0/F_{O2}$ (g/kN) or AVERAGE SN (MAX)</td>
<td>2.58</td>
<td>46.81</td>
<td>40.71</td>
<td>13.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIGMA ($L_0/F_{O2}$ in g/kN, or SN)</td>
<td>0.37</td>
<td>2.6</td>
<td>1.2</td>
<td>4.1</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RANGE ($L_0/F_{O2}$ in g/kN, or SN)</td>
<td>2.18 to 2.9</td>
<td>43.8 to 48.7</td>
<td>39.8 to 42.1</td>
<td>8.4 to 16.2</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
We want to have: **Non-volatile PM Mass and Number Data**

### ICAO ENGINE EXHAUST EMISSIONS DATA BANK

#### SUBSONIC ENGINES

**ENGINE IDENTIFICATION:**
- **BYPASS RATIO:** 5.1
- **PRESSURE RATIO (\( \pi_{pa} \)):** 27.7
- **RATED OUTPUT \( (F_{oa}) \) (kW):** 117

**REGULATORY DATA**

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<tr>
<th>CHARACTERISTIC VALUE:</th>
<th>HC</th>
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<th>nvPM Mass</th>
<th>nvPM Number</th>
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<td></td>
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<tr>
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**DATA STATUS**
- PRE-REGULATION
- CERTIFICATION
- REVISED (SEE REMARKS)

**EMISSIONS STATUS**
- 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**

<table>
<thead>
<tr>
<th>MODE</th>
<th>POWER SETTING ( (%_{oa}) )</th>
<th>FUEL FLOW ( kg/min )</th>
<th>EMISSIONS INDICES ( (g/kg) )</th>
<th>nvPM Mass</th>
<th>nvPM Number</th>
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<tr>
<td>TAKE-OFF</td>
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<td>0.25</td>
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<tr>
<td>CLIMB OUT</td>
<td>84</td>
<td>2.2</td>
<td>0.996</td>
<td>0.32</td>
<td>0.314</td>
</tr>
<tr>
<td>APPROACH</td>
<td>30</td>
<td>4.0</td>
<td>0.331</td>
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<td>-</td>
</tr>
</tbody>
</table>

**NUMBER OF ENGINES:**
- 3
- 3

**NUMBER OF TESTS:**
- 7
- 7

**AVERAGE \( \frac{L}{F_o} \) (g/kN) or AVERAGE SN (MAX):**
- 2.58 | 46.81 | 40.71 | 13.07 | 0.0X | X.XXE14

**SIGMA \( \frac{L}{F_o} \) (g/kN, or SN):**
- 0.37 | 2.6 | 1.2 | 4.1 | X | X

**RANGE \( \frac{L}{F_o} \) (g/kN, or SN):**
- 2.18 to 2.94 | 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!!)

nvPM Number Measurement (AVL APC)

Make-up Flow with CO₂ Measurement

nvPM Mass Measurement (AVL MSS)

Raw Gas Instrumentation (from current standard)

Raw Gas Instrumentation

CO₂, CO, THC, NOₓ, SO₂

Special multi-orifice sampling probe manufactured by FOCA

Dilutor ~ 1:10

1 μm Cyclone

25 SLPM

60°C

160°C
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

![Graph showing correlation between BC MSS and EC NIOSH]

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Cal Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVL Graz (commissioning)</td>
<td>0.475</td>
</tr>
<tr>
<td>National Research Council Canada</td>
<td>0.462</td>
</tr>
<tr>
<td>Empa</td>
<td>0.466</td>
</tr>
</tbody>
</table>

- 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**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Average Pre-Post Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net. Heat of Combust.</td>
<td>MJ/kg</td>
<td>43.3</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>mass %</td>
<td>13.98</td>
</tr>
<tr>
<td>Tot. Aromatics</td>
<td>volume %</td>
<td>17.7</td>
</tr>
<tr>
<td>Naphthalenes</td>
<td>volume %</td>
<td>0.75</td>
</tr>
<tr>
<td>Sulfur, total</td>
<td>mass %</td>
<td>0.042</td>
</tr>
<tr>
<td>H/C ratio</td>
<td>n/m</td>
<td>1.94</td>
</tr>
</tbody>
</table>
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.**
First standardized nvPM data of an aircraft engine

The reported data include the thermophoretic loss correction in the sampling probe
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
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)

![Bar chart showing measured CPC counting efficiency for different particle sizes and experimental conditions.](chart.png)

- **X-axis:** Particle size [nm]
- **Y-axis:** Counting efficiency [%]
- **Legend:**
  - Pre-Experiment
  - Post-Experiment

**Key Points:****
- Low limit for 10 nm:
  - Pre-Experiment: [Value]
  - Post-Experiment: [Value]
- Low limit for 15 nm:
  - Pre-Experiment: [Value]
  - Post-Experiment: [Value]
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/m³
    - 30 s average number concentration must be less than 2.0 particles/cm³

- **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 CO² 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

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

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

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

- 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