DEMONSTRATION
OF SELECTIVE CATALYTIC REDUCTION WITH DIESEL PARTICULATE FILTERS ON A PASSENGER FERRY

Chair's Seminar Series
California Air Resources Board
July 7, 2010

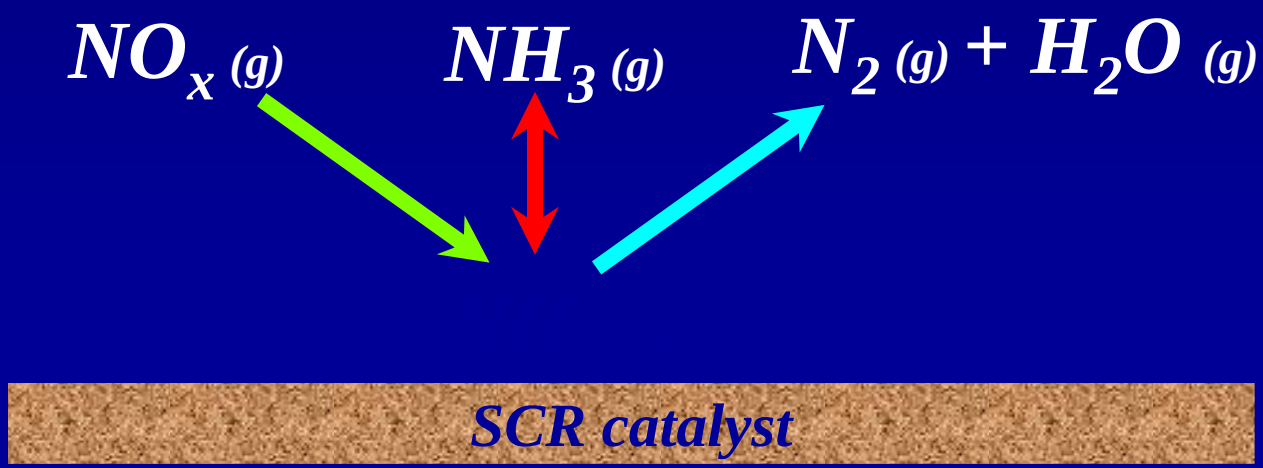
Christopher Weaver P.E.
President

Outline

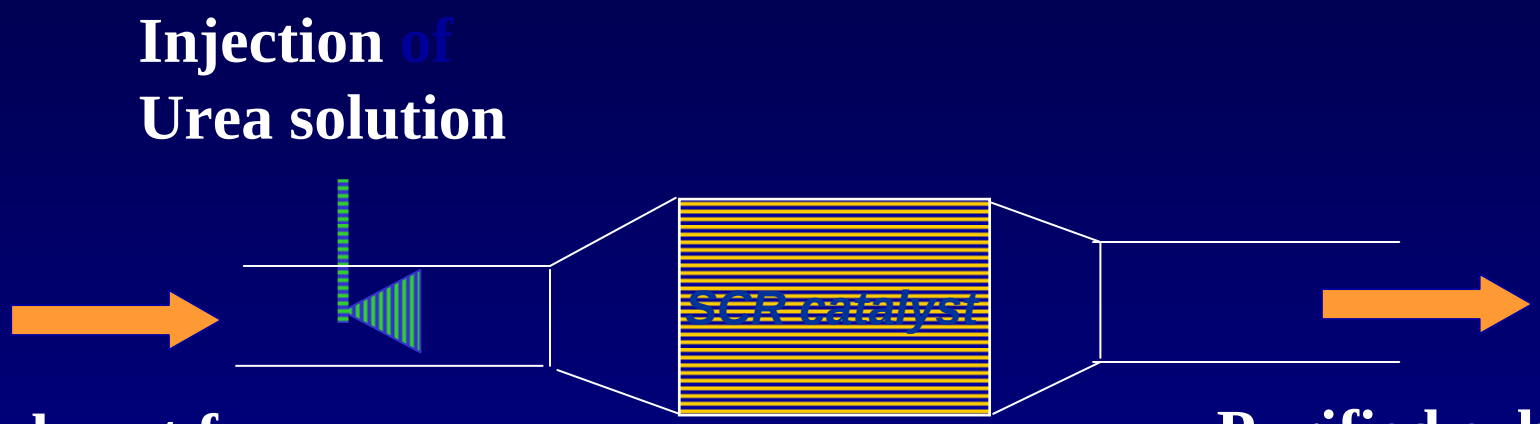
- **Selective Catalytic Reduction (SCR)**
- **Compact SCR™ Applications**
  - Marine vessels
  - Locomotive
  - Distributed generation
- **ICAT Project - Compact SCR™ + Diesel Particulate Filters (DPF)**

Selective Catalytic Reaction (SCR)

- Widely used in power plants, stationary sources
- Like a three-way catalyst for diesel / lean-burn engines
- Oxidizes HC, CO, and organic fraction of PM
- Reduces NOx in presence of O_2, but requires ammonia (NH_3) to drive the reaction
- Urea $(NH_2)_2CO + H_2O$ + heat → $2\ NH_3 + CO_2$

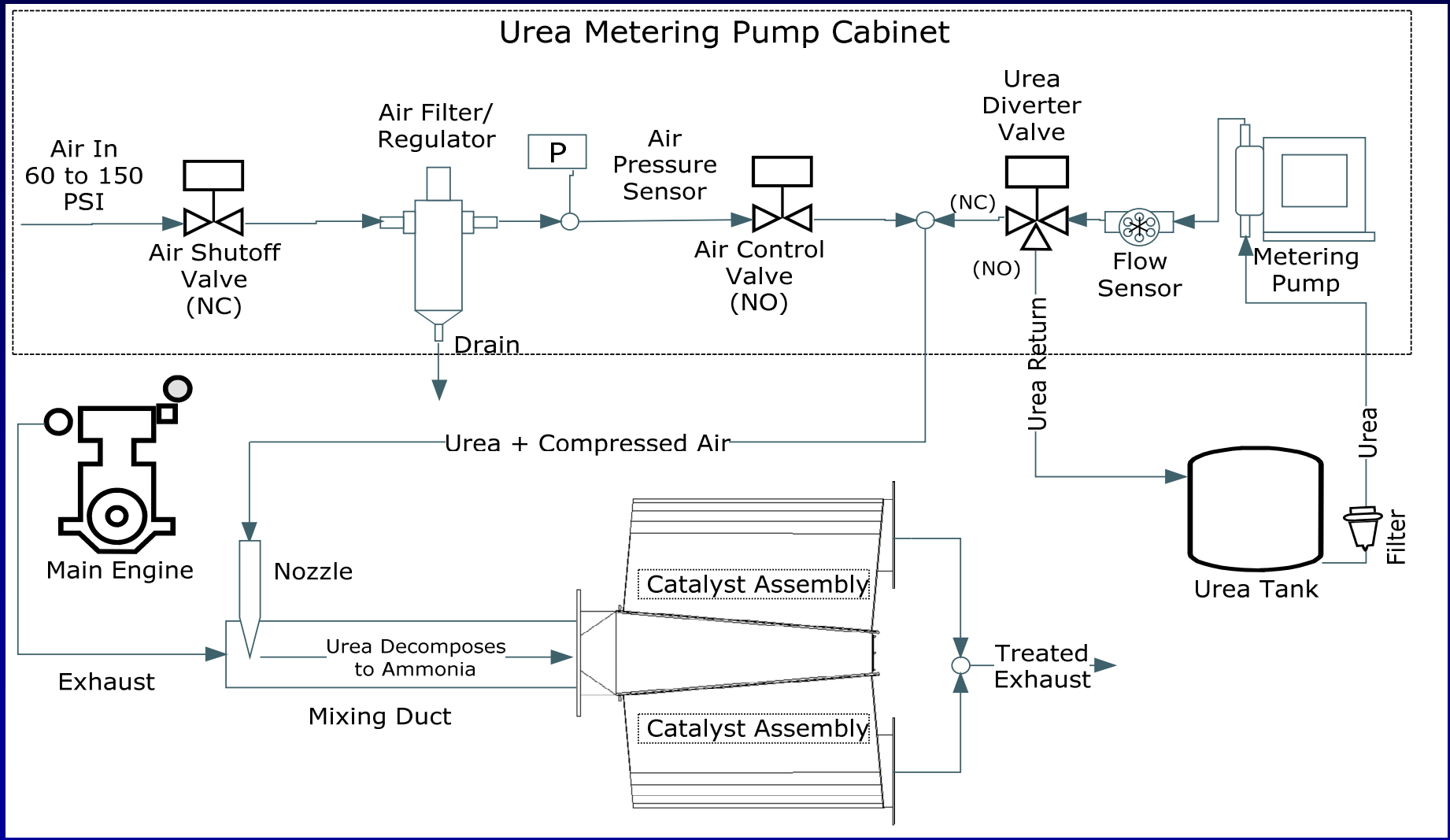


Urea-SCR System



- > 95% NO_x reduction
- PM reduced 30-60%, VOC ~80%
- Temperature range 200 - 550°C
- No or only slight increase in back pressure
- Combination with particle filter if desired
- Sulphur tolerant

Compact SCR™ Flow Diagram



e Compact SCR systems to be installed in California Hornblower will be very simila
ol will be incorporated into the PLC that controls the SCR system. The goal of the
ed to bring the Tier 0 marine engines on the California Hornblower up to Tier 4 sta
SCR systems and DPFs.

COMPACT SCR APPLICATIONS TO DATE

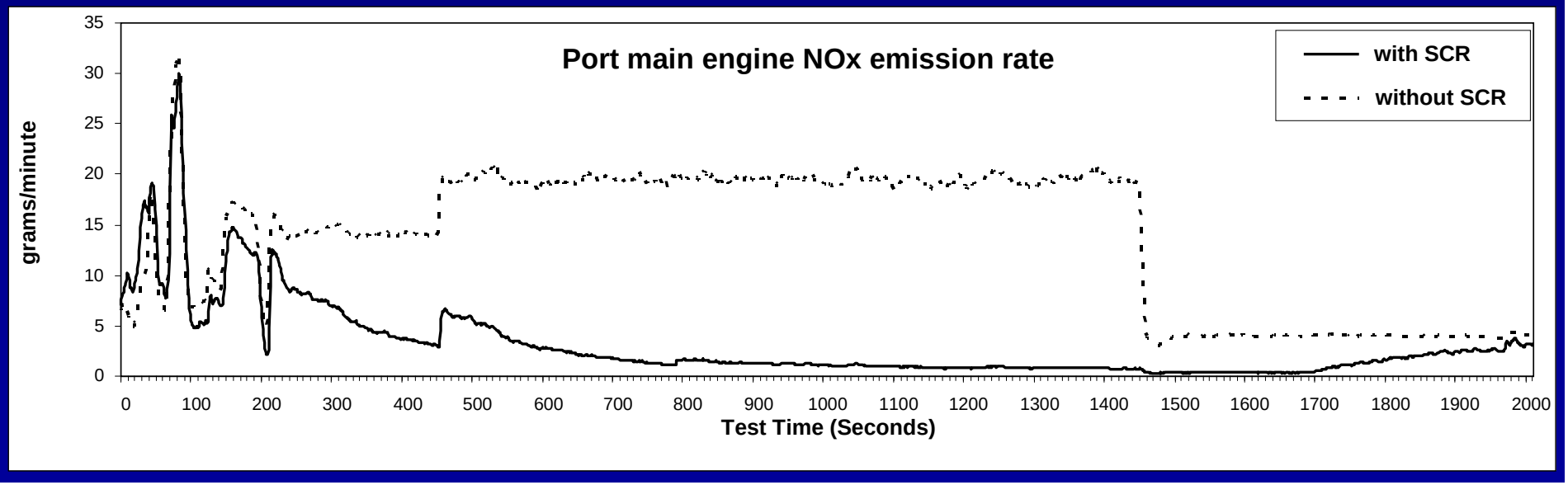
- **Six Ferryboats**
  - Total of 12 main engines and four generator engines
  - All in San Francisco
  - BACT for new passenger ferries
- **One Locomotive**
- **Three Distributed Generation Systems**

Alcatraz Cruises

- **Compact SCR systems for four 625-hp main engines and four 30-39 kW gensets on two monohull ferries**
  - Delivered December 2007 and February 2008
  - Calibration and limited emission testing on M/V *Alcatraz Flyer* February 2008
    - > 4000 engine hours so far
    - Minor fixes and design improvements
  - M/V *Alcatraz Clipper* in September, 2008
    - >3000 engine hours so far

Preliminary Testing of *Alcatraz Flyer* SCR

- Main engines: 2 x DDC Series 60, 625 HP Tier 2 marine diesels
- 6 catalyst modules per engine, reactor wt ~350 lb
- Gensets: 2 x Onan 39 kW
- One catalyst module per genset, one urea injection system shared between both gensets
- Preliminary measurements conducted to set urea injection rates and verify system performance.
- NOx reduction > 90% at all but lowest power settings



Water Emergency Transportation Authority
New Fast Ferries

- **Compact SCR™ systems for eight 1410-hp main propulsion engines on four new fast ferries**
  - System weight ~ 900 lb/engine
  - M.V. *Gemini* in service December '08
    - > 2000 hours so far
  - M.V. *Pisces, Scorpio, Taurus* in service April '09 to May '10

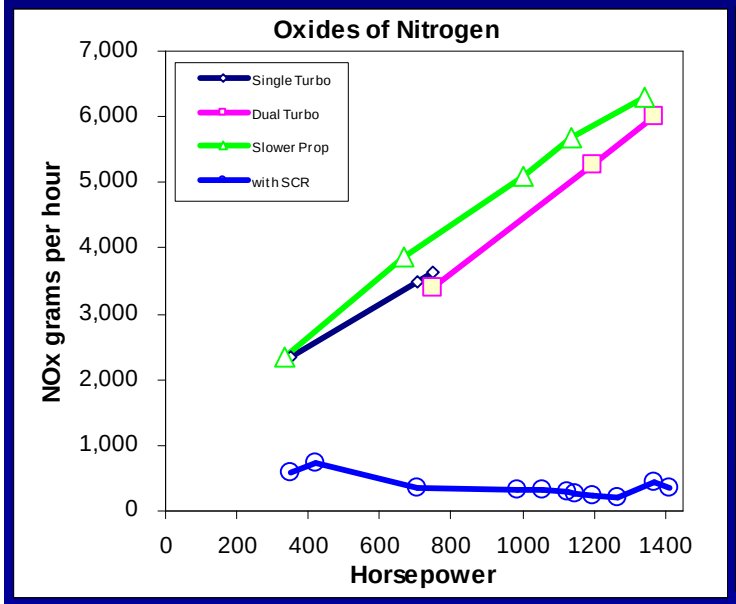
SCR Catalytic Converter

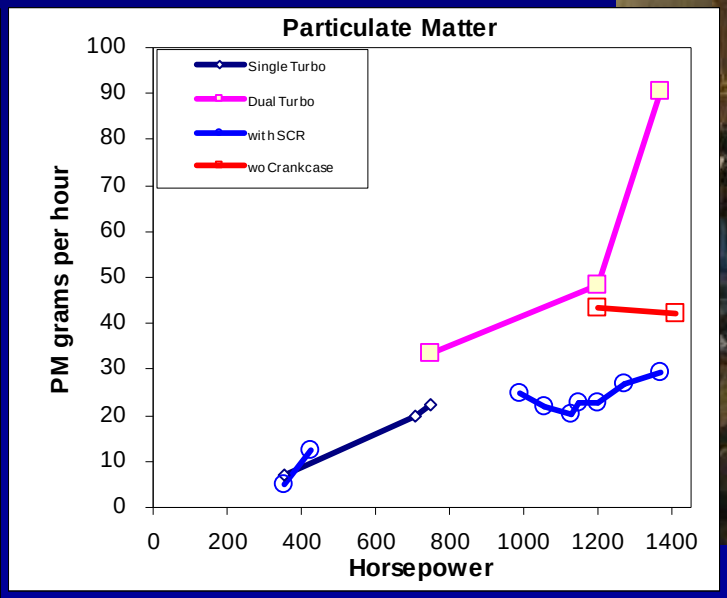
Dyno Test Results for WETA Ferry SCR

- MTU 16V2000 M70 -- 16-cylinder, sequential turbo, 1410 hp high-speed marine diesel
- Measured emissions were 1/3 of contract limit, ~95% reduction from baseline
- Cruise NOx 0.2 g/BHP-hr, PM 0.02 g/BHP-hr
- Tier 2 engine → Tier 4 compliance w SCR
- Exhaust backpressure at full power 42% below engine manufacturer's limit

Testing at Pacific Power Products

Kent, WA Jan. 10-12 2008

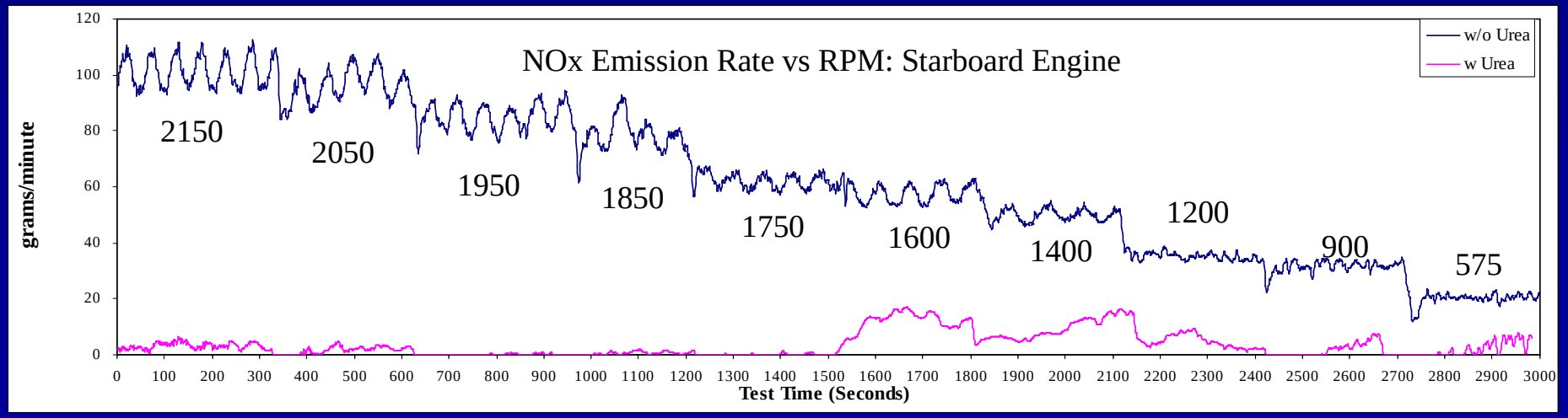




Sea-Trial Emission Results for M.V. *Gemini*

Acceptance Condition
85% Power Cruise

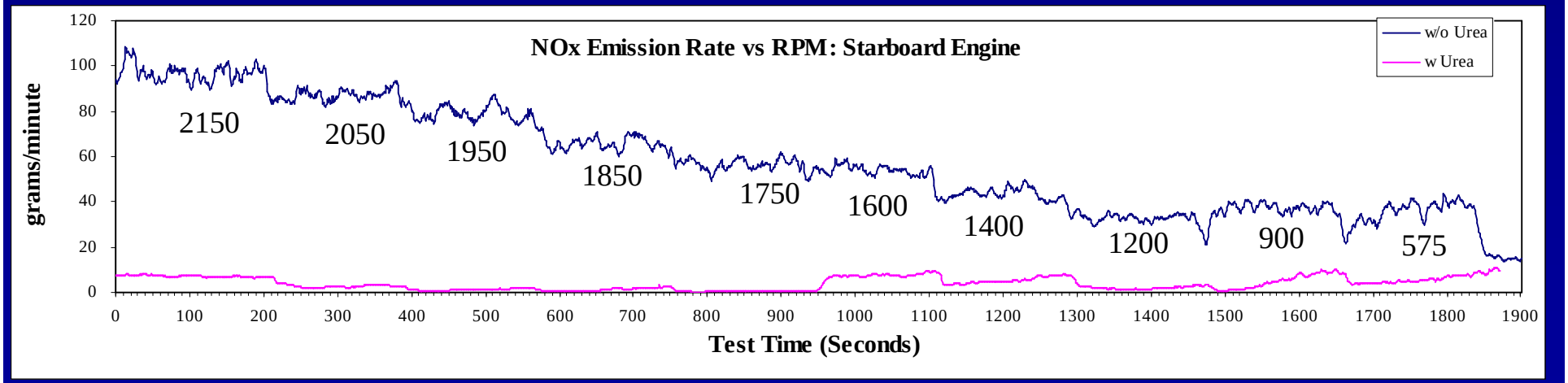
	Emissions (g/kWh)	
	Port	Starboard
NOx	0.01	0.18
PM	0.048	0.021
CO	0.04	0.10
HC est.	0.02	0.02
NOx+PM+HC	0.08	0.22
Contract Limit	1.11	1.11



Sea-Trial Emission Results for M.V. *Pisces*

Acceptance Condition
85% Power Cruise

	Emissions (g/kWh)	
	Port	Starboard
NOx	0.18	0.28
PM	0.023	0.022
CO	0.02	0.03
HC est.	0.02	0.02
NOx+PM+HC	0.22	0.32
Contract Limit	1.11	1.11



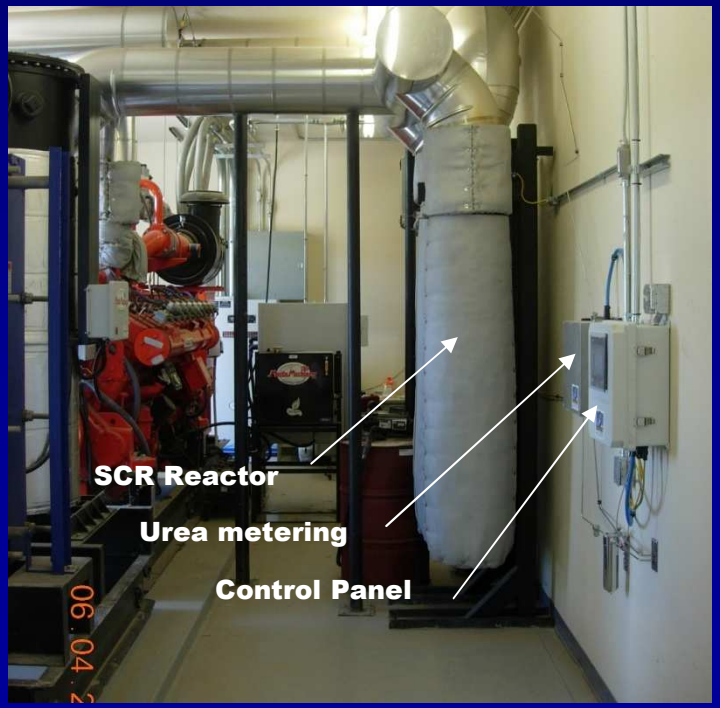
Other Compact SCR Applications

LOCOMOTIVE

- **EMD 12-710G3 engine**
  - 3000 hp
- **Durability demo under way**
- **71% NOx / 56% PM reduction so far**

DISTRIBUTED GENERATION

- **Meeting natural gas engine BACT on biogas**
  - 0.15 g/BHP-hr
  - 7500 hours so far
- **Targeting ARB DG standard**
  - 0.07 lb/MWH



EF&EE ICAT PROJECT
Compact SCR™ + DPF
on M/V Royal Star

- Funded in part by ARB Independent Clean Air Technology (ICAT) Grant No. 06-04
- Additional funding from EF&EE and Blue and Gold Fleet

M/V Royal Star

M/V Royal Star

- **650 Passenger Monohull Ferry**
- **Built 1969**
- **Owned and Operated by Blue and Gold Fleet, S.F.**
- **Sausalito/S.F. Ferry run**
- **Main engines**
  - Two Caterpillar 3412s
  - 520 hp @ 1800 RPM
  - Turbo / aftercooled
  - No emission control
- **Generator Engines**
  - Two Caterpillar D377s
  - 50 kW at 1800 RPM
  - Prechamber injection
  - Naturally aspirated

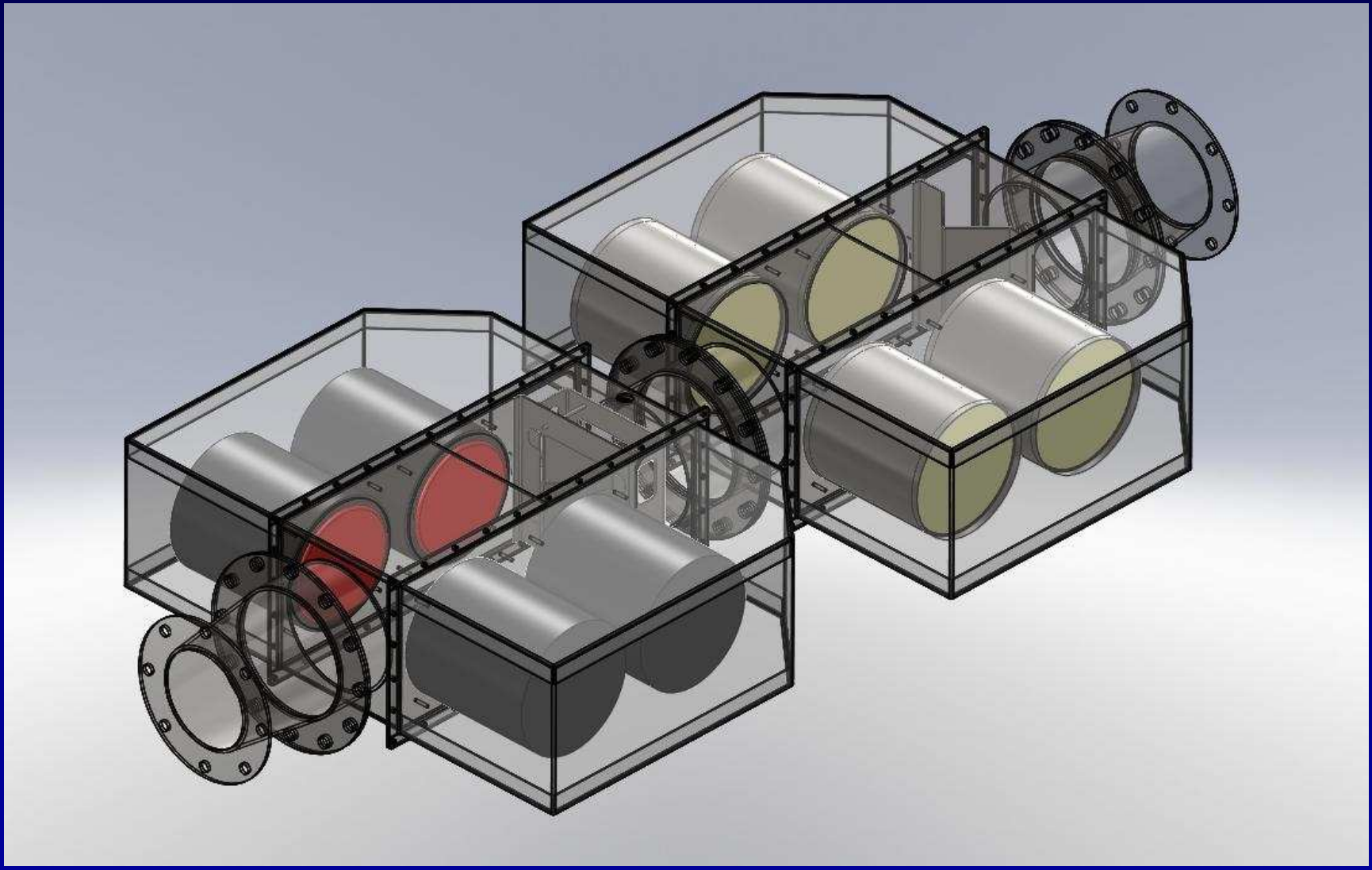
Diesel PM Filters and Harborcraft

- **Main engines see prolonged near-full power operation**
  - Promotes passive regeneration
  - Backpressure limits more stringent than trucks
- **Genset engines see very light load**
  - Active regeneration needed
  - Plenty of kW available
- **Engine replacement is very expensive**
  - Many engines are quite old, rebuilt in place
  - DPF retrofit a relatively economical option for PM compliance
  - Engine PM emission levels can be >> modern engines
- **Safety is even more critical**
  - PM filter blockage must not disable engine
  - Fire safety argues against diesel fuel burners
  - Exhaust piping is internal to vessel

Design Approach

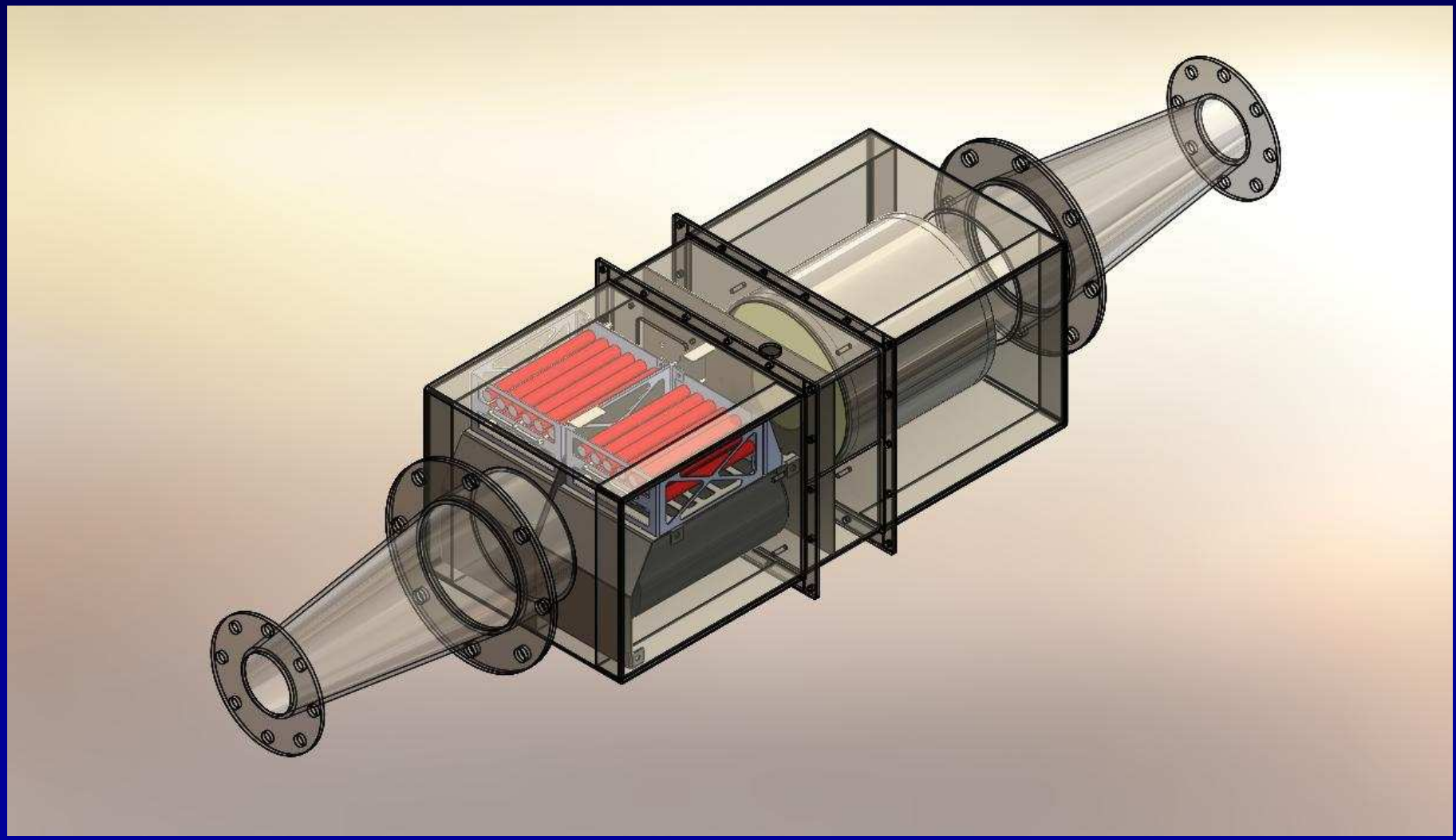
- **Main engines: passive regeneration with active backup using electric heaters**
- **Generators: active regeneration using electric heaters**
- **SCR: same as previous**
- **DPFs located upstream from SCR catalysts**
  - Protects SCR catalysts from soot
  - Maximizes potential for passive regeneration
  - Risk of thermal damage to SCR catalysts during regeneration
- **Multiple DPFs allow regenerating one at a time**
- **Pressure-actuated (spring+plate) bypass damper in each DPF assembly limits exhaust backpressure**

Main Engine DPF and SCR Catalyst Assemblies



Main Engine DPF and SCR Catalyst Assemblies

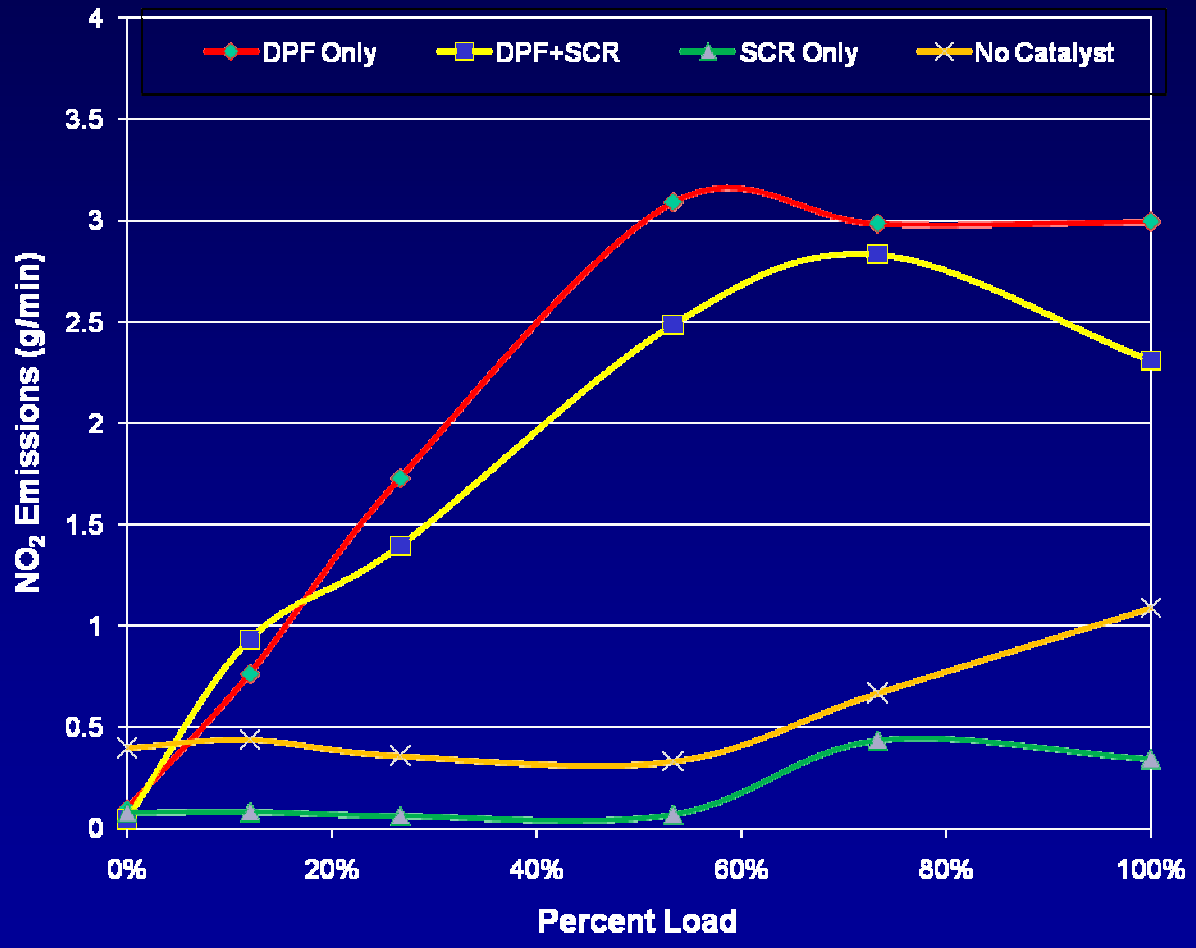
Generator Engine DPF and SCR Catalyst Assembly



Generator Engine DPF and SCR Catalyst Assembly

NO_2 Emissions with SCR Catalyst and DPF

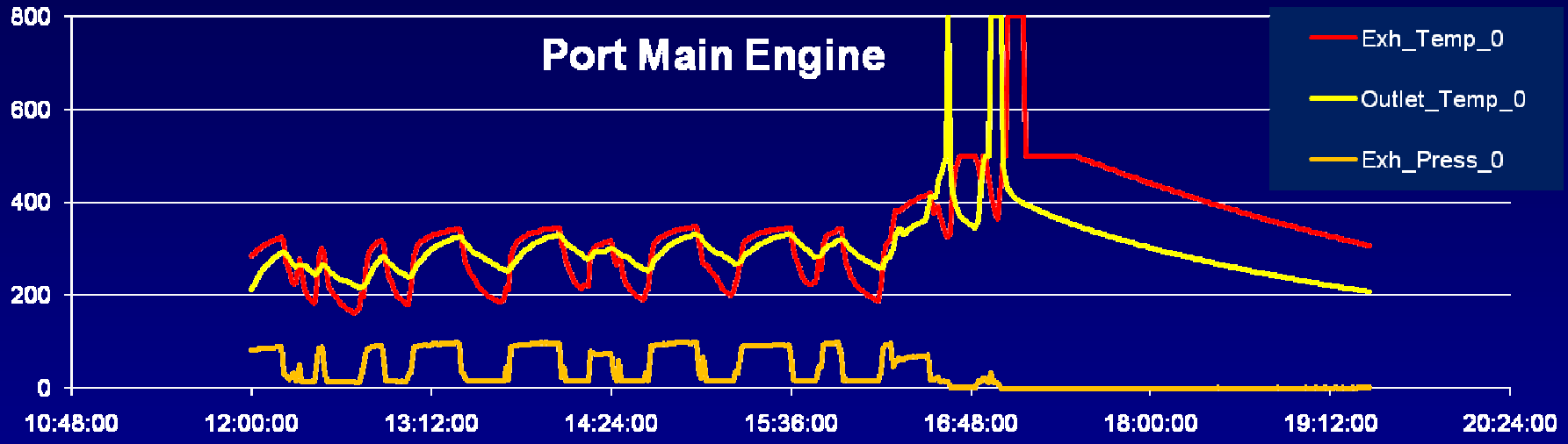
- Laboratory engine testing
- SCR Catalyst reduces NO_2 below baseline
- Aggressive DPF catalyst increases NO_2
- Two less-aggressive DPF catalysts selected for Royal Star demo

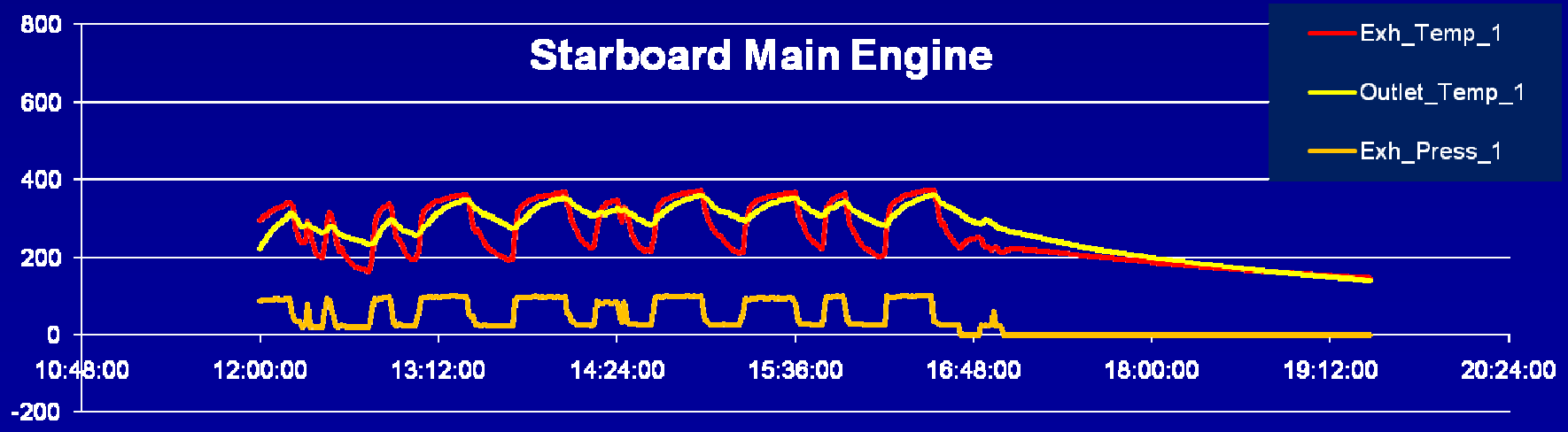


Operating Experience

- **Main engine SCR ~ 90% efficient**
- **Genset exhaust temperatures mostly too low for SCR**
- **Passive DPF regeneration less effective than expected**
  - Less-aggressive DPF catalyst for NO_2 control
  - High total PM and PM/NOx ratio
- **Active electric heaters <u>also</u> less effective than expected**
  - Unable to regenerate when engine is running
  - Regeneration successful with engine off and supplemental air
- **DPF bypass valves worked well**
  - Prevented exhaust backpressure from exceeding limits
  - Opening pressure reduced as springs annealed in exhaust heat
- **Overloading Port engine => uncontrolled regeneration**
  - Damage to SCR catalysts and bypass valve springs
  - Open bypass valve allowed SCR catalysts to clog with soot

Uncontrolled Regeneration Event
Port Engine – March 6, 2010





Emission Testing *in Situ*

- **EF&EE RAVEM™ portable emission measurement system**
  - Partial-flow CVS sampling
  - Complies with 40 CFR 1065
- **Extract and dilute exhaust gas sample**
- **Measure CO_2, CO, NOx, PM, (HC) concentrations**
- **Calculate grams of pollutant per kg of fuel by carbon balance**
- **Separately measure fuel flow (fuel tank on a scale)**
- **Multiply g/kg by fuel flow to get total mass**
- **Estimate power from fuel flow rate and BSFC to get g/kwh**

Starboard Main Engine Emissions with DPF Overloaded

	Emissions (grams per kWh)					
	PM		NOx		CO	
Load	Pre	Post	Pre	Post	Pre	Post
100%	0.341	0.188	5.201	0.801	1.122	0.054
75%	0.339	0.208	4.910	0.577	1.315	0.117
50%	0.418	0.096	5.256	0.517	1.355	(0.075)
25%	0.205	NA	5.260	NA	0.690	NA
EPA Wtd.	0.331	0.169	5.072	0.614	1.189	0.057

DPF bypass valve active at higher load

Next Steps

- **Replace damaged SCR catalysts on Port main**
- **Replace bypass valve springs with Inconel™**
- **Experiment with regeneration techniques**
  - Engine off / supplemental air
  - Others TBD
- **Demonstrate durability**
- **ARB verification**
- **Commercial sales**

Harborcraft Retrofit Benefits

- Relieve constraints on port traffic posed by air pollution limits
- Reduce pollutant emissions and mitigation costs in dredging, drilling, and similar operations
- Lower cost of compliance with harborcraft rule, thus improving the competitiveness of California ports
- Reduce health costs to workers and the general public from exposure to diesel exhaust

Cost-Effectiveness

- **Cost-effectiveness threshold for Carl Moyer Program is $16,400 per ton of combined emissions**
  - Calculated as the sum of NOx + HC + (20 x PM)
  - Rough estimate of marginal social cost / ton to reduce air pollution
- **For a typical harborcraft (e.g. Royal Star)**
  - NOx ~ 10 TPY PM ~ 0.25 TPY Wtd sum ~ 15 TPY
  - 90% reduction yields 13.5 TPY
  - Cost ~ $200,000 initially + $25,000 / year
  - Cost/effectiveness ~ $3,500 / wtd ton
- **Social cost saving from retrofitting a typical harborcraft instead of the reaching the same emission reduction elsewhere (at assumed marginal cost) ~ $174,000 per year**

Conclusions

- **Compact SCR™ is well-demonstrated and commercially available for harborcraft**
  - 95 to 99% NOx reduction / 50-60% PM reduction at cruise
  - Tier 2 engines to Tier 4 emission levels
  - ARB verification pending ARB acceptance of *in-situ* emission measurements
- **Compact SCR + DPF systems are in testing**
  - Expect to bring most Tier 0 engines to Tier 4 emission levels
  - Economical alternative to repowering
- **Retrofitting emission controls to harborcraft (and other long-lived diesel vehicles) is cost-effective and has important social benefits**