

Measurement of Exhaust Particulate Matter

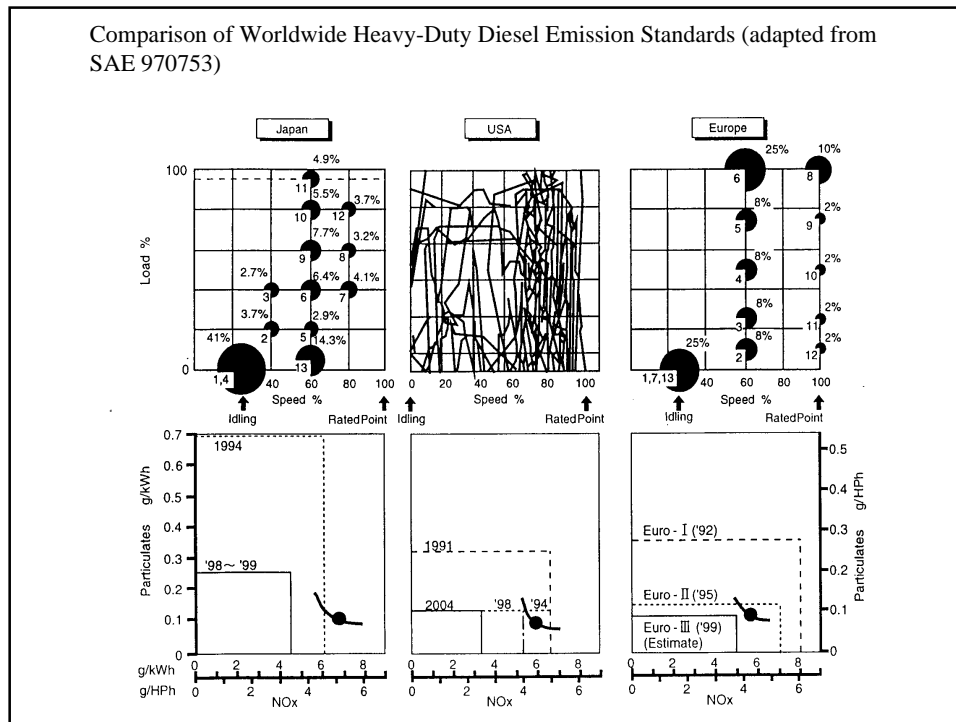
David B. Kittelson
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AAAR Tutorial, 11 October, 1999

Outline

- Emission standards
- Diesel cycle
- Particle formation
- Nature of particles
- Particle size
- Measurement issues
 - Mass measurements
 - Size, number, and surface measurements

“Ultrafine Particulate Matter in the Exhaust from Diesel and Gasoline-powered Mobile Sources”

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Diesel engines have large fuel economy advantage over SI engines, especially at light load

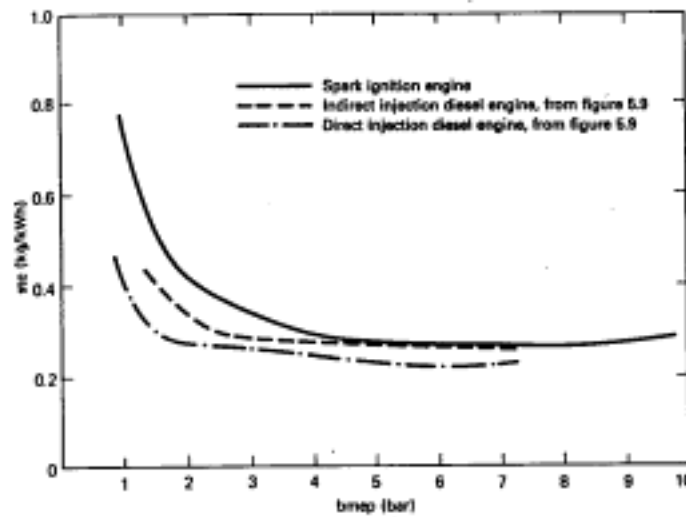
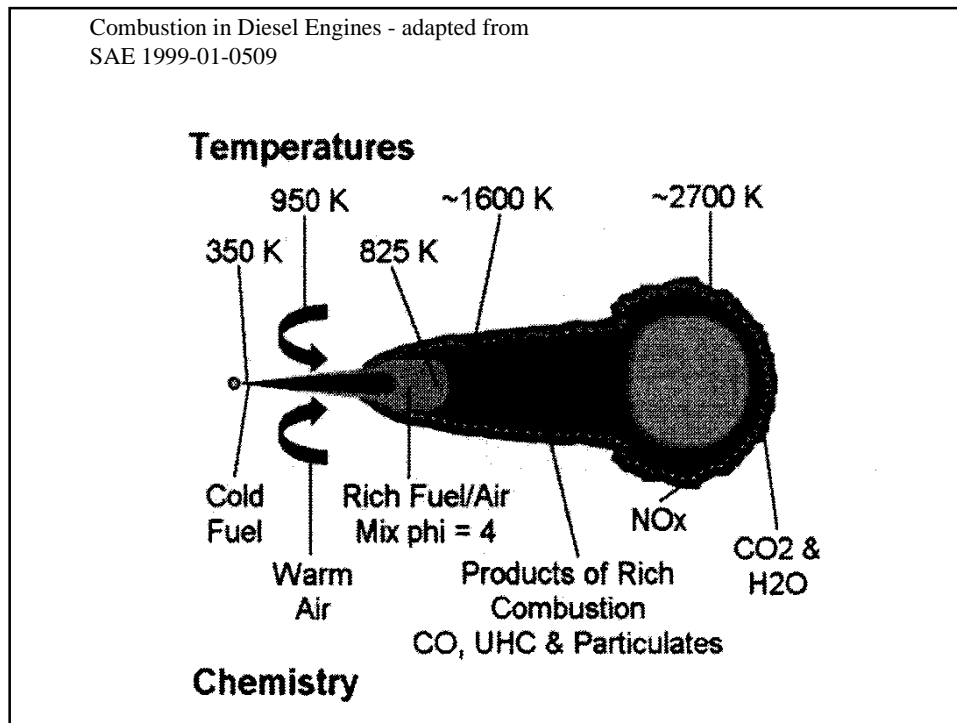
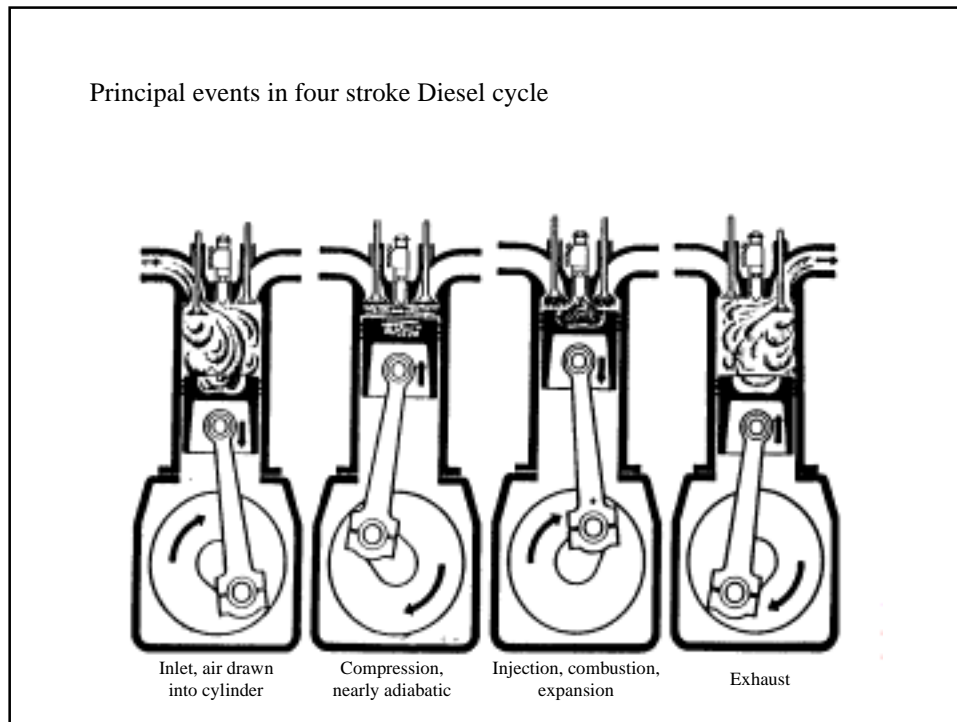


Figure 5.1 Comparison of the part load efficiency of spark ignition and Diesel engines at 2000 rpm (Stone, R. (1989a))

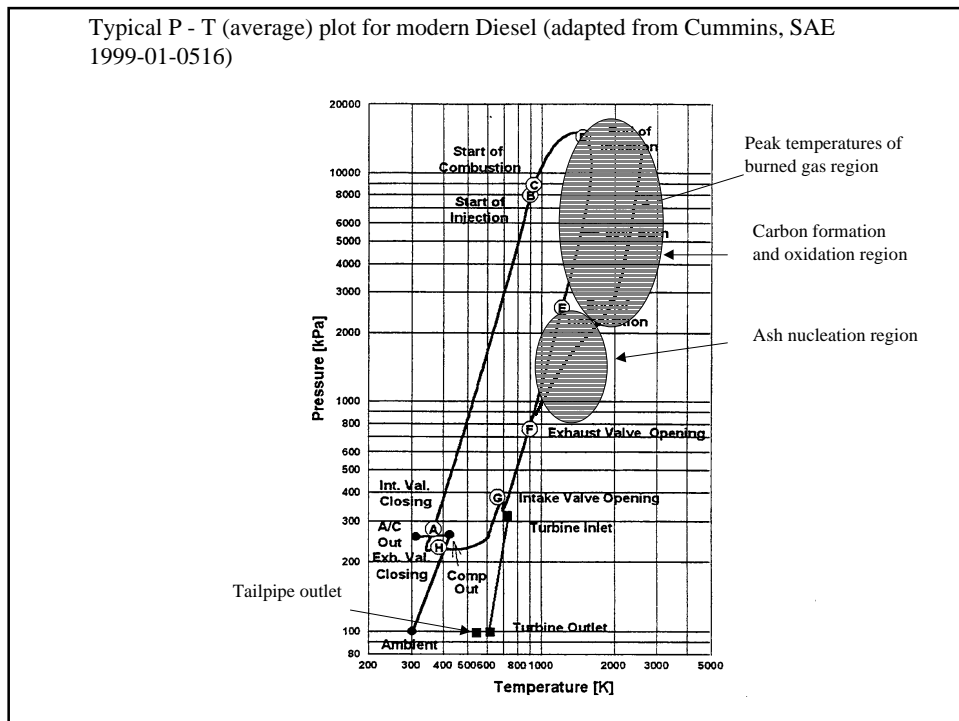
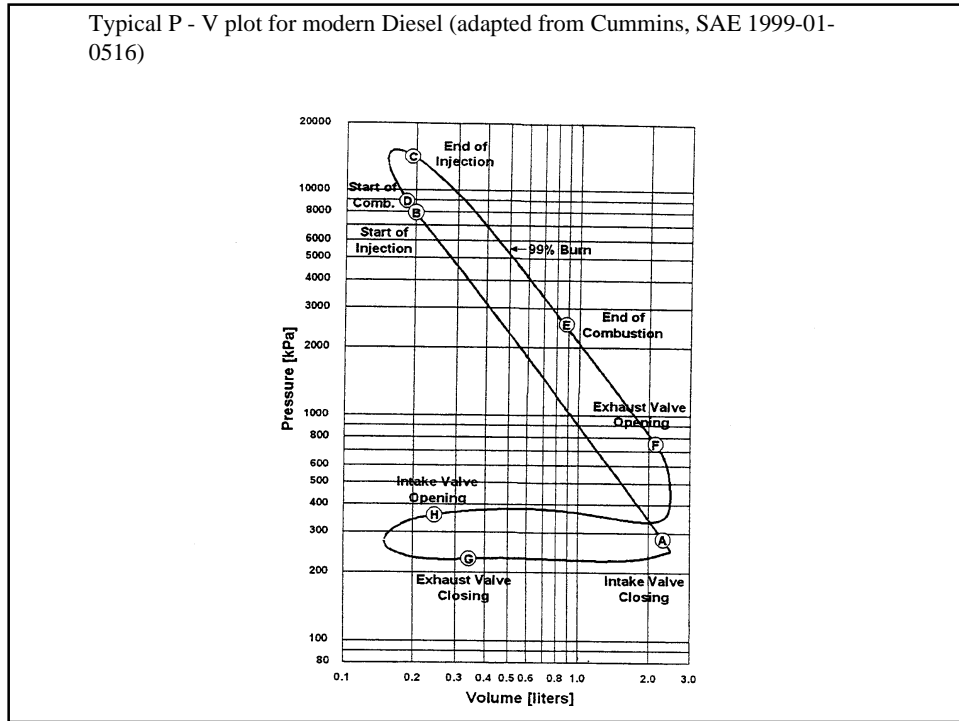
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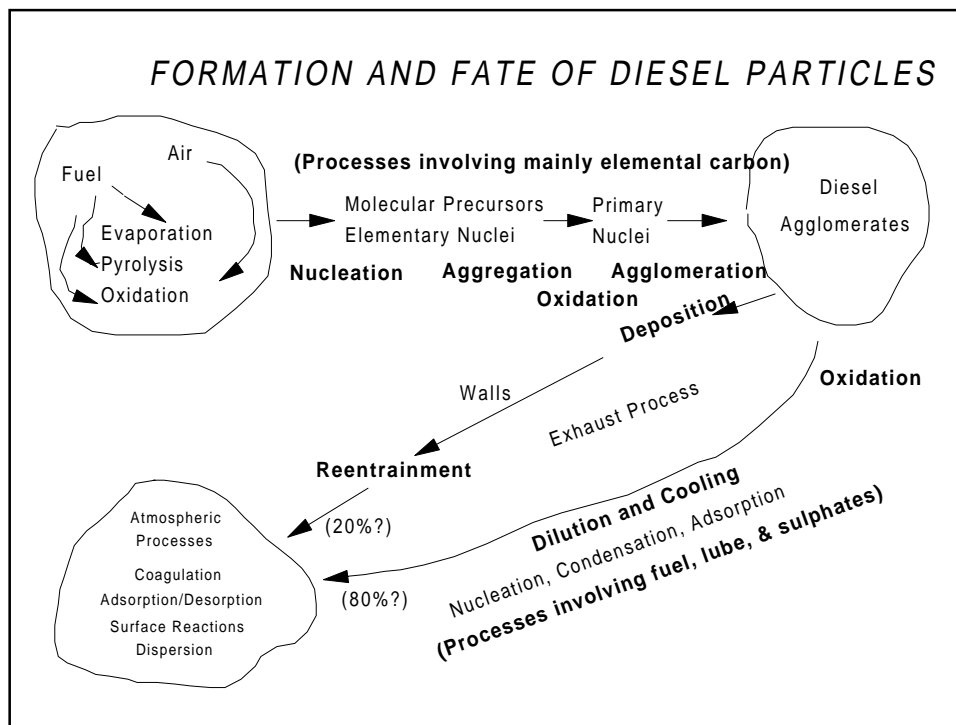
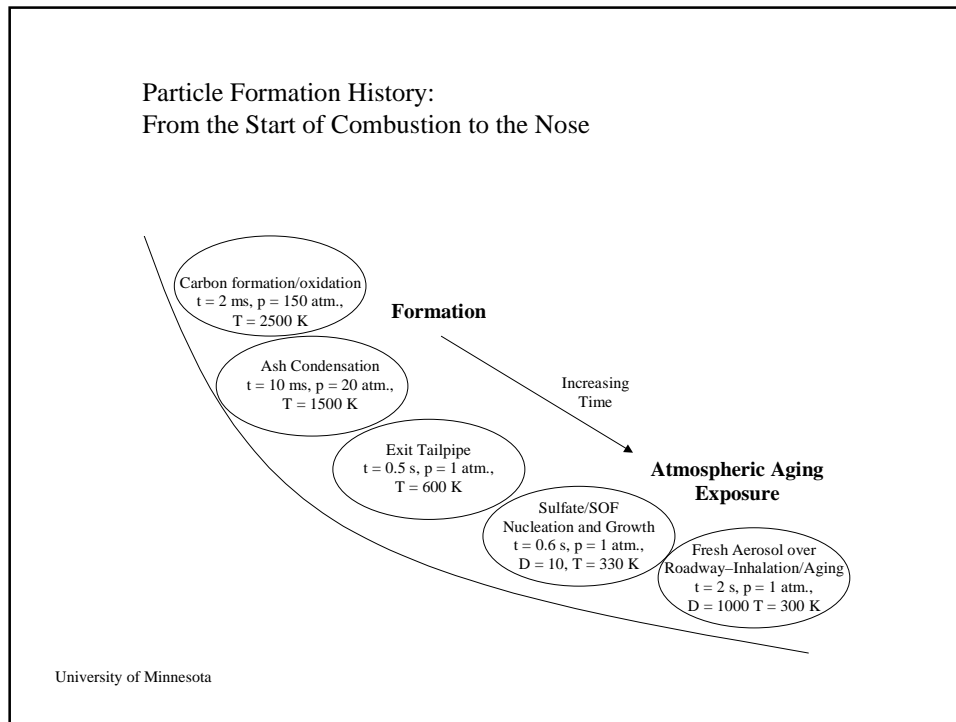
“Ultrafine Particulate Matter in the Exhaust from Diesel and Gasoline-powered Mobile Sources”

Presented to the Mobile Sources Technical Review Subcommittee - 10/13/99

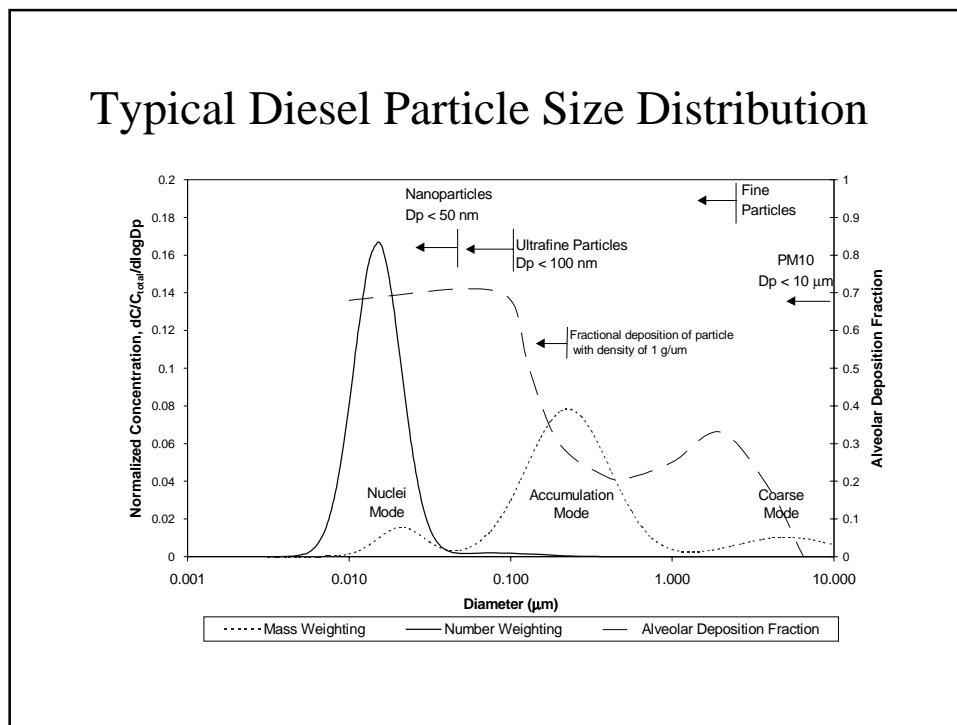
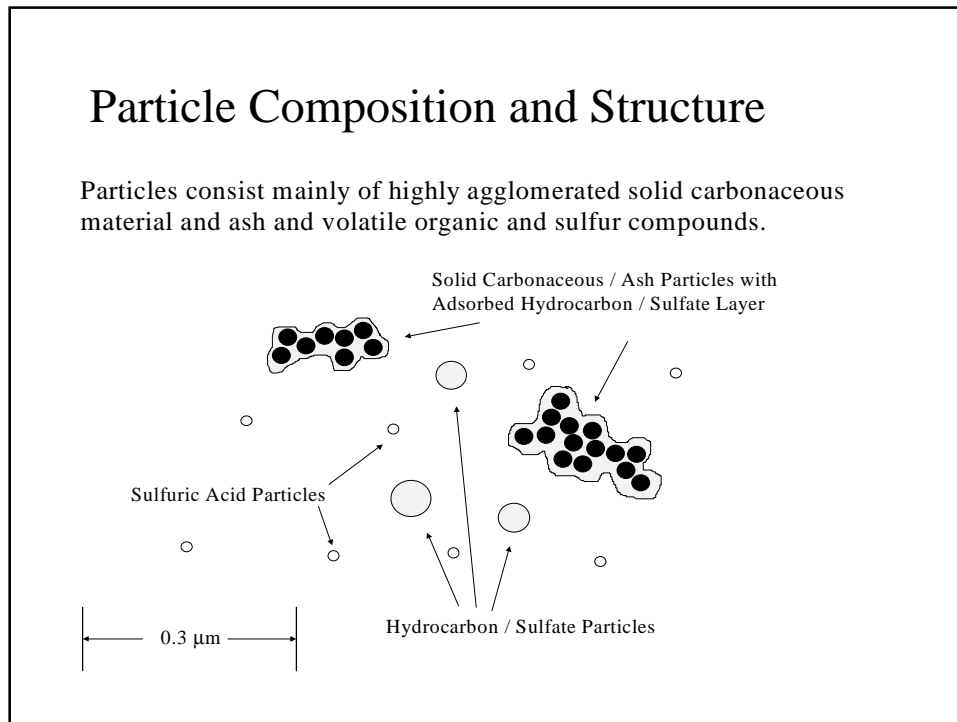
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**Current emission standards are mass based
Recently interest in other measures, i.e, size,
number, surface, has increased**

- Concerns about particle size
 - New ambient standards on fine particles
 - Special concerns about ultrafine and nanoparticles
 - Indications that reductions in mass emissions may increase number emissions
- Difficulties associated with measurement of ultrafine and nanoparticles
 - Often more than 90% of particle number are formed during exhaust dilution
 - Particle dynamics during sampling and dilution are highly nonlinear - large changes in of particle number may result from small changes dilution and sampling conditions

Health

- Correlations between fine particles and excess deaths
- Increased asthma in children living near roadways
- Special concerns about ultrafine and nanoparticles

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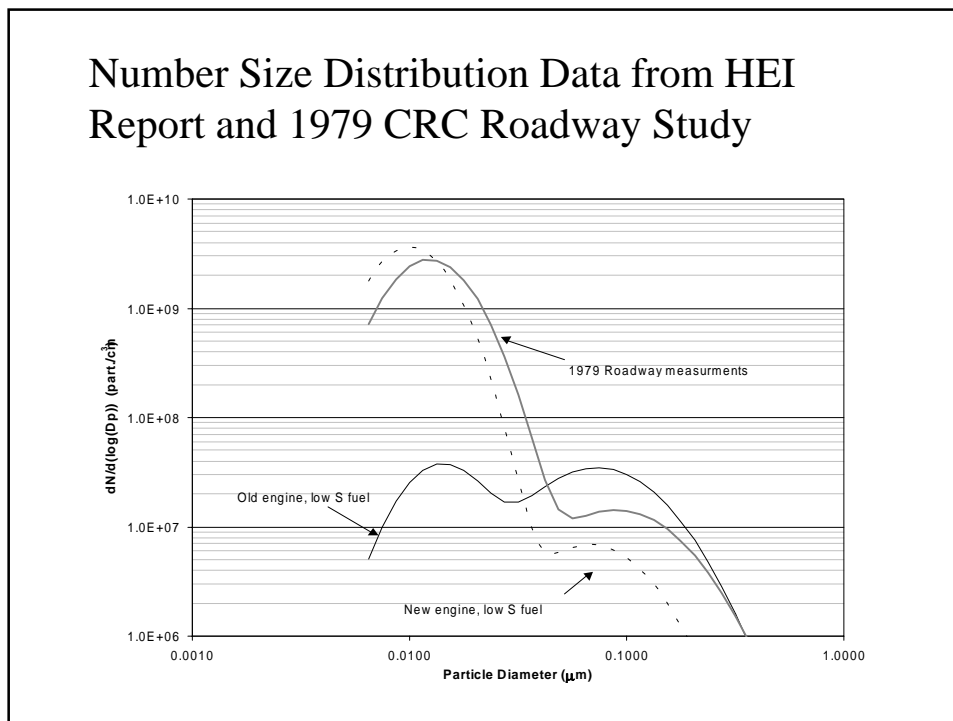
Special Concerns about Nanoparticles and Health

- Increased deep lung deposition
- Increased number and surface area at same mass exposure
- Particles which are non-toxic in μm size range may be toxic in nm range
 - Rats exposed to the same mass of 0.25 and 0.02 μm diameter TiO₂ retain more nanoparticles in the interstitial tissue of the lung and develop marked inflammatory response. (Seaton et al., 1995).
 - Comparison of surface free radical activity of ambient PM10 particles, and 0.5 and 0.025 μm diameter TiO₂ showed significant activity for PM10 and much more activity for 0.025 than for 0.5 μm TiO₂ (Donaldson et al., 1996).
 - Modest concentrations of 0.03 μm Teflon fume particles caused acute pulmonary toxicity in rats (Ferin et al., 1992).

A Recent HEI Study Gave a Surprising Result for a Low Emission Engine

- Particle concentrations and size distributions were measured for a 1988 and a 1991 engine
 - When run on very low sulfur fuel particle number emissions were much higher, 30 -100 times, from the new engine although mass emissions were about 3 times lower
 - The 1988 engine produced high number emissions, but not as high as the 1991 engine when run on a 1988 type fuel (higher sulfur)
 - This raised concerns that new engines might be producing large numbers of nanoparticles while still meeting mass emission standards and focused attention on nanoparticle emissions
- However reviews of measurements made on and near roadways in the 70's and 80's show high nanoparticle emissions. **High nanoparticle emissions may be a problem but are not a new development!**

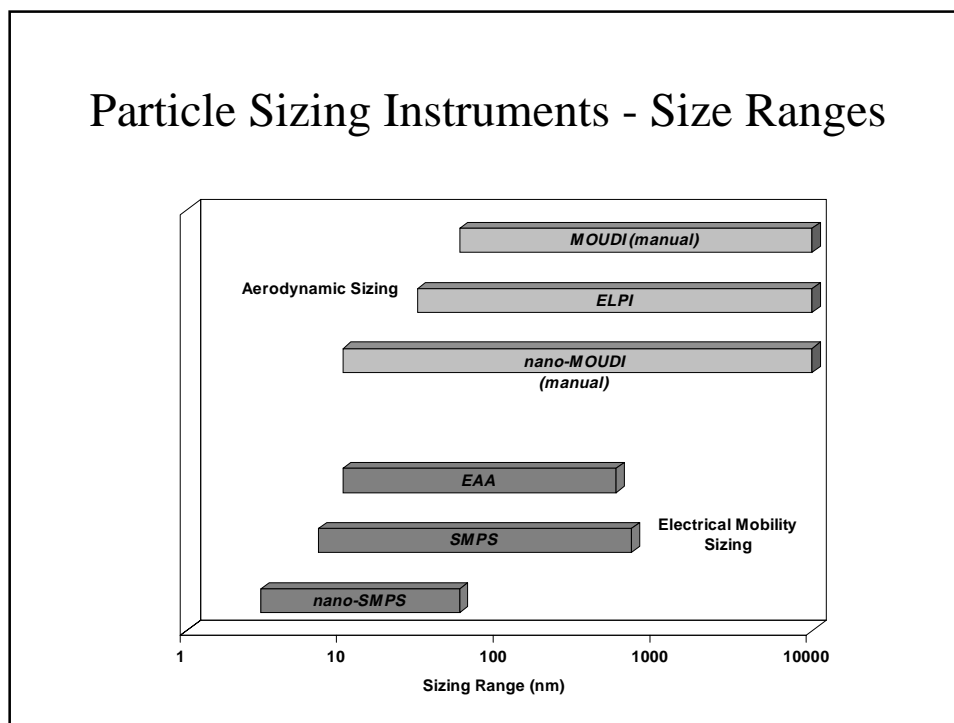
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Particle Sizing Instruments

- Electron Microscope
- Mechanical Mobility
 - Aerodynamic diameter (size, shape, density)
 - Inertial impactors (10 nm - 10 μm)
 - Aerodynamic particle sizer (0.5 - 10 μm)
 - Stokes diameter (size and shape)
 - Electrical mobility diameter - EAA, DMA, SMPS (3 - 700 nm)
 - Diffusion diameter - Diffusion battery (10 - 200 nm)
- Light scattering (size, shape, refractive index) (100 nm - 10 μm)
 - New method based on elastically polarized light claims sizing capability to 2 nm (A. Hunt, LBL)

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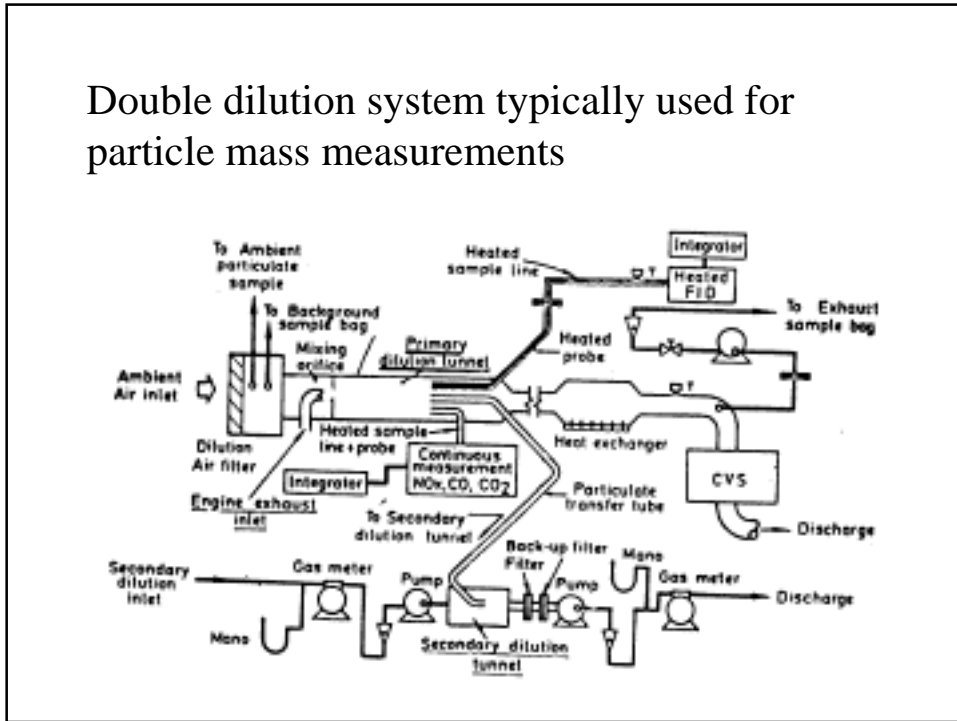
Measurement of Emissions

U.S. Heavy-Duty Cycle

- Current standards are mass based
 - Collect particles by filtration from diluted exhaust stream
 - Sampling zone temperature not to exceed 191 C
 - Filter face temperature not to exceed 52 C
 - Teflon or Teflon coated filters
 - Two filters in series, recommended mass > 5.3 mg
 - It is nearly impossible to collect this much mass with modern low emission engines
- What are the sources of variability in such measurements?
- Variability likely to be even greater for size, surface, or number measurements

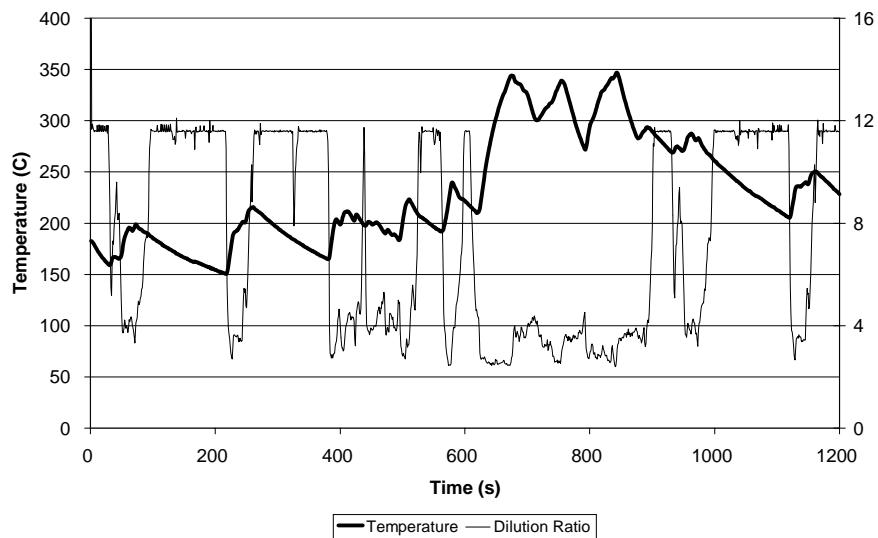
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Double dilution system typically used for particle mass measurements



Dilution ratio and temperature vary strongly during the U.S. transient heavy-duty cycle. Typical results are shown here.

Tunnel Inlet Temperatures and Primary Dilution Ratios



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DILUTION RATIO LIMITS

1. To collect sufficient particle mass

A mass balance gives:

$$m_p = \frac{((\rho_e EI) / BSFC)(F / (1 + F))(V_f A_f t)}{D}$$

where m_p is the minimum particle mass required for accurate measurement, ρ_e is the standard exhaust density, EI is the particle emission standard, $BSFC$ is the brake specific fuel consumption, F the fuel-air ratio, V_f the filter face velocity, A_f the filter face area, t the sampling time, and D the overall (average) dilution ratio.

The overall dilution ratio is the product of the primary and secondary tunnel dilution ratios, $D = D_p D_s$. Thus the maximum dilution ratio product that allows the required mass to be collected is:

$$D_p D_s = \frac{((\rho_e EI) / BSFC)(F / (1 + F))(V_f A_f t)}{m_p}$$

DILUTION RATIO LIMITS

2. To prevent exceeding temperature limits in the sampling zone and at the filter face.

Adiabatic dilution of the exhaust gives a diluted sample temperature, T , of

$$T = \frac{T^e}{D} + \frac{(D-1)T^a}{D}$$

where the subscripts a and e refer to the dilution air and exhaust, respectively. Solving for D gives a primary dilution ratio of:

$$D_p = \frac{T^e - T^a}{375 - T^a}$$

and an overall dilution ratio of:

$$D_p D_s = \frac{T^e - T^a}{125 - T^a}$$

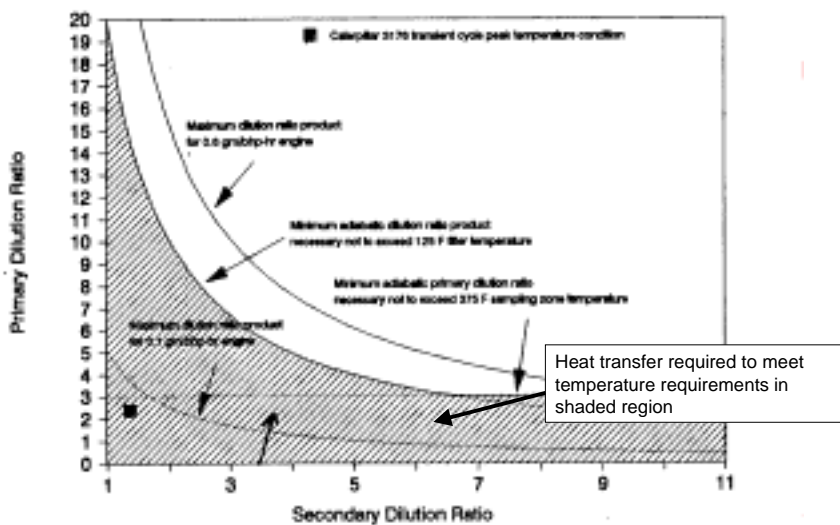
These are the minimum dilution ratios required not to exceed temperature limits in adiabatic dilution. They may be higher if the sample loses heat during dilution.

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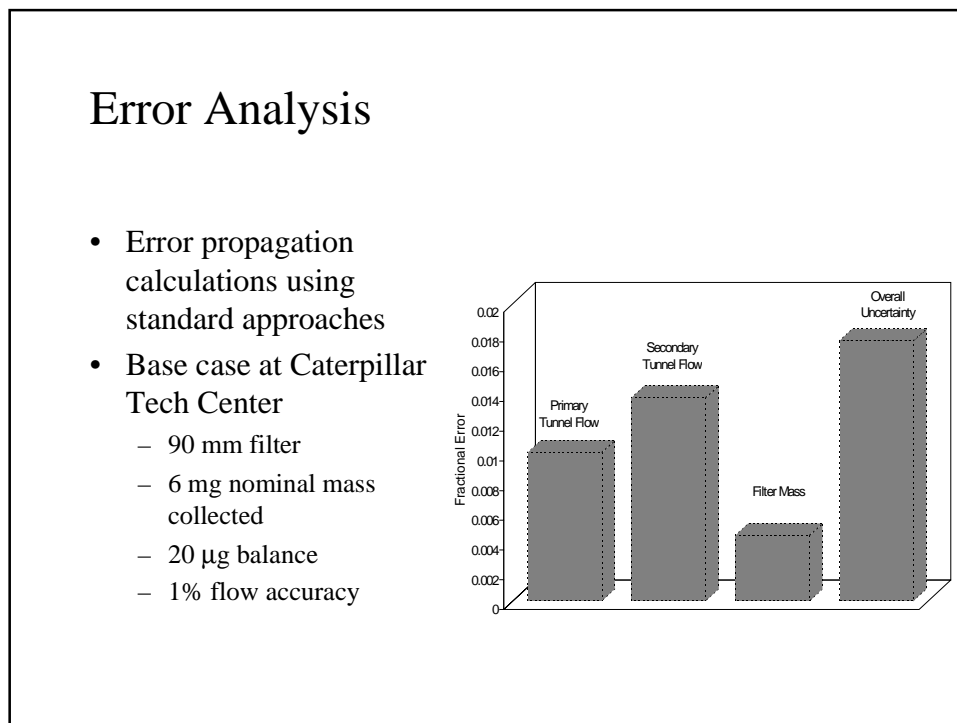
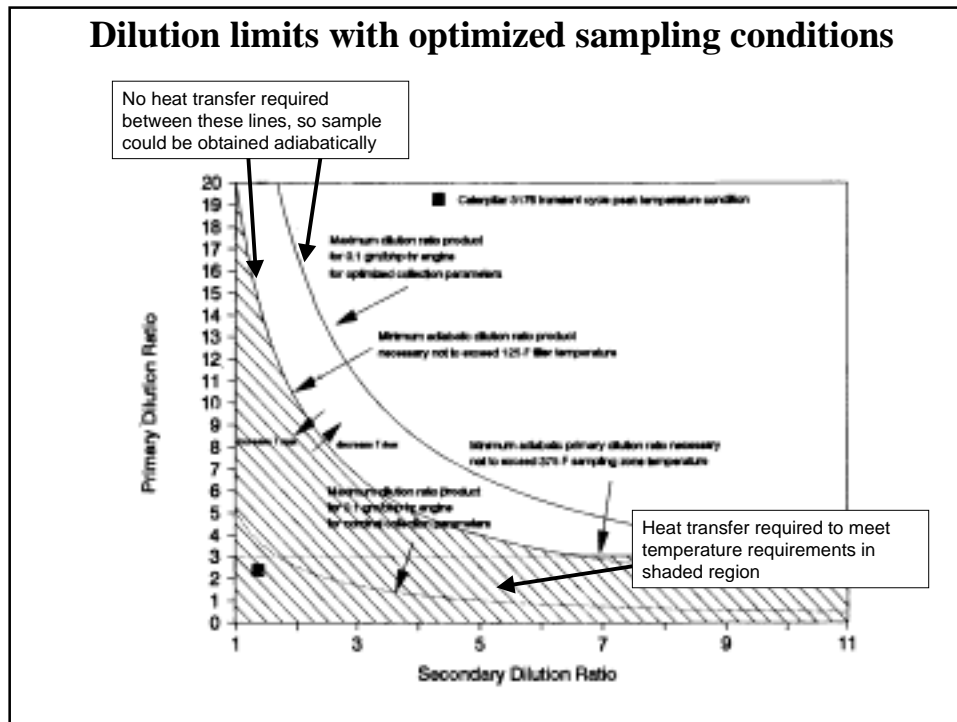
Dilution ratio limits - The following plots show dilution ratio limits imposed by both sampling temperature and mass collection requirements

- The first plot is for typical sampling conditions
 - 5.3 mg filter mass
 - 70 mm filter
 - 50 cm/s face velocity
 - A great deal of heat transfer would be required to avoid exceeding temperature limits for the low emission engine - leads to thermophoretic deposition
- The second is for optimized sampling conditions
 - 2.0 mg filter mass
 - 90 mm filter
 - 50 cm/s face velocity
 - Temperature requirements easily met without significant heat transfer

Dilution limits with typical sampling conditions



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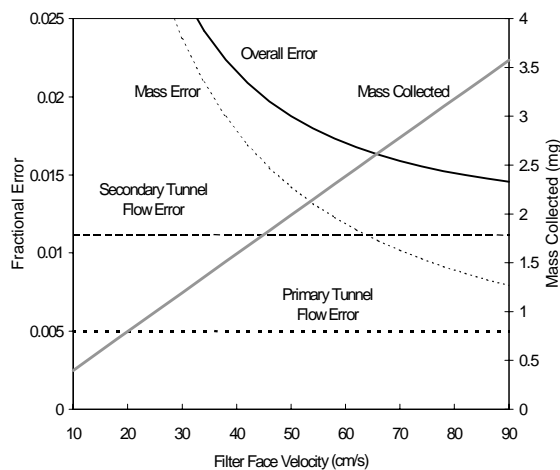


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Error Analysis

Sampling optimized for low uncertainty

- Low emission engine, EI = 0.06 gm/bhp-hr
- Conditions
 - 2000 CFM primary tunnel flow
 - Secondary dilution ratio 2
 - 0.5% flow accuracy
 - 20 mg mass uncertainty



Particle Mechanics and Variability

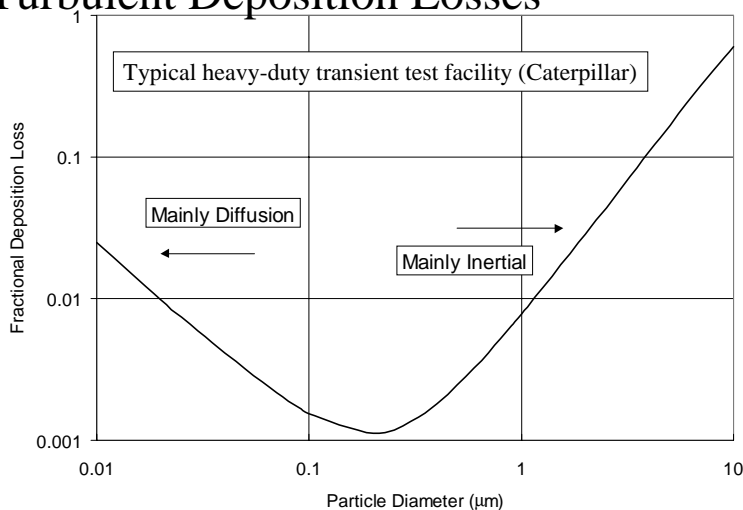
- Much of variability not associated with traditional propagation of error
- Deposition / reentrainment - wall interactions
 - Mechanical
 - Phoretic
 - Electrostatic
- Sampling dynamics - homogeneous
 - Nucleation
 - Absorption / adsorption
 - Coagulation
- Filter related gas to particle conversion

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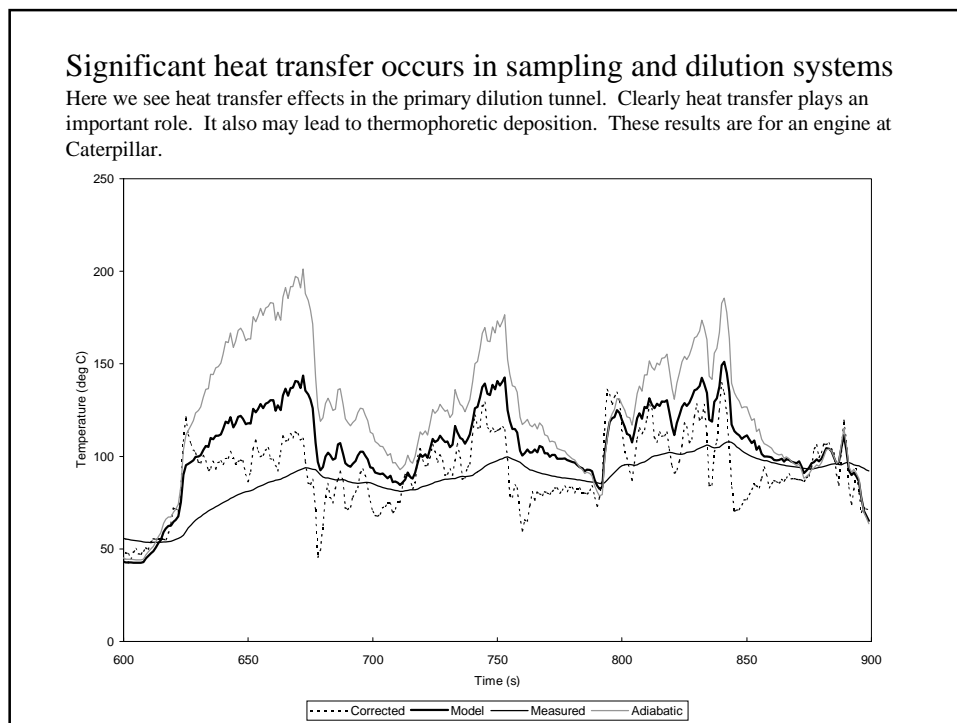
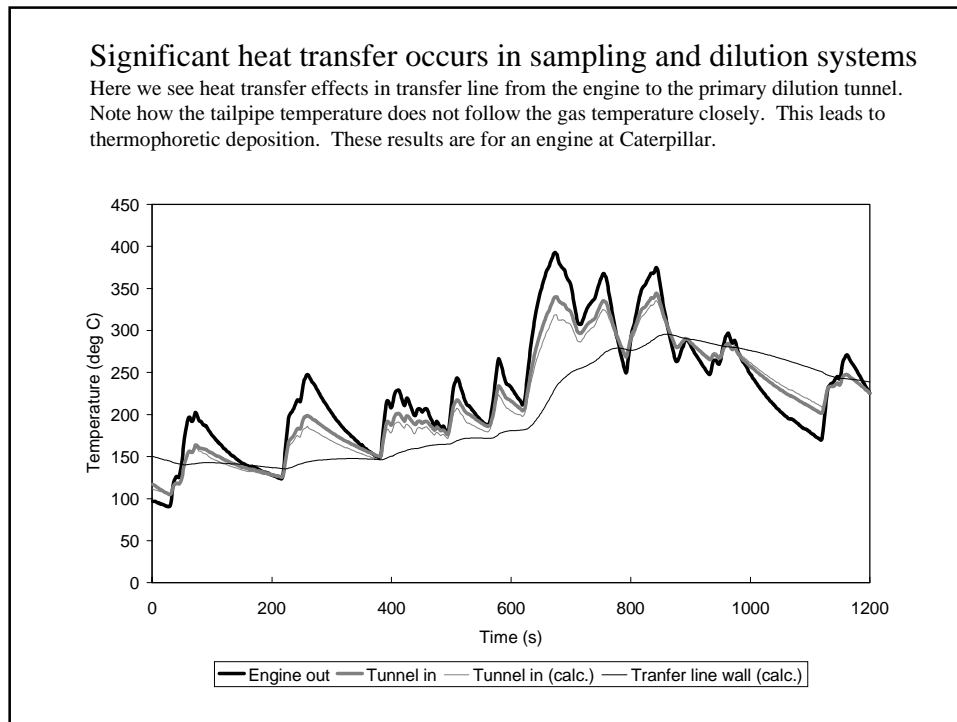
Sampling Problems - Wall Interactions

- Losses
 - Thermophoresis
 - Inertial
 - Diffusion
 - Particles
 - Particle precursors
- Additions
 - Reentrainment
 - Outgassing

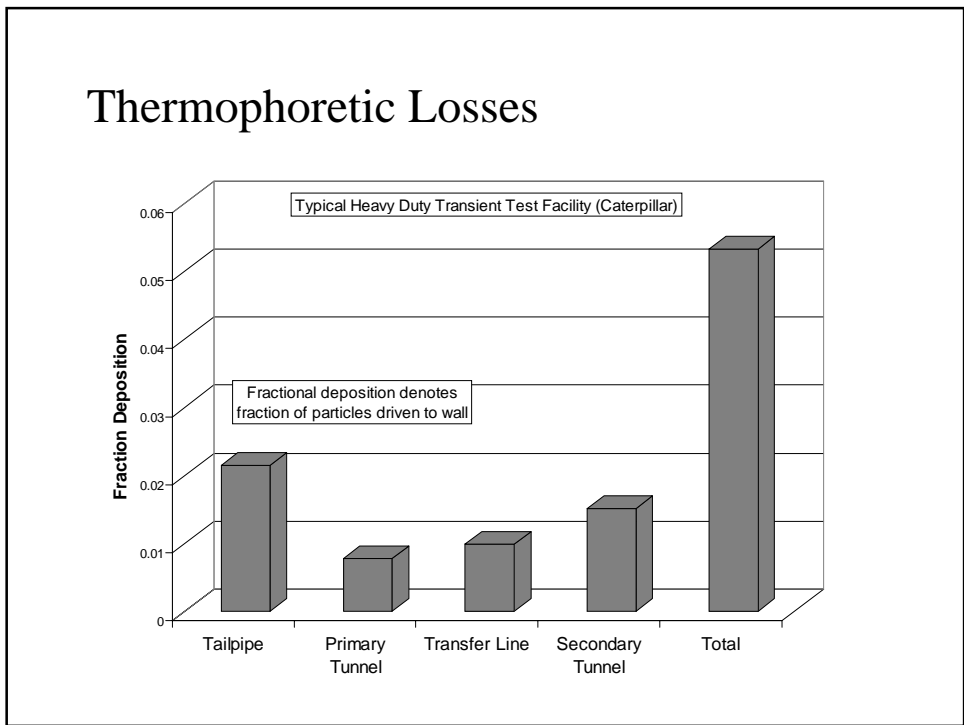
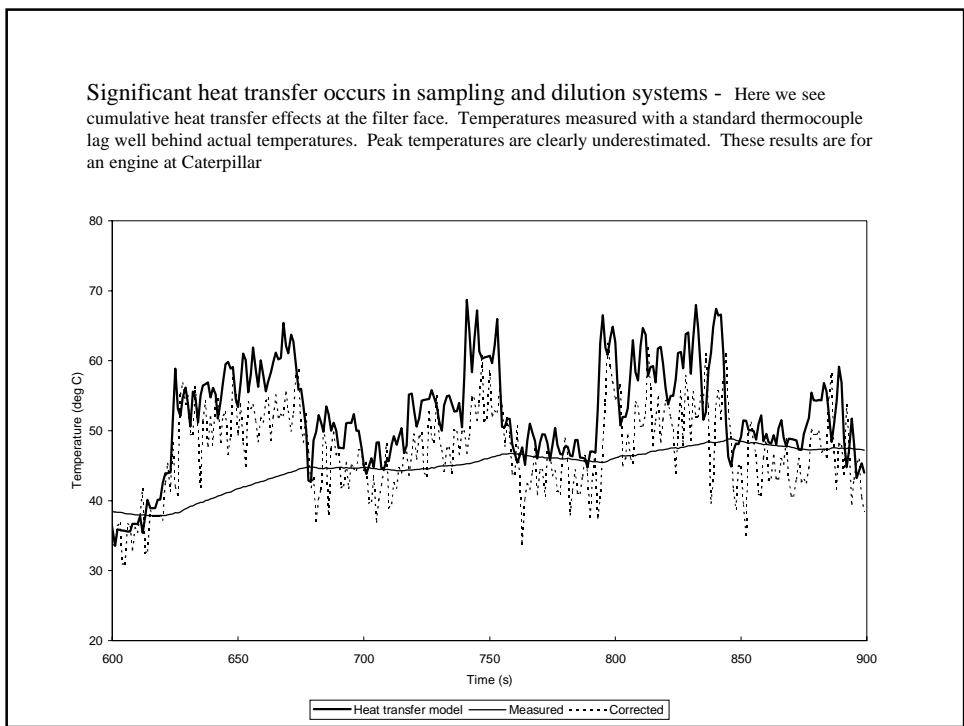
Inertial, Settling, Diffusion, and Turbulent Deposition Losses



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Sampling Problems - Homogeneous

Processes sensitive to correct simulation of
atmospheric dilution

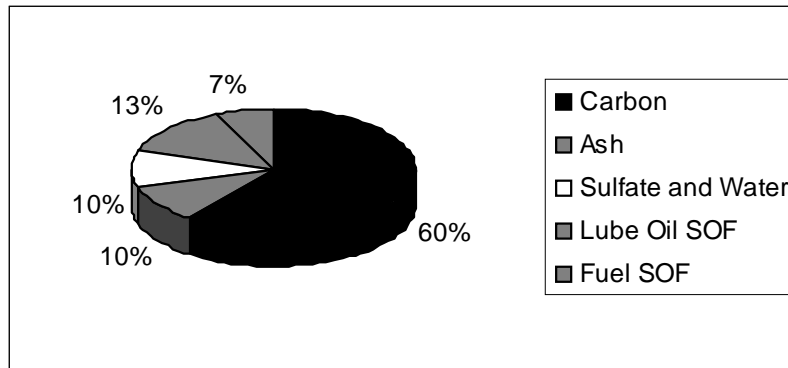
- Gas to particle conversion
 - Nucleation
 - Adsorption / condensation
- Coagulation

Significant Gas to Particle Conversion Takes Place as the Exhaust Dilutes and Cools

- More than 90% of the particle number may form through homogeneous nucleation of nanoparticles
- From 5 to more than 50% of the particle mass may form through adsorption, absorption, and nucleation
- These processes are very sensitive to dilution conditions

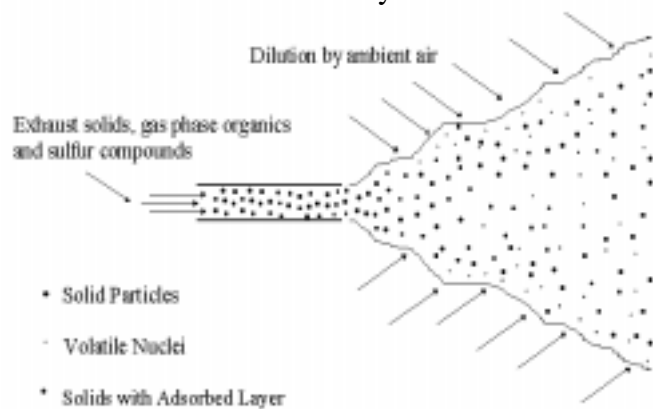
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Typical Composition of Diesel Particulate Matter: Lube oil contributes to SOF, ash, sulfate



Atmospheric Dilution Leads to Nucleation, Absorption, and Adsorption

A dilution ratio of 1000 may be reached in 1 - 2 s



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Influence of Dilution and Cooling on Volatile (extractable) Materials

The saturation ratio, S , is defined as:

$$S = \frac{p}{p_v}$$

where p is the partial pressure and p_v is the vapor pressure of the volatile component. The dilution ratio, D , is defined as:

$$D = \frac{Q_{mix}}{Q_{exh}}$$

where Q_{mix} and Q_{exh} refer to the standard volumetric flows of diluted and raw exhaust, respectively. Also:

$$p \propto \frac{1}{D}$$

and

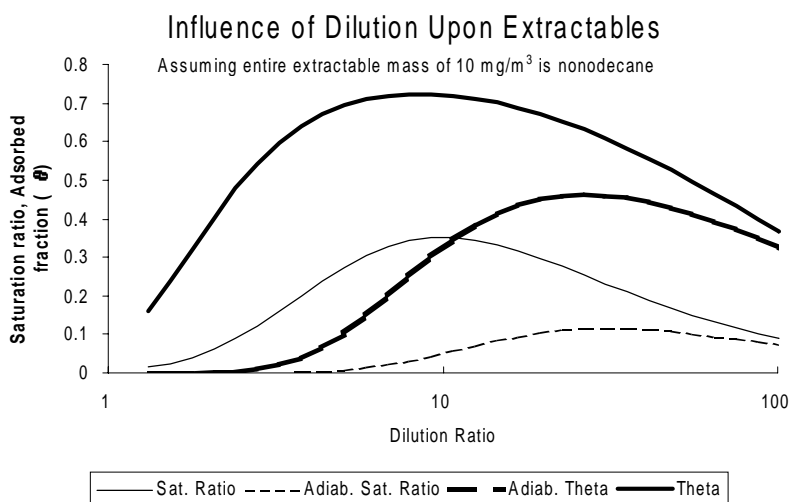
$$p_v \propto e^{\frac{-\Delta H}{RT_{mix}}}$$

so that

$$S \propto \frac{1}{De^{\frac{-\Delta H}{RT_{mix}}}}$$

and for adiabatic dilution.

Driving Force for Nucleation, Condensation, and Adsorption



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Driving Force for Adsorption, Absorption, Nucleation

- 10 mg/m³ nonodecane, SOF mass assumed. This is as much as 5 times higher than some modern engines
- Even this gives a maximum saturation ratio of about 0.3, far too low for homogeneous nucleation
- However significant adsorption may occur. A simple Langmuir model predicts up to 70 monolayer filling, θ .
- Absorption may also occur if an absorbing medium is present.

Binary Nucleation of H₂SO₄-H₂O - Empirical Prediction of Nucleation Threshold

- An extreme dependence of the nucleation rate upon temperature, H₂SO₄, and H₂O concentrations makes theoretical predictions of nucleation difficult.
- Seinfeld and Pandis give an empirical expression to predict the onset of nucleation in this system:

$$C_{crit} = 0.16 \exp(0.1T - 3.5RH - 27.7)$$

where C_{crit} is the threshold H₂SO₄ concentration in $\mu\text{g}/\text{m}^3$, T is temperature, RH is relative humidity (0 to 1).

- I have used this expression and mass and energy balances applied to the dilution process to predict the ratio of the actual H₂SO₄ concentration to the critical one, C/C_{crit} . When this ratio exceeds one, nucleation is likely.

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Binary Nucleation of H_2SO_4 - H_2O - Empirical Prediction of Nucleation Threshold

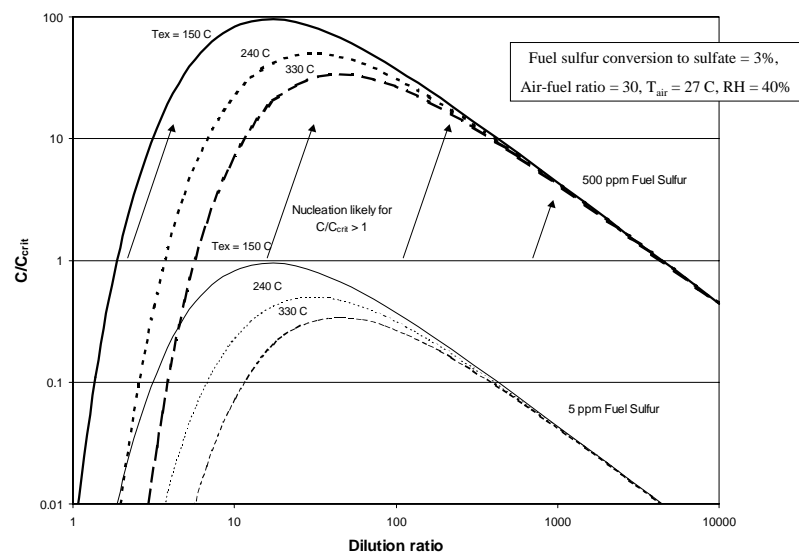
- An extreme dependence of the nucleation rate upon temperature, H_2SO_4 , and H_2O concentrations makes theoretical predictions of nucleation difficult.
- Seinfeld and Pandis give an empirical expression to predict the onset of nucleation in this system:

$$C_{crit} = 0.16 \exp(0.1T - 3.5RH - 27.7)$$

where C_{crit} is the threshold H_2SO_4 concentration in $\mu g/m^3$, T is temperature, RH is relative humidity (0 to 1).

- I have used this expression and mass and energy balances applied to the dilution process to predict the ratio of the actual H_2SO_4 concentration to the critical one, C/C_{crit} . When this ratio exceeds one, nucleation is likely.

Influence of Fuel and Exhaust Conditions on Sulfuric Acid Nucleation



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Suppression of Nucleation by Existing Particles

- The presence of adsorbing or absorbing particles may significantly suppress nucleation
- The effectiveness of existing particles in suppressing nucleation depends upon relative rates of vapor adsorption and dilution
- The rate of collision of vapor phase molecules, Z , with particle surface in the free molecular regime is given by:

$$Z = \left(\frac{RT}{2\pi M} \right)^{0.5} A_p N$$

where R is the gas constant, T is temperature, M is molecular mass, A_p is the particle surface area concentration, and N is the concentration of molecules.

Dimensionless Adsorption Rate

- From the expression for Z the time constant for molecular adsorption becomes:

$$\tau_a = 1 / \left(\left(\frac{RT}{2\pi M} \right)^{0.5} A_p \right)$$

- If the variation of dilution ratio with time can be described as:

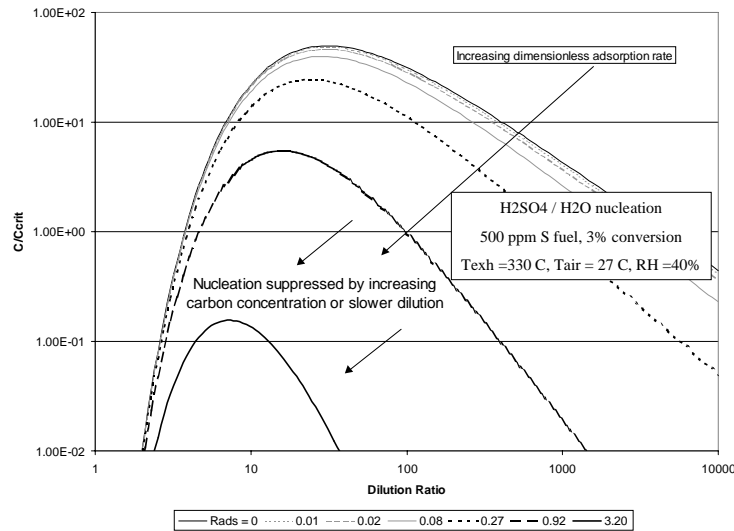
$$D = 1 + t / \tau_d$$

- A dimensionless adsorption rate can be defined as:

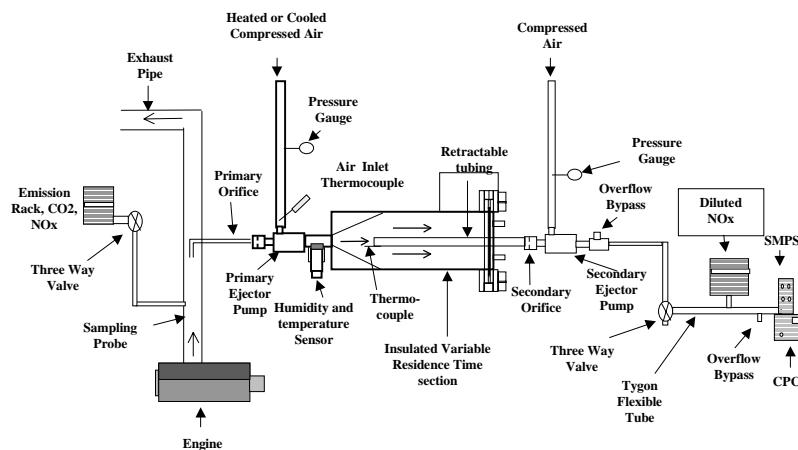
$$R_{ads} = \tau_d / \tau_a$$

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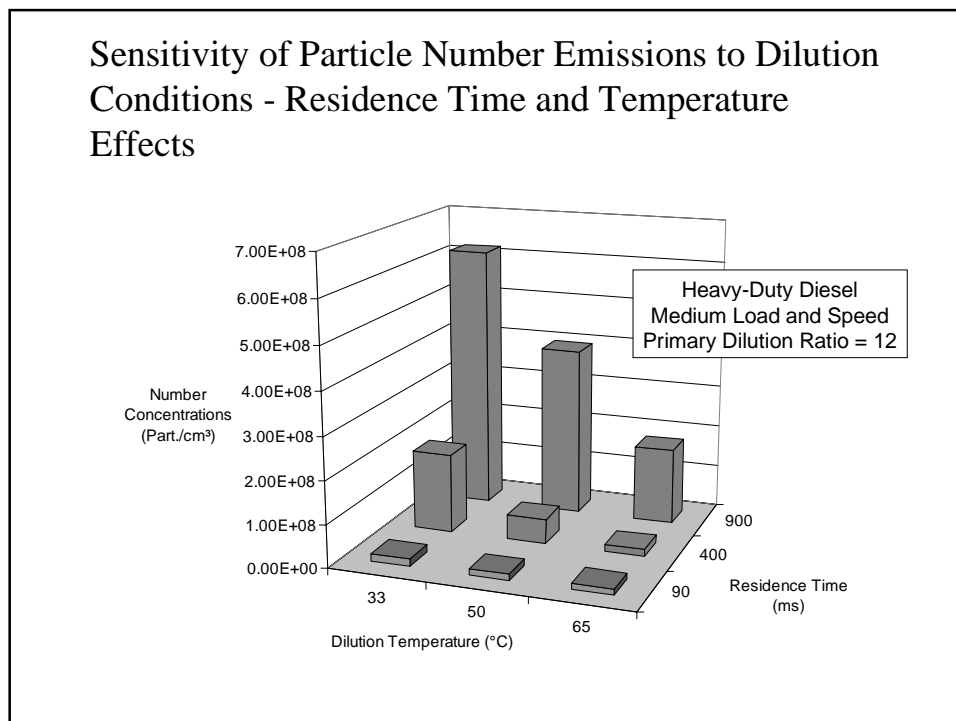
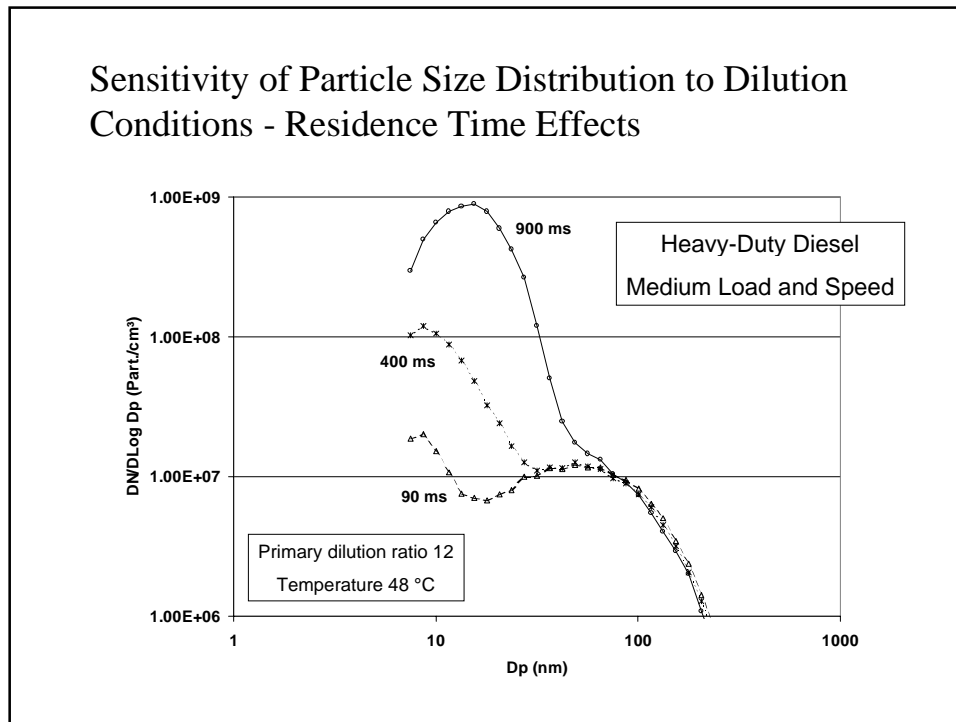
Influence of Dimensionless Adsorption Rate, R_{ads} , on H_2SO_4 Nucleation



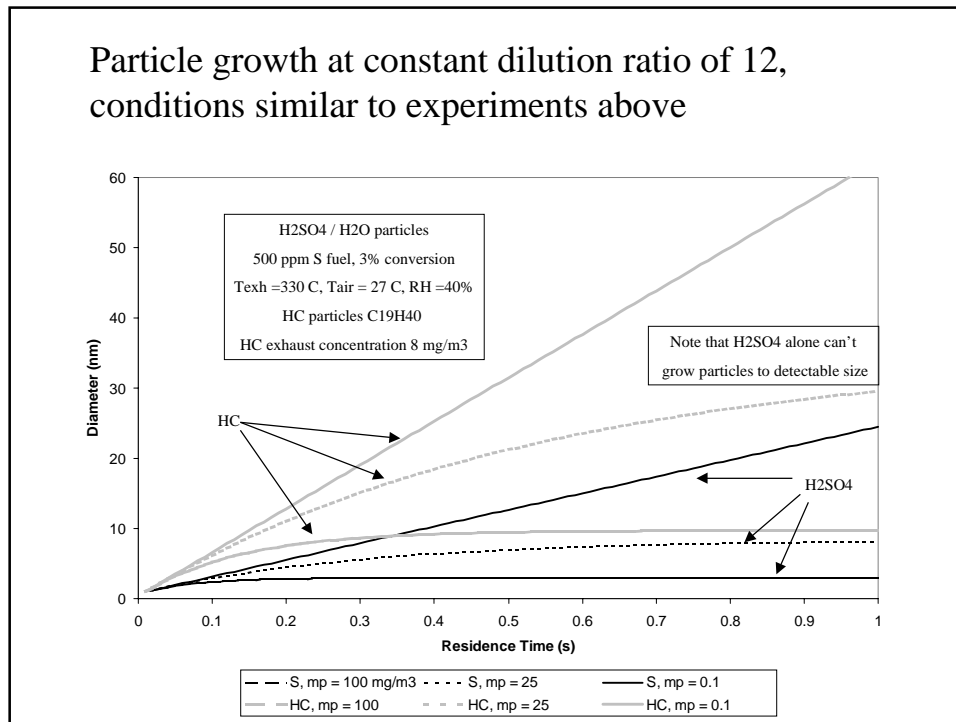
Studies of Nanoparticle Formation Using a Variable Residence Time Dilution System



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Nanoparticle Nucleation and Growth

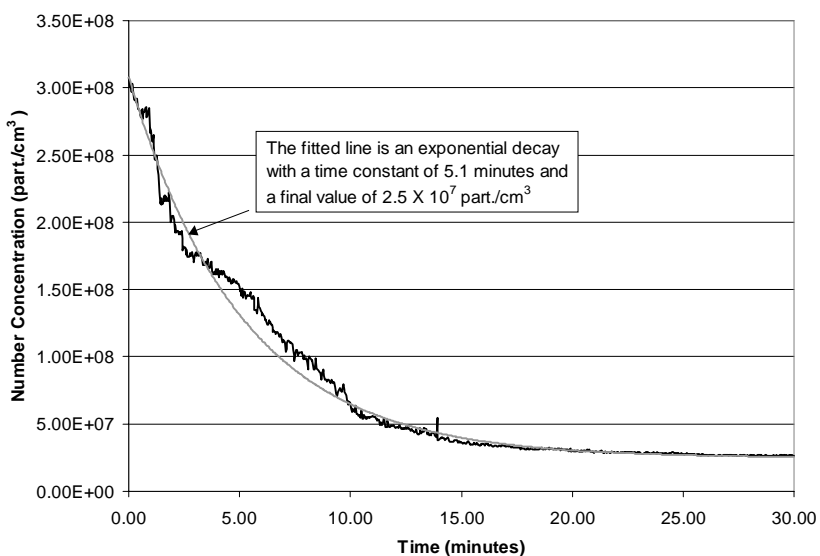
- It appears that with current engines binary sulfuric acid - water nucleation triggers the process.
- The initial size of these nuclei is about 1 nm.
- In most cases there is not enough sulfuric acid present in the exhaust to explain the observed rates of particle growth.
- Hydrocarbons normally associated with the soluble organic fraction apparently are absorbed by the concentrated sulfuric acid nuclei leading to the observed growth rates.

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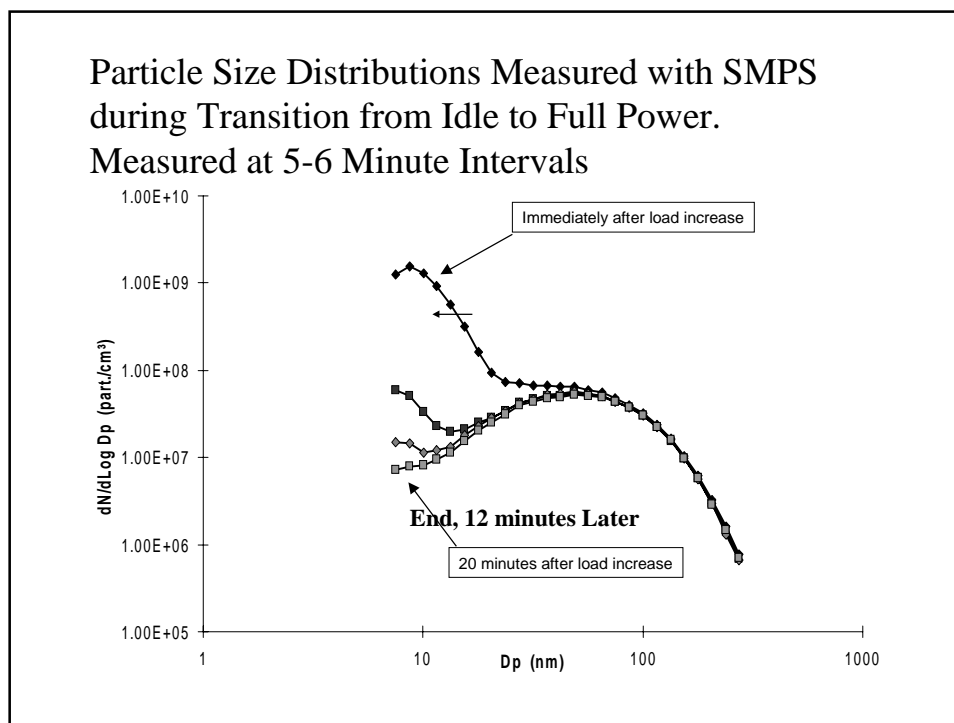
Transient Behavior

- Storage and release of volatile particle precursors
 - Stored on exhaust system and transfer line surfaces
 - Stored on dilution and sampling system surfaces
 - Released from inappropriate materials in sampling system (elastomers)
- Transient stabilization of oil consumption

Transient Number Concentration Measured with CPC after Transition from Idle to Full Power



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Coagulation Effects

- Particle-particle collisions may dramatically reduce the number concentration but conserve mass
- Collisions between nuclei mode particles and accumulation mode particle causes the small particles to lose their identity
- Coagulation is an issue in the sampling and dilution system and in the atmosphere

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Aerosol Coagulation

For a continuous particle size distribution function, the rate of change of number concentration, n , of particles of volume, v , is given by:

$$\frac{\partial n}{\partial t} = \frac{1}{2} \int_0^v \beta(v, v-\tilde{v})n(\tilde{v})n(v-\tilde{v})d\tilde{v} - \int_0^\infty \beta(v, \tilde{v})n(v)n(\tilde{v})d\tilde{v}$$

where $\beta(v, \tilde{v})$ is the collision frequency between particles of volume v and \tilde{v} . For nearly monodisperse systems this simplifies to:

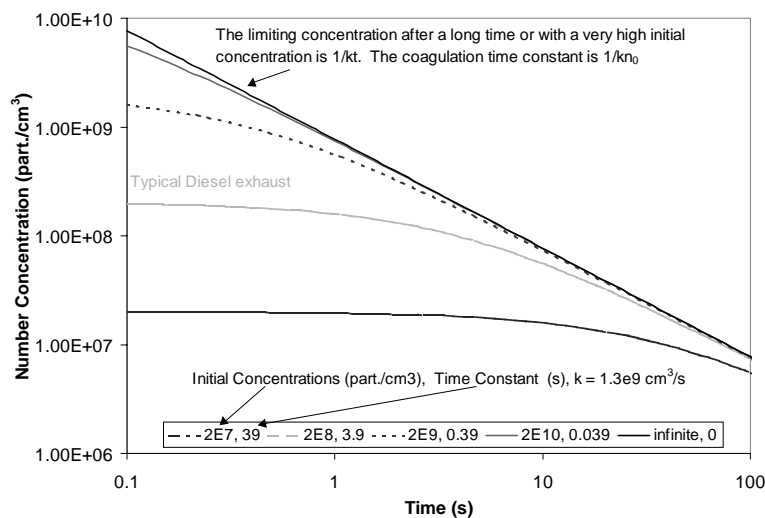
$$\frac{dn}{dt} = -kn^2$$

where k is the coagulation constant. If k is essentially constant this may be integrated to give:

$$\frac{n}{n_0} = \frac{1}{1 + kn_0 t} = \frac{1}{1 + t/\tau}$$

where n_0 is the initial concentration and, $\tau = 1/kn_0$, is the coagulation time constant. For modern diesel particles k is in the range of $1.3 \times 10^9 \text{ cm}^3 \text{ s}^{-1}$ and n_0 in the raw exhaust may range from 10^7 to $2 \times 10^9 \text{ part. cm}^{-3}$. This gives times for reducing the particle number concentration by a factor of 2 ranging from 0.4 to 80 s in the raw exhaust.

Particle Number Loss by Coagulation



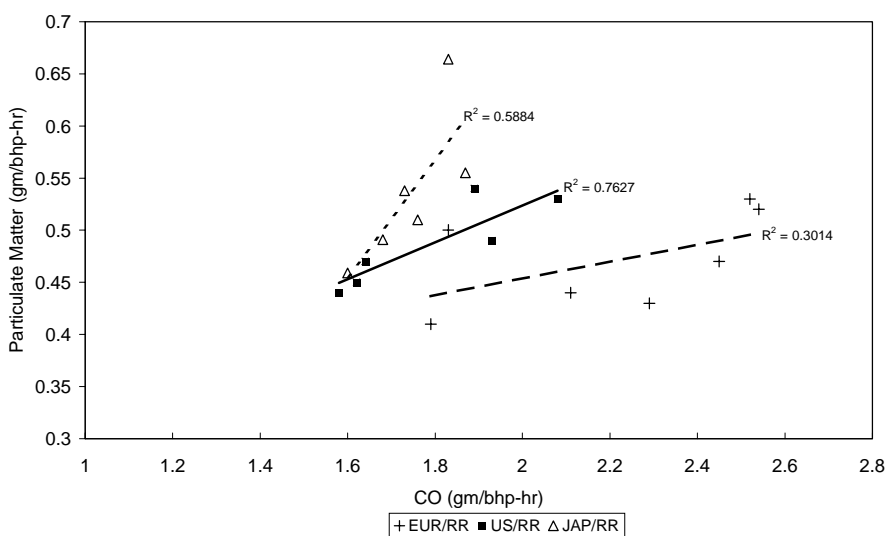
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Other factors influencing variability

- Cycle Matching
- Tunnel and Sampling System Design
- Combustion and Dilution Air Conditioning
- Filtration Errors
 - Area and Face Velocity
 - Weighing and Handling
 - Conditioning
 - Media
- Engine and Tunnel Conditioning

Emissions of PM and CO are often closely linked. Both respond to small changes in accuracy of following transient cycle.

ROUND ROBIN STUDIES OF CROSS VARIABILITY



Recommendations - mass measurements

- Sample dilution and collection system should be designed to avoid deposition/reentrainment
 - Avoid long sample lines and bends
 - Minimize heat transfer in sample lines
 - Sample line conditioning may be helpful
- Dilution and cooling should simulate atmosphere as closely as possible
 - Dilution ratio control
 - Sample temperature control
- Sample and dilution air flows must be carefully measured ($\pm 0.5\%$)

Recommendations - mass measurements, continued

- Combustion and dilution air conditioning
- Combustion air humidity and temperature
- Dilution air filtration, temperature, scrubbing
- Filter conditioning and handling
 - Static control
 - 90 mm, 70 cm/s, 2 mg
 - 22 ± 2 °C, $50 \pm 4\%$ RH
 - 2 - 6 hr conditioning time
- Condition tunnel and sampling system to engine

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Conclusions - 1

- Although only particle mass emissions are currently regulated, recently attention has focused on emissions of nanometer size particles.
- Although they have only recently attracted attention, nanoparticles have been measured over roadways for many years.
- The most difficult problem associated with the characterization of submicron diesel particulate matter is the design of the dilution and sampling system, not the choice of appropriate instruments.

Conclusions - 2

- A significant amount of particulate matter (e.g. 90 % of the number and 30% of the mass) is formed during exhaust dilution from material present in the vapor phase in the tailpipe (e.g., sulfuric acid, fuel and oil residues).
 - New particles are formed by nucleation. This is likely to be the source of most of the ultrafine and nanoparticles (and particle number) associated with engine exhaust.
 - Preexisting particles grow by adsorption or condensation.
 - Nucleation and adsorption are competing processes. Soot agglomerates provide a large surface area for adsorption that suppresses nucleation. Thus, diesel engines with low soot mass emissions, may have high number emissions.

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Conclusions - 3

- Nucleation and adsorption depend on dilution rate, (or residence time at intermediate dilution ratio), humidity, temperature, and relative concentrations of carbon and volatile matter.
 - Changes of more than two orders of magnitude in nanoparticle concentration may occur as dilution conditions are varied over the range that might be expected for normal ambient dilution, e.g., 0.1 to 2 s dilution time scales.
 - Even larger changes may occur downstream of exhaust filters or with very clean engines where exhaust carbon concentrations are low
- Coagulation may dramatically reduce number concentrations if exhaust is not diluted rapidly.
- Sampling systems should mimic atmospheric dilution to obtain sample streams representative of human exposure for size analysis.

Conclusions - 4

- Currently most of the particles in the nanoparticle size range are volatile. However, as engines become cleaner, metallic ash particles from the lubricating oil (or fuel if metallic additives are present) may become more important.
- Spark ignition engines typically emit smaller particles than diesel engines and are an important source of fine particles and nanoparticles.
 - A recent study in Colorado concluded that up to 2/3 of the fine particle mass emitted by vehicles was from spark ignition engines
 - New gasoline direct injection engines emit much higher particle concentrations than conventional engines and may approach diesel levels under some conditions

Note: this document contains most of the overheads that he presented
at the meeting on the 10/13.

Measurement of Exhaust Particulate Matter

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AAAR Tutorial, 11 October, 1999

Reference materials:

I have attached a file with most of my slides. I have also listed some of our recent publications below.

Abdul-Khalek, I., D.B. Kittelson, and F. Brear (Perkins). 1999. “The Influence of Dilution Conditions on Diesel Exhaust Particle Size Distribution Measurements,” International Congress and Exposition, Detroit, MI, March 1-4, 1999, SAE Paper No. 1999-01-1142.

Graskow, B.R., D.B. Kittelson (U of MN), M.R.Ahmadi, and J.E. Morris (Chevron). 1999. “Exhaust Particulate Emissions from Two Port Fuel Injected Spark Ignition Engines,” International Congress and Exposition, Detroit, MI, March 1-4, 1999, SAE Paper No. 1999-01-1144.

Graskow, B.R., D.B. Kittelson (U of MN), M.R.Ahmadi, and J.E. Morris (Chevron). 1999. “Exhaust Particulate Emissions from a Direct Injection Spark Ignition Engine,” International Congress and Exposition, Detroit, MI, March 1-4, 1999, SAE Paper No. 1999-01-1145.

Kittelson, D.B. 1998. “ENGINE AND NANOPARTICLES: A REVIEW,” J. Aerosol Sci., Vol. 29, No. 5/6, pp. 575-588, 1998

Note: this document contains most of the overheads that he presented
at the meeting on the 10/13.

Abdul-Khalek, I.S., D.B. Kittelson (U of MN), F. Brear (Perkins). 1998. “Diesel Trap Performance: Particle Size Measurements and Trends,” SAE Paper No. 982599, SAE Meeting, San Francisco, October 19-22, 1998.

Abdul-Khalek, I.S., D.B. Kittelson, B.R. Graskow, Q. Wei (U of MN), and F. Brear (Perkins). “Diesel Exhaust Particle Size: Measurement Issues and Trends,” SAE Paper No. 980525 and SP-1326, SAE International Congress & Exposition, Detroit, MI, February 23-26, 1998, also in 1998 Transactions of the Society of Automotive Engineering, Vol. 3, Engine, Fuels and Lubricants, pp. xx-xx.

Graskow, B.R., D.B. Kittelson, I.S. Abdul-Khalek (U of MN), M.R. Ahmadi, and J.E. Morris (Chevron). “Characterization of Exhaust Particulate Emissions from a Spark Ignition Engine,” SAE Paper No. 980528 and SP-1326, SAE International Congress & Exposition, Detroit, MI, February 23-26, 1998, also in 1998 Transactions of the Society of Automotive Engineering, Vol. 3, Engine, Fuels and Lubricants, pp. xx-xx.

Du, C.J. (Generac), J. Kracklauer (Econalytic), and D.B. Kittelson. “The Influence of a Fuel Additive on Diesel Combustion,” SAE Paper No. 980536 and SP-1326, SAE International Congress & Exposition, Detroit, MI, February 23-26, 1998, also in 1998 Transactions of the Society of Automotive Engineering, Vol. 3, Engine, Fuels and Lubricants, pp. xx-xx.

Abu-Qudais, M. and D.B. Kittelson. 1997. “Experimental and Theoretical Study of Particulate Re-entrainment from the Combustion Chamber Walls of a Diesel Engine,” Proc. Instn. Mech. Engrs., Vol. 211, Part D, pp. 49-57.

Johnson, J.E. and D.B. Kittelson. 1996. "Deposition, Diffusion, and Adsorption in the Diesel Oxidation Catalyst," Applied Catalysis B: Environmental 10:117-137.

Johnson, J.E. and D.B. Kittelson. 1994. "Physical Factors Affecting Hydrocarbon Oxidation in a Diesel Oxidation Catalyst," SAE Paper No. 941771, presented at SAE International Off-Highway & Powerplant Congress & Exposition, September 12-14, 1994. Also appears in: Diesel Engines: Fuel Injection, Combustion, Emissions, and Exhaust Aftertreatment (SP-1050), pp. 119-136, 1994 Transactions of the SAE.

Kittelson, D.B. and J.H. Johnson. 1991. "Variability in Particle Emission Measurements in the Heavy-Duty Transient Test," SAE Paper No. 910738. Also in Diesel Particulate Emissions: Measurement Techniques, Fuel Effects and Control Technology (PT-42) pp. 137-162, Edited by: J.H. Johnson, T.M. Baines and J.C. Clerc, published by SAE, Inc., Warrendale, PA, 1991 Transactions of the SAE, Vol. 100, Sec. 3, pp. 1378-1403, 1992.

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