

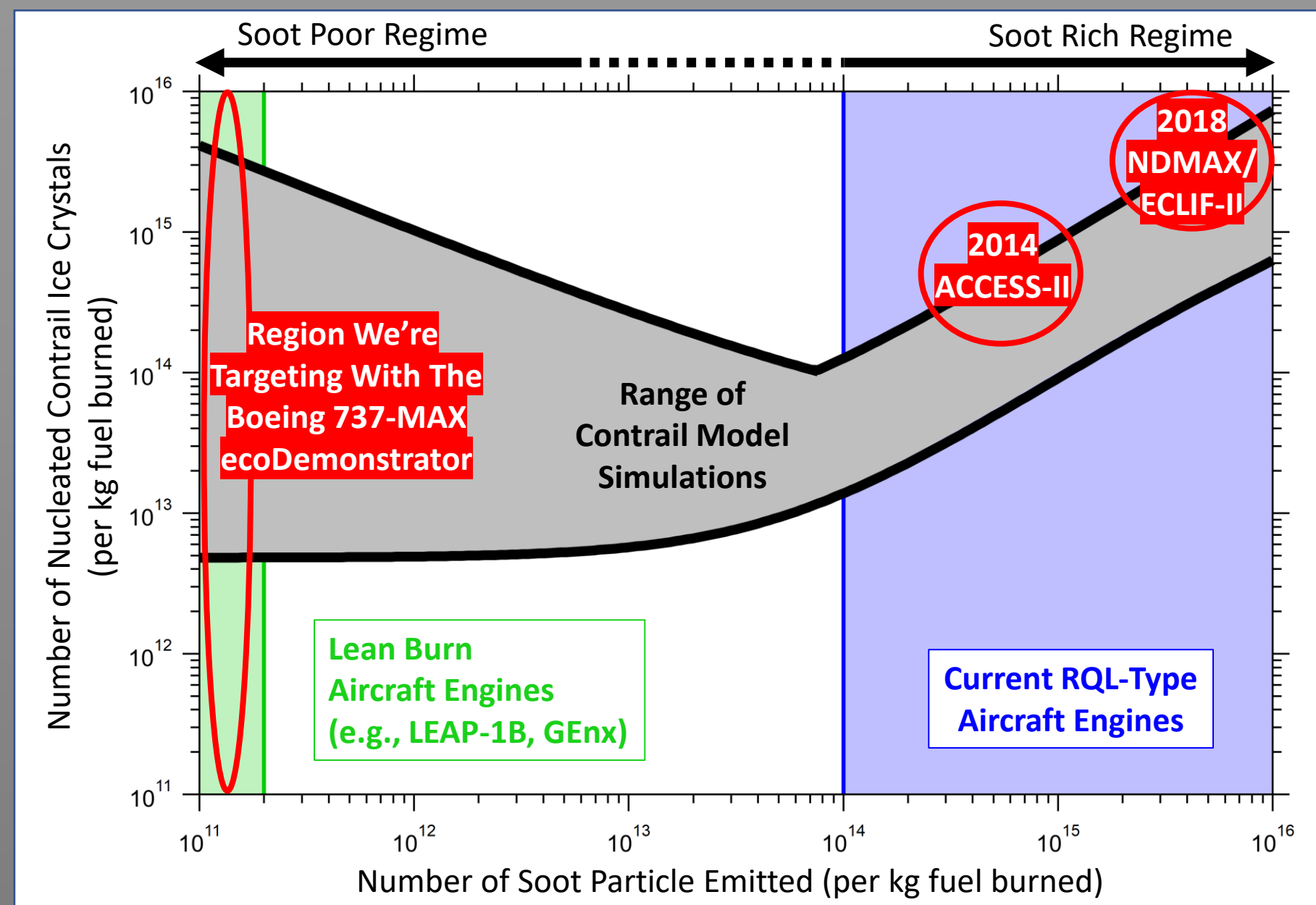


# Particle and Trace Gas Emissions Indices Measured During the 2021 Boeing ecoDemonstrator Emissions Ground Test

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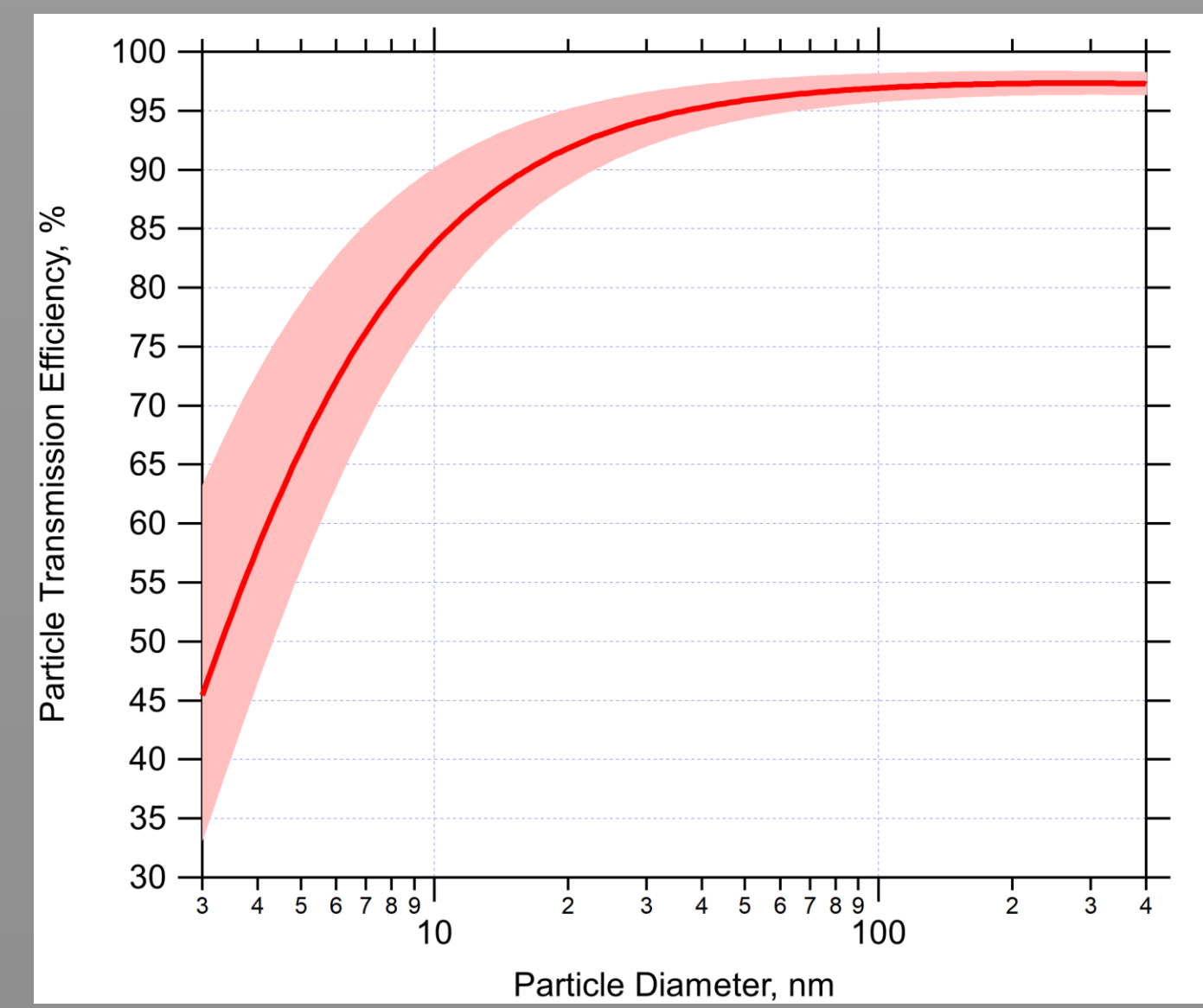
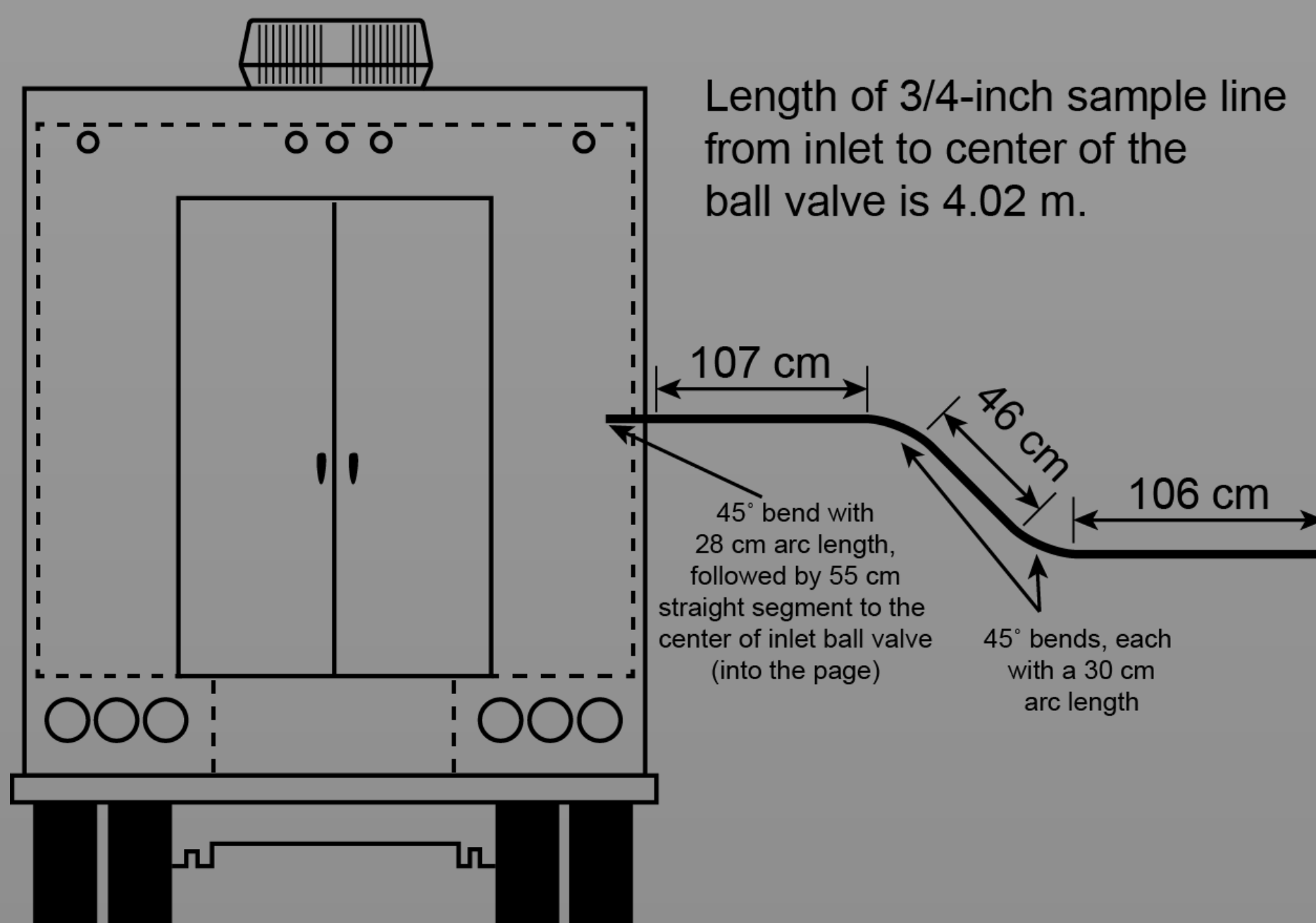
## The Boeing ecoDemonstrator Emissions Measurement Project



- Need to understand engine particle emissions in “soot-poor” regime to connect to contrail formation impacts
- Emissions reductions beneficial for air quality
- 2021 Boeing ecoDemonstrator provided chance to sample 4 different fuel types emitted from LEAP-1B engine on 737-9 Boeing ecoDemonstrator airplane

Figure adapted from Kärcher, *Nature Communications*, 2018. Red circles show the approximate Number EIs observed during the 2014 ACCESS-II and 2018 ND-MAX/ECLIF-II flight test series. Moore et al., *Nature*, 2017; Voigt et al., *Nature Comms. Earth & Environ.*, 2021

## Boeing ecoDemonstrator Fuel Emission Test



The NASA Langley mobile lab was parked behind the Boeing ecoDemonstrator with a blast fence between lab and airplane. The probe was ~32 m behind left engine.

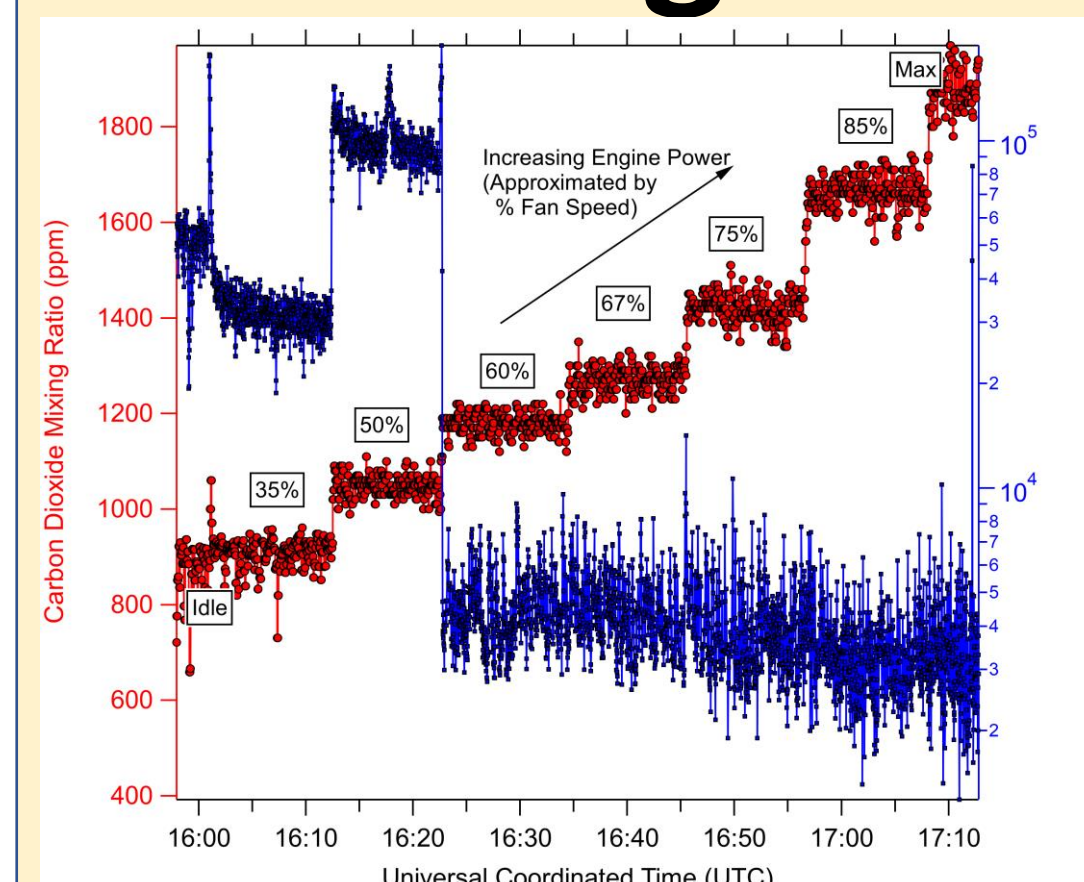
Owing to the short sample line, the potential (and measured) particle loss was low.

Fuel	Description	Specification	Aromatics (%)	Sulfur (ppmv)
100% SAF	HEFA-SPK		0.6	11
100% Jet-A	Seattle source Jet-A	ASTM 1655	14.2	1300
30% SAF/70% Jet-A	Commercially available SAF blend, used Jet A Source in California	ASTM 7566	13.9	502
50% SAF/50% Jet-A	Special blend for ecoDemonstrator using Jet A sourced in California	ASTM 7566	10.6	195

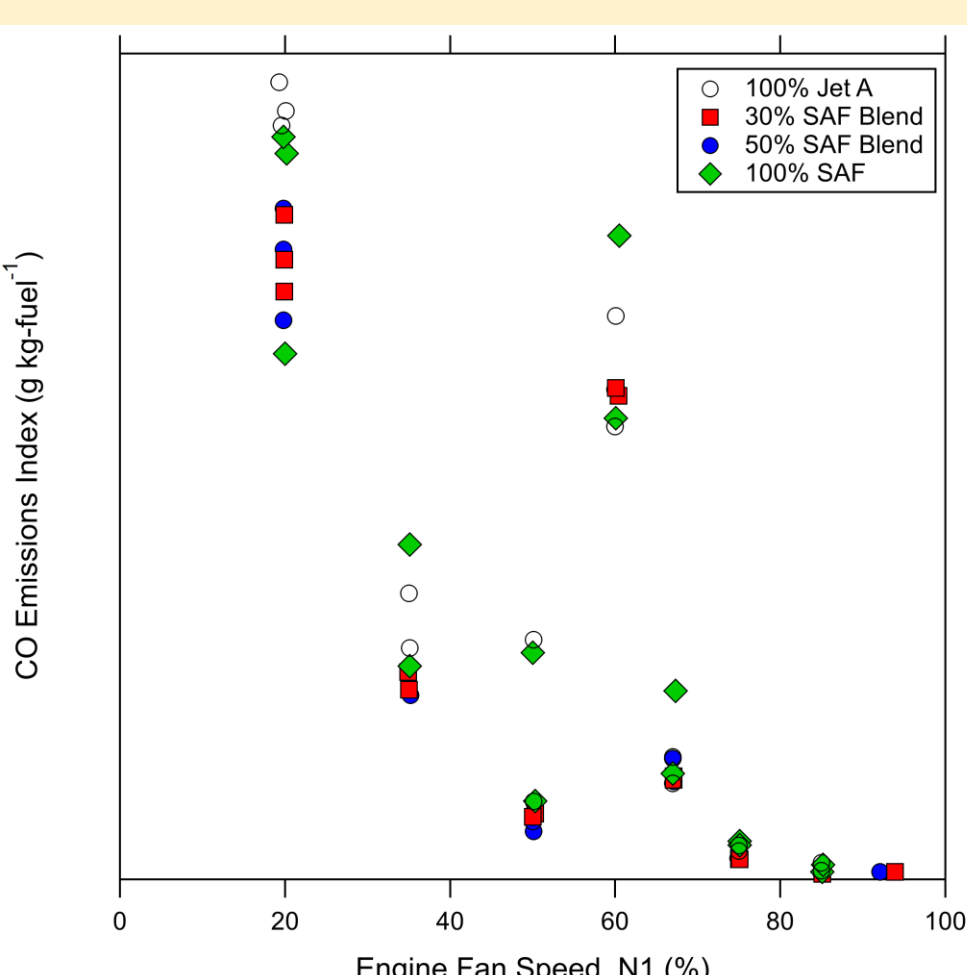
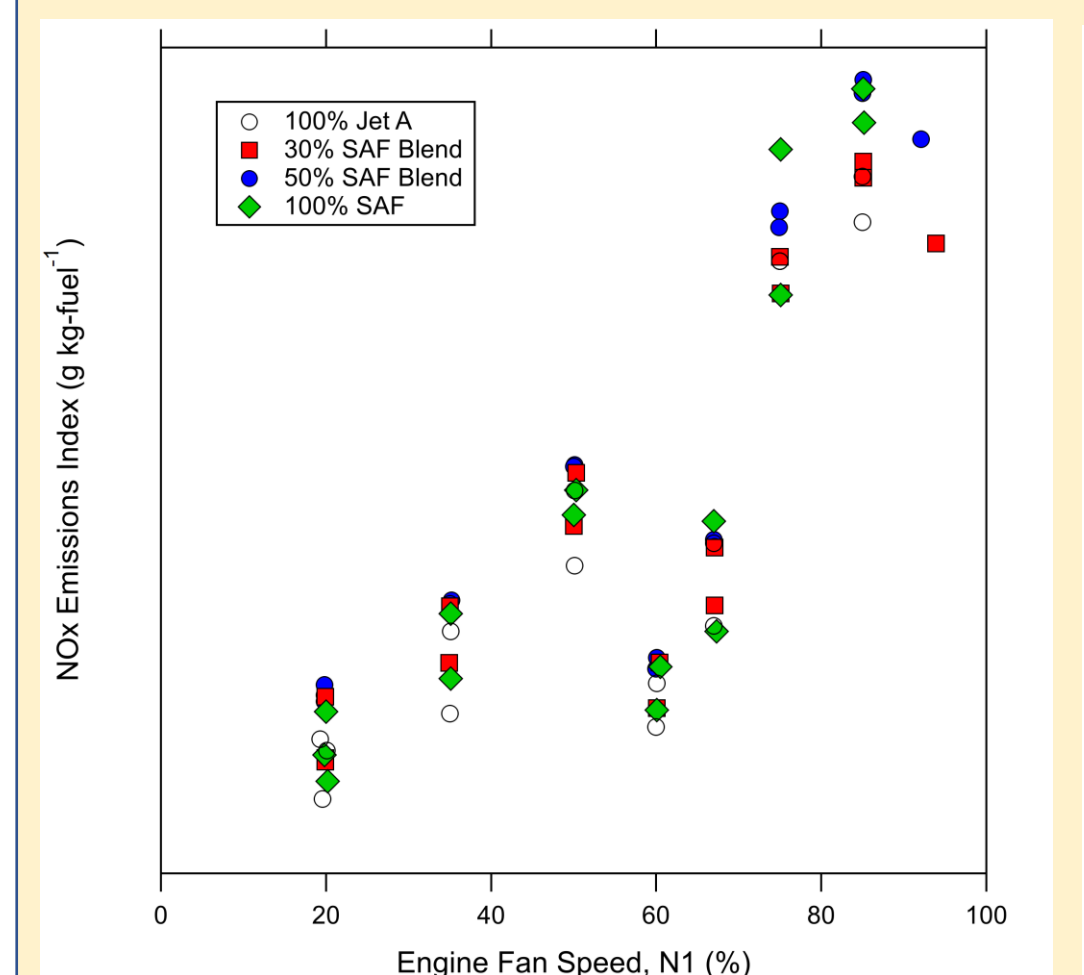
## Take Home Message

- Staged lean burn engines + 100% SAF yield dramatic particle emission reductions
  - $\sim 10^{14}$  to  $\sim 10^{11}$  per kg-fuel for non-volatile particle number
  - $\sim 10^{16}$  to  $\sim 10^{14}$  per kg-fuel total particle number
  - $\sim 10$ -100 to  $<1$  mg kg-fuel for particle mass
- 100% SAF also lowers particle emissions even at lower power conditions
- High fuel sulfur content yield large numbers of volatile particles even at high thrust
- Low-emitting engines emphasize the need for on-wing measurements

## Boeing ecoDemonstrator Test Results

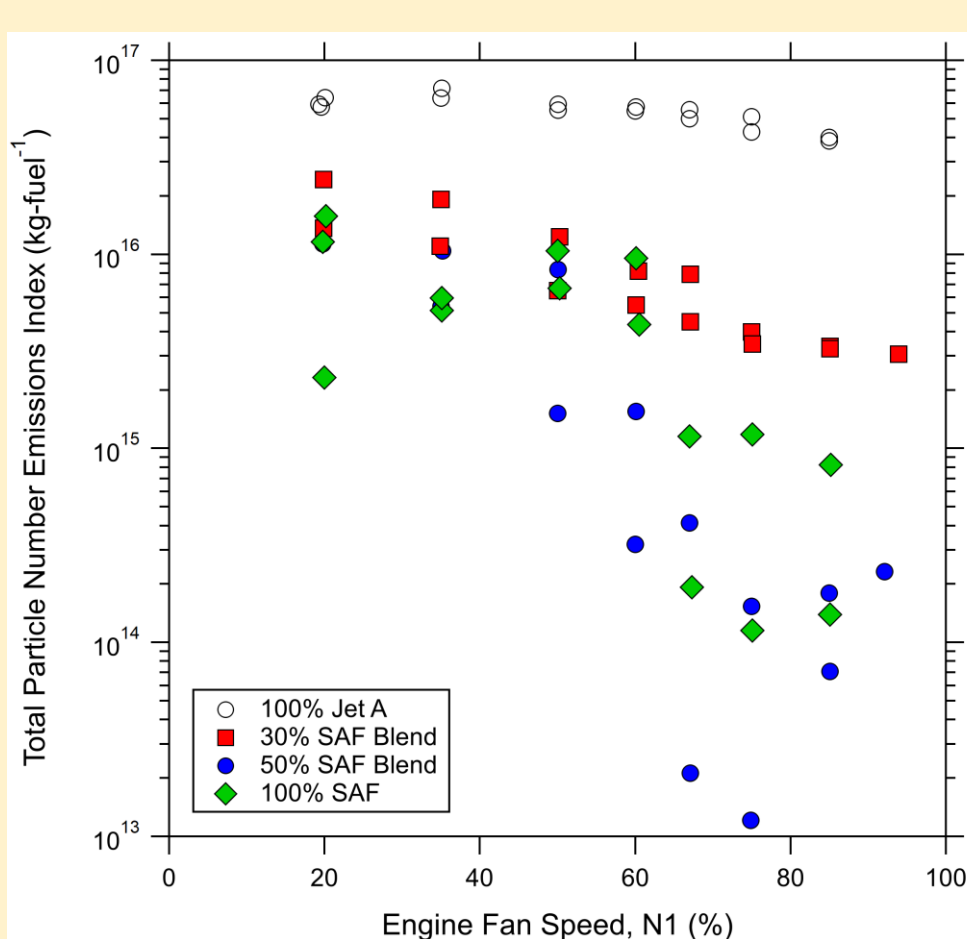
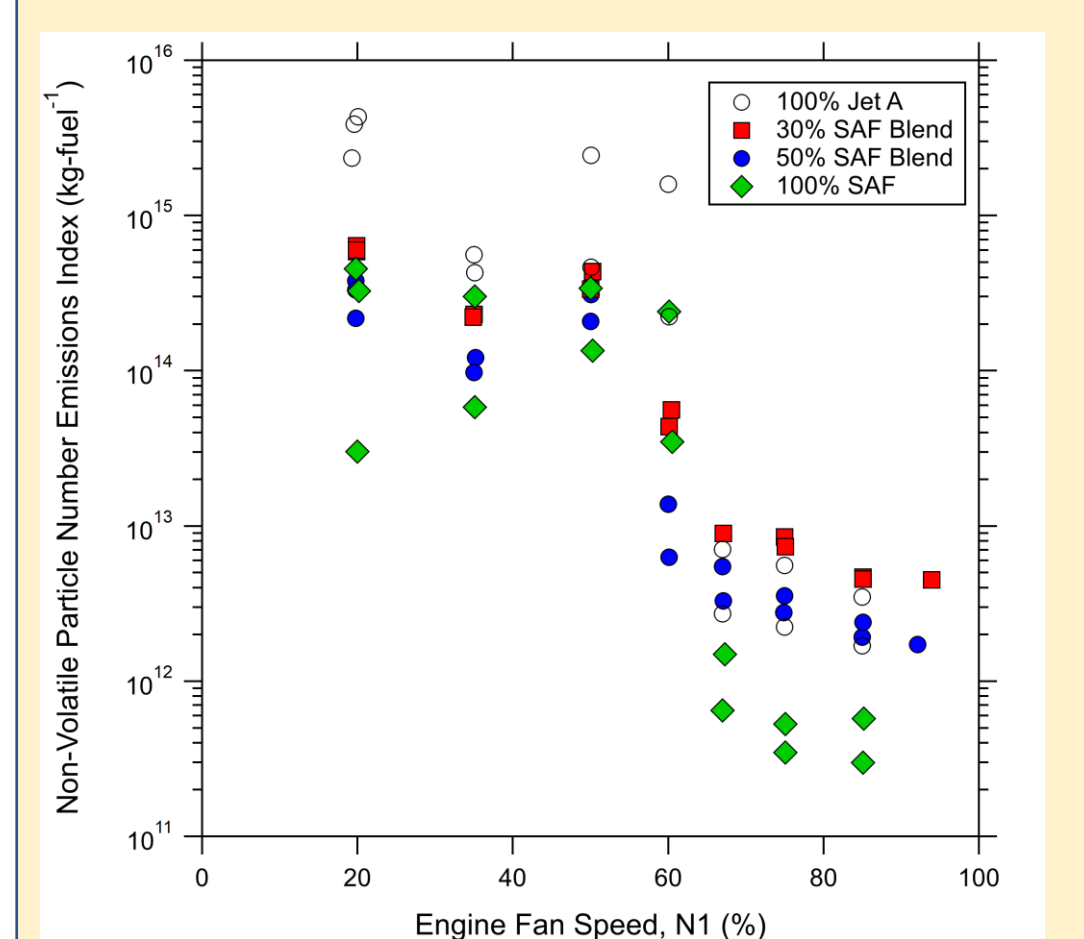


For each fuel type, the engine was ramped up to different set points, as shown to the left. The emissions were sampled for ~10 min. Then, the engine was ramped down in same sequence.



Example emission index for  $\text{NO}_x$ . NOTE LINEAR BUT NOT BEING SHOWN AT THIS TIME.

Found that for both  $\text{NO}_x$  and CO, emission indices invariant with fuel.



Example emission index for “non-volatile” (particles heated to 350°C) and volatile particles. NOTE LOG Scale.

At low engine setting, large decrease in non-volatile, all (not shown), and black carbon (not shown) emission indices from switching between 100% Jet A to SAF.

**At higher power, 100% SAF consistently lower for all particle measurements. Note, getting into “soot-poor” regime.**

## Instrumentation

Measurement Parameter	Analytical Instrument
Particle Number Concentration (including low diameter cutoffs of 2.5, 3, 7, 8, 16, 32 & 64 nm)	<ul style="list-style-type: none"> <li>• Nucleation-Mode Aerosol Size Spectrometer (NMASS)</li> <li>• BMI Mixing Condensation Particle Counter (mCPC 1720)</li> <li>• TSI Ultrafine Condensation Particle Counter (CPC3756)</li> </ul>
Particle Size Distribution (3 – 20,000 nm diameters)	<ul style="list-style-type: none"> <li>• Nucleation-Mode Aerosol Size Spectrometer (NMASS)</li> <li>• TSI Scanning Mobility Particle Sizer (SMPS)</li> <li>• TSI Engine Exhaust Particle Sizer (EEPS 3090)</li> <li>• TSI Aerodynamic Particle Sizer (APS 3321)</li> </ul>
Particle Composition	<ul style="list-style-type: none"> <li>• Aerodyne Soot Particle High-Resolution Time-of-Flight Aerosol Mass Spectrometer (SP-HR-TOF-AMS)</li> <li>• EC/OC Quartz Filters</li> </ul>
Trace Gas Mixing Ratios	<ul style="list-style-type: none"> <li>• Picarro In-Flight Gas Concentration Analyzer (<math>\text{CO}_2</math>, CO, <math>\text{CH}_4</math>, &amp; <math>\text{H}_2\text{O}</math>)</li> <li>• Licor 7000 <math>\text{CO}_2</math> Analyzer</li> <li>• LGR <math>\text{NO}_2</math> Monitor + Ozone Add Flow (<math>\text{NO}_x</math>)</li> <li>• LGR <math>\text{NO}_2</math> Monitor (<math>\text{NO}_2</math>)</li> </ul>
Non-Volatile (350°C) Particle Number Concentration (including low diameter cutoffs of 2.5, 3, 7, 8, 16, 32 & 64 nm)	<ul style="list-style-type: none"> <li>• Nucleation-Mode Aerosol Size Spectrometer (NMASS)</li> <li>• BMI Mixing Condensation Particle Counter (mCPC 1720)</li> </ul>
Non-Volatile (350°C) Particle Size Distribution (3 – 300 nm diameters)	<ul style="list-style-type: none"> <li>• Nucleation-Mode Aerosol Size Spectrometer (NMASS)</li> <li>• TSI Scanning Mobility Particle Sizer (SMPS)</li> </ul>
Particle Light Absorption, Scattering, and Extinction Coefficients <i>Used to Calculate Black Carbon Mass</i>	<ul style="list-style-type: none"> <li>• Aerodyne Cavity Attenuated Phase Shift Monitor (CAPS)</li> <li>• Aerodyne CAPS Single Scatter Albedo Monitor (CAPS-SSA)</li> <li>• TSI Nephelometer</li> <li>• BMI Tri-Color Absorption Photometer (TAP)</li> <li>• ThermoScientific Multi-Angle Absorption Photometer (MAAP)</li> <li>• AVL Micro Soot Sensor (MSS+)</li> </ul>
Particle Chemical Composition	<ul style="list-style-type: none"> <li>• Aerodyne Soot Particle High-Resolution Time-of-Flight Aerosol Mass Spectrometer (SP-HR-TOF-AMS)</li> <li>• EC/OC Quartz Filters</li> </ul>