OVERVIEW OF A FEW PM PROJECTS AT NVFEL

A Few Projects at NVFEL

- PM Generator
  - SwRI work (location of main research program)
  - NVFEL (beginning implementation here)
- PM number Initiative
  - Respond to current focus on PM number
  - Develop measurement method
    - Understand measurement complexities
    - Include all parts of PM that have human health impacts
- nvPM from turbine aircraft engines
  - Regulatory initiative under the United Nations International Civil Aviation Organization (ICAO)
  - Test procedure development under International Society of automotive Engineers (SAE)

PM Generator Project

Participants :

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Southwest Research Institute

Teresa Barone and John Storey

Oak Ridge National Laboratory

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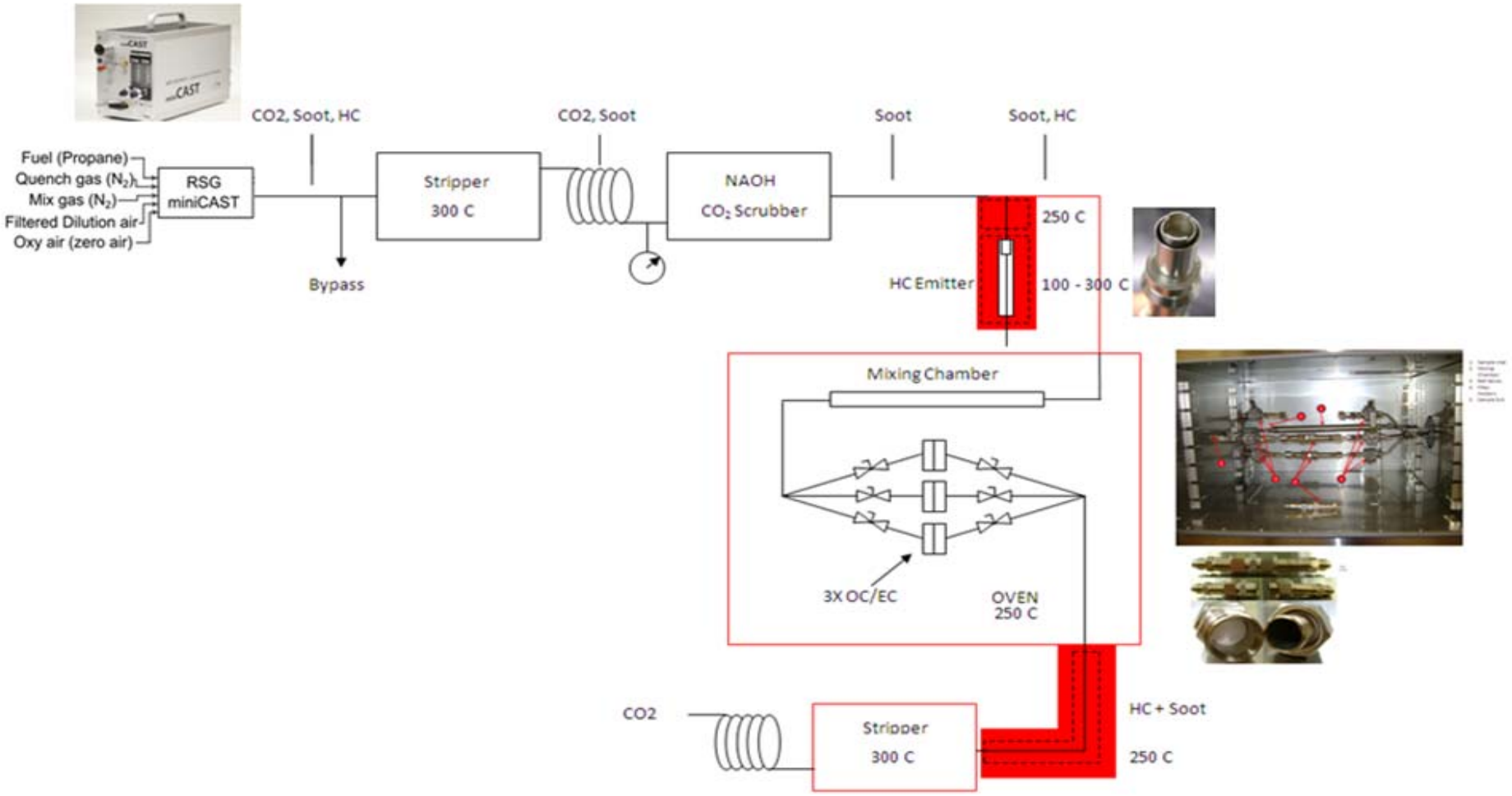
U.S. EPA

Motivation

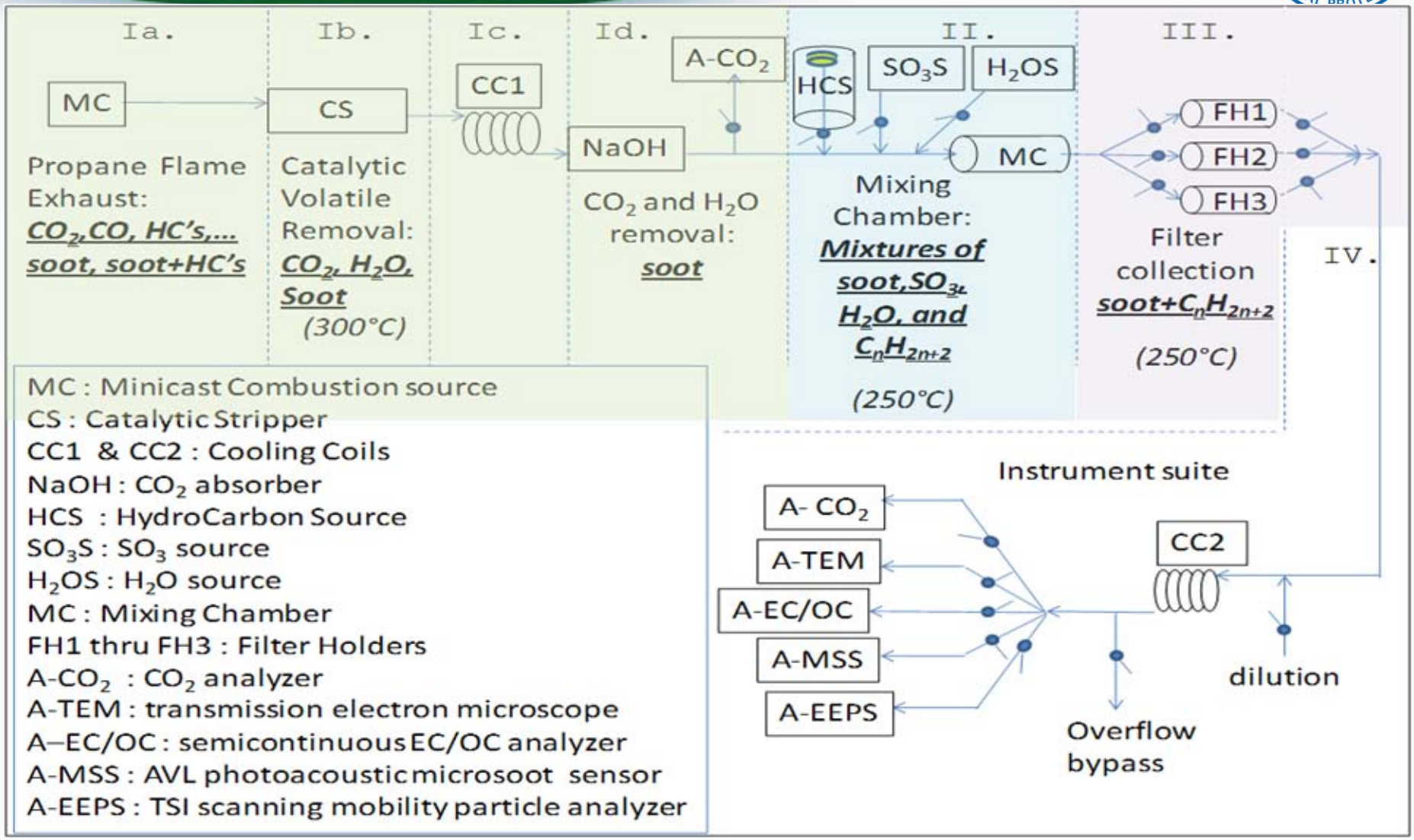
- Difficulty of measuring combustion PM
  - Instrument sensitivity to differing PM species
  - Sampling system design
  - Produce chemical thermodynamics in a controlled environment (vs. combustion engine source)

- Need some standard mechanism to produce combustion PM that is
  - stable
  - reproducible
  - can vary characteristics (i.e., size, chemistry, and mass) over a wide range in a simple manner (vs. engine source)

PM Generator Schematic (Housed at SwRI Nanoparticle Laboratory)



PM Generator (Housed in SwRI Nanoparticle Laboratory)



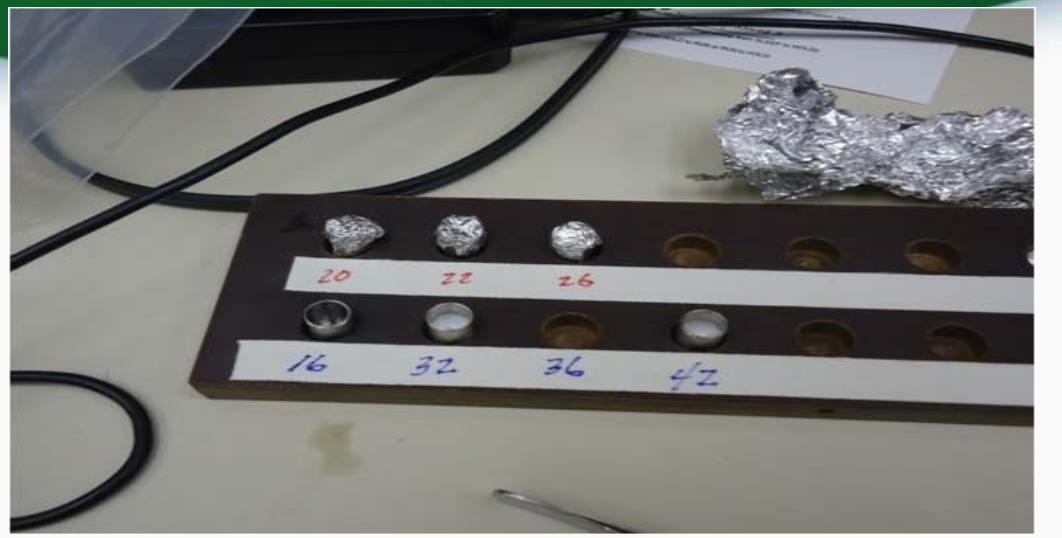
Soot / Carbon Source

- Carbon source
  - Re-design
    - Jing mini-Cast Soot generator
      - With catalytic stripper (removes semi-volatile HC's and converts them to CO_2)
    - CO_2 scrubber : $CO_2 + H_2O \Rightarrow H_2CO_3$

      $H_2CO_3 + 2NaOH \Rightarrow Na_2CO_3 + 2H_2O$

      $[CO_2 + 2NaOH \Rightarrow Na_2CO_3 + H_2O]$
  - Soot Output Characterization
    - Size distribution (SMPS, EEPS)
    - Concentration (AVL microsoot sensor, EC/OC analyzer)
    - Stability
    - Morphology (ORNL TEM studies)
    - CO_2 scrubber characterization

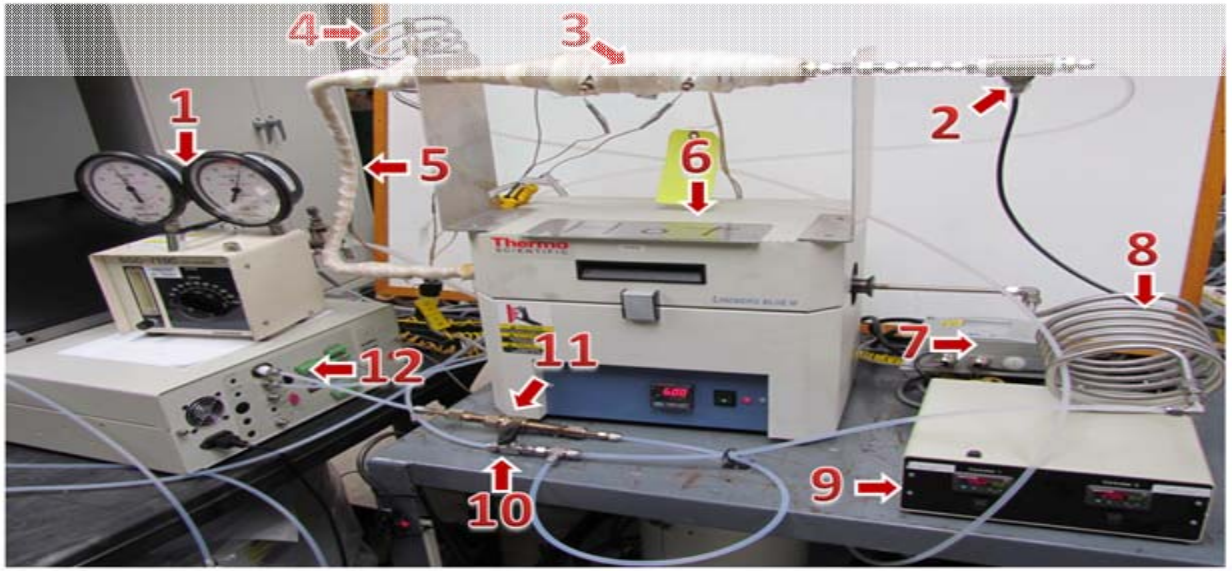
HC Sources



- HC sources
  - $C_{16}H_{34}$, $C_{19}H_{40}$, $C_{20}H_{42}$, $C_{26}H_{54}$, $C_{32}H_{66}$, $C_{36}H_{74}$, $C_{42}H_{86}$
- HC source characterization
  - Temperature dependence of HC concentrations
    - Mass measurements
    - Summed CO_2 mass from concentration measurements
  - Nucleation of individual species
  - Soot and HC mixing
  - Transport and modeling in a short section of tubing

SO_3 Source

1. SO_2 to SO_3 catalytic conversion
   i. SO_2 and O_2 bottled gases
   ii. Commercial diesel palladium/platinum oxidation catalyst
   iii. $O_2 + 2SO_2 \rightarrow 2SO_3$
2. SO_2 to SO_3 conversion monitoring
   i. 1100° C oven (SO_3 to SO_2 decomposition)
   ii. SO_2 UV Fluorescence analyzer



1. Gas Divider	6. Oven	11. TX Filter
2. RH Sensor	7. RH Analyzer	12. SO2 Analyzer
3. Catalyst	8. Cooling Coil Oven Out	
4. Bypass After Catalyst	9. Temperature Control Box	
5. Heated Tube from Catalyst to Oven	10. Bypass After Oven	

Continuing Work

- HC sources
  - HC species production : evaporation and CO_2 detection
  - HC particulate nucleation
  - Transport studies begun
  - Stability and repeatability demonstrated
- Soot source characterization
  - Morphology of bare soot and HC – soot mixing
  - Stability and repeatability demonstrated
  - Fine tuning of miniCAST to get desired soot morphology
- SO_2 source design
  - SO_3 catalyzed from SO_2, O_2, and DOC catalyst

Continuing Work

- Conduct preliminary fundamental PM formation experiments
- Theoretical
  - PM and gas transport modeling to simulate losses
  - PM formation modeling
- Replicate Apparatus at NVFEL
- Modifications when needed

PM Number Initiative Overview

Participants :

Mike Olechiw, Joe McDonald, Angela, Cullen, Bob Giannelli, Chris Laroo, Chuck Schenk, James Sanchez
U.S. EPA

Roger Dornberger
ISS

Motivation I

- Use of Solid Particle Number (SPN) as the primary metric for mobile source PM
  - Adoption in Europe for LDV SI-GDI and diesel
    - Still no PM or PN standard for SI-PFI
  - Under consideration in China
  - California is considering SPN with a conversion factor as a mass metric

Motivation II

- Stakeholder concerns
  - Environmental community often equates mobile source SPN with total PN and Ultrafine Particulate Matter (UFP, typically <100nm)
  - Ethanol lobby is pointing towards LDV/LDT SPN reduction as reason to adopt higher EtOH blends even though filter mass measurement often shows PM increases
    - Potential increase in SVOC due to fuel impingement into lubricating oil film on cylinder wall surfaces

Motivation III

- Current PMP-SPN measurement methods only measure “solids”
  - Significant (>40%) contributors to PM mass are not measured
    - Organic carbon PM (largely due to lubricating oil consumption)
    - Semi-volatile ions (nitrate and sulfate)
    - The majority contributors to particle number, nucleation aerosols and UFP are also not measured
- Components that are excluded from SPN measurement include mutagens and suspected carcinogens
  - Controls for SVOC components of PM (catalysts, cold-start improvements) generally reduce PM mutagenic activity
- “Conversion factors” from solid particle number measurements to PM mass as originally proposed by CARB for LEV III are problematic because the relationships are engine- and technology-specific
  - Conversion necessary for linkage to current PM-NAAQS
  - Relationship to mass changes with combustion technology (diesel, PFI, GDI, possibly EGR) and engine calibration
  - The increase in SPN emissions over a vehicle’s useful life is likely to be significantly less than increases in PM mass emissions
    - No measurement of lubricating oil contribution to PM – a significant contributor to PM near the end of useful life
  - Dropped from final LEV III regulation in part due to EPA concerns but likely to resurface within 2018 technology review
- There is risk that an SPN standard would be less constraining than stringent PM mass standards (at 1mg/mile)
  - Particularly near the end of useful life as consumption of lubricating oil increases

Guiding Thoughts on Implementation

- EU Number Regulations Do not consider Total PM
  - a negative and a opportunity to improve method
    - *Total PM* must be measured because of its negative impacts on human health and welfare
    - Realize the inclusion of volatiles adds a high degree of difficulty and will require more than a simple number measurement (size, probably some chemistry, and modeling)

Reference Method for PM Number (or Probably More Appropriately UFP)

- Start with the current PM sampling system configuration (40 CFR Parts 1065 &1066)
- A “scalar” number measurement is not enough to address all health and welfare effects of PM
  - Size distributions will give information on the lung deposition
  - Chemical signatures are needed to address atmospheric chemistry (SOA and climate forcing) and future epidemiology
- Measure total PM, i.e., volatiles and soot
  - Volatiles are the major source of measurement difficulty
    - Careful attention must be paid to temperature, dilution, and flow
  - Modeling of sampling system can be used to help understand the relative importance of sampling system variables
    - Traceable PM chemistry/predictable system, i.e., using model, emissions (PM and chemical concentrations) measurements, sampling system thermodynamic and flow conditions the system chemistry should be definable
    - Uncertainties understood from the standpoint of model and testing

Current Status

- Laboratory modifications
- PM source and DAQ
  - NVFEL PM generator
- Finite element software tools

Emission Standard Development for Non-volatile PM Emissions from Commercial Aircraft Turbofan Engines

Participants :

Glenn Passavant, Mike Samulski, Bryan Manning, Cullen Leggett, John Kinsey, Solveig Irvine, John Mueller, Bruce Maeroff, and Bob Giannelli

U.S. EPA

E31 – many others

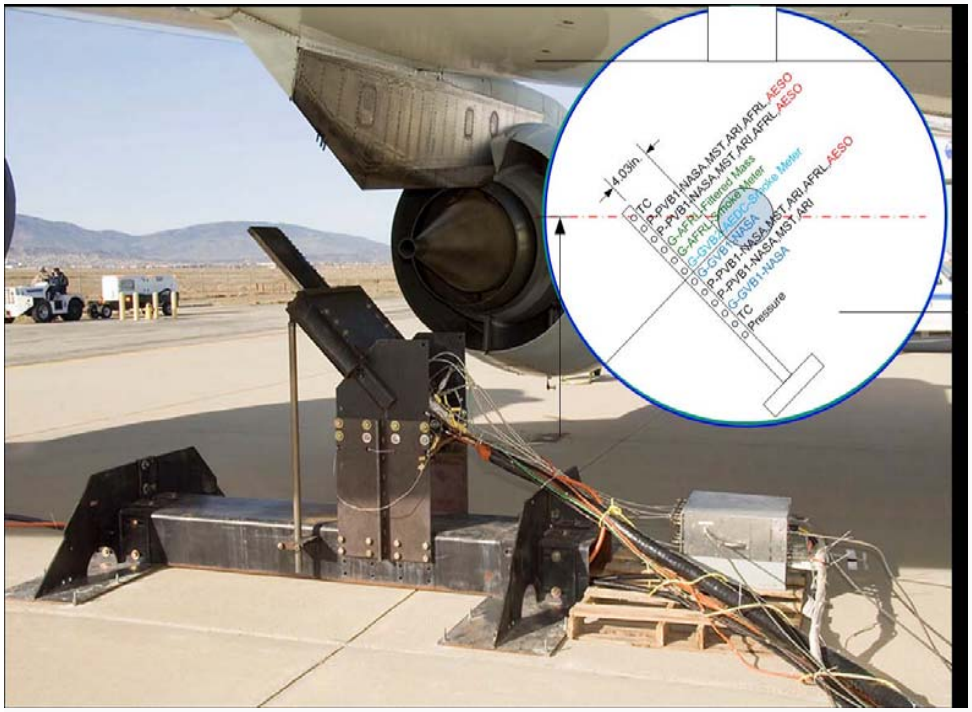
International Aircraft Regulatory Scheme

- International Civil Aviation Authority (ICAO)
  - (http://www.icao.int/about-icao/Pages/default.aspx)
  - Agency of UN created in 1944
  - Sets standards and regulations for environmental protection, safety, security, efficiency, and regularity
  - Member states
  - Aircraft Engine Emissions
    - Volume II of ANNEX 16 to the Convention on International Civil Aviation
      - Historical : EC-NEP Air : Work Package 1 Aircraft engine emissions certification – a review of the development of ICAO Annex 16, Volume II, D.H.Lister and P.D.Norman
    - Committee on Aviation Environmental Protection (CAEP)
      - Individual CAEP's (1,2,3,4,5,6,7,…) refer to the meeting years (1991, 1995, 1998, 2001, 2004, 2007, 2010, …), respectively
      - Each formal meeting produces a report with specific recommendations for the consideration of the ICAO Council
      - Working Group (WG) 3 is subcommittee for PM
        - » Member states and interested parties
      - SAE was assigned by WG 3 to update PM sampling and measurement method
        - » SAE E31 standards committee to produce an Aircraft recommended practice (ARP) for nonvolatile PM
    - Future
      - Engines, APU's, … < 27.6kN
      - Volatile PM

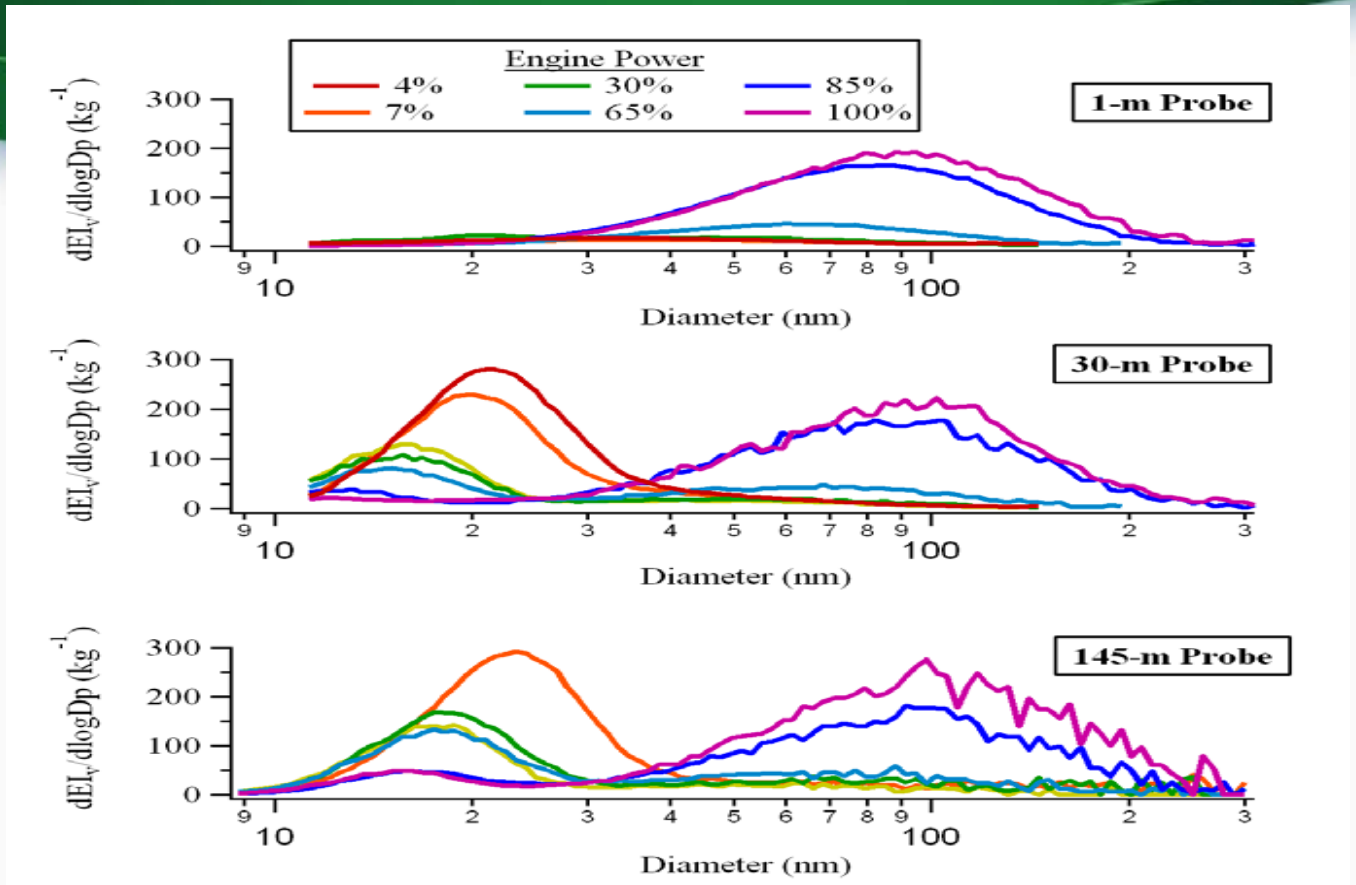
SAE E31 Work

- E31 (gaseous and) PM standards group
  - PM
    - Currently only nvPM
    - Only engines with thrust >27.6kN
    - Technical teams
      - Mass Team
      - Sample Team
      - Number Team
      - Calculation Team
    - Main participants
      - E.U. (EASA and FOCA), U.S. (EPA, FAA, and Airforce) , Canada (TC and NRC), U.K. (C.A.A.)
      - Rolls Royce, G.E., Pratt and Whitney, Honeywell
      - instrument manufacturers

Example of Early Emissions Studies : Alternative Aviation Fuel Experiment (AAFEX)



AAFEX Sampling stand and inlet rake used behind the left inboard engine; inset shows arrangement of gas (G) and particle (P) probes and sensors (thermocouple and pressure tap) in the water-cooled rake.



Volume size distributions [$dEI_v/dlogDp$ (mg/ kg)] as a function of sampling probe position and engine power for JP-8 fuel.

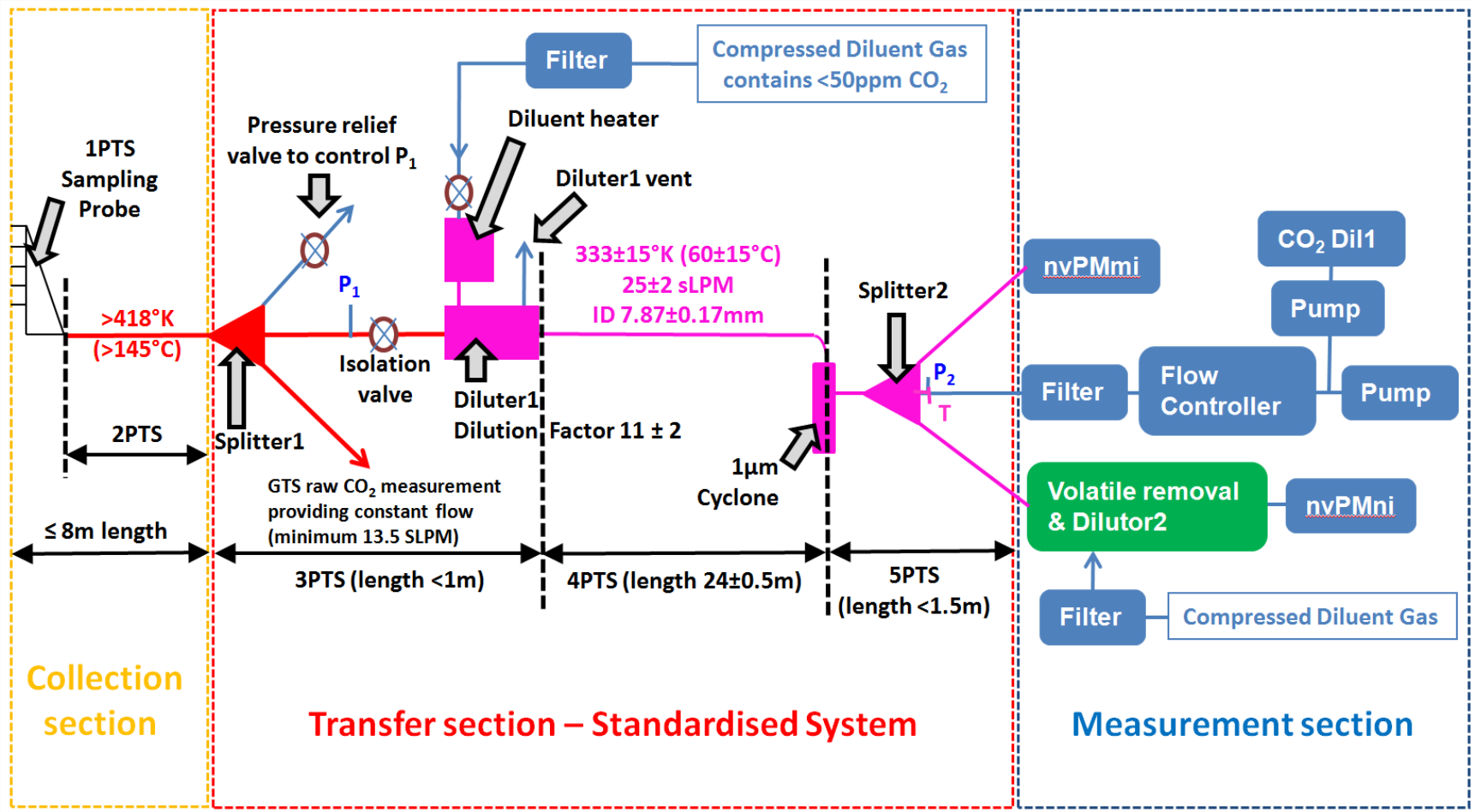
exhaust plane - particles are comprised of a single soot mode

downwind -nucleation mode appears, peaking at 15 to 25 nm in the volume (10 to 20 nm in number) distribution

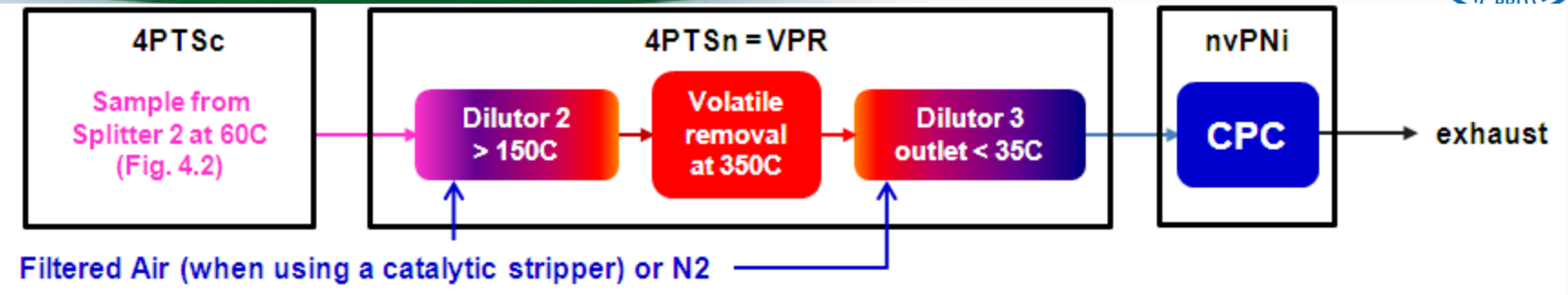
low power - nucleation mode dominates the PSD in downstream samples

increasing power -nucleation mode decreases and the soot mode increases with the soot mode dominating at high power

Schematic of Particle Measurement System



Particle number measurement system



- Similar to E.U. PMP protocol for solid number
  - VPR (either thermal or catalytic stripper)
  - CPC particle penetration of 90% at 15nm
  - VPR
    - Particle Penetrations Specified

Particle size, d_i	15 nm	30 nm	50 nm	100 nm
Penetration, $Pen(d_i)$	≥30%	≥65%	≥70%	≥75%

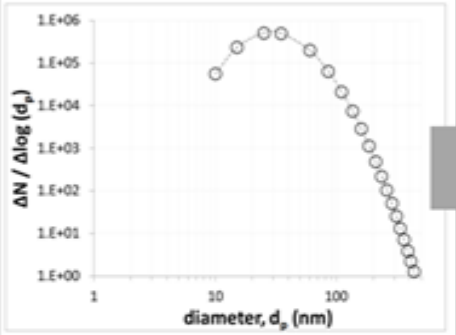
    - Volatile removal efficiency specified (tetracontane)
  - Calibration
    - Similar to E.U. PMP

Mass measurement

- Instruments
  - Laser induced incandescence (LII)
  - Photoacoustic spectrometer
  - Calibration
    - NIOSH 5040
    - PM combustion source : diffusion flame
    - EC fraction ≥ 0.8 and soot concentrations of 0, 50, 100, 250, 500, and 1000μg/m^3

Loss Estimation Method

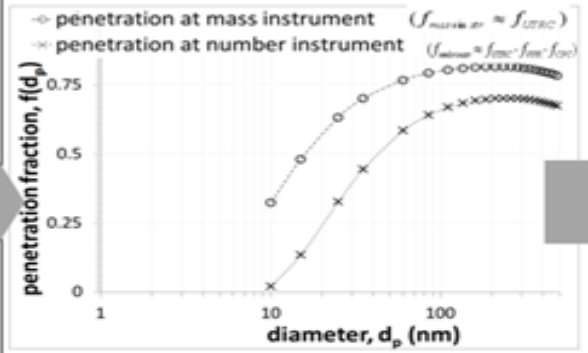
(A.)
Use measured mass and number to determine a lognormal size distribution

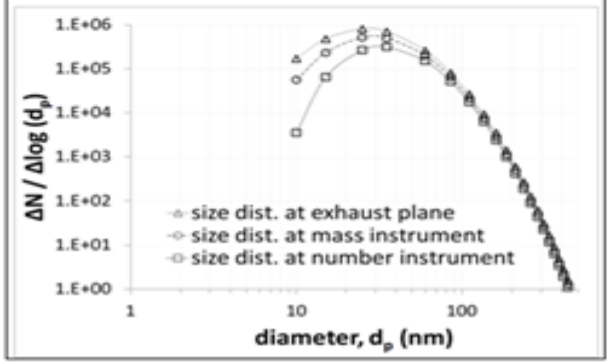


$$GMD = \left(\frac{6 \cdot M_{meas}}{\pi \rho N_{meas}} \right)^{1/3} \cdot e^{-3 \cdot s^2/2}$$

$$s = \ln(\sigma_g),\ \sigma_g = 1.77$$

(B.)
Apply sampling system penetration fraction functions to determine mass and number at engine exit





(C.)
Apply corrections to mass and number

$$C_N = \frac{N_{exitplane}}{N_{measured}}$$

$$C_M = \frac{M_{exitplane}}{M_{measured}}$$

Thanks!