



# Membrane Production of Nitrogen-Enriched Air for Diesel Engine Emissions Reduction

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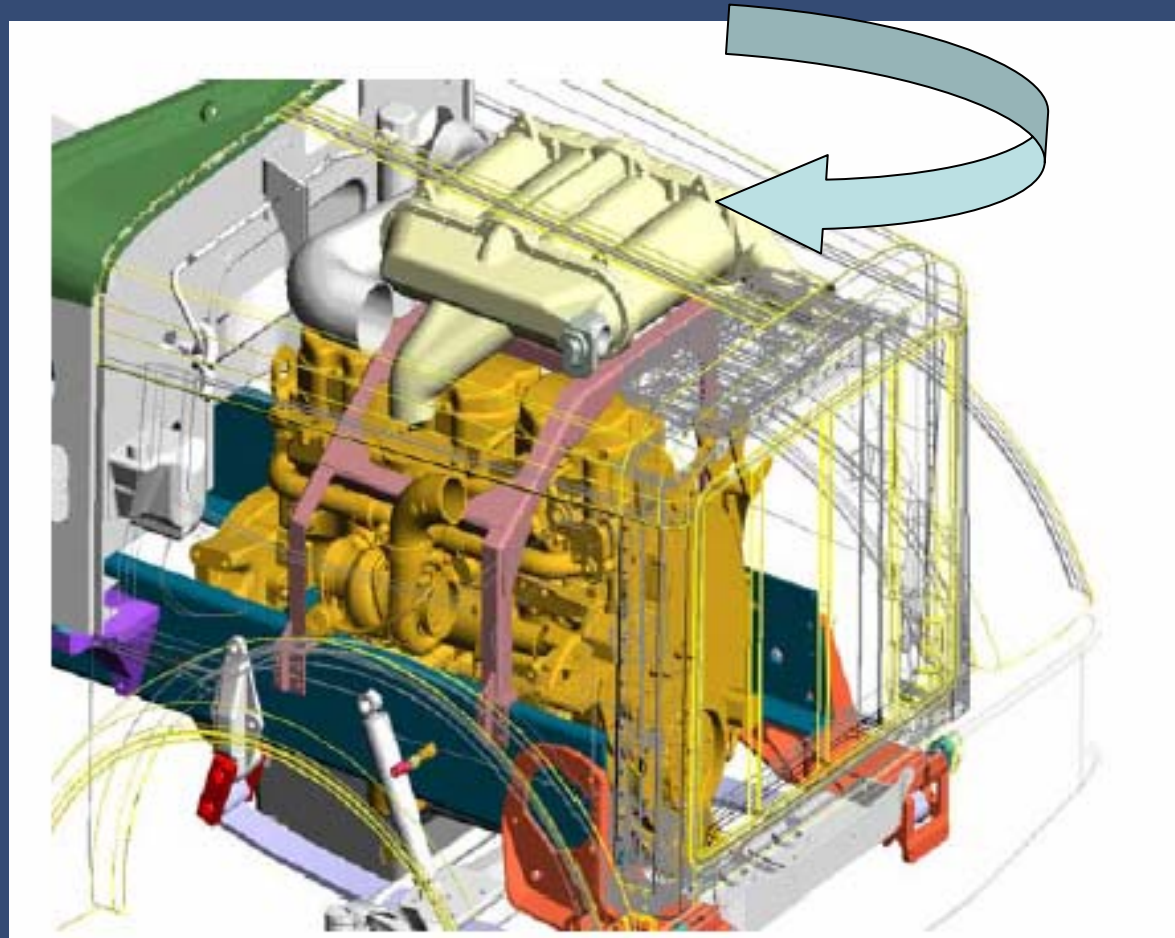
# NOx Emissions Reduction

- NOx, oxides of nitrogen, formed during combustion
- Particularly high temperature combustion
- Reducing combustion temperature reduces NOx
- Dilution of engine cylinder charge with inert gases lowers temperature and thereby reduces NOx
- Possible diluents
  - nitrogen
  - carbon dioxide
  - exhaust gases
  - water vapor or steam

## The CMS approach ...

- Nitrogen Enriched Air (NEA)
- from cooled turbocharged air
- with an air separation membrane
- integrated into the diesel engine and
- preferably on-board diesel powered trucks and mobile equipment

# NEA Membrane in Engine Compartment



# *Air Separation Membranes*

- Gas molecules absorb in polymer skin
- Then diffuses through the membrane
- And desorb from opposite surface
- Migration driven by partial pressure diff.
- Gas species transport at different rates.

**H<sub>2</sub>O, H<sub>2</sub>, He, H<sub>2</sub>S**

**CO<sub>2</sub>, O<sub>2</sub>**

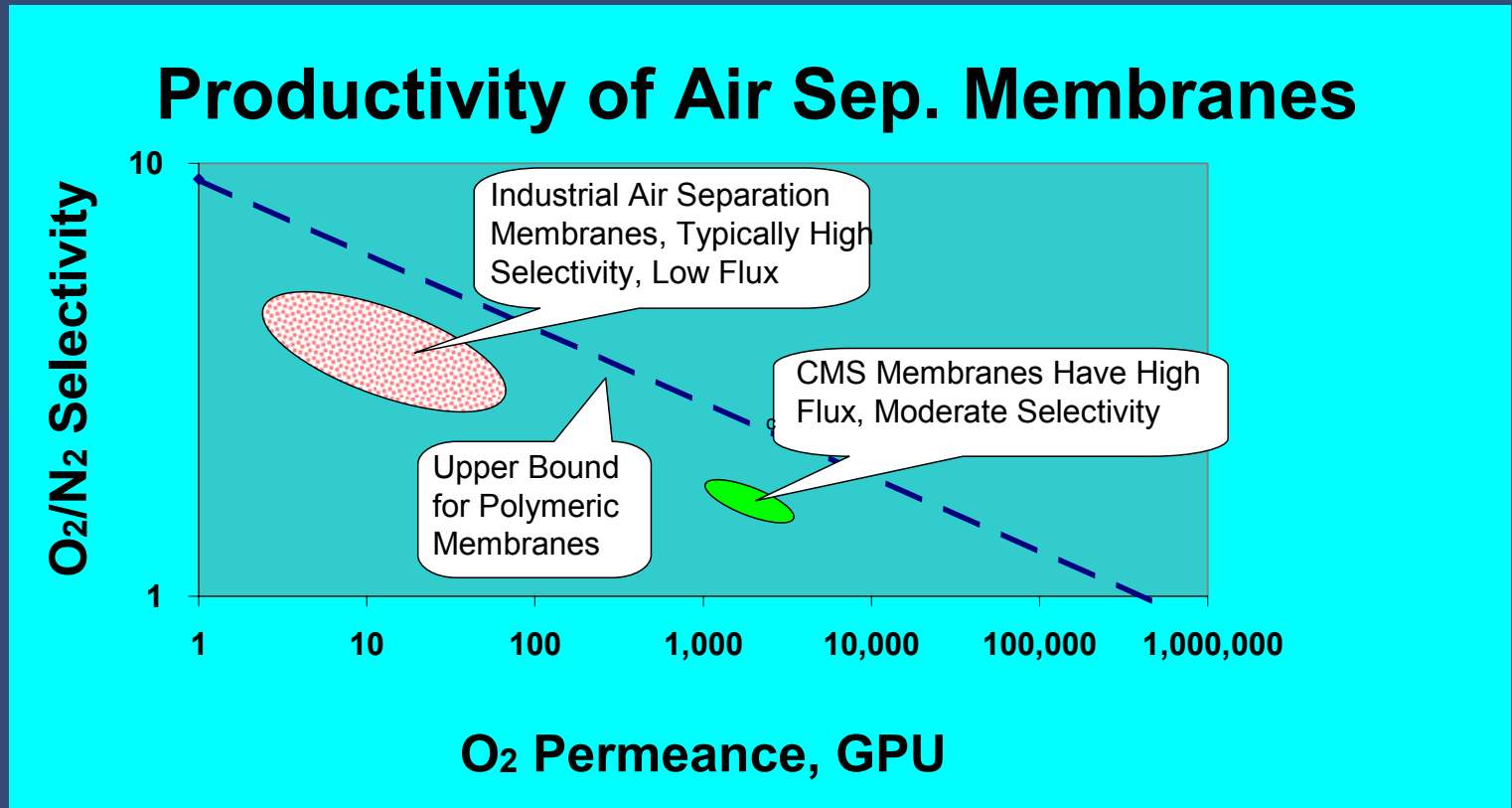
**Ar, CO, N<sub>2</sub>, CH<sub>4</sub>**

**“Fast”**

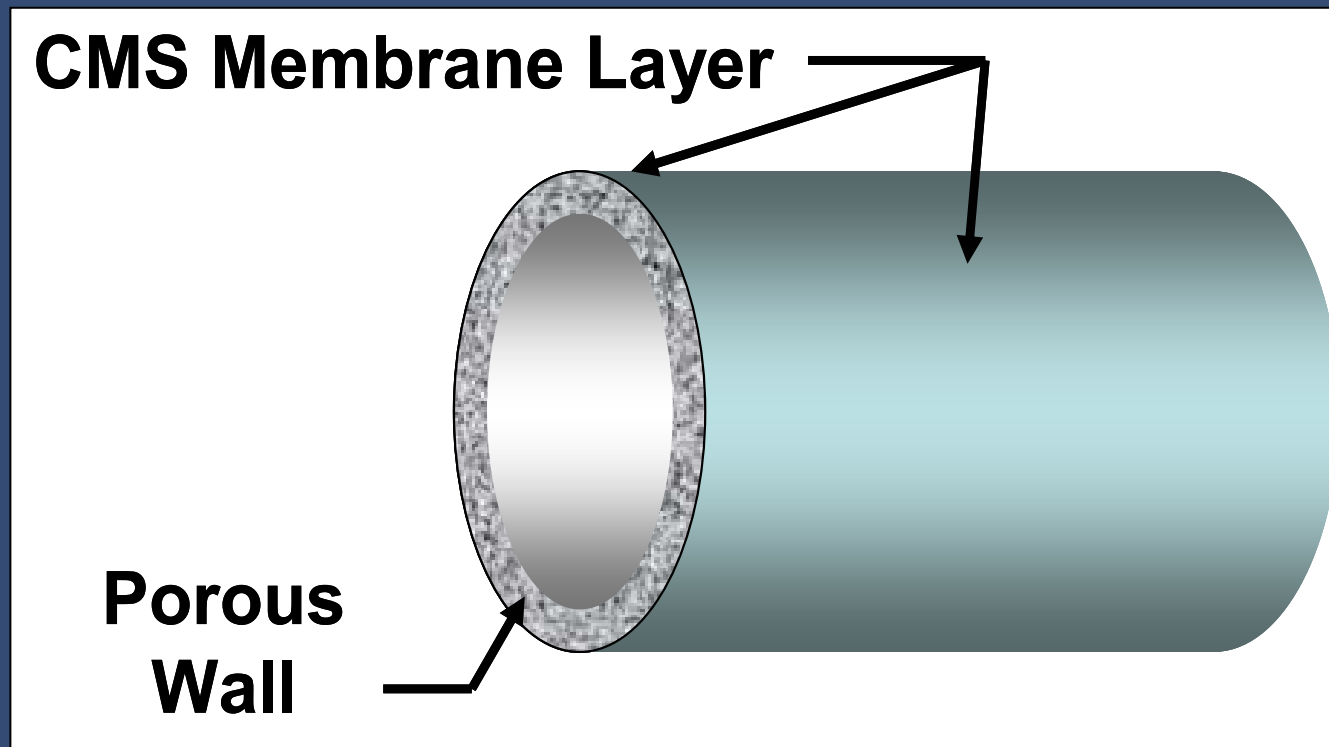
**“Slow”**

Relative Permeation Rates

# Productivity of Polymeric Air Separation Membranes

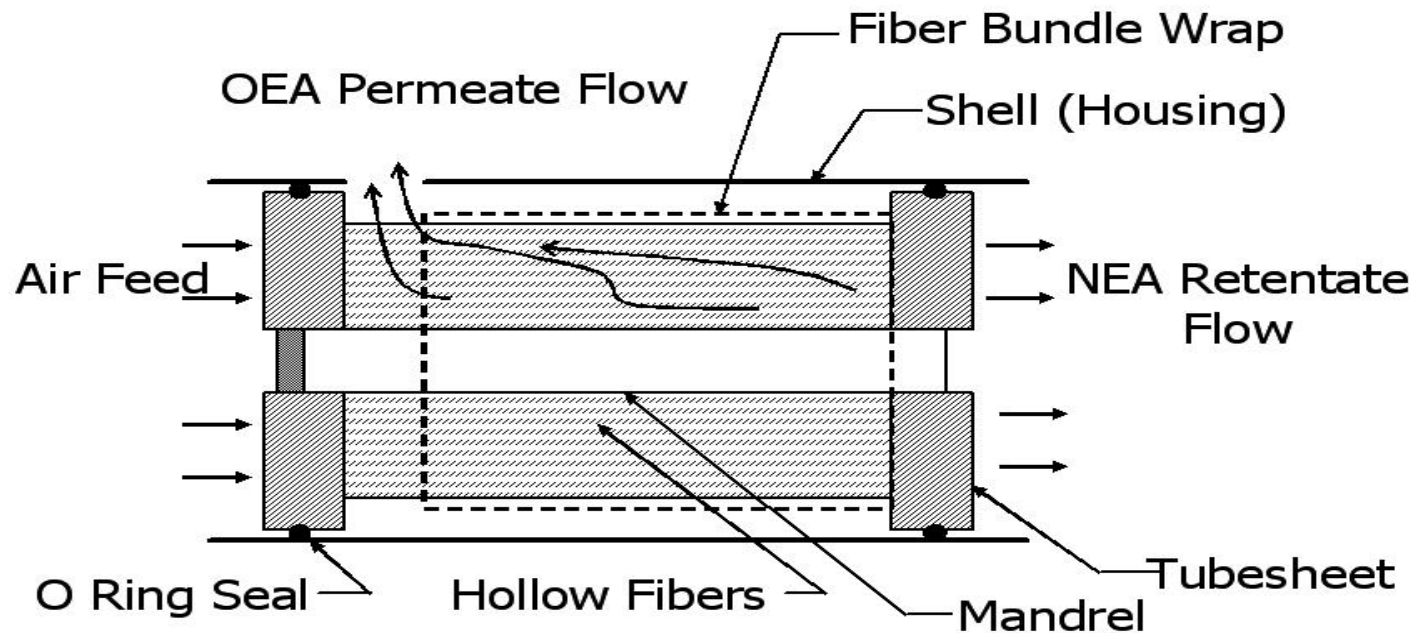


# Hollow Fiber Membrane

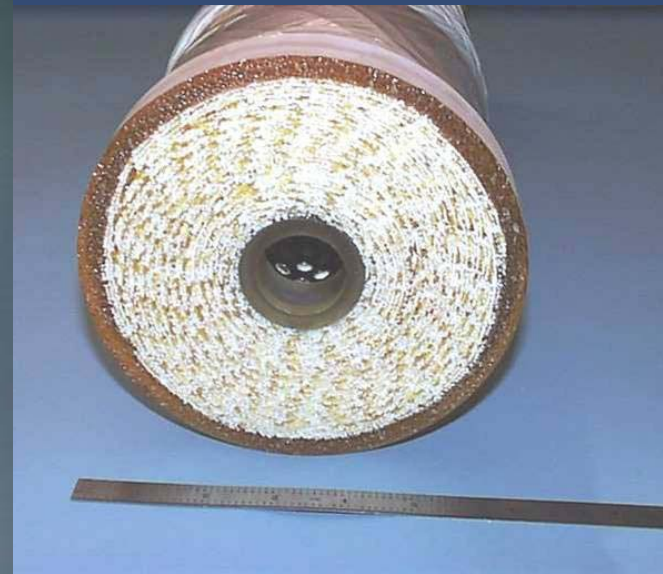


# Membrane Cartridge

## Flow Schematic

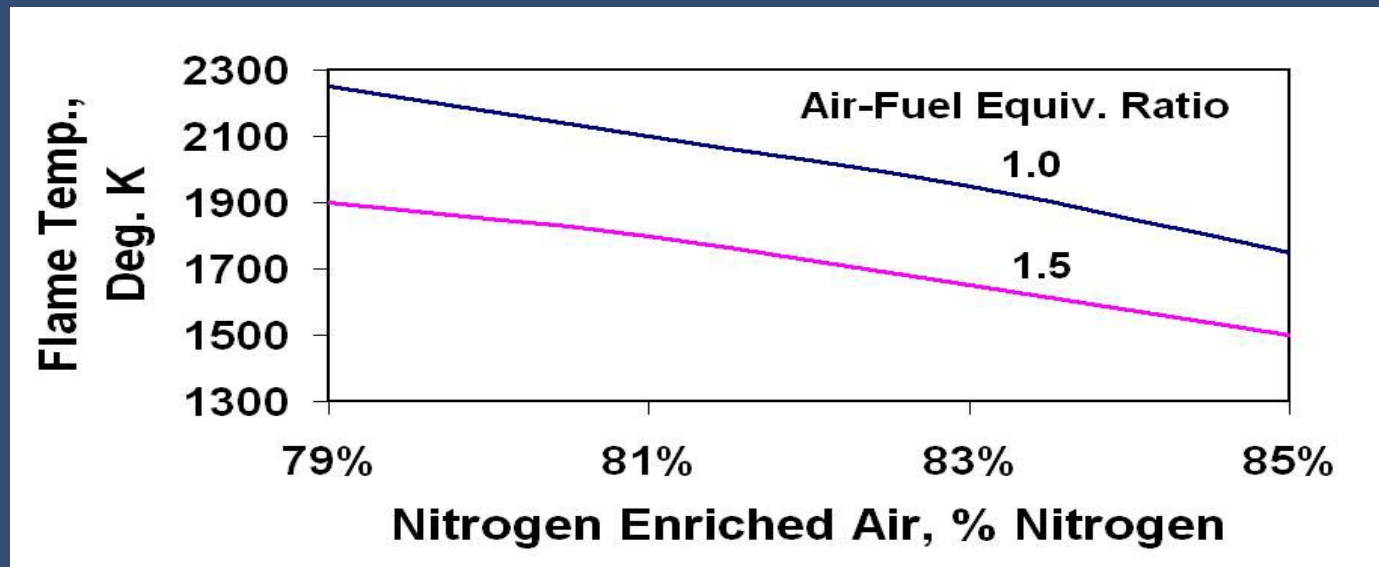


# IMS Hollow Fiber Membrane Cartridge, 6" dia. x 17"

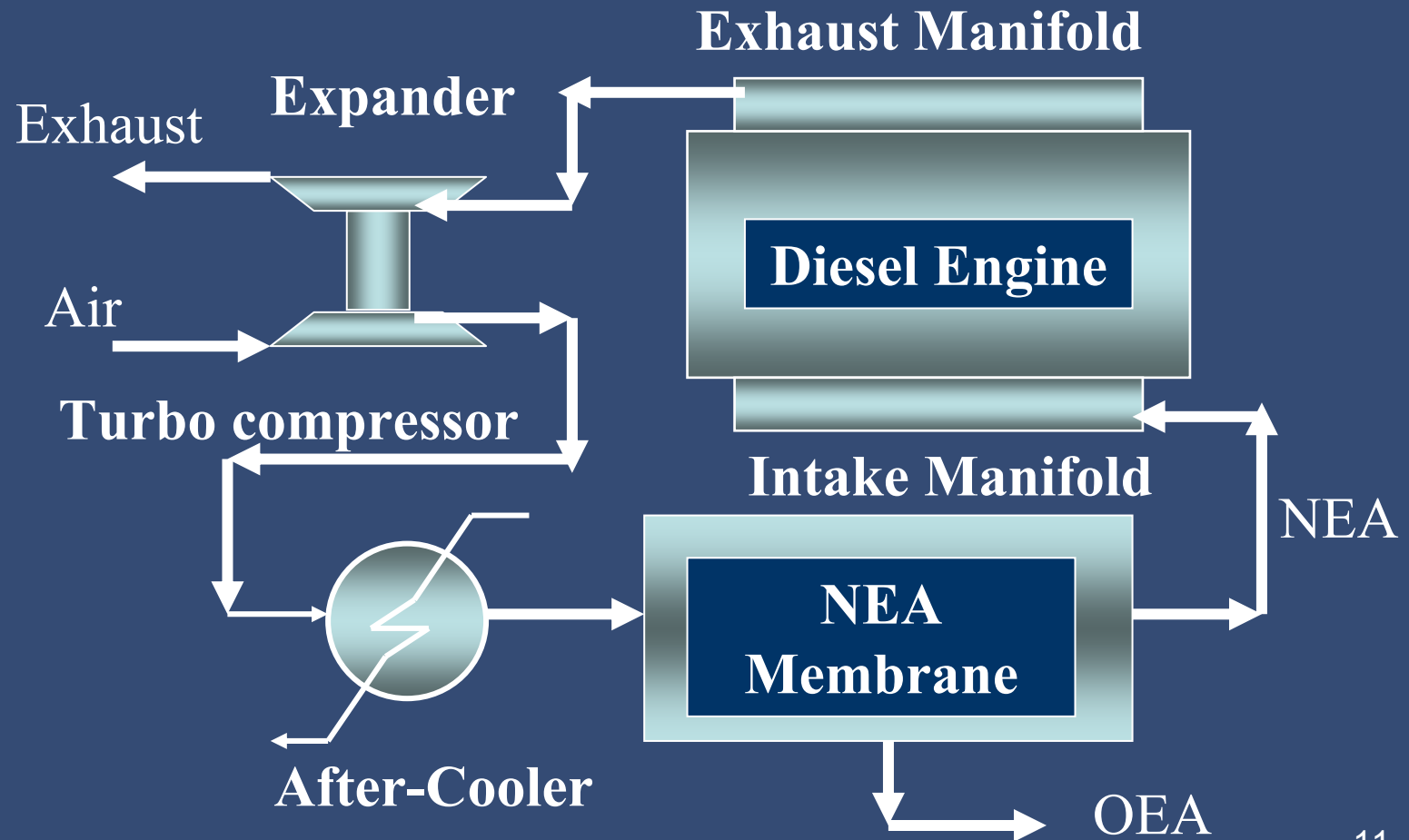


# Lower Flame Temperature Favors Lower NO<sub>x</sub> Formation

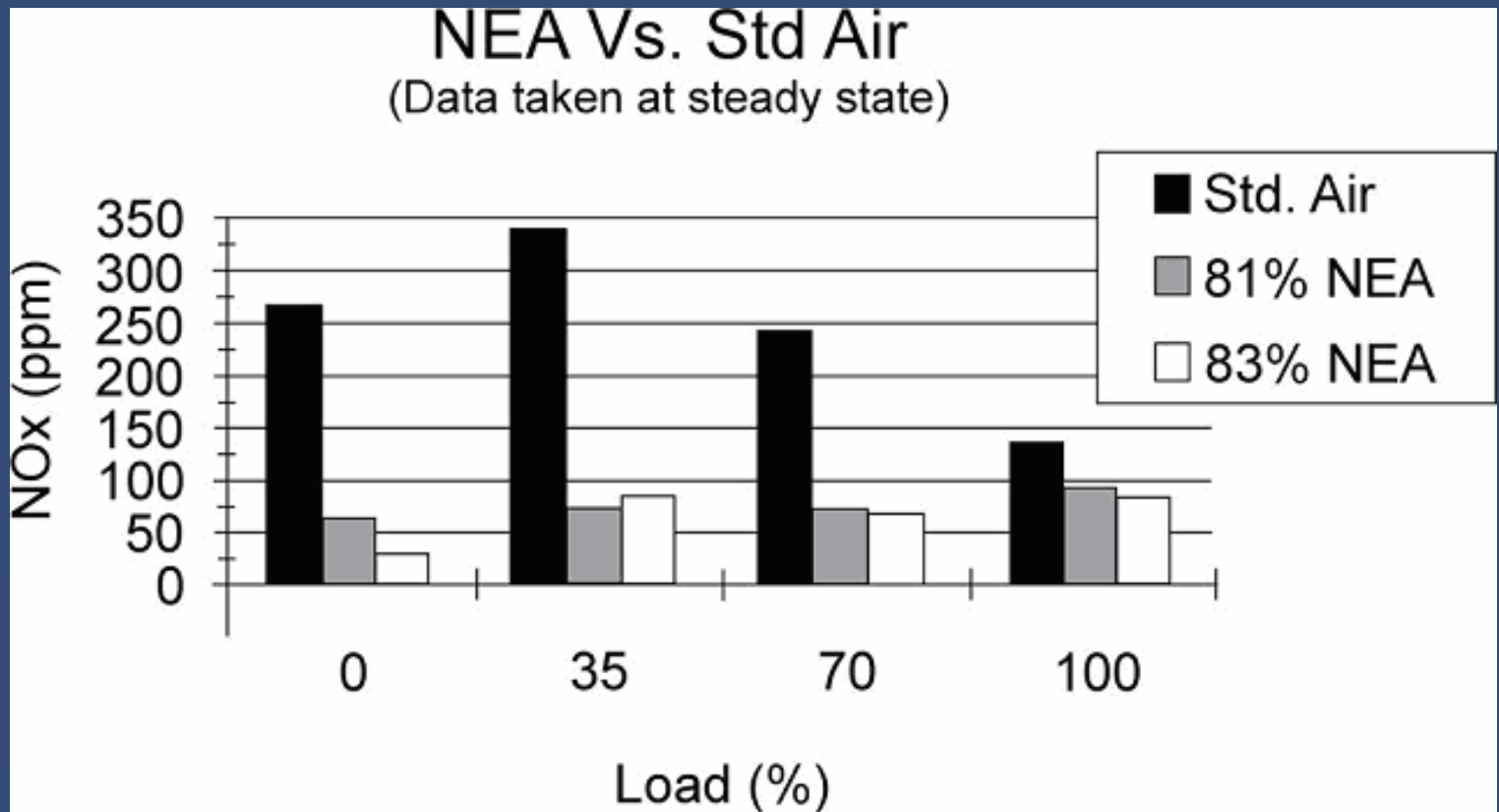
- Influence of NEA and Air-Fuel Ratio on Adiabatic Flame Temperature



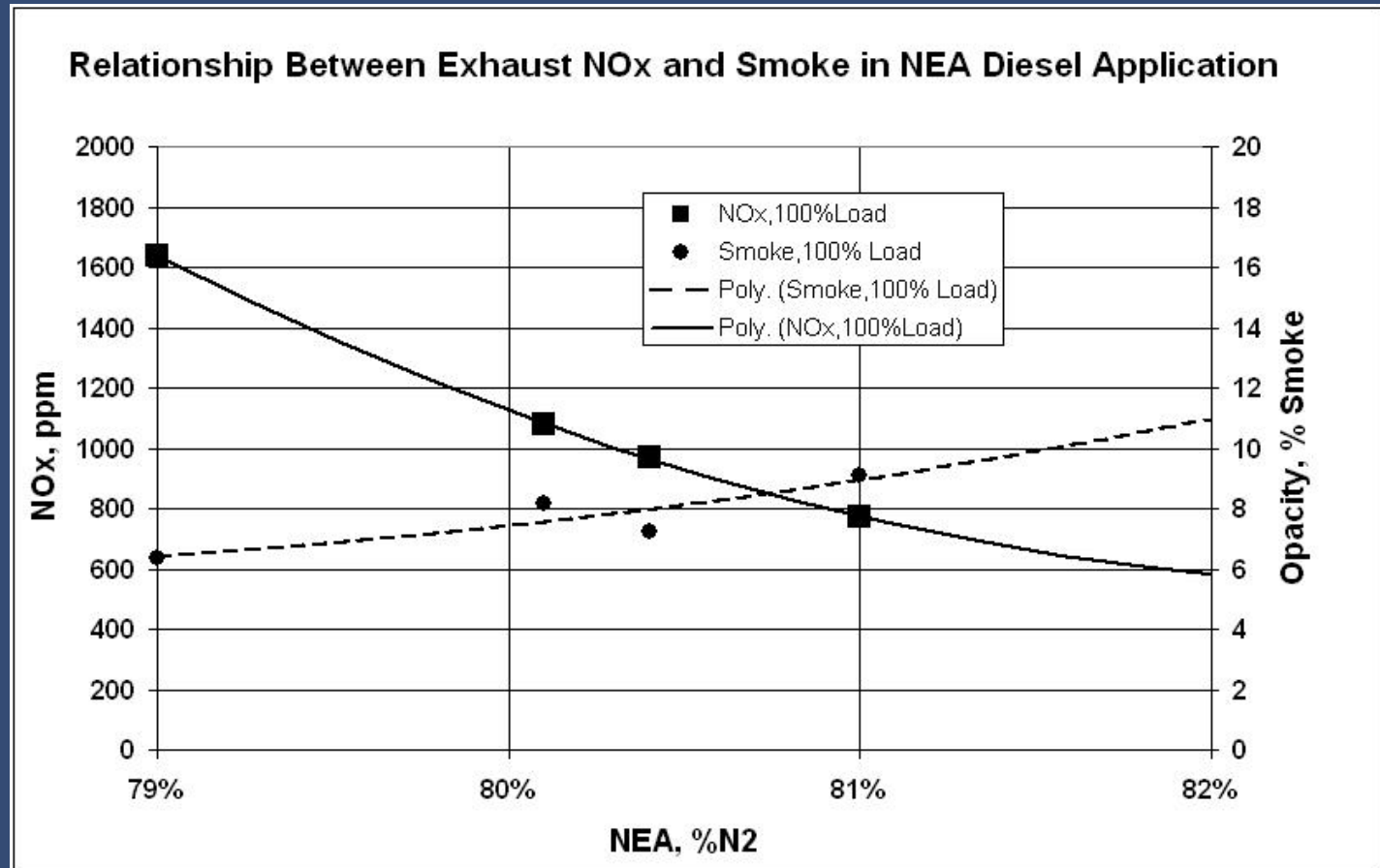
# Diesel Engine with NEA Membrane



# NOx for One Cyl. Lab Engine with NEA



# NOx Emissions on L-P Genset

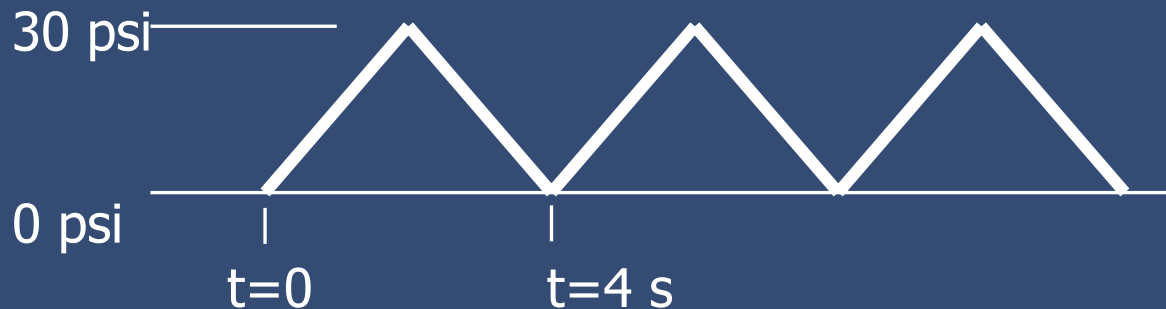


## *Okay! Lab and Stationary Engines ... But ... Highway Truck Engines?!*

- Laboratory Testing
  - Accelerated Durability Tests
    - Pressurization cycles
  - High Temperature Aging Effects
    - Membrane properties with cycling
  - Road Dust Test
  - Emissions Tests on Laboratory Engine
- Field Tests

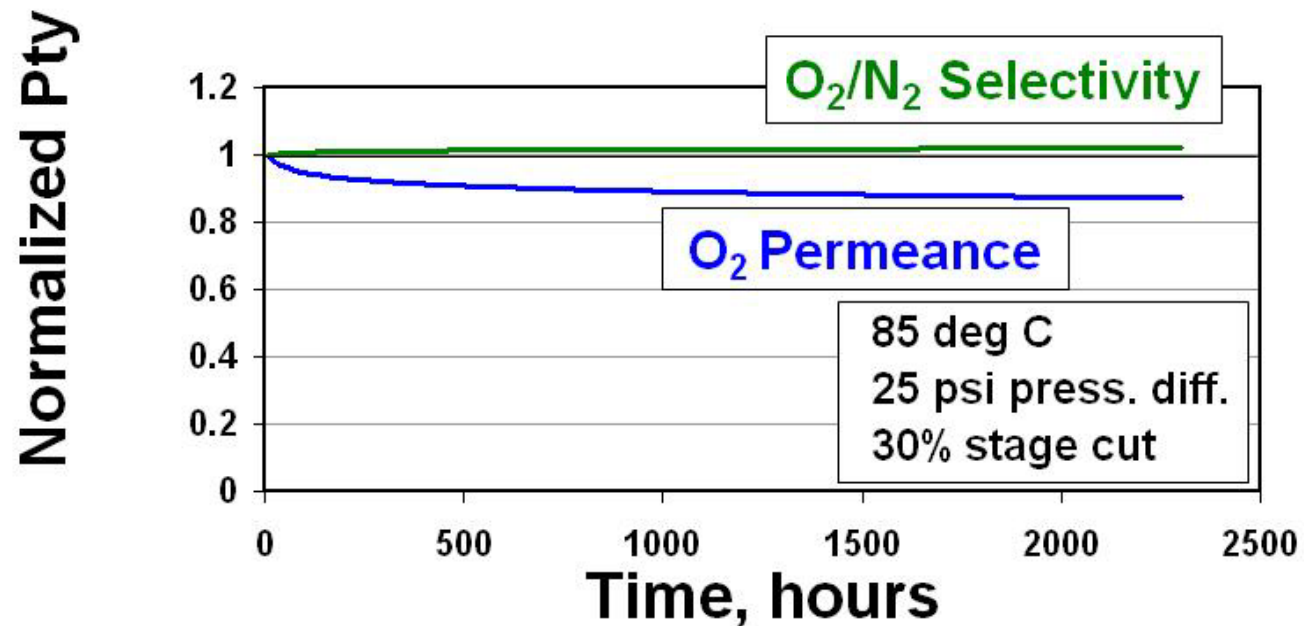
# Accelerated Durability Tests

- Durability – Resistance to pressure cycling
  - 0 to 30 psig at extreme temperature of 85 deg C
- Goal – 300,000 cycles at 0 to 30 psi
  - Simulates 435k miles for engine on-highway truck
- Rate – 2 seconds up, 2 seconds down
  - Simulates typical boosting rate in transient loading
- Two weeks to achieve 300,000 cycles
- Ultimately, demonstrated > 1,000,000 cycles to onset of failure

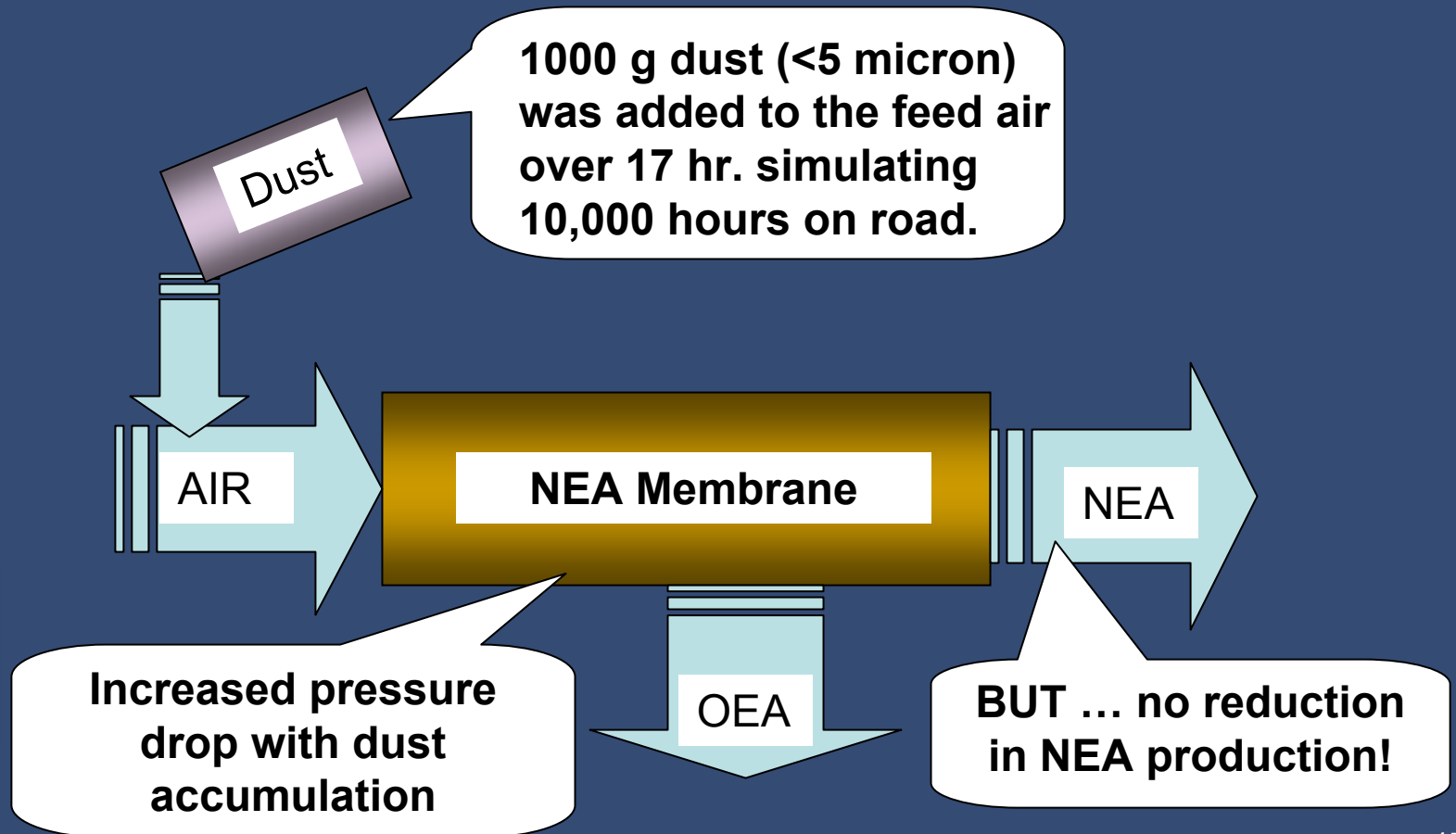


# Life at High T – Keeps ON ...

## Long-Term NEA Cartridge Performance

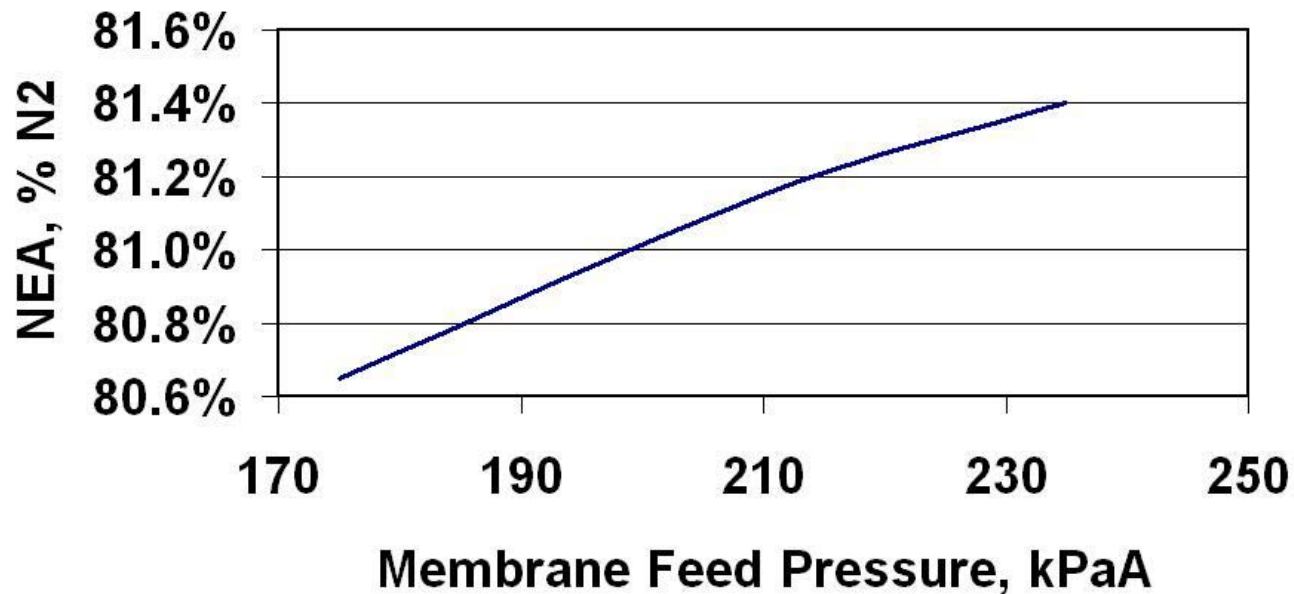


# SwRI Accelerated Road Dust Test



# Fixed Memb. Area, Variable Boost

## Influence of Boost Pressure on NEA Product (typical)

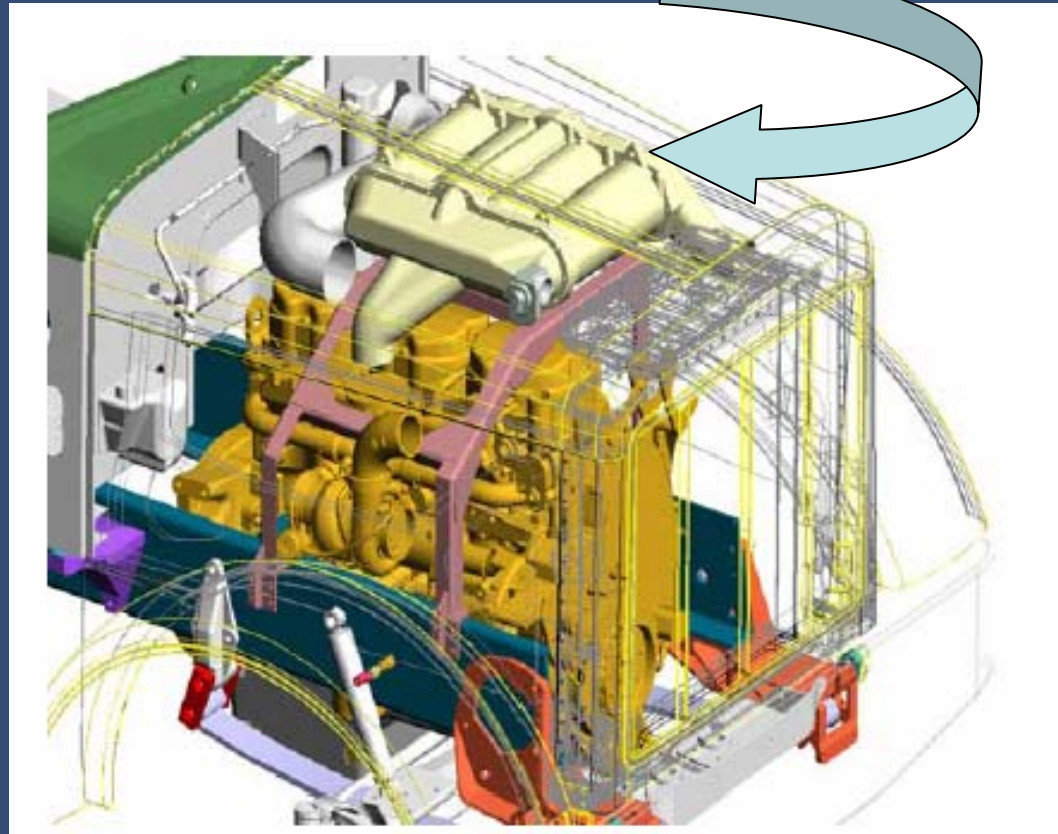


# Lab Engine Emissions Tests

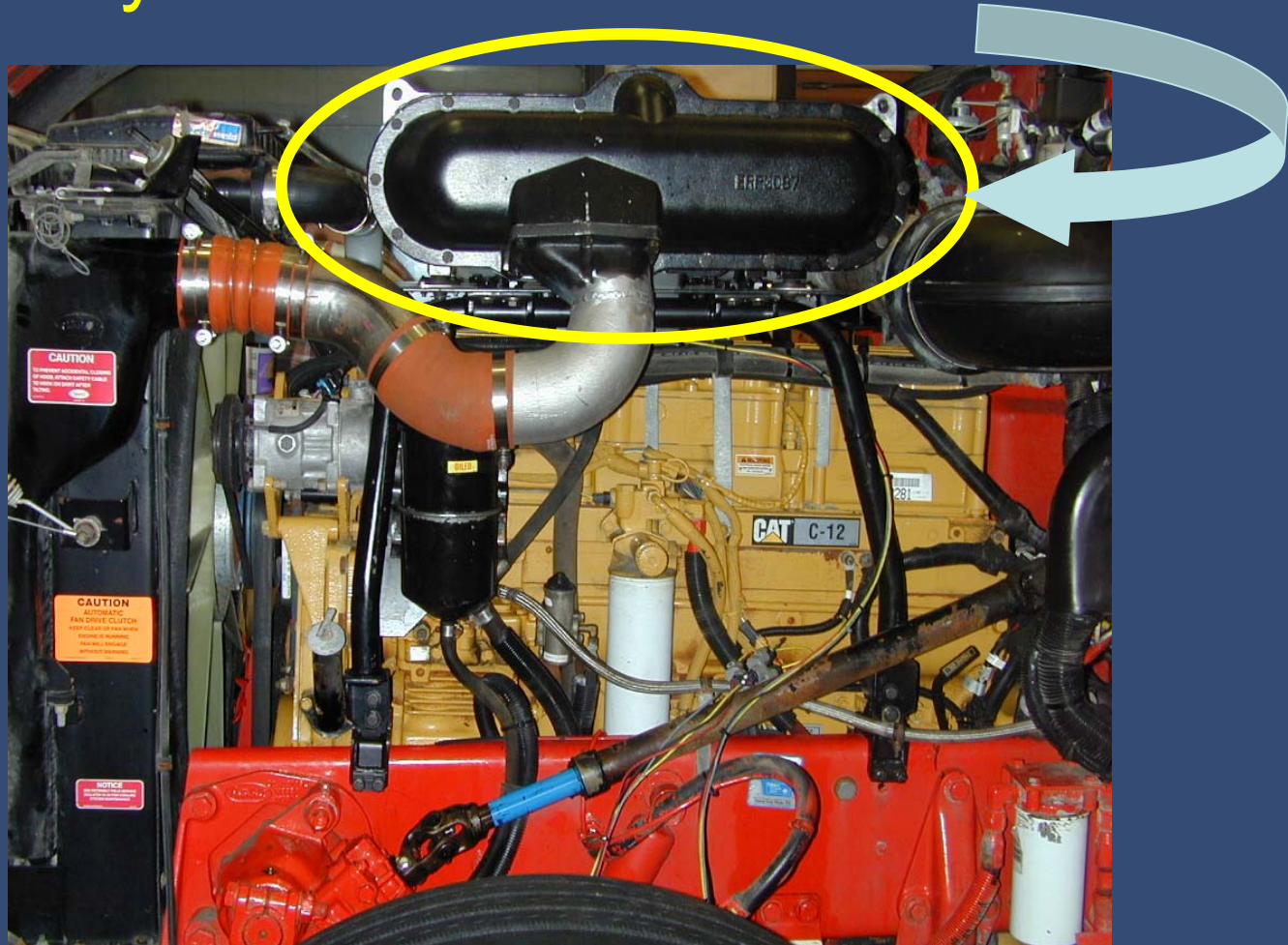
## Steady State 13 Mode Cycle Results on NEA Modified CAT C-12 Engine

(g/hphr)	2000 6g NOx Production C-12 Engine	C-12 Engine With NEA	2004 EPA Standard
<b>NOx</b>	<b>5.5</b>	<b>2.41</b>	
<b>NOx + HC</b>	<b>5.6</b>	<b>2.50</b>	<b>2.50</b>
<b>Particulate</b>	<b>0.04</b>	<b>0.097</b>	<b>0.100</b>

# NEA Membrane in Engine Compartment



# Reality - Membranes Under the Hood!



# Membrane Housing above Engine



# Field Durability Test Program

- Five Class 8 Highway Trucks
- Outfitted with NEA Membranes
- Exceeded total of **1 million miles** on the road
- No evidence of Membrane Fouling
  - All Five Over 150,000 miles
  - One over 270,000 miles

# Status

- Commercialization Phase
  - Membrane Supply
  - NOx Reduction Certification by EPA
- OEM Engine Manufacturers
  - Truck and Off-Road
  - Generators and stationary power
  - Locomotive
  - Marine
- Distributors
  - Retrofit of existing diesel engines
  - Compliance with local or regional emission regulations

# CMS' Partners and Supporters

- DuPont
  - Licensor to CMS
  - Perfluorinated Polymer Supply
- Praxair Innovative Membrane Systems Inc.
  - Licensee of CMS Technology
  - Cartridge Manufacturer
- Argonne National Lab
  - Engine Research with OEA and NEA
- Caterpillar, Inc.
  - Application Development
  - Demonstration
  - Field Testing



# Grants and SBIR Support

- Environmental Protection Agency
- US Department of Energy
- US Department of Defense
- National Science Foundation
- State of Delaware



Thanks for your attention

Questions Anyone?



The End