



# **Vacuum-driven membrane supplies nitrogen-enriched air for NOx emissions reduction on a large diesel engine.**

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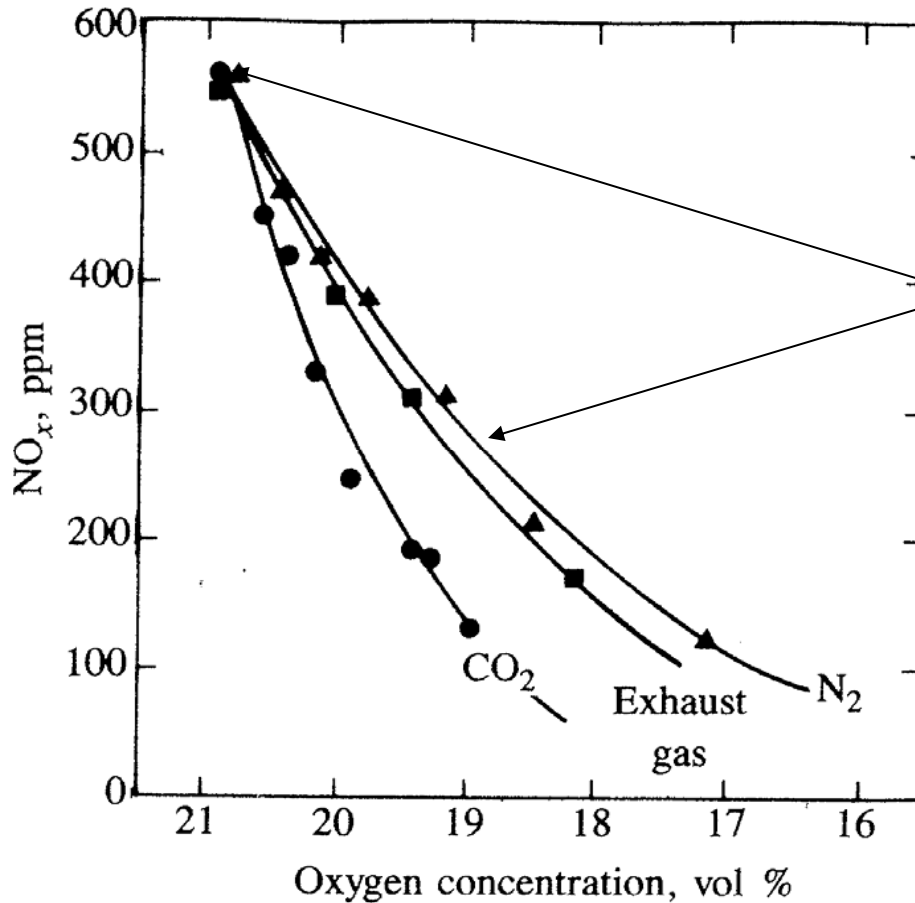
*NOx, a major smog component*

*On a hot, smoggy summer day, have you ever wondered: Is the air safe to breathe? Should I be concerned about going outside? [epa.gov](http://epa.gov)*

# Diesel Engines See Increasing Regulation for NOx Emissions

- Nitrogen oxides,  $\text{NO}_x = \text{NO} + \text{NO}_2$
- Primary Chemistry
  - $\text{N}_2 + \text{O}_2 \xrightarrow{\text{heating}} 2\text{N}^\bullet + 2\text{O}^\bullet \xrightarrow{\text{cooling}} \text{N}_2, \text{O}_2, \text{NO}, \text{NO}_2$
  - Driven exponentially with temperature
- High Combustion Temperatures
  - Energy release on fuel combustion
  - Heat capacity of reactants and products
- Controlling NOx Formation
  - Limit temperatures by diluent addition
  - Diluents = water, carbon dioxide, exhaust, nitrogen

# Minor Changes in Oxygen Concentration Can Substantially Reduce NOx Formation



*Reducing diesel engine intake O<sub>2</sub> concentration as little as 2% ... from 21% to 19% ... reduces NO<sub>x</sub> formed by 50%.*

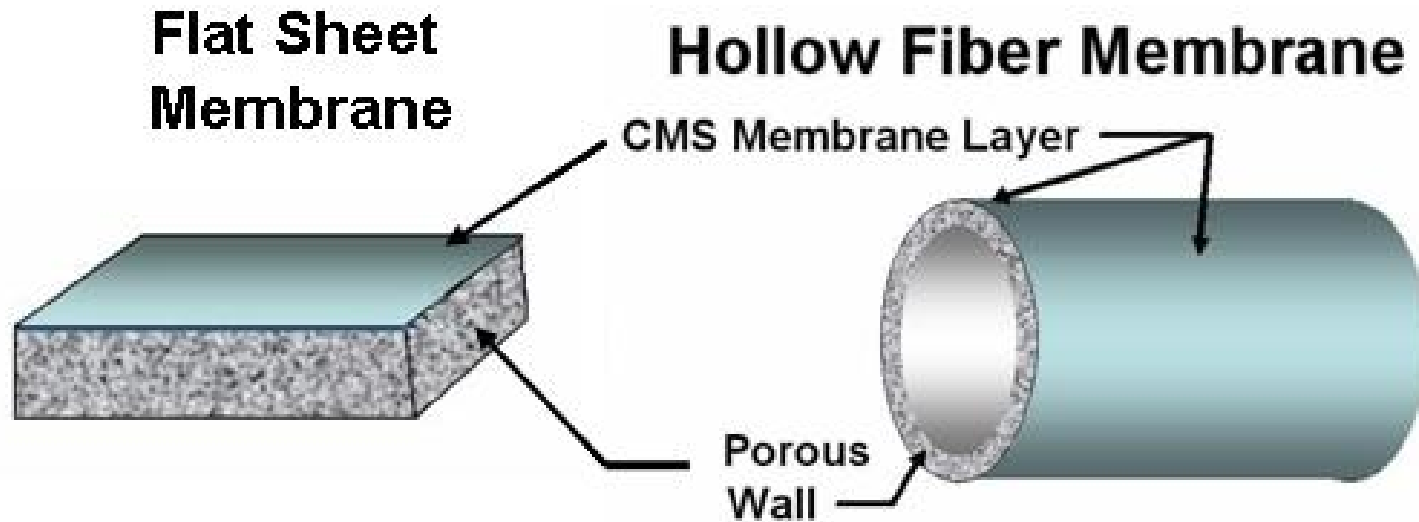
Ref. John B. Heywood; "Internal combustion engine fundamentals". McGraw-Hill (1988)

# The Diluent of Choice

- Selection criterion
  - Availability
  - Quality of supply
  - Conditioning and handling issues
  - Energy requirements
  - Costs of supply
- Nitrogen enriched air (NEA) is good choice
  - No significant change in combustion species
  - No changes in engine materials or mechanical design
  - High flux air separation membranes deliver NEA

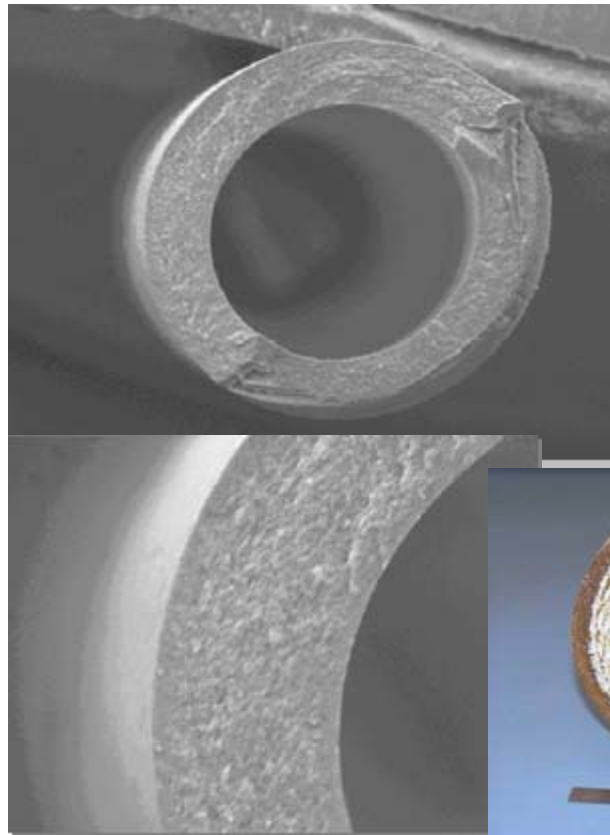
# CMS Composite Membranes

- Submicron perfluorinated polymeric coating applied on porous flat sheet and hollow fiber supports
- Highest gas permeation fluxes enable small, portable, point-of-use membrane systems

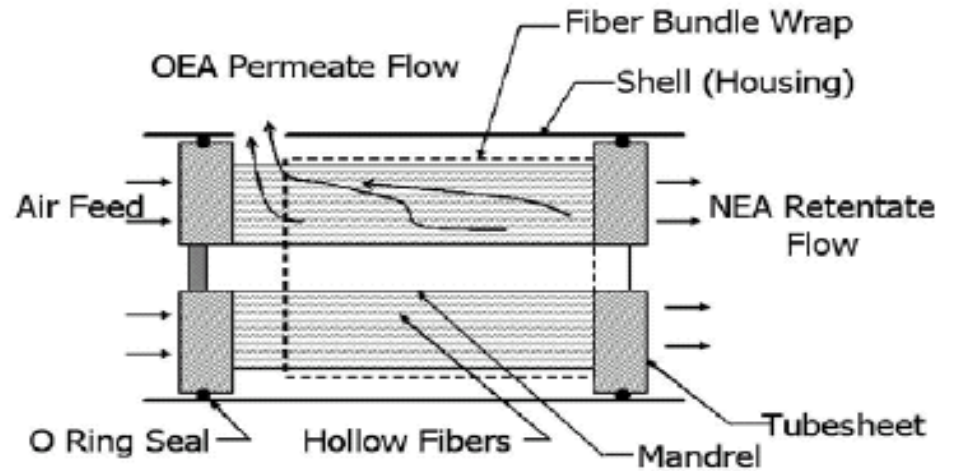


# NEA Membrane Cartridges

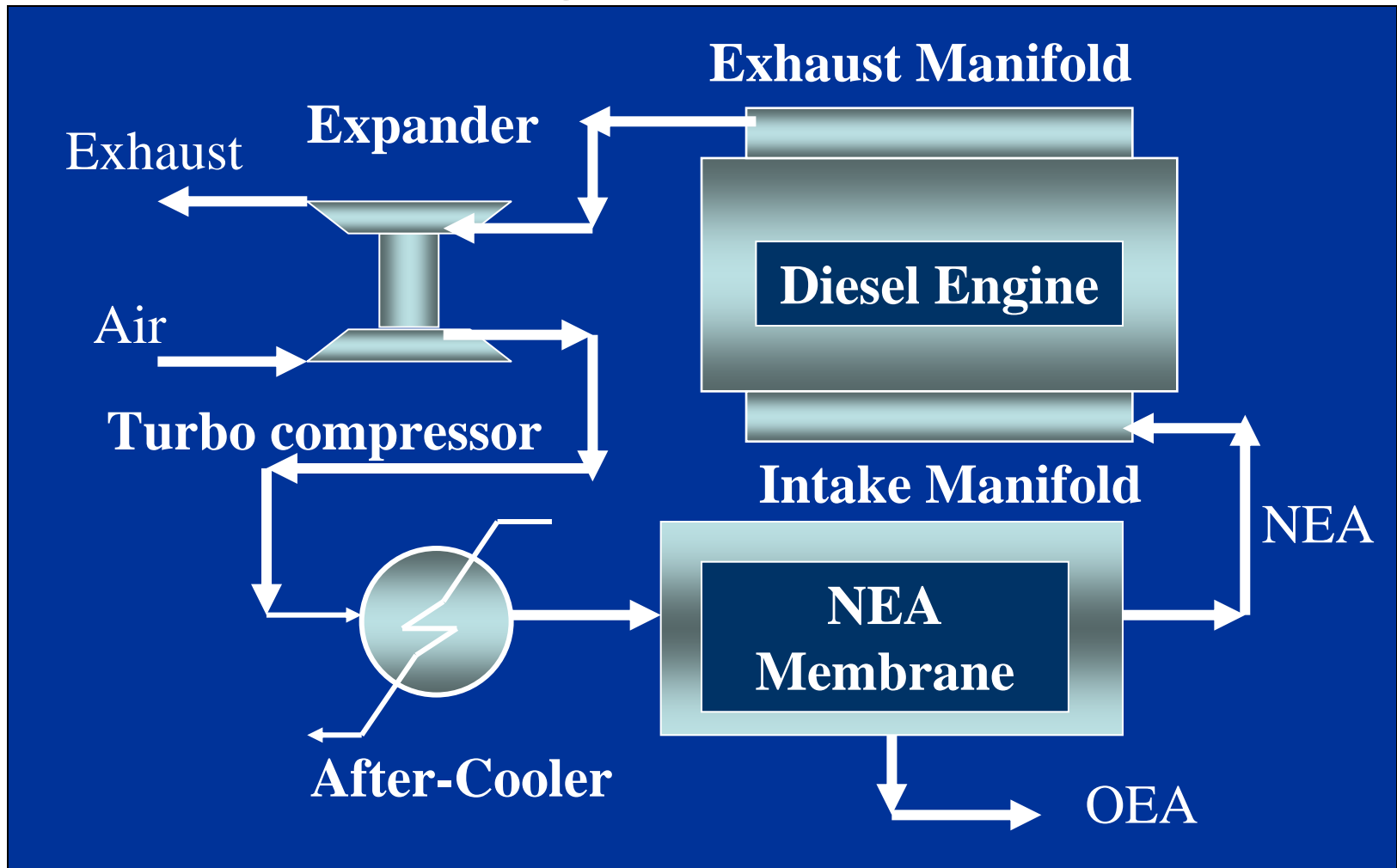
## Hollow Fiber Membranes



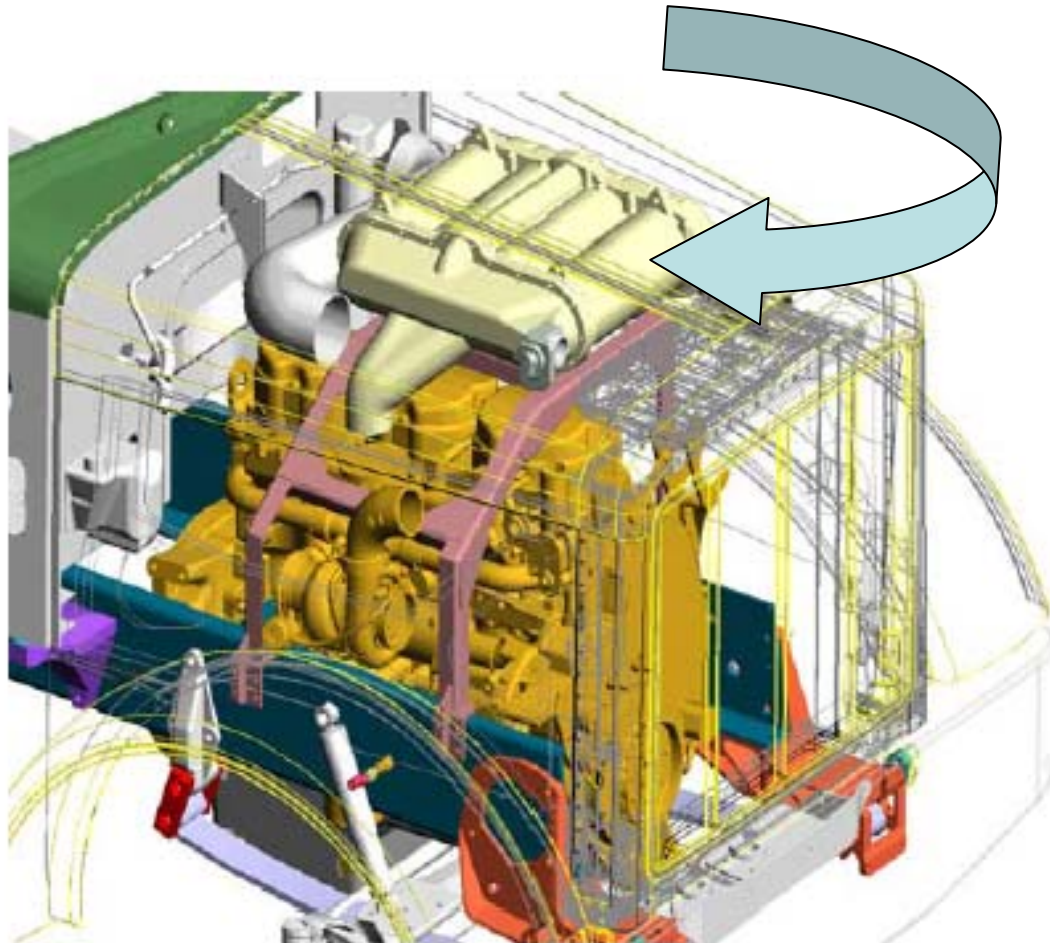
## Membrane Cartridge Cross-section



# Diesel Engine Schematic Showing NEA Membrane



# Concept: A NEA Membrane within a Truck Engine Compartment



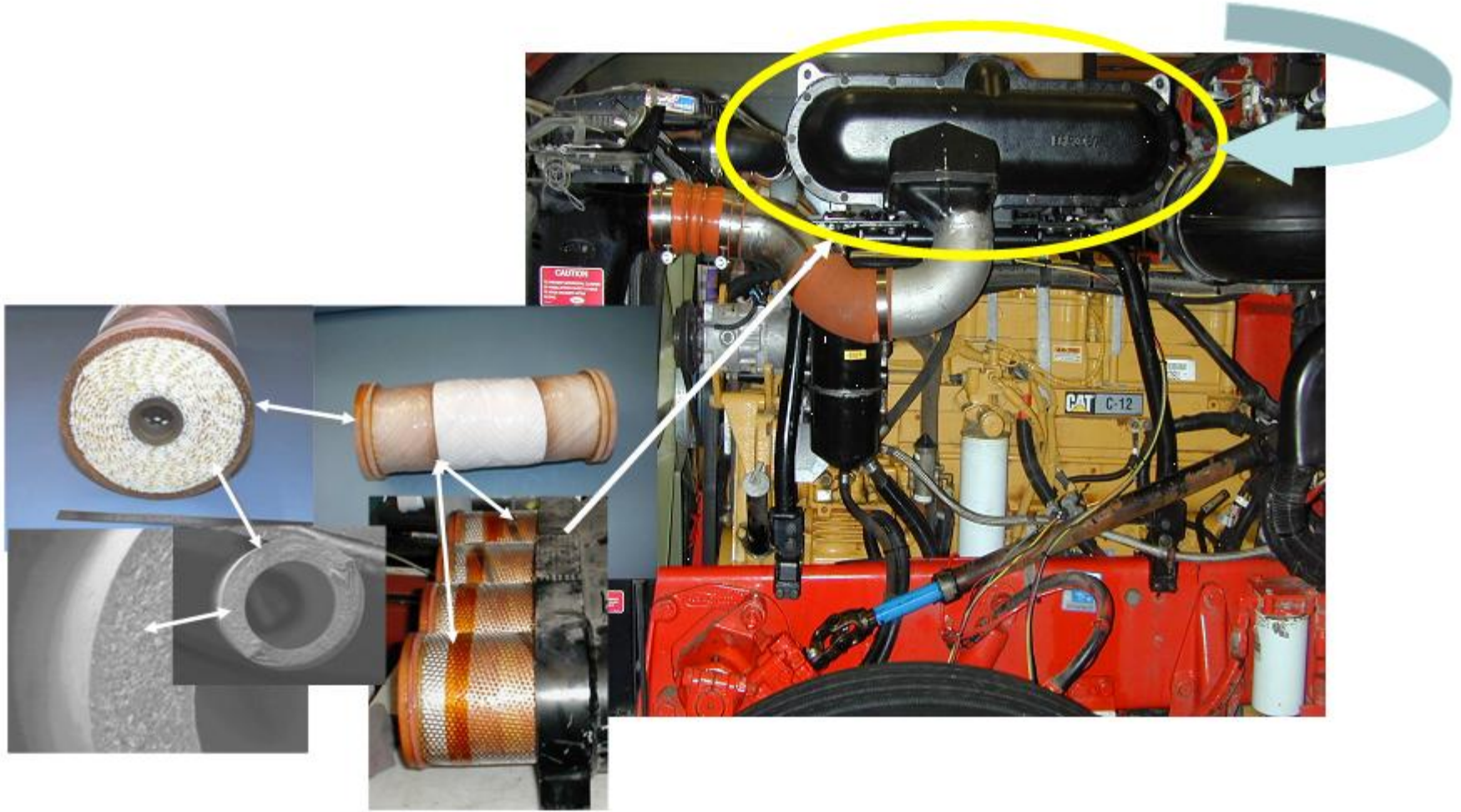
# Lab Engine Emissions Tests by Caterpillar

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

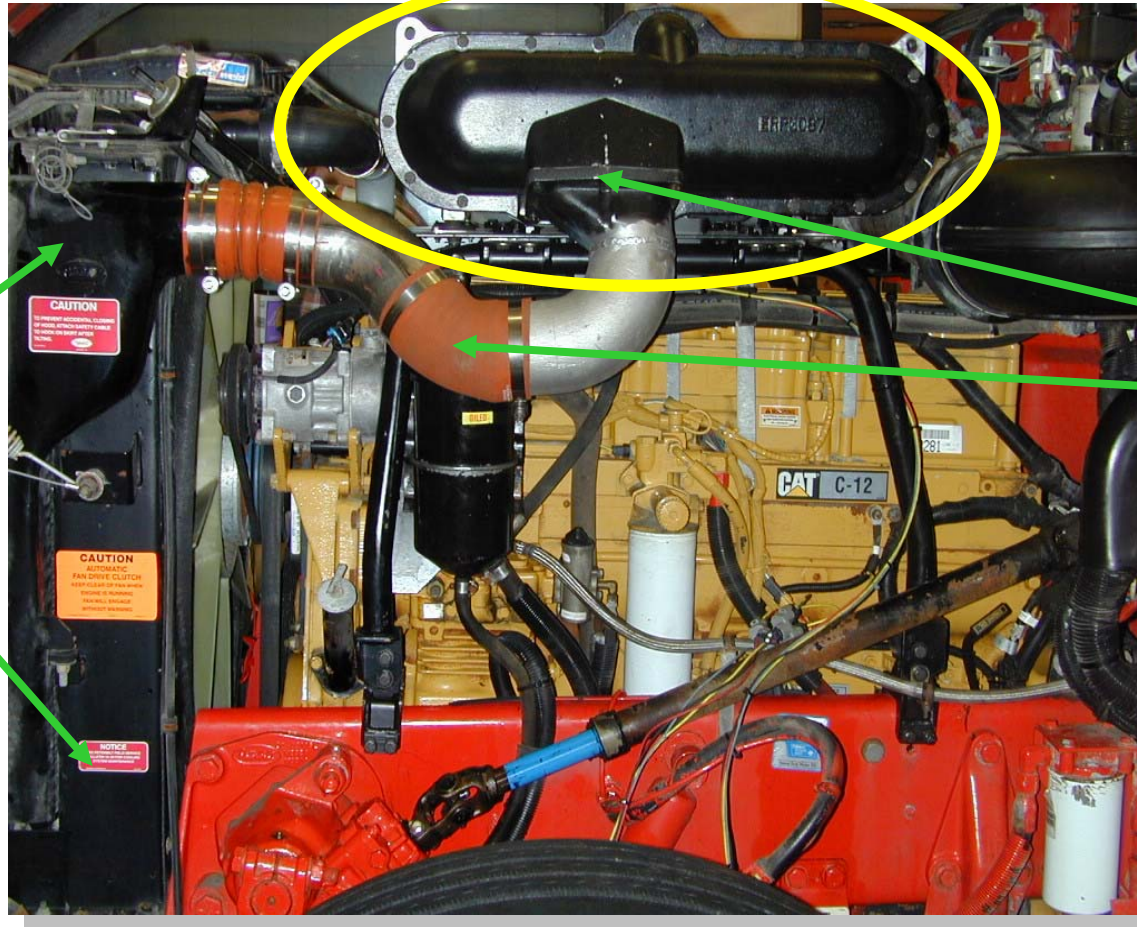
(g/hphr)	2000 6g NOx Production C-12 Engine	C-12 Engine With NEA	2004 EPA Standard
<b>NOx</b>	<b>5.5</b>	<b>2.41</b>	
<b>NOx + HC</b>	<b>5.6</b>	<b>2.50</b>	<b>2.50</b>
<b>Particulate</b>	<b>0.04</b>	<b>0.097</b>	<b>0.100</b>

56% NOx Reduction

# Reality! Hollow Fiber Air Separation Membranes Under the Truck's Hood!



# Membranes Process Cooled Turbocharged Air and Deliver NEA to Engine Intake Manifold



Truck's  
Air  
Cooler

Cooled Air  
Line & Inlet  
to NEA  
Membrane

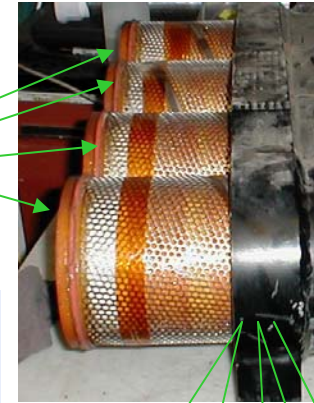
# NOx Reduction on a Ferry



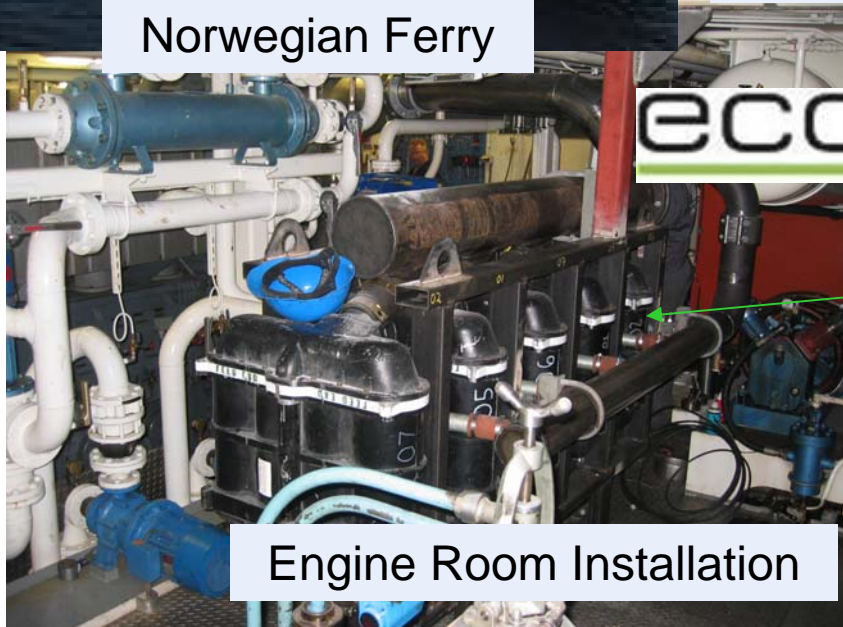
Norwegian Ferry



NEA Hollow Fiber Membrane Cartridge



Four Cartridge Housing



Engine Room Installation



Five Housing Assembly

# Retrofitting Engines for NO<sub>x</sub> Reduction with NEA Membranes

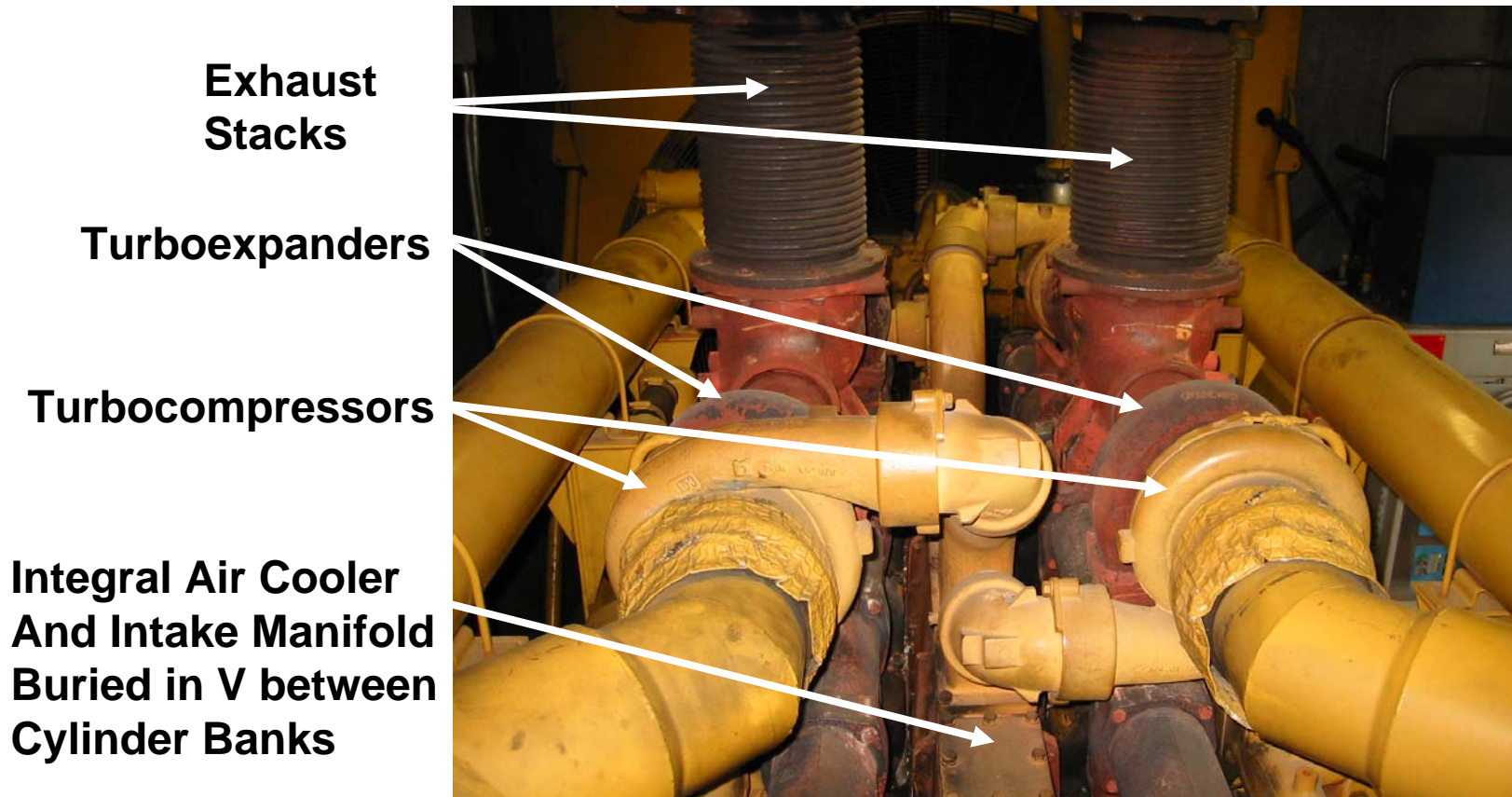
- Membrane installation in the turbocharged air system requires turbo resizing, ducting, and engine downtime.
- Half of the diesel engines under 100 hp (75 kW) are air aspirated engines and lack the turbo-boost pressure used to drive the membrane air separation
- Many large engines designed for power, marine, and locomotive applications, typically larger than 800 hp (600 kW), employ air coolers that are integral to the intake manifold.
- In either case, without access to turbocharged air, retrofitting for NEA membranes can involve major, costly engine modifications.

# Caterpillar 3516 marine engine

2 banks, 8 cylinders each in V-arrangement



# Air and Exhaust Systems on CAT 3516 (view from above)

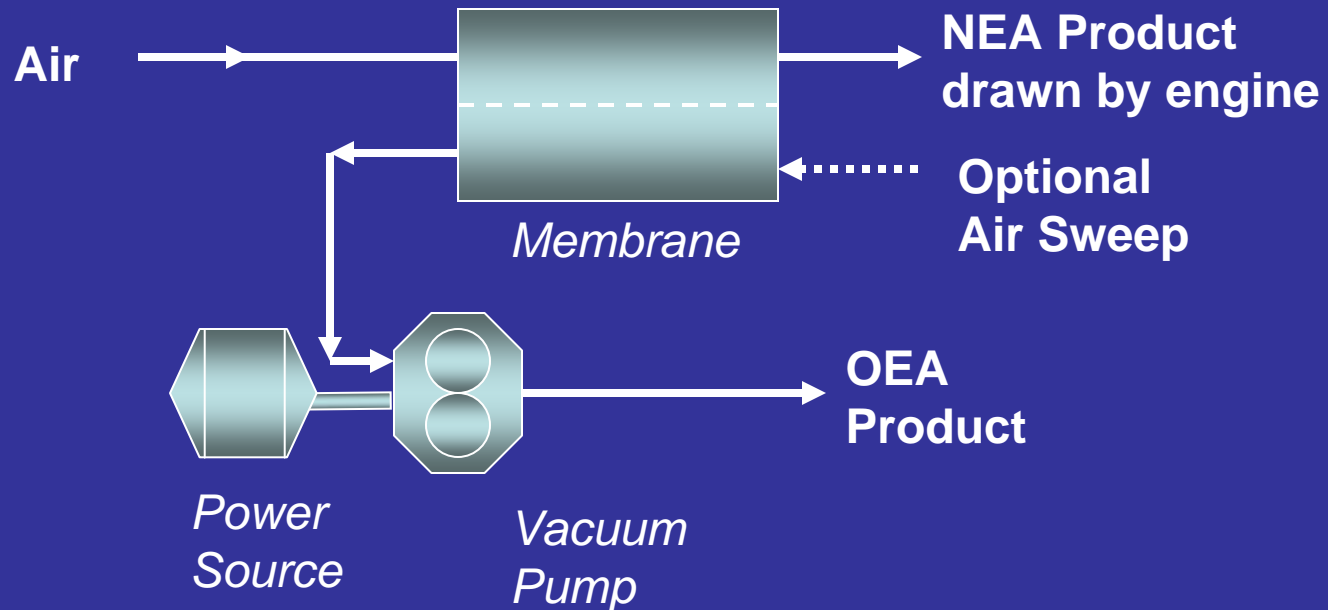


*Problem: No access to the cooled turbocharged air to feed NEA membrane.*

# Alternative Retrofit Approach

- An independent, stand-alone membrane unit driven by a vacuum pump
- NEA generated is supplied directly to the normal engine air intake filter
- OEA (oxygen enriched air) is expelled from the vacuum pump
- Offers opportunity to retrofit with no engine modifications and no or minimal downtime
- Vacuum membrane system can be located remote from the engine

# Alternative Vacuum Driven NEA Membrane System



*The NEA vacuum driven system is a stand-alone package.*

# Demonstration Tests

- Basis:
  - CAT 3508B Diesel Engine, 1500 rpm, 800 kW Generator
  - NEA generation by vacuum driven membrane system
  - Target NEA containing 19.95% O<sub>2</sub> for > 30% NO<sub>x</sub> reduction
  - Demonstration on engine installed at Karmsund Vidregående Skole, Haugesund, Norway
- Participants from
  - Ecoxy AS
  - Compact Membrane Systems
  - CAT Pon Power
  - Statoil Hydro
  - Norwegian Research Council
  - Asahi Kasei Chemicals

# The Test Site...A Technical High School in Haugesund, Norway



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# Two 24-Cartridge Housings Assembled



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# The CAT 3508B Engine

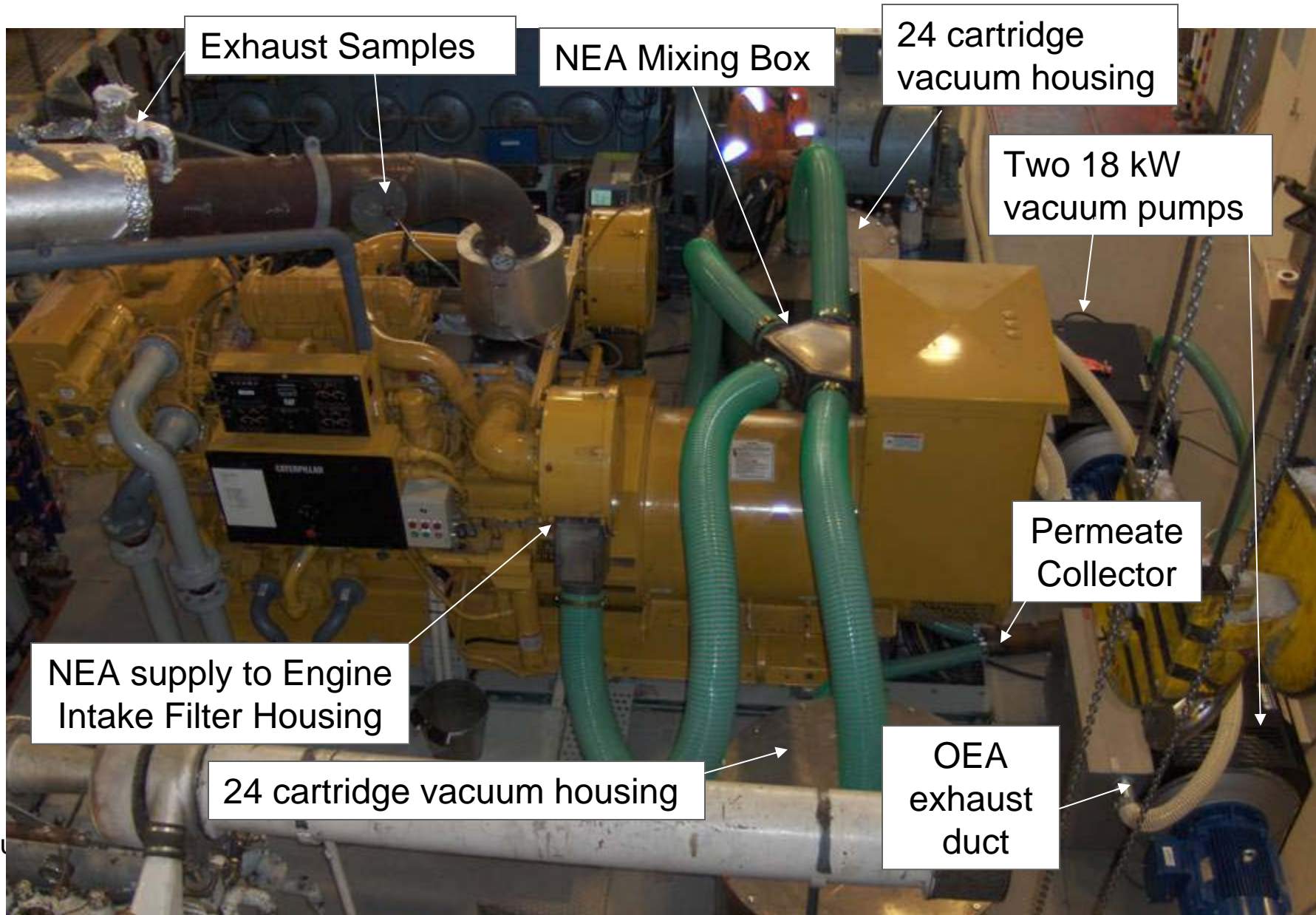


The NEA is fed to the two charge air filter housings, one on each side of the engine.

# Connecting Two Cartridge Housings to the NEA Mixing Box



# Demo System Assembly on Cat 3508



# NEA, OEA, and Exhaust Gas Analysis



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# Demonstration Test Results

Engine load [%]	EcoNOx On/Off	Fuel penalty*	CO [ppm]	NOx [g/kg fuel]	NOx, % Reduction
75	Off	0.0%	49	40.0	-
50	Off	0.0%	76	36.7	-
25	Off	0.0%	117	33.8	-
75	On	4.6%	95	27.6	31.1
50	On	5.0%	113	27.2	25.9
25	On	6.2%	138	27.2	19.6
75	On	6.8%	112	24.4	38.1
50	On	5.4%	124	27.5	25.1
25	On	10.5%	151	23.1	31.5

\*Fuel Penalty = incremental fuel requirement to power vacuum pumps



- The targeted 30% NOx reduction was achieved with less than 5% fuel penalty

# NEA Vacuum System vs Pressure Mode

## Vacuum System Pros

- Enables NEA technology to be retrofitted on any engine.
  - Turbocharged, or
  - Air aspirated
- NEA is simply substituted for air at the engine air intake filter.
- No engine or turbocharger modifications are required
- Vacuum route requires less energy to produce the NEA than the earlier turbocharged route.
- System can be installed without taking vessel or generator out of service
- Membrane operates at very low severity conditions (low temperature, low pressure, no cycling or pulsation, etc.).

## Vacuum System Cons

- Requires a larger membrane system than the cooled turbocharged air system due to:
  - Lower membrane pressure differential
  - Lower membrane operating temperature
- Unless suitably interlocked to the engine or continuously monitored NO<sub>x</sub>, emissions regulators might suspect operator's disuse.
- Added machinery is required, notably a vacuum pump, and possibly a supply air blower

# The Installation Team



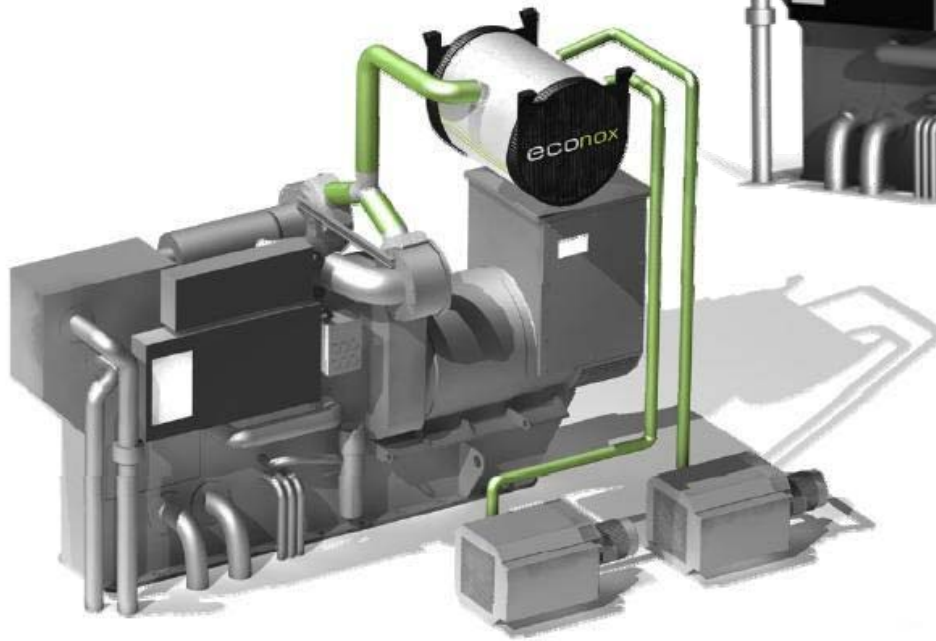
Don Stookey  
CMS

Yosuke Koizumi & Atsuo Kubota  
Asahi Kasei Chemical

Øyvinn Melhus, Christer Heimtoft, & Ingvar Garåsen  
Ecoxy AS

# Ecoxy econox™ System Concepts

econox™ 1 MW



econox™ 2 MW

