Determination of aircraft gas turbine combustion engine nvPM charge state and its impact on sampling system losses

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Overview

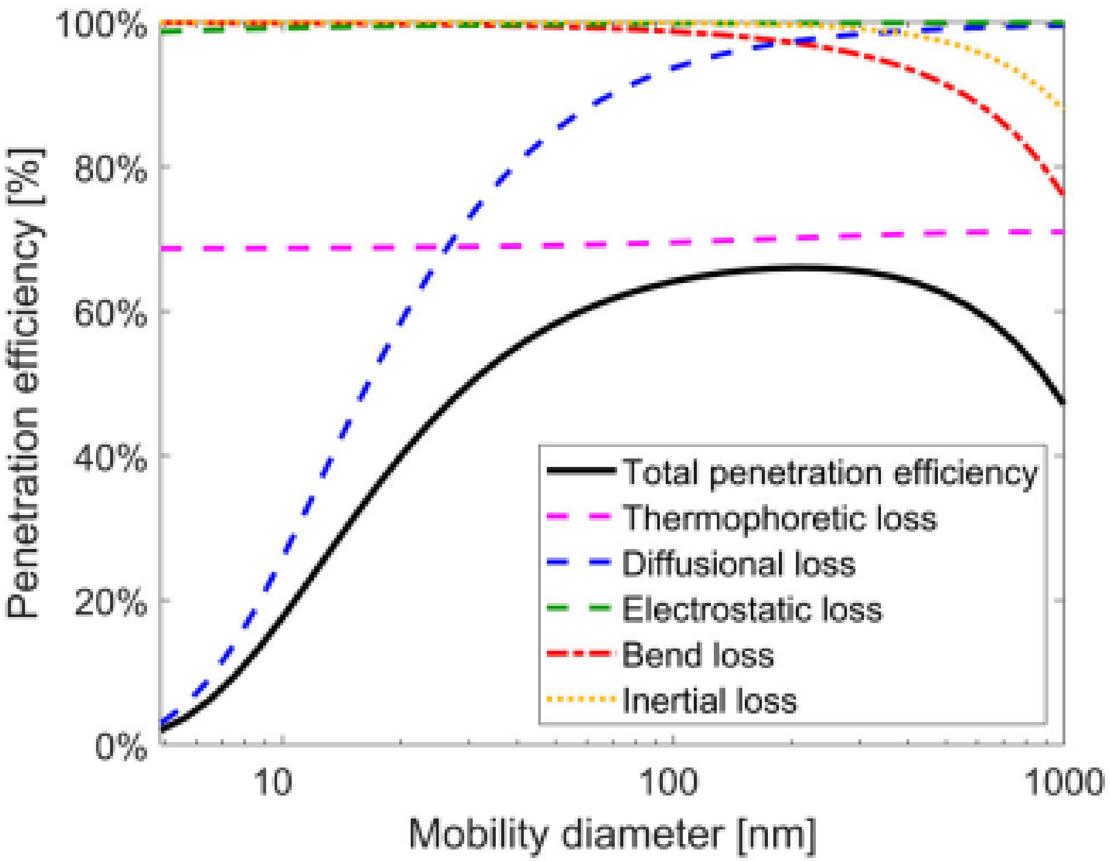
- Background
- Methodology
- Results
- Implications
- Conclusion

Background

Aircraft nvPM emissions and regulations

[2]

- ➢ Aircraft nvPM emissions are damaging for the environment and public health.
  - ➢ 16,000 premature death [1]
- ➢ Regulations used to measure, quantify, and reduce nvPM emissions.
- ➢ nvPM is very difficult to measure due to large particle losses.
- ➢ Corrections used to determine to 'real' engine exit nvPM concentrations.



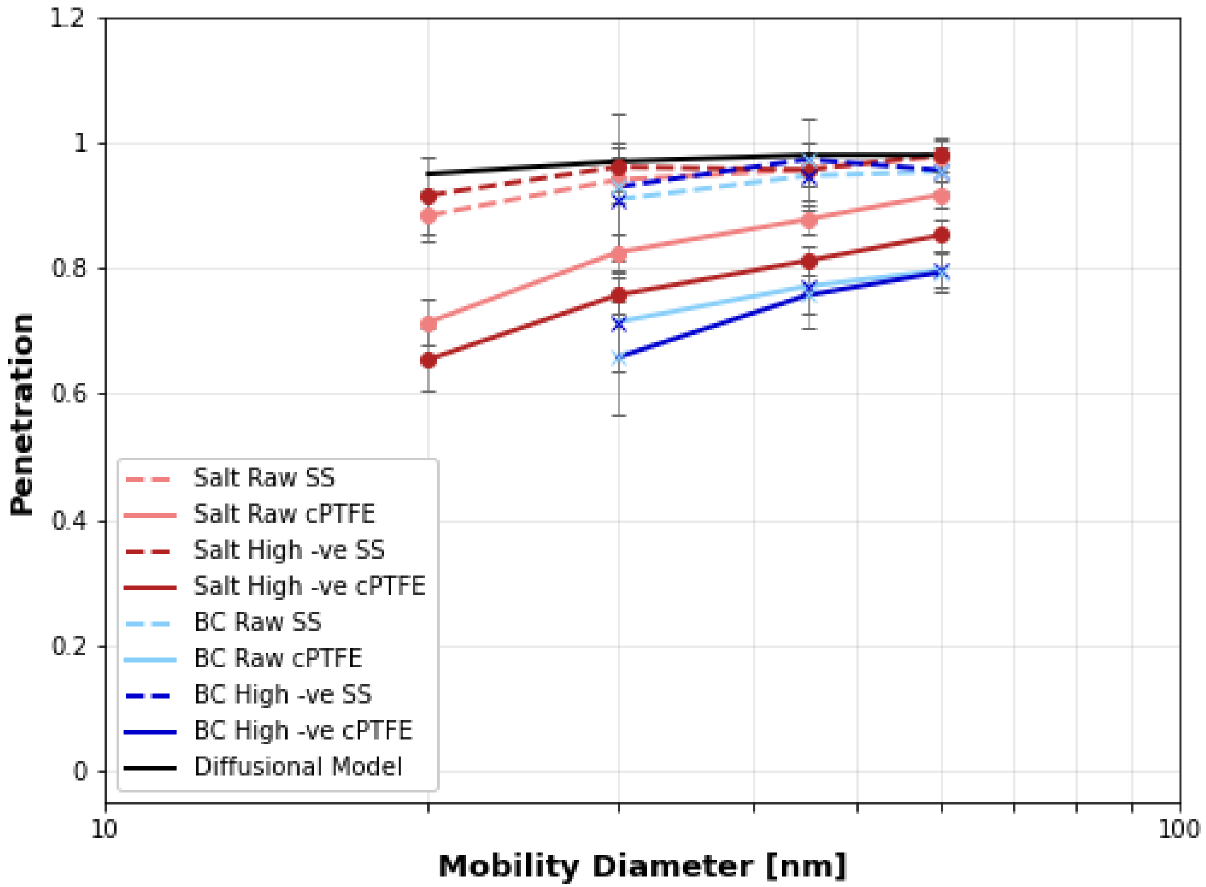
Corrections contain various assumptions

1. Jonsdottir, H, R. et al. (2019). *Non-volatile particle emissions from aircraft turbine engines at ground-idle induce oxidative stress in bronchial cells.* Communication Biology. 2:90
2. Durand, E, F. et al. (2020). *Experimental validation of thermophoretic and bend loss for a regulatory prescribed aircraft nvPM sampling system.* Aerosol Science and Technology. 17(3):2012

Study on electrostatic loss

[1]

- Electrostatic loss accounts for below 3% in correction models.
- Conducted a laboratory study to try and test model assumptions and validate its use.
- Representative tubing and a range of particles and charge states where used.
- Large additional losses from electrostatic loss were observed.



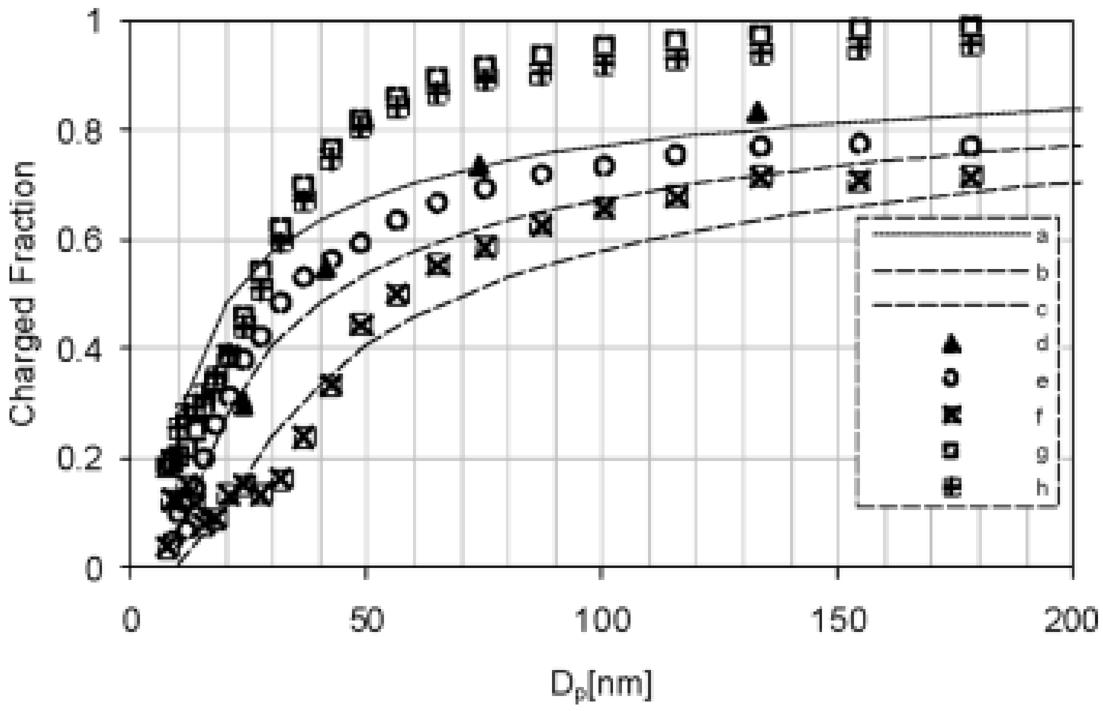
But was this representative of aircraft nvPM charge?

1. Lidstone-Lane et al (2025). *Experimental characterisation of electrostatic loss relevant to aircraft nvPM sampling.* Aerosol Science and Technology. 59(1):79-95

nvPM charge – previous studies

- Combustion particles are generally considered to be highly charged bi-polar.[1]
- Previous studies on diesel engine found nvPM to be highly charged bi-polar.[2]
- Theoretical studies have shown the nvPM is highly charged bi-polar.[3]
- Some studies have measured high ion concentrations in aircraft engine combustion test rigs and in exhaust plumes.[4]

[2]

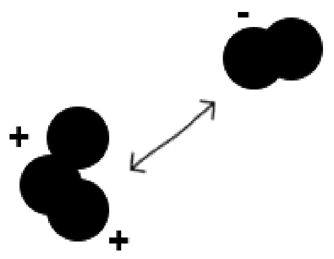


1. Hinds, C, H & Zhu, Y. (2022). *Aerosol Technology.* Third Edition. Wiley. New Jersey, USA
2. Jung, H & Kittelson, D, B. (2007). *Measurement of electrical charge on diesel particles.* Aerosol Science and Technology. 39(12):1129-1135
3. Sorokin, A & Arnold, F. (2004). *Electrically charged small soot particles in the exhaust of an aircraft gas-turbine engine combustor: comparison of model and experiment.* Atmospheric Environment. 38:2611-2618.
4. Starik, A. M. (2008). *Gaseous and particulate emissions with jet engine exhaust and atmospheric pollution.* Advances on propulsion technology for high-speed aircraft. 1:1-15

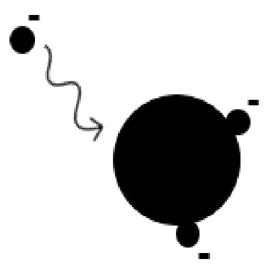
nvPM charge – basic theory

Ion emissions from flames well known and generated through chemiionisation - bi-polar charge distribution expected.[1]

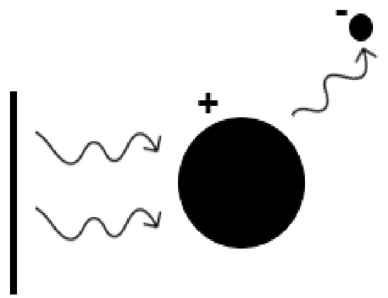
[2]



Recombination



Electron attachment



Thermal ionization

Recombination of oppositely charge ions – bipolar charge.

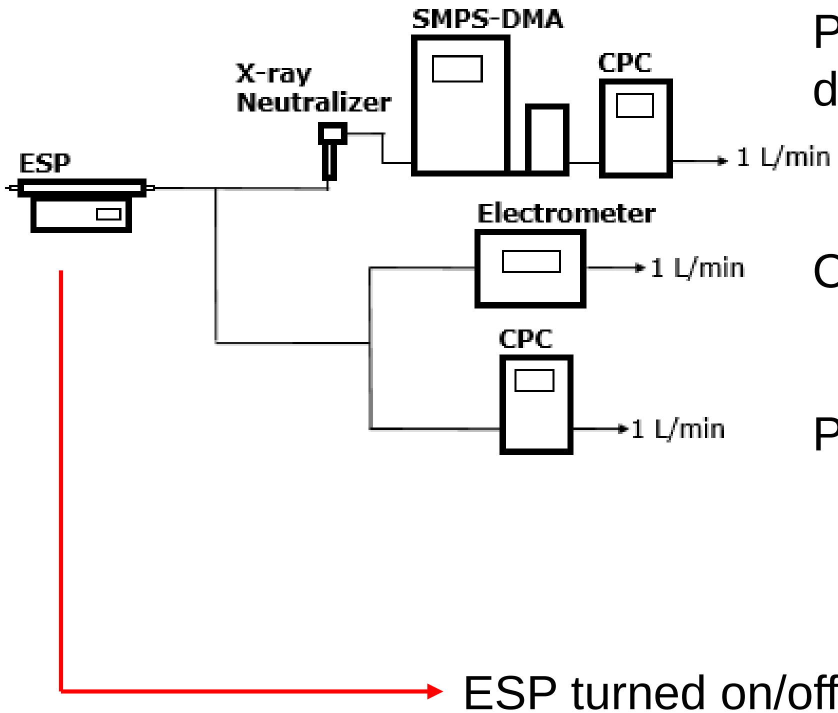
Electrons attracted to positive ions – bipolar charge.

If hot enough, electron ejection can occur - positively charged particle

1. Fiakow. (1997). *Investigation on ions in flames.* Progression in Energy and Combustion Science. 23:399-528
2. Burthscher. (1992). *Measurement and characteristics of combustion aerosol with special consideration of photoelectric charging and charging by flame ions.* Journal of Aerosol Science. 32(2):549-595

Methodology

Test Rig – general charge measurement



Particle size distribution ($N(d_p)$)

Current (i)

Particle concentration (N)

ESP turned on/off to get $N_{uncharged}$ and N_{total}

Particle size resolved charge fraction

$$F_q(N(d_p)) = \frac{\left(N(d_p)_{total} - N(d_p)_{uncharged}\right)}{N(d_p)_{total}}$$

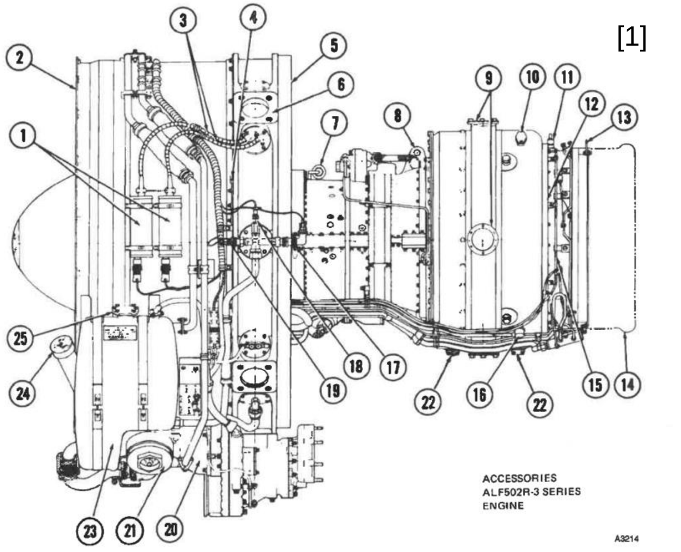
Charge fraction

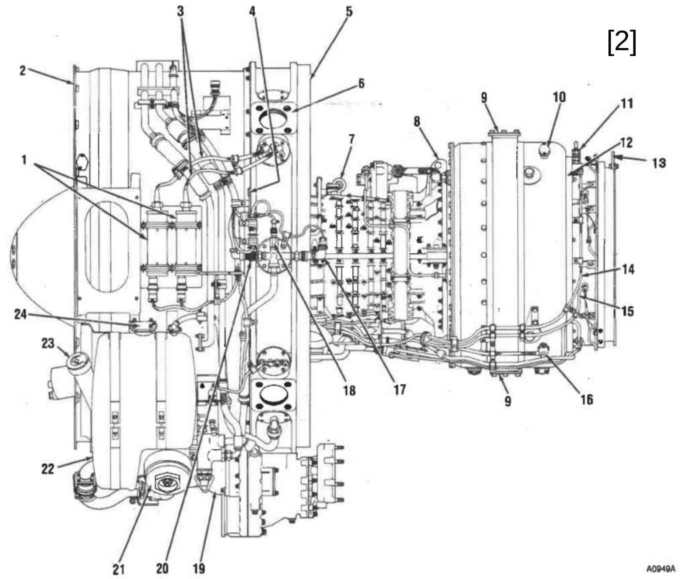
$$\bar{q} = \frac{i}{N_{total} Q e}$$

$$F_q = \frac{\left(N_{total} - N_{uncharged}\right)}{N_{total}}$$

Mean charge per particle

Engines and fuels





Honeywell ALF502R-3 turbofan engine (502)

- Reverse flow annular combustion
- ~30 kN of thrust
- **1 LP compressor**

Honeywell LF507-1H turbofan engine (507)

- Reverse flow annular combustion
- ~31 kN of thrust
- **2 LP compressor**

Fuel

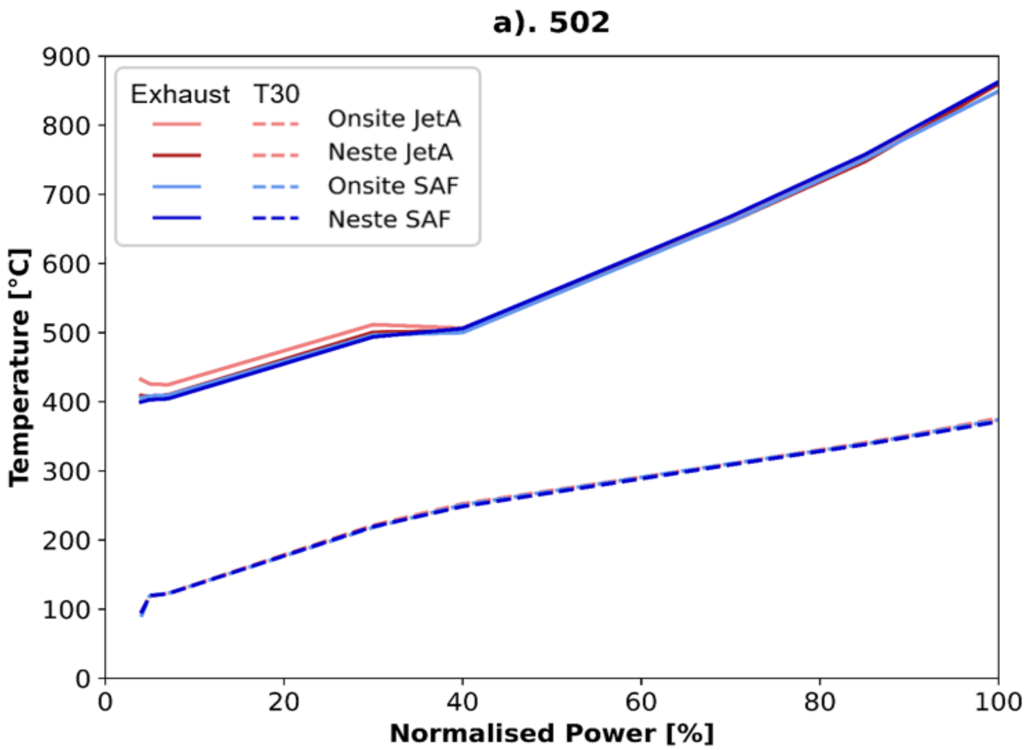
- Hawardan airport onsite JetA & SAF, Neste JetA & SAF
- SAF = 50% blended JetA + HEFA SAF

1. CFS Aeroproducts ltd. (2022). *Engine manual ALF502R*. CFS Aeroproducts ltd. Warwick, UK
2. AlliedSignals Aerospace. (1996). *Engine manual KF507-1H.* AlliedSignals Aerospace. New Jersey, USA

Test matrix and temperatures

Test Point	Engine Condition	Nominal Normalized Power [%]
0	Ground Idle	4
1	Idle	5
2	Taxi	7
3	Approach	30
4	Approach (NO_x)	40
5	Cruise	70
6	Climb	85
8	Take-off	100

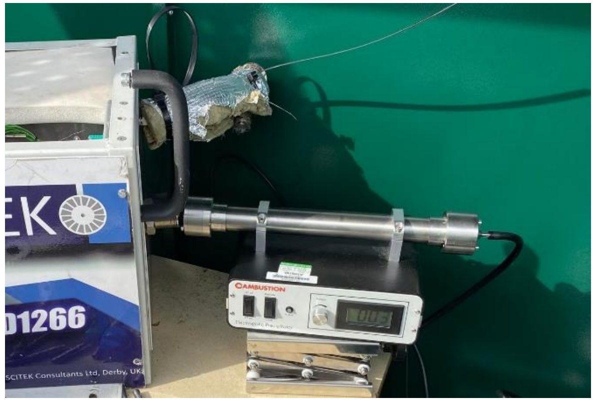
[1]

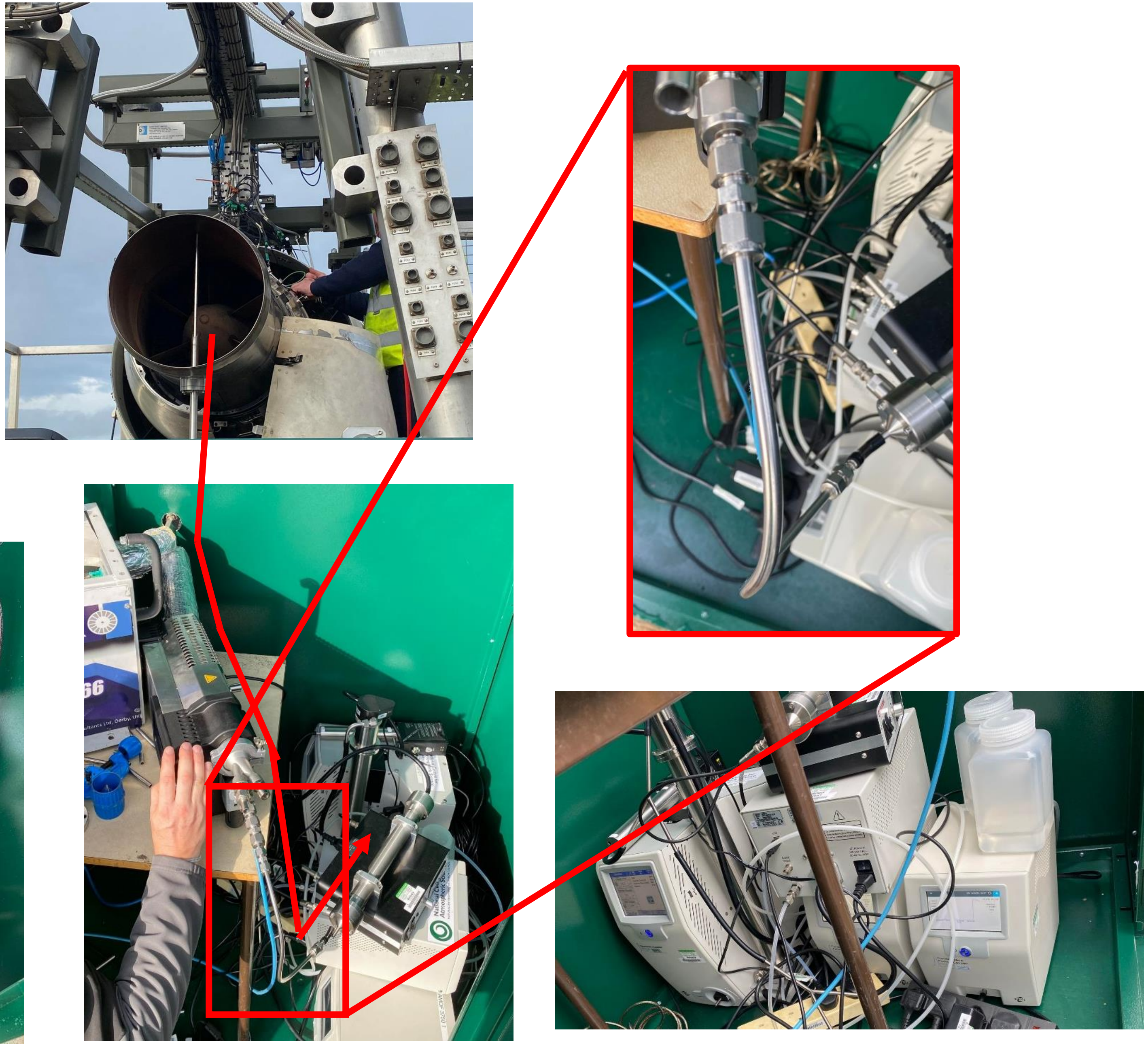


- ➢ Both up and down cycles.
- ➢ Engine temperatures recorded – assumed most relevant temperature for charge is exhaust.

1. Paper under review. Lidstone-Lane et al. (2025)

Test Rig – CFS Aero

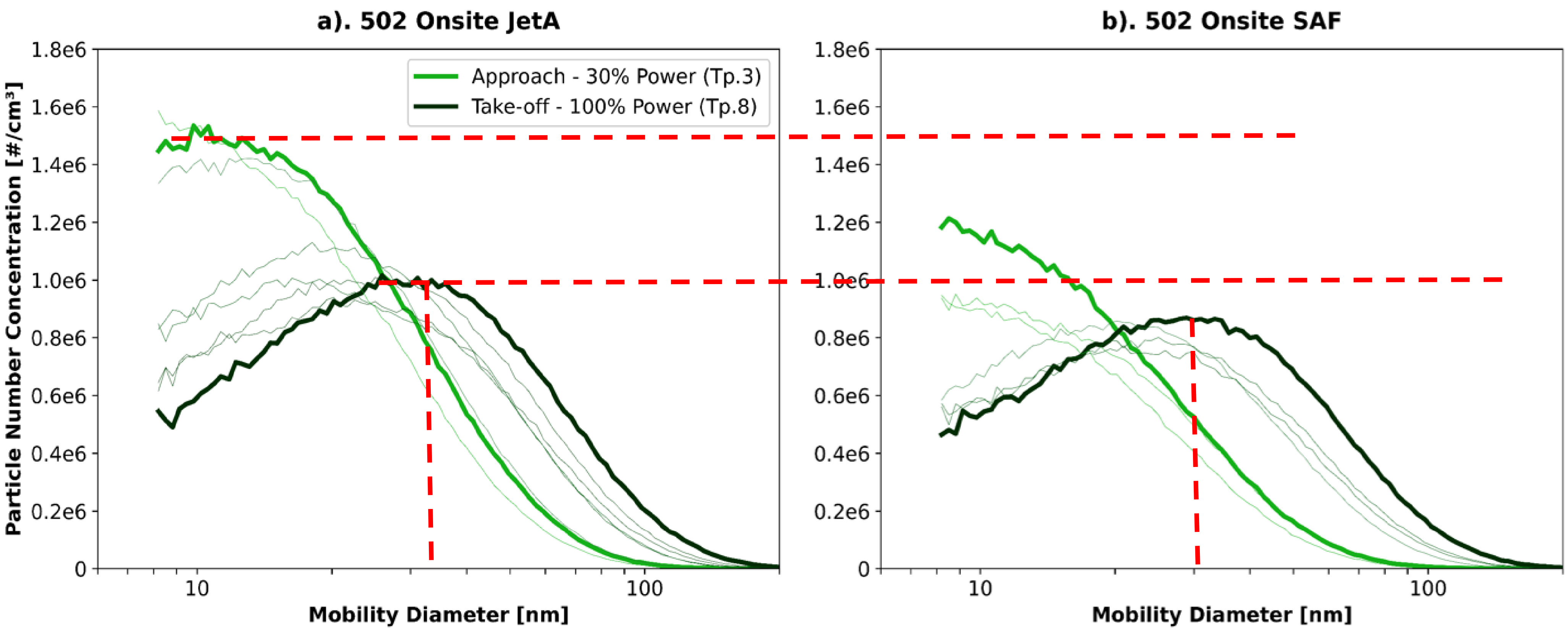




Results

nvPM particle size distributions

[1]



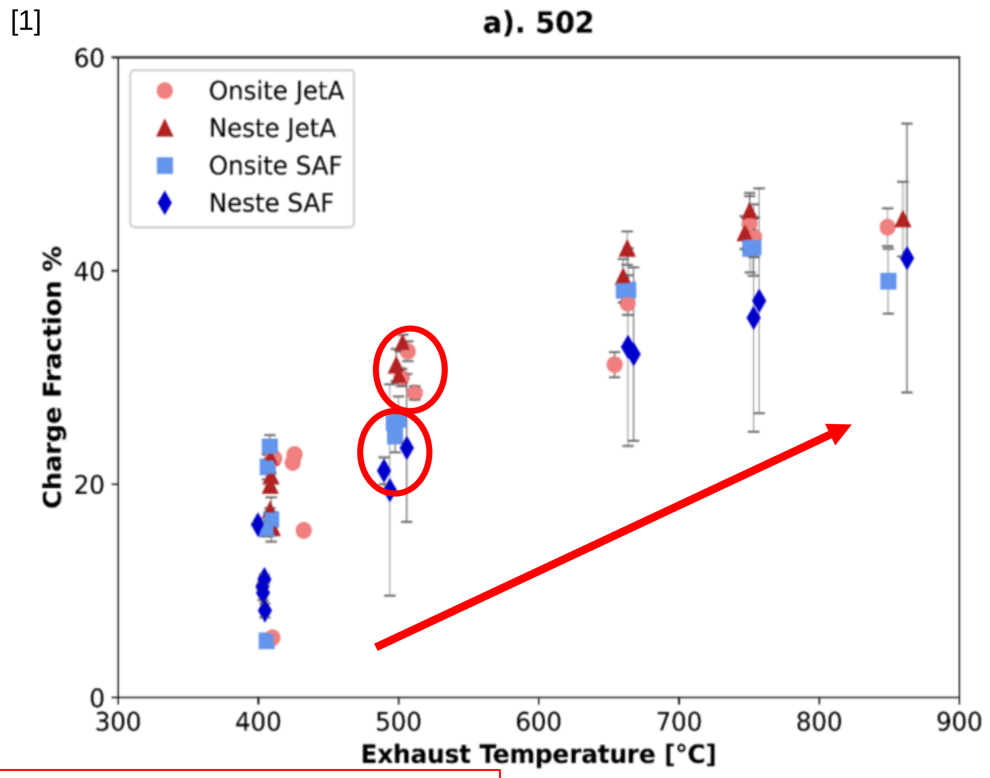
JetA produced larger and more nvPM compared to SAF

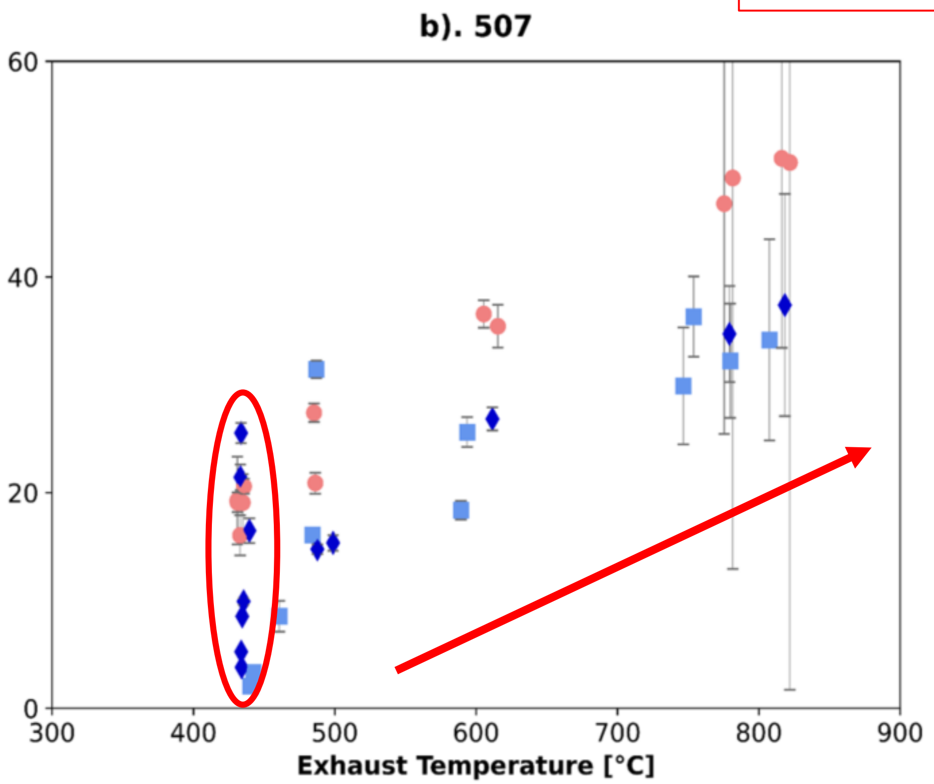
1. Paper under review. Lidstone-Lane et al. (2025)

Total charge fraction

507 significantly more variable – engine stability issues?

[1]





JetA more charged than SAF – larger particles carry more charge.

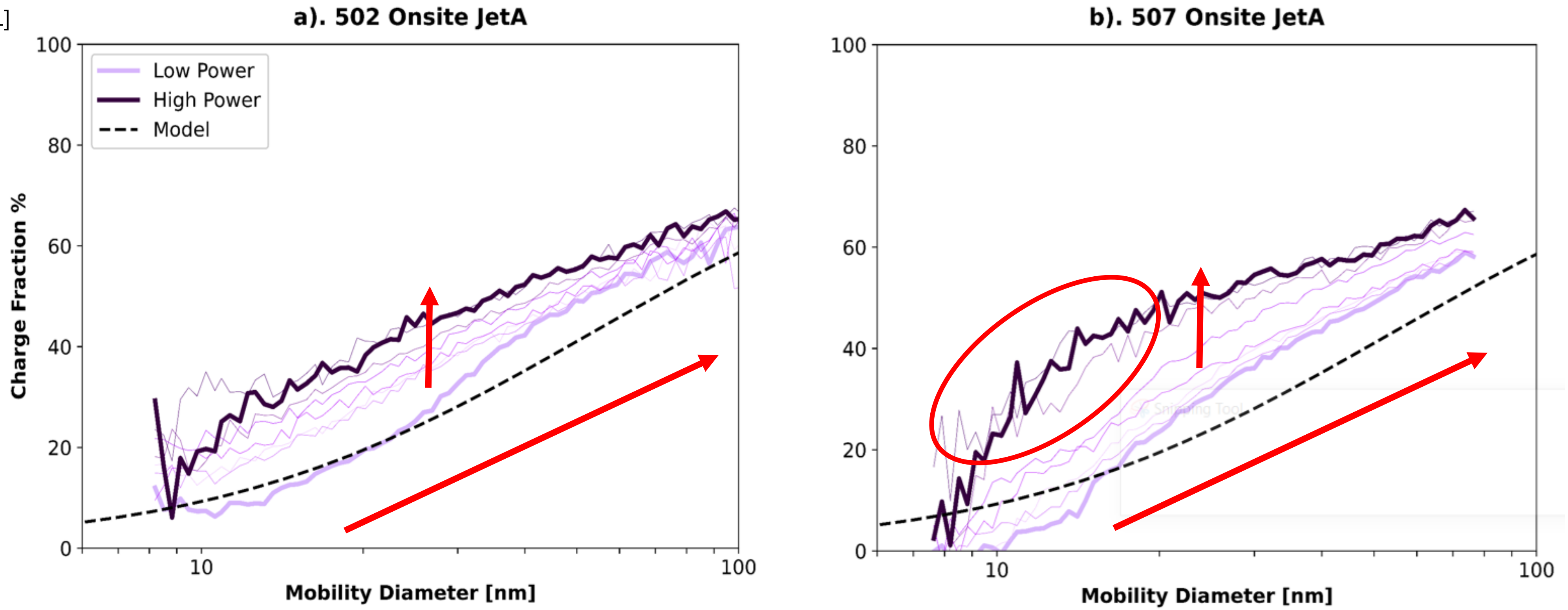
Charge increases with engine temperature

1. Paper under review. Lidstone-Lane et al. (2025)

Size-resolved charge fraction – engine comparison

Shoulder present at lower sizes for 507

[1]



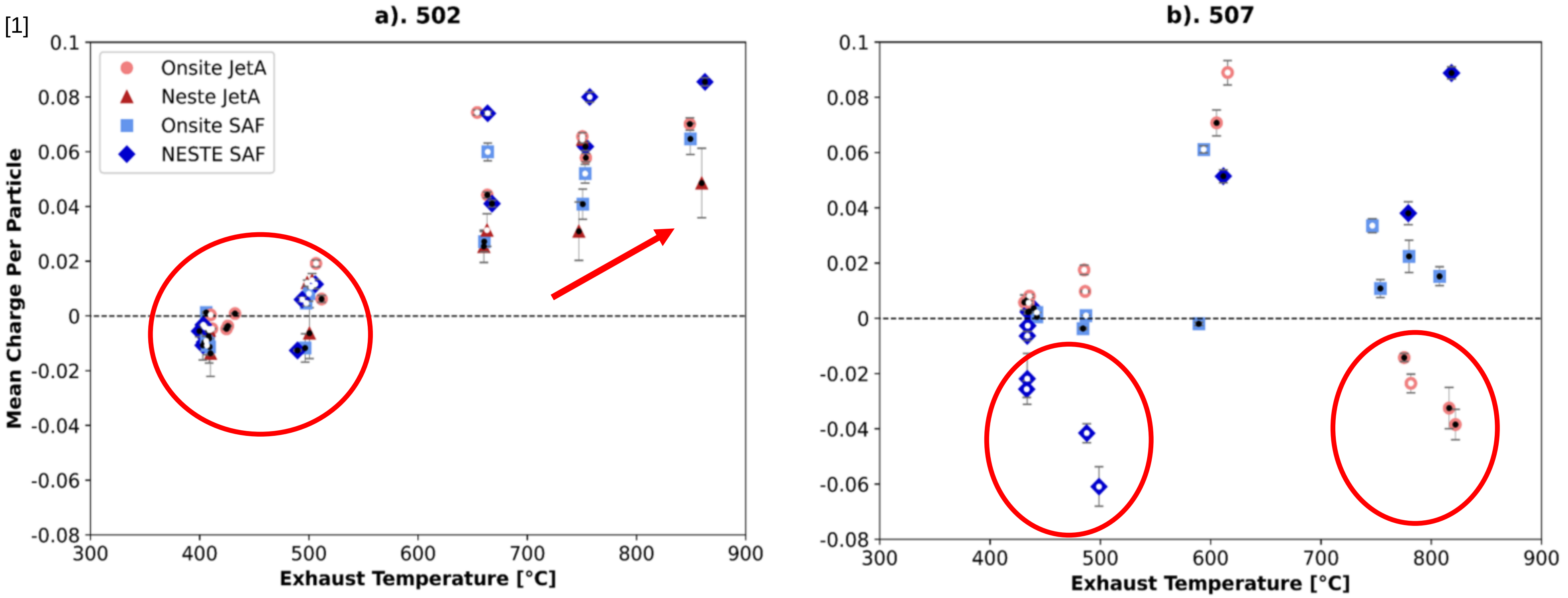
Increase in charge with engine power and size

1. Paper under review. Lidstone-Lane et al. (2025)

Mean charge per particle

507 very variable – perhaps due to engine stability and rain ingested into the engine (humidity effects).

[1]



Increase in charge to positive with increase in engine power – due to increase in thermal ionization.

Charge becomes more positive with increasing power

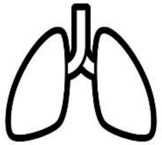
1. Paper under review. Lidstone-Lane et al. (2025)

Implications

Implication of charged emissions

Increase in electrostatic loss mechanism causing an under-predicting of nvPM reporting.

Increased formation of contrails due to ions acting as centres for rapid concentration and coagulation of aerosol clusters from enhanced electrostatic effects.[1]



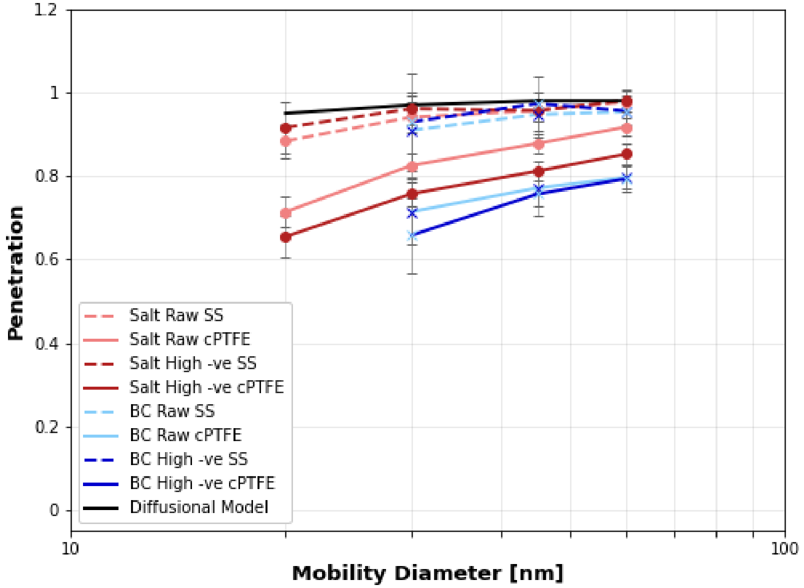
Increase human uptake of nvPM particles through airways – negatively charged particles have been found to have enhanced penetration through mucus and into the deep lung.[2]

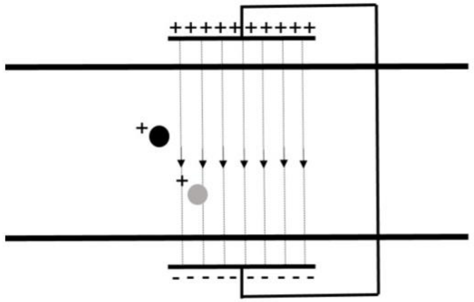
1. Yu, F & Turco, R, P. (1997). *The role of ions in the formation and evolution of particles in aircraft plumes.* Geophysical Research Letters. 24(15):1927-1930
2. Zhu, J et al. (2024). *Inhaled immunoantimicrobials for the treatment of chronic obstructive pulmonary disease*

Increased electrostatic loss?

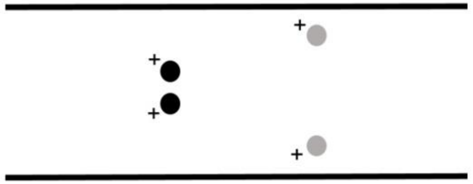
Potential losses could occur through precipitation from charged particles setting up an electric field.

[1]





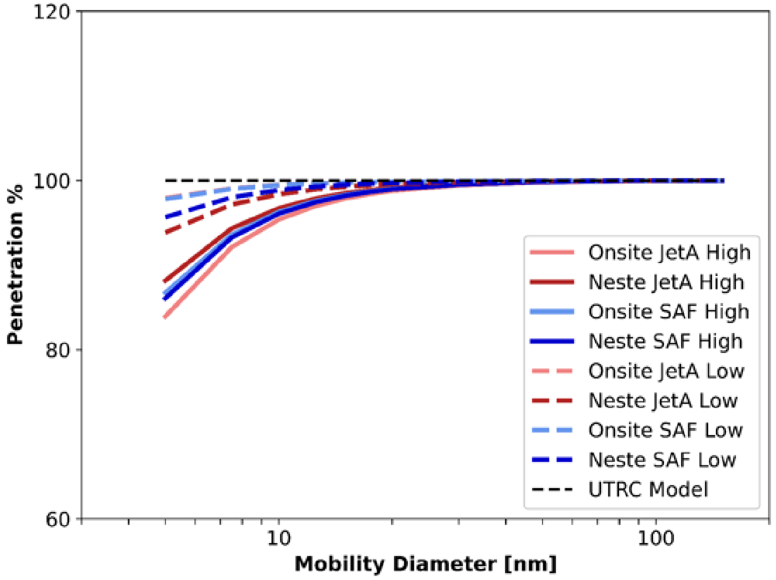
B. Precipitation in an electric field



C. Electrostatic dispersion

Potential losses could occur through sample system due to a charge bias – note this assuming one charge per particle.

[2]



Note these are only preliminary estimates – lots of assumptions!

1. Paper under review. Lidstone-Lane et al. (2025)
2. Lidstone-Lane. (2024). *Particle transport and loss when sampling aircraft gas turbine combustion emissions.* PhD thesis. University of Manchester.

Conclusion

Summary & future work

Summary:

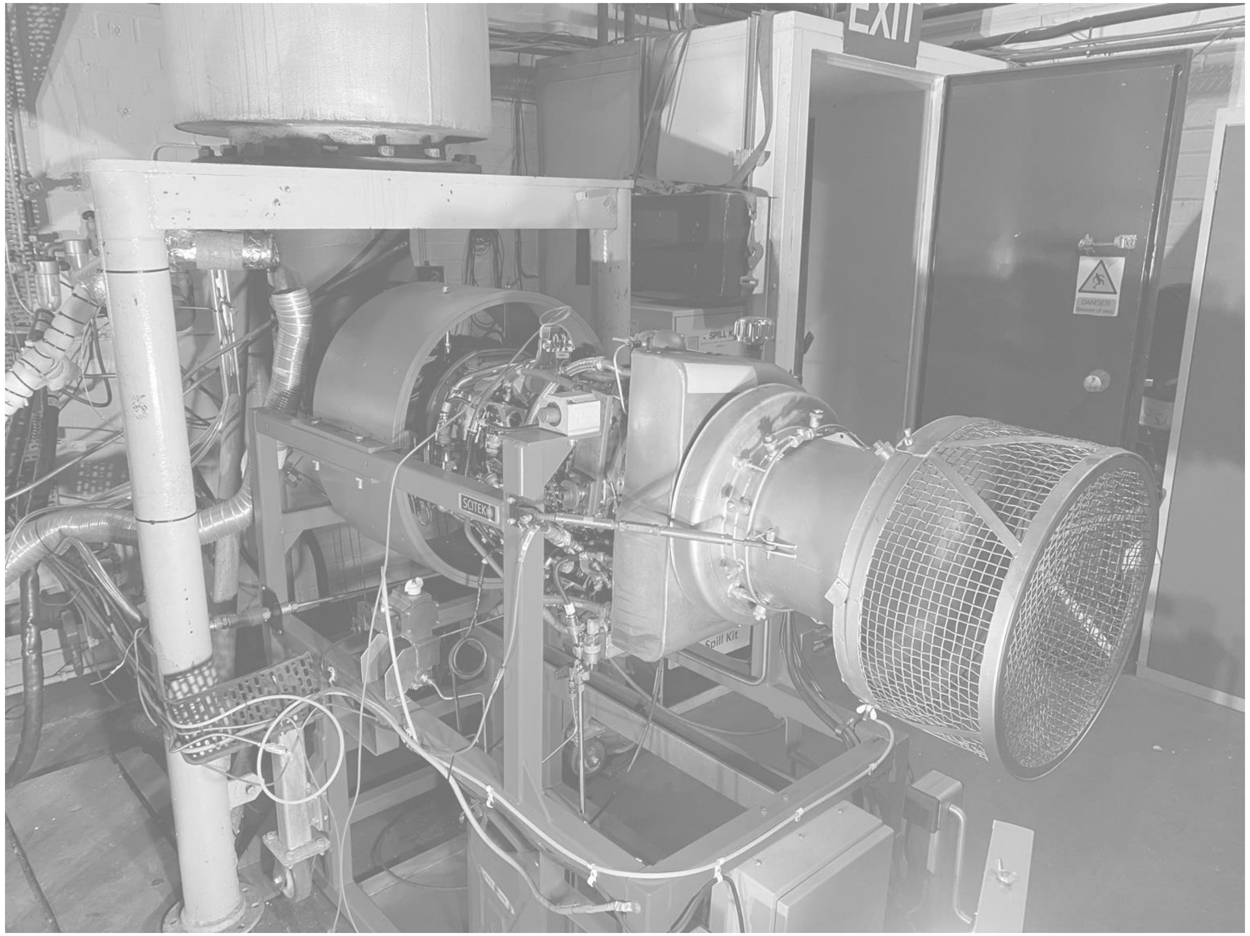
- Charge of two aircraft engine using four fuels was measured
- Increase in charge as particle size and engine power increased - increase in particle size provided a better ability for the particles to carry charge.
- Positive charge bias observed as engine power increased – thermal ionization.
- Some indication of more electrostatic losses occurring.

Future Work:

- Investigate the charge state of the emissions produced in other combustors and engines – particularly where larger exhaust temperatures are possible.
- Investigate the charge state of emissions through different lengths of sample tubing along with various distances inside of exhaust plumes.
- Separate polarities to investigate electrostatic dispersion more accurately

Q&A


Silver Particle Generator
OUTLET


EXIT
DANGER
SPILL KIT
SCITEK
Spill Kit

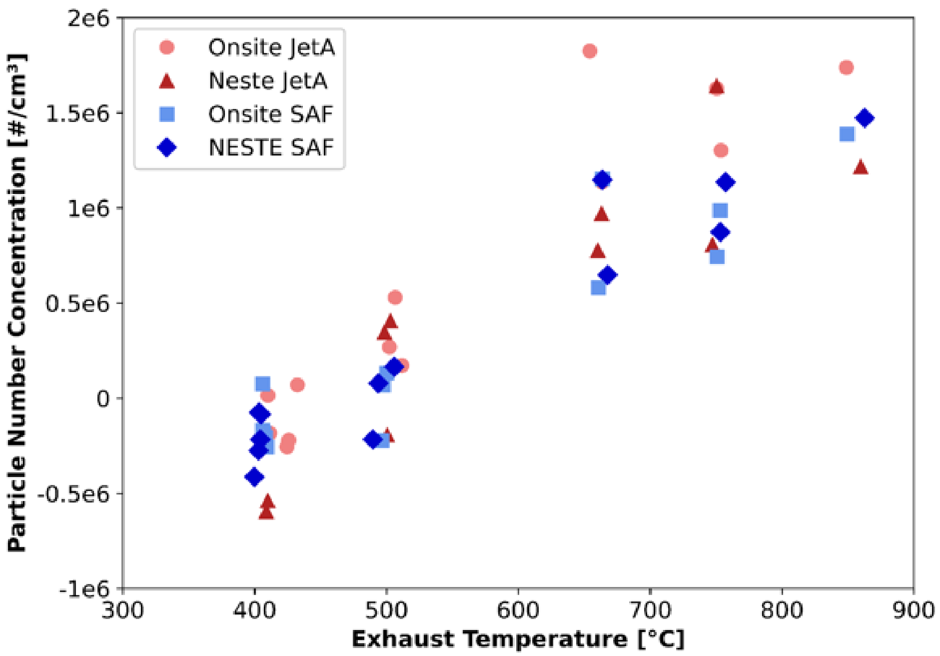
Electrostatic dispersion prediction – bias

- Prediction of the electrostatic dispersion mechanism can be derived from electrostatic charge measurements of nvPM
- First: estimate the **charged particle concentration bias,** assuming the 1 charge per particle using electrometer current:

$$N_{bias} = \frac{i}{\bar{q} \cdot Q \cdot e}$$

- Correct charged particle concentration bias to that of the engine exit – 25:1 dilution and estimated diffusional + thermophoretic loss of 20%

[1]



Large particle concentration bias at high engine power (exhaust temperature)

Electrostatic dispersion prediction - loss

- Now the electrostatic dispersion loss, through the transport tubing before the measurement instrumentation, can be estimated.

- Assuming a tube ID of 10 mm, flowrate of 35 L/min, a tube length of 5 m, and all conditions at STP.

- The particle concentration bias is taken as the probe inlet concentration

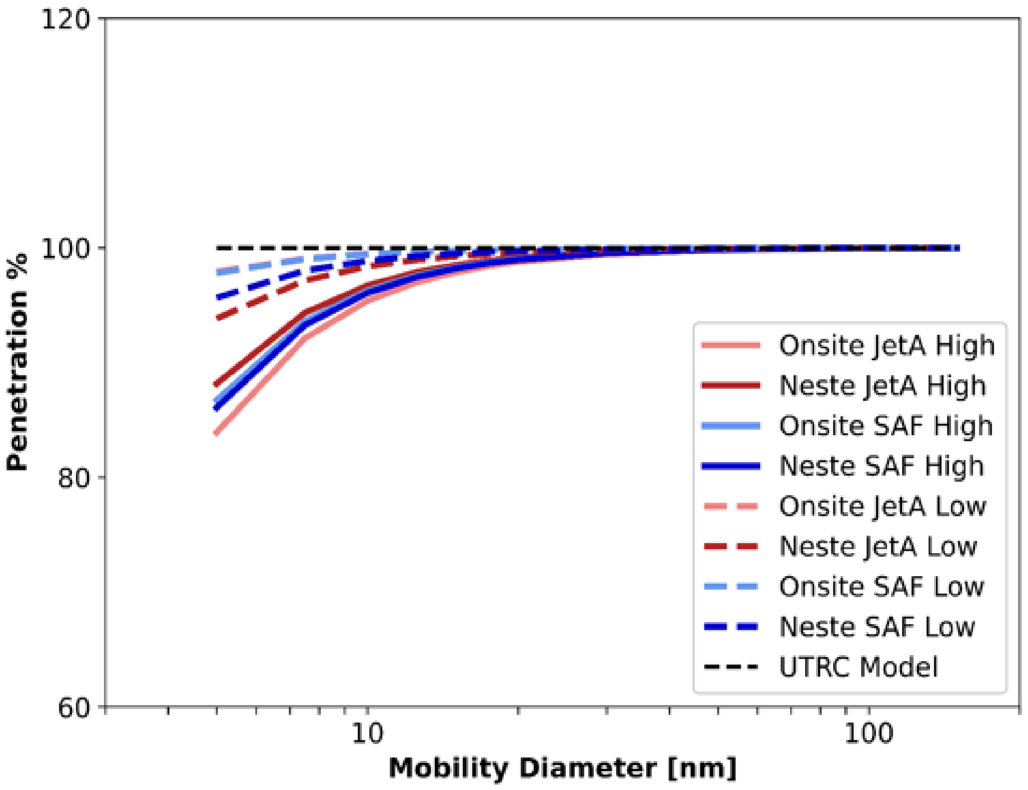
$$P = \frac{1}{1 + 4\pi Z e {n_p}^2 N_o t}$$

Z = Electrical Mobility
e = Elementary Charge
n_p = Number of Charges
N_o = Inlet Number Concentration
t = time in plug flow

- Note **stainless steel** tubing was used throughout all experimental setups.

Electrostatic dispersion prediction – loss (502)

[1]



- Problem bounded for high and lower power with the UTRC model electrostatic prediction included for comparison.
- Potentially around ~**15% additional particle losses**
- **Most particle losses occur for small particles** due to the balance between electrical migration (to wall) and momentum (to outlet).

ESTIMATION!! Lots of assumptions!!