

Emission ABC's: Formation, Reduction, & Control + Leading Engine Technologies

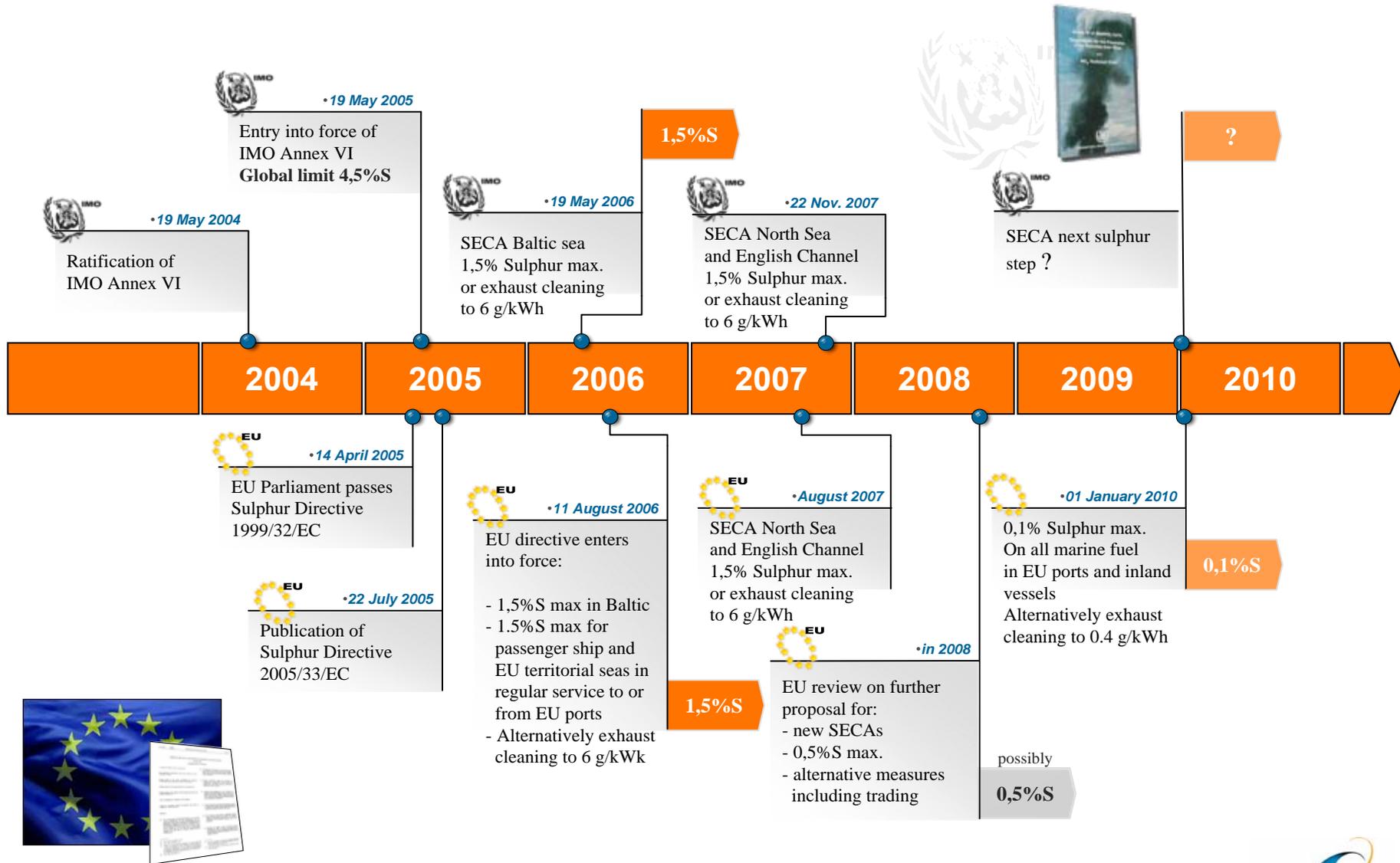
**SNAME Climate Change Symposium
Linthicum Heights, MD
February 16, 17 2010**

**Presenter John Hatley PE
Americas VP Ship Power
Wartsila North America
john.hatley@wartsila.com**

Agenda

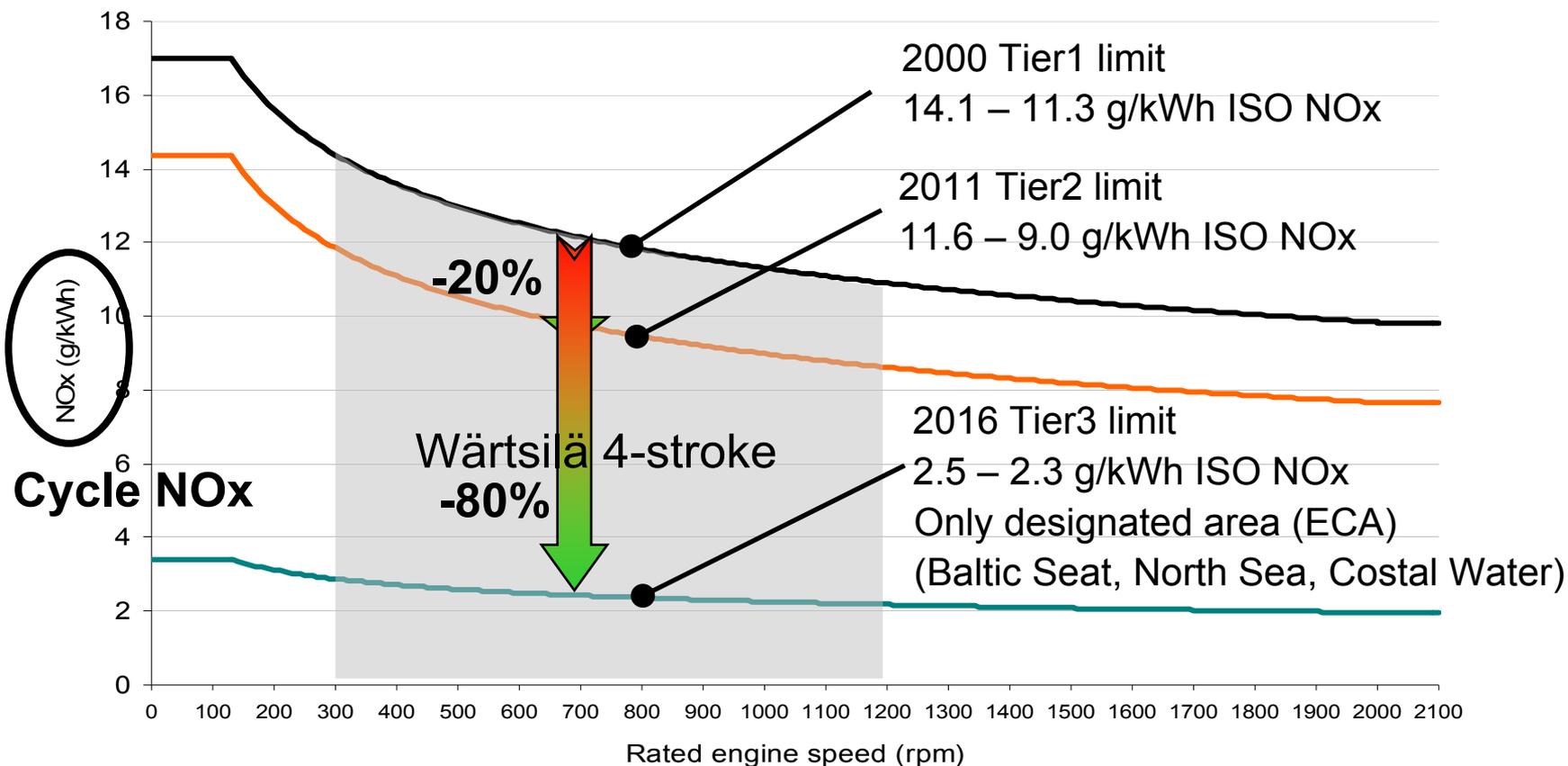
- Current Legislation
- Exhaust Components
- Overview Formation, Reduction, Control Technologies
- Leading Engine Technologies
 - Primary Wet / Dry Means
 - Secondary Wet / Dry Means
- Case Example
- Value Mapping Analysis
- Summary

IMO & EU



Current Legislation

Revised Marpol Annex VI (9.10.2008)



Cycle NOx

Cycle\Load	NOx weight factor				
	100	75	50	25	10
E2/E3	29%	55%	11%	5%	0%
D2	11%	40%	32%	16%	2%

Tier 3 load point limit < 1.5
NOx cycle average

US Implementation MARPOL Annex VI

**President Bush Signed
Maritime Pollution Prevention Act 2008
21 July 2008**

Act to Prevent Pollution from Ships “ APPS”

**EPA retains sole authority over US Vessels
Engine Certifications for Annex VI**

USCG enforcement provisions

Annex VI Implementation

**US Ratification Instrument
as Party MARPOL Provided IMO
8 October 2008**

**Enforcement US MARPOL commences
8 January 2009**

US / Canada Emission Control Area “ ECA ”

Submitted IMO 27 March 2009

200 Nautical Miles off Coastlines

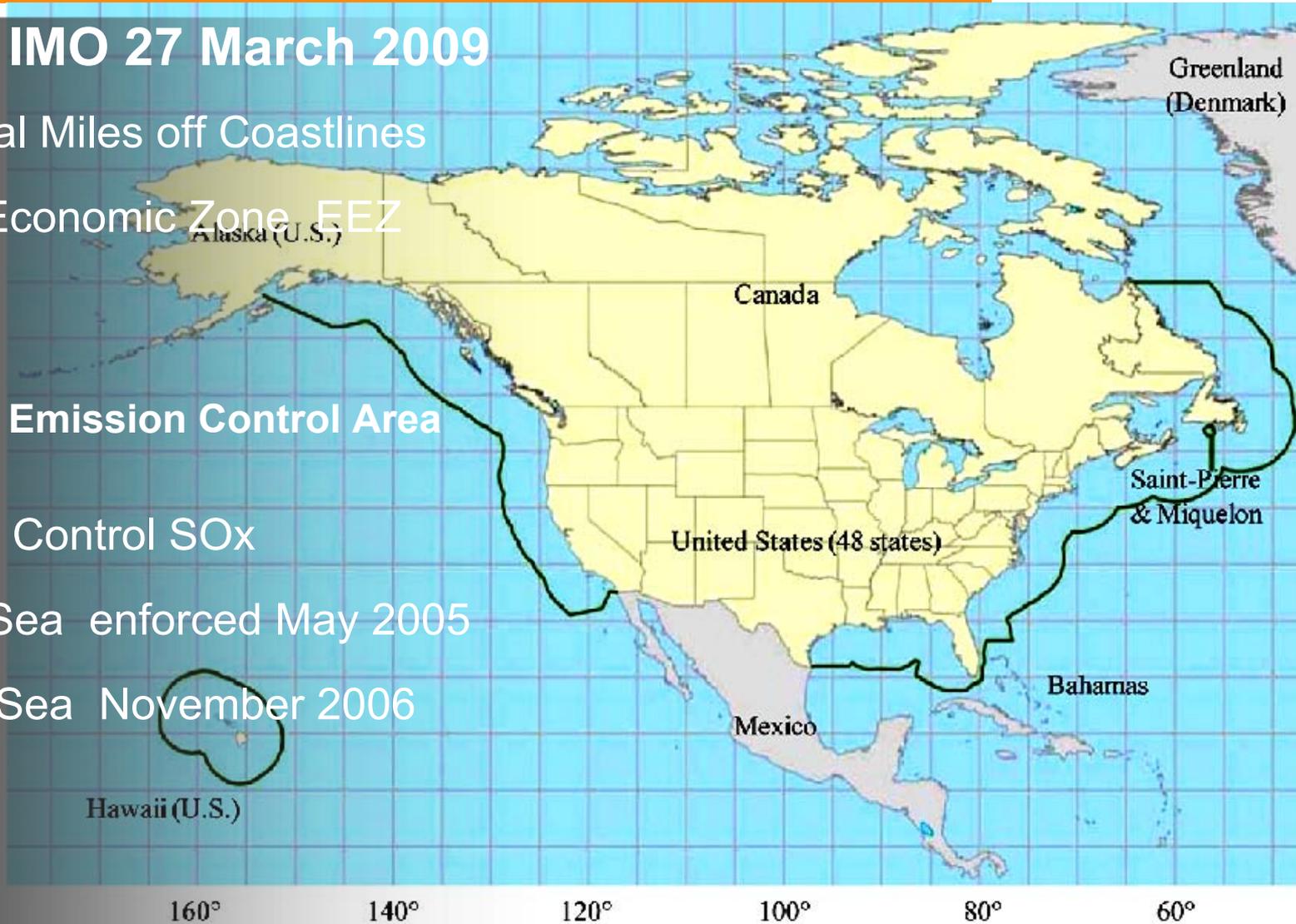
Exclusive Economic Zone EEZ

History Sulfur Emission Control Area
SECA

Exclusively Control SO_x

1st Baltic Sea enforced May 2005

2nd North Sea November 2006



USCG Enforcement MARPOL Annex VI

8 January 2009

US & Foreign Flag Vessels US Waters

US Flag Verification

International Air Pollution Prevention Certificate IAPP
Demonstrates Compliance Annex VI
Not required IF

Keel laying before 18 July 1994 & Tonnage < 400 GT

Keels Before 8 January 2009

IAPP required first dry-docking or by 8 January 2012

Keels After 8 January 2009

Certificate required in Service valid 5 years

Associated Engine International Air Pollution Certificate
EIAPP Issued by EPA



Commandant
United States Coast Guard

2100 2nd Street, S.W.
Washington, DC 20593-0001
Staff Symbol: CG-543
Phone: (202) 372-1251
Fax: (202) 372-1917

16711
CG-543 Policy Letter
09-01

FEB - 4 2009

From: E. P. Christensen, CAPT
COMDT (CG-543)

To: Distribution

Subj: GUIDELINES FOR ENSURING COMPLIANCE WITH ANNEX VI TO THE
INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION
FROM SHIPS (MARPOL) 73/78; PREVENTION OF AIR POLLUTION FROM SHIPS

Ref: 210001CG-543/W/SP/09-01/DC 301904 Z DEC 08

1. Purpose. To provide guidance to ensure compliance with the provisions of MARPOL 73/78, Annex VI for U.S. flagged vessels and all foreign flagged vessels 400 Gross Tons (ITC) and above that engaged on international voyages and call on U.S. ports.

2. Directives Affected. MOC Policy Letter 05-02 is cancelled effective 08 January 2009.

3. Action. As discussed in reference (a), MARPOL 73/78, Annex VI entered into force for the United States on 8 January 2009. U.S. Coast Guard Commanders/OCMIs shall direct their staffs to use the guidance in enclosures (1) and (2) during U.S. flag vessel inspections and Port State Control examinations respectively, to ensure all U.S. inspected and uninspected vessels and all foreign flag vessels over 400 Gross Tons operating in U.S. waters comply with the provisions of MARPOL 73/78, Annex VI. OCMIs should bring this policy to the attention of appropriate individuals in the marine industry.

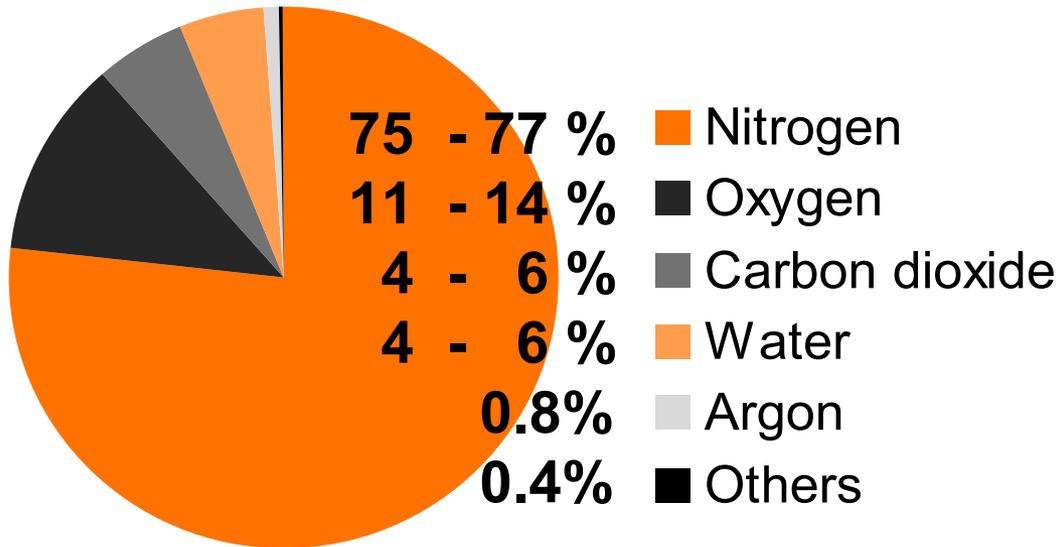
4. Background. MARPOL 73/78, Annex VI outlines international requirements for vessel air emissions and pollution prevention measures for vessels. On October 8, 2008, the United States deposited an instrument of ratification with the International Maritime Organization for Annex VI of the International Convention for the Prevention of Pollution by Ships, 1973 as modified by the Protocol of 1978 (MARPOL 73/78). Under the terms of the convention, nations that are

Agenda

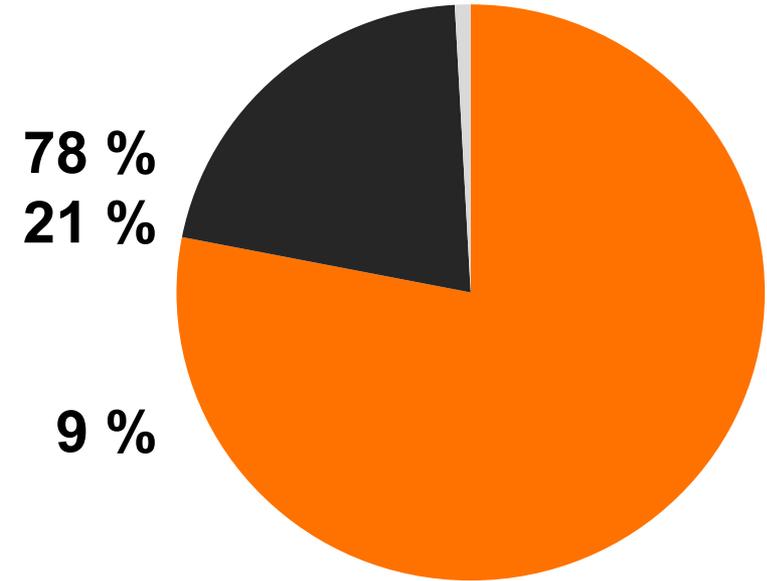
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Gas Volumetric Composition

Exhaust



Ambient Air



Exhaust Gas Components are similar to those of ambient air

Components

Nitrogen oxides	NO_x	Relatively high, unless controlled
Sulphur oxides	SO_x	Fuel choice related
Carbon monoxide	CO	Good combustion lowers
Total Hydrocarbons	THC	Good combustion lowers
Volatile Organic Compounds	VOC	Good combustion lowers
Particulate Matter	PM	Relative low at steady state ops Fuel ash and sulphur content influence
Smoke	Opacity	Related to low load (<50% load) Start-up and fast load increase

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Formation & Reduction

Emission	What	Cause	Formation	Reduction
Nitrogen Oxide	Nitrogen and oxygen dissociation react forming nitric oxide.	Combustion zone dissociation reactions form Nitric Oxide NO.	Exponentially temperature dependent, also dependent on residence time	Lower peak combustion temperature.
"NO ₂ "		Flame region reactions yield Nitrogen Dioxide NO ₂		Reduce combustion time duration. Inhibit dissociation.
Particulate Matter, Soot	Carbon soot mixture plus some volatile organic and sulfate compounds.	Later combustion oxidizes most carbon particles.	Temperature, combustion residency time, and oxidation availability.	Improve mixing. Reduce fuel sulfur content. Exhaust catalyst treatment. Shorten ignition delay. Remove crevices.
"PM"		Organic fraction from unburned fuel and lube oil consumption. Sulfate dependent upon sulfur proportion in fuel.	After-cooling and exhaust air dilution foster sulfate PM and volatile organic	
Hydrocarbon	Fuel and trapped lubricant.	Crevice traps in top ring land and injector sac promote incomplete combustion mixing.	Cold start white smoke.	Exhaust catalyst treatment. Shorten ignition delay. Remove crevices. Reduce sac volume. Eliminate secondary injections.
"HC"		Excessive swirling promote fuel related overmixing during ignition delay.		

Emission engineering first principle fundamentals form root basis

Control Technologies

What	How	Means	Target	Effectiveness
Charge Air Cooling	Low temperature cooling "LT"	Lowers manifold air temperature to reduce combustion temperature and improve charge air density.	NO_x	Lower NO _x 5% - 7% NO _x per 10C chilling intake air, improved fuel economy.
Fuel Management	Rate Shaping	Brief initial fuel charge restrains rapid pressure rise and promotes stable controlled flame.	NO_x	Improved NO _x – fuel consumption trade-off
	Multiple Injections	Electronic controlled high pressure multiple burst injections key delay preceding final pulse and duration.		Improved NO _x – fuel consumption trade-off
	Common Rail	Sustained ultra high fuel pressure removes compromises; expands operational range.		Improved NO _x – fuel consumption trade-off
Injection Timing Retard	Delay Combustion start.	Aligns heat release to expansion stroke facilitating lower combustion temperatures	NO_x	Lower NO _x . Negatives; higher fuel consumption, HC, CO, and PM.
	Shorter premix phase.	Concurrent with lower combustion temperature and pressures.		

Engineering fundamentals drive target technologies

Control Technologies

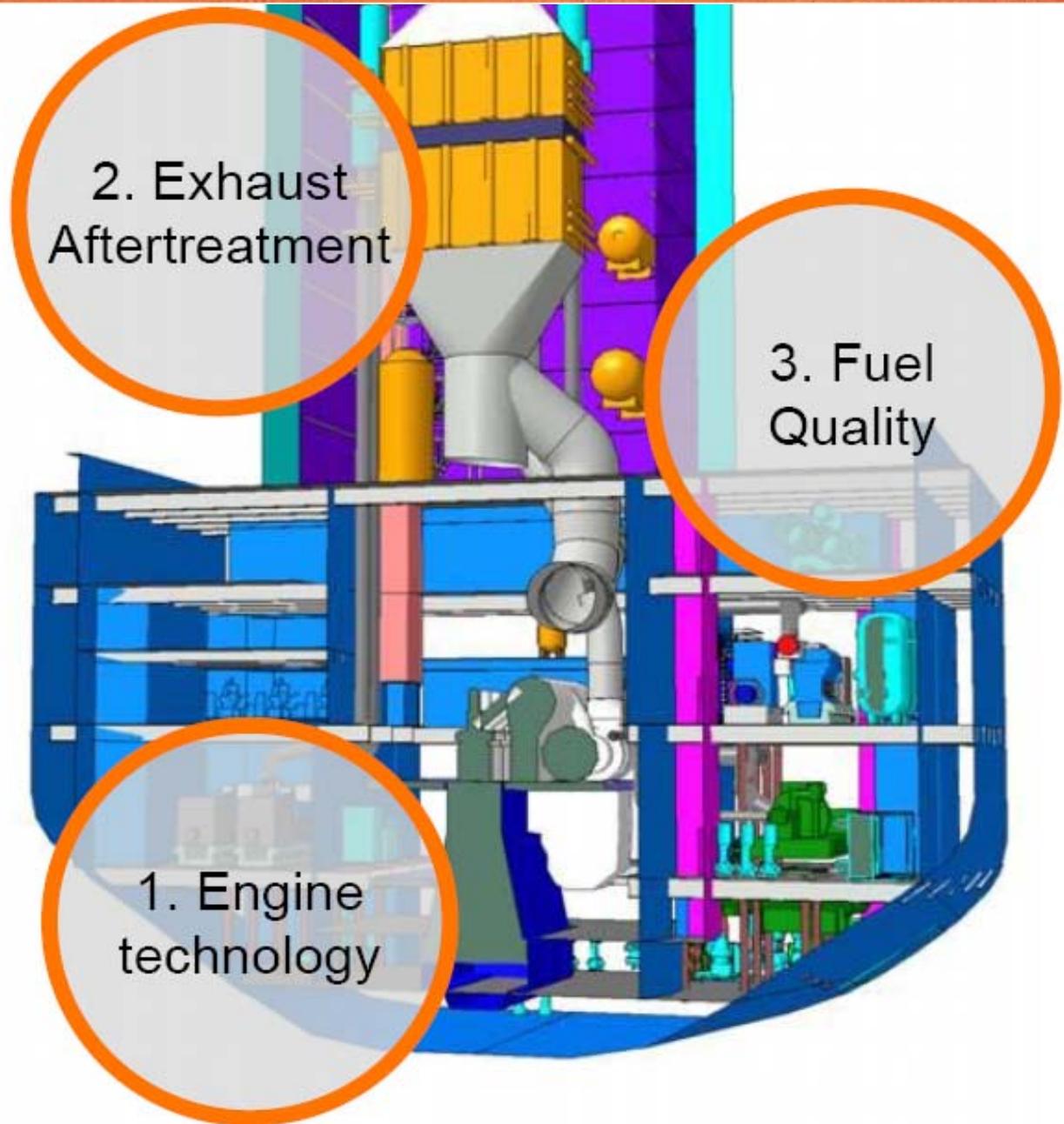
What	How	Means	Target	Effectiveness
Exhaust Gas Recirculation	Reintroduces exhaust gases to cylinder.	Increased presence carbon dioxide and water vapor reduces combustion temperatures.	NO_x	Lower NO _x Negatives: higher fuel consumption resulting from longer burn duration and pumping work.
Induced Mixing Turbulence	High Injection Pressure	Boosts fuel spray velocity for improved coverage	HC, PM, Smoke	Tradeoff: increased NO _x for gains elsewhere
	Multiple Split Injection	Added dwell significantly reduces particulates and breaks up soot.		
	Enhanced Swirl	Improved intake valve and piston bowl designs extend swirl time.		
Selective Catalytic Reduction "SCR"	Catalytic Reduction	Reducing agent (ammonia, urea) injected into exhaust is channeled through a catalyst.	NO_x	Lower NO _x to 90%, effective over narrow power range; durability requires low sulfur fuel
Water Injection	Fuel Emulsification	Water emulsification to reduce combustion temperature.	NO_x	Lower NO _x up to 50%
	Direct Injection	Parallel water and fuel injection into Cylinder – acts as diluent.		
	Air Humidification	Water injection into combustion air – acts as diluent.		

Engineering fundamentals drive target technologies

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NOx reduction technologies

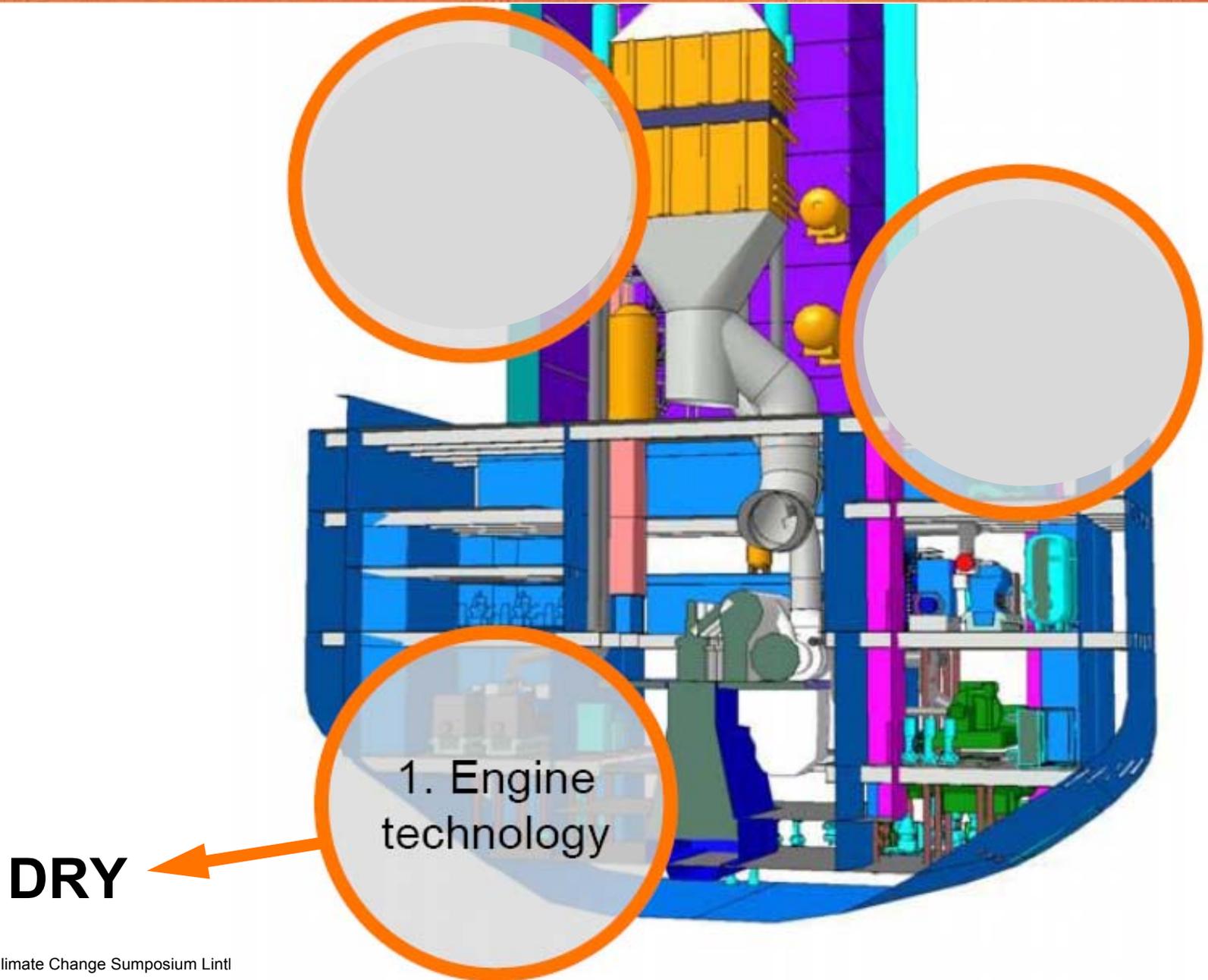


Emissions Control Technologies

		NOx	SOx	PM	Smoke
<i>primary</i>	Low NOx tuning	★★			
	VIC	★		★	★★
	Common Rail	★★		★	★★★★
		★			
		★★			
		★★			
<i>wet</i>	WETPAC -H	★★★★		★	
	WETPAC -DWI	★★★★★		★	
	WETPAC -E	★★★★		★	
<i>secondary</i>	SCR	★★★★★		★	
	Scrubber	★	★★★★★		★
	ESP	★		★★★	★
<i>conv.</i>	Switching to light fuel		★★★★★	★	
	Conversion to gas	★★★★	★★★★★	★★★★	★★



NOx reduction technologies



Low NO_x Engine Tuning

NO_x
★ ★

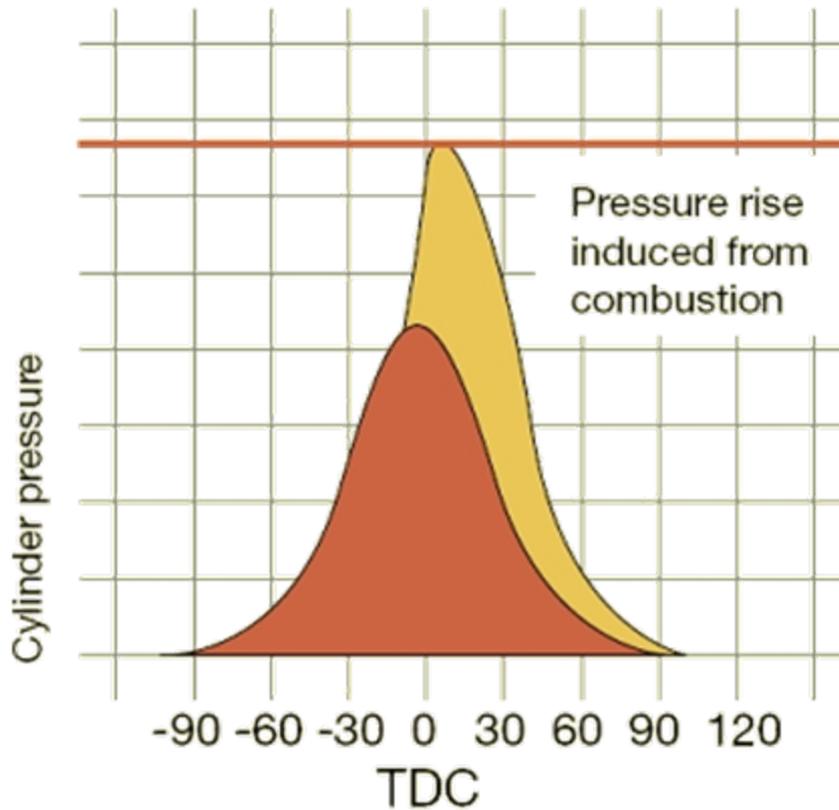
SO_x

PM

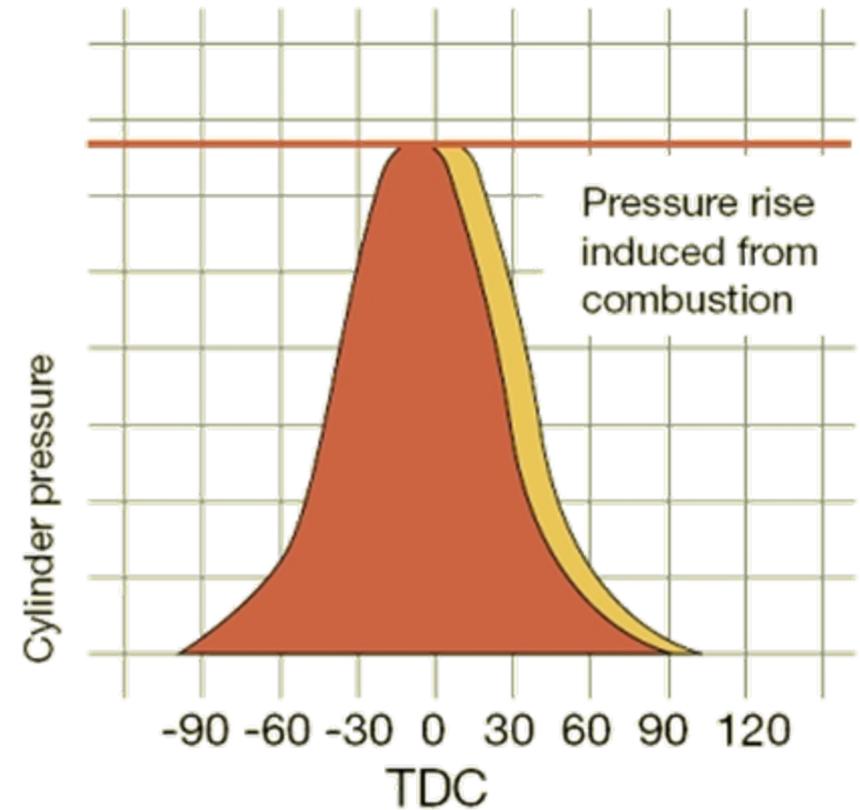
Smoke

Application: All fuel types
NO_x reduction potential typically: 30-50%

Conventional design
Engine maximum firing pressure



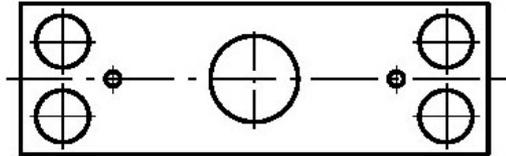
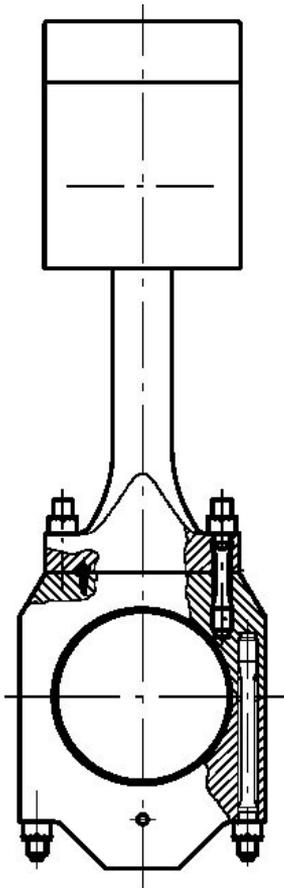
Low NO_x design
Engine maximum firing pressure



Increased Compression Ratio

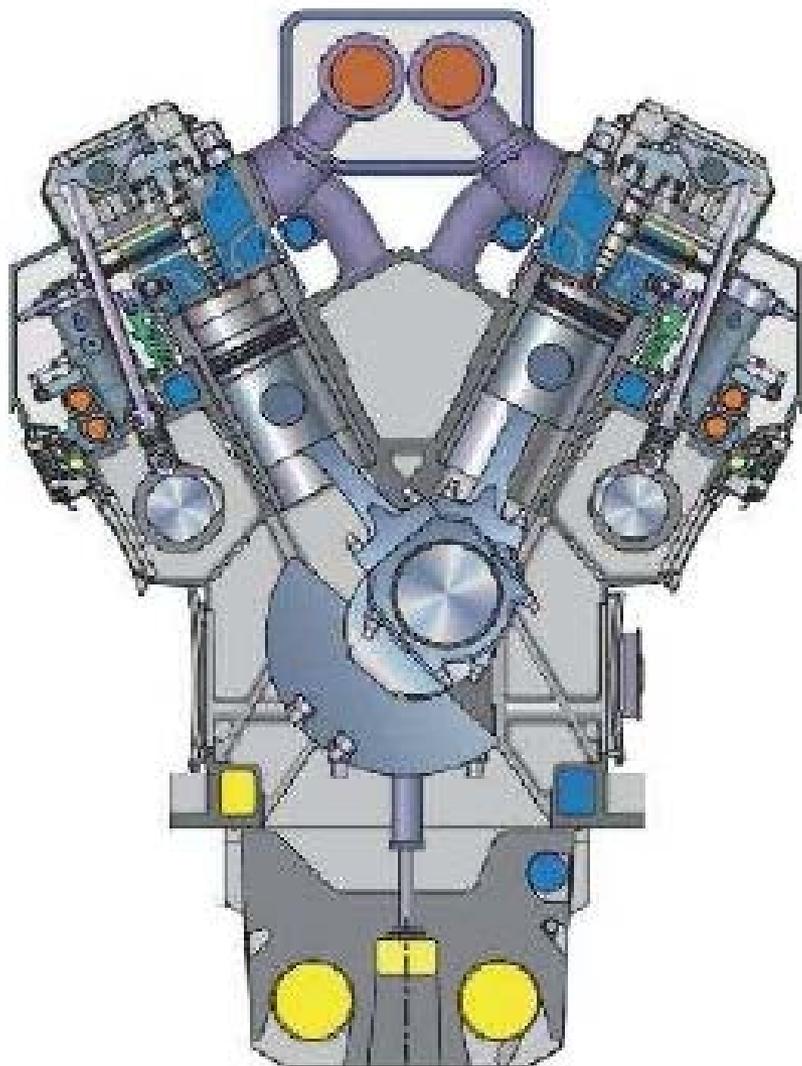
Longer connecting rods or shims

Fuel pumps and injection valves settings to retard fuel injection & increase opening pressure of fuel injection.



Optional

- Piston machined clearance for inlet and exhaust valves.
- New cylinder liners and anti/polishing rings matched to increased compression ratio.
- Turbocharger specification with air waste gate to optimize charge air pressure.
- Modification of the charge air cooling system to reduce charge air temperature.



Low NOx Technology

Later fuel injection start

High compression ratio

Optimized combustion chamber

Fuel system:

4-stroke: Fuel rate shaping
(CR Technology)

2-stroke: Flexible fuel injection pattern
(RT-flex Technology)

Valve system

4-stroke: Early inlet valve closing
(Miller timing)

2-stroke: Flexible (late) exhaust valve
closing (RT-flex Technology)

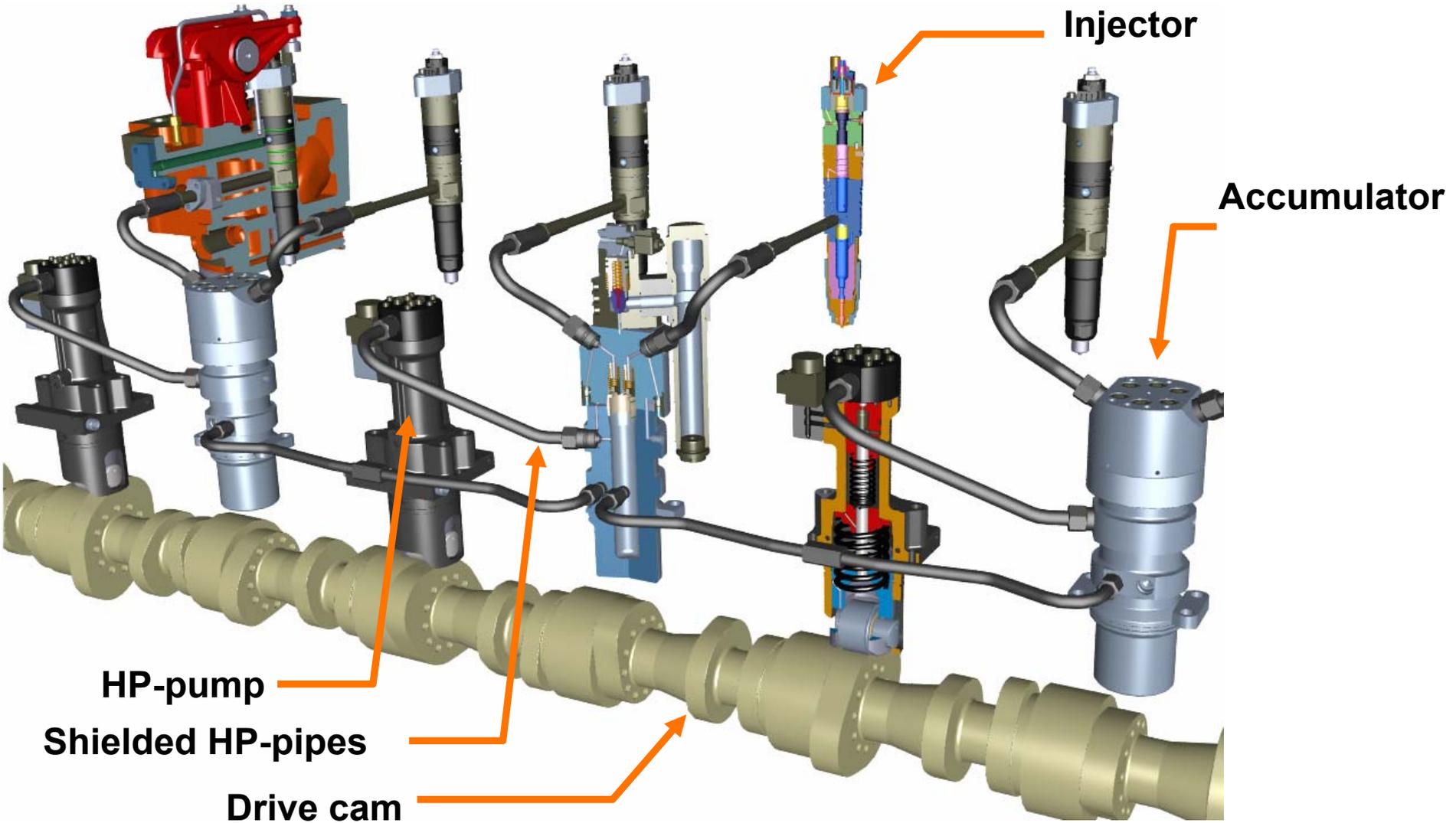
Common Rail, 4-stroke

NOx
★★★

SOx

PM
★

Smoke
★★★★★



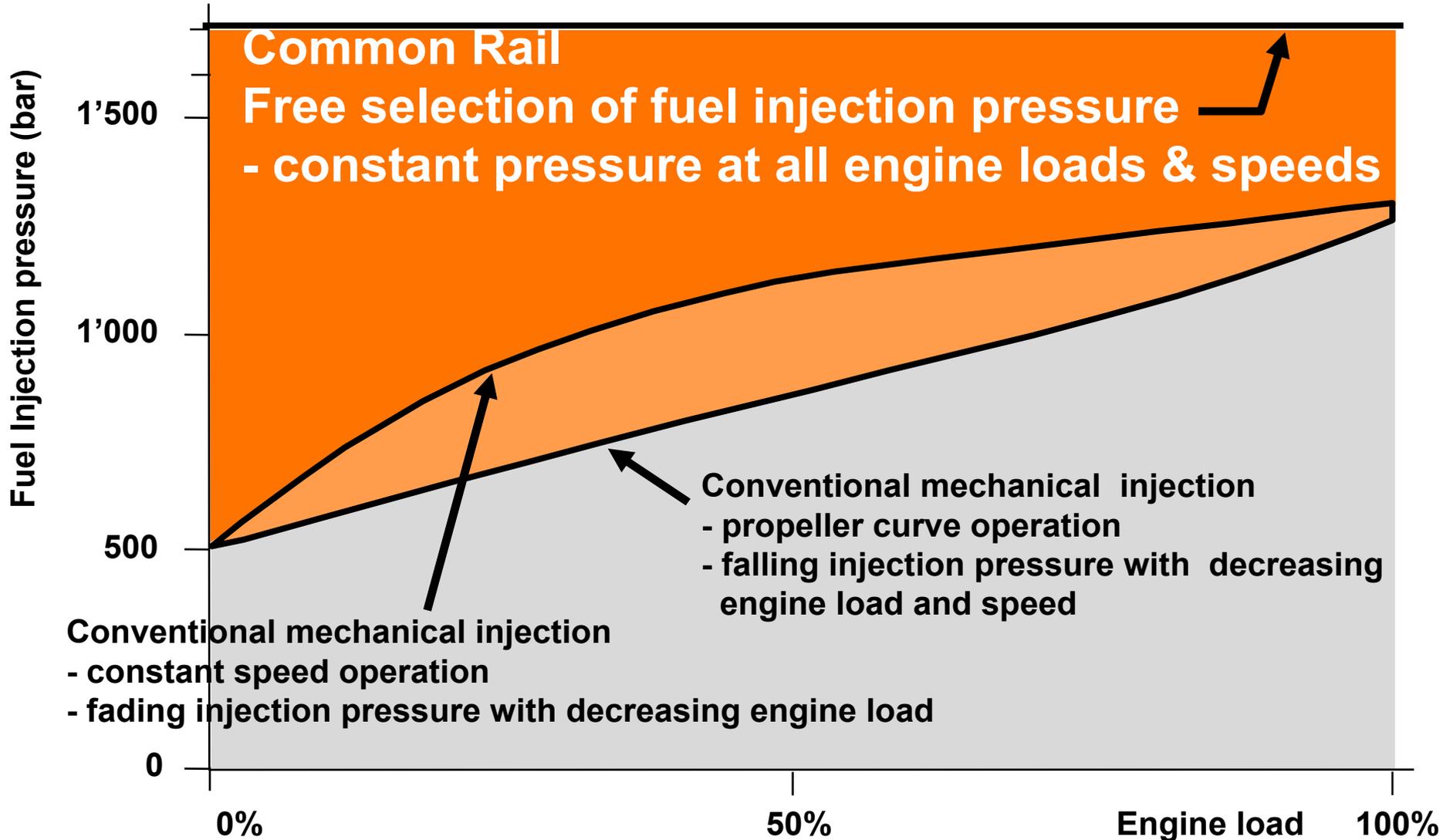
Fuel Injection

NOx
☆☆☆

SOx

PM
☆☆

Smoke
☆☆☆☆



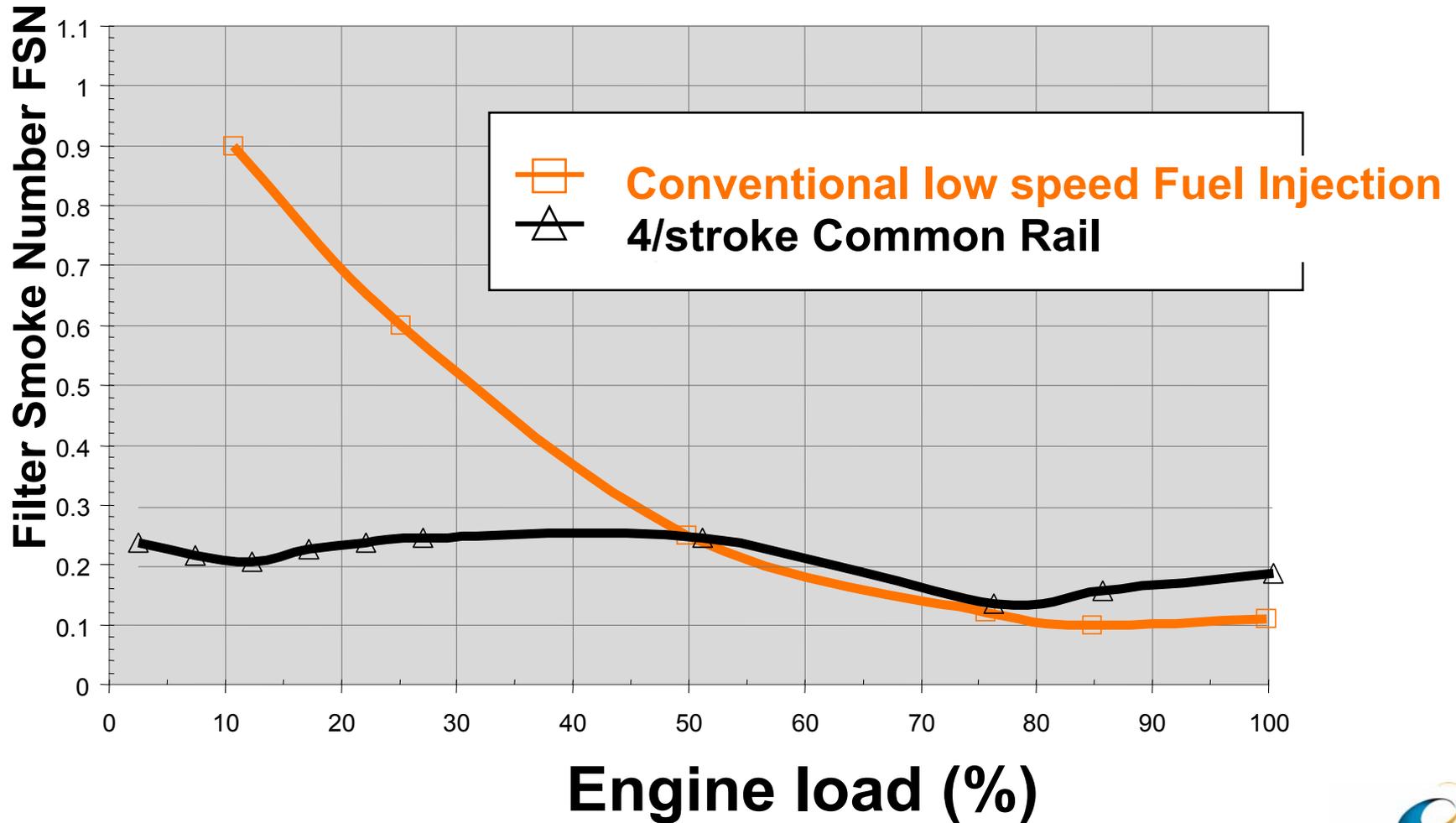
Common Rail 4-stroke

NOx
☆☆

SOx

PM
☆

Smoke
☆☆☆☆



Common Rail, 2-stroke

NOx
☆☆

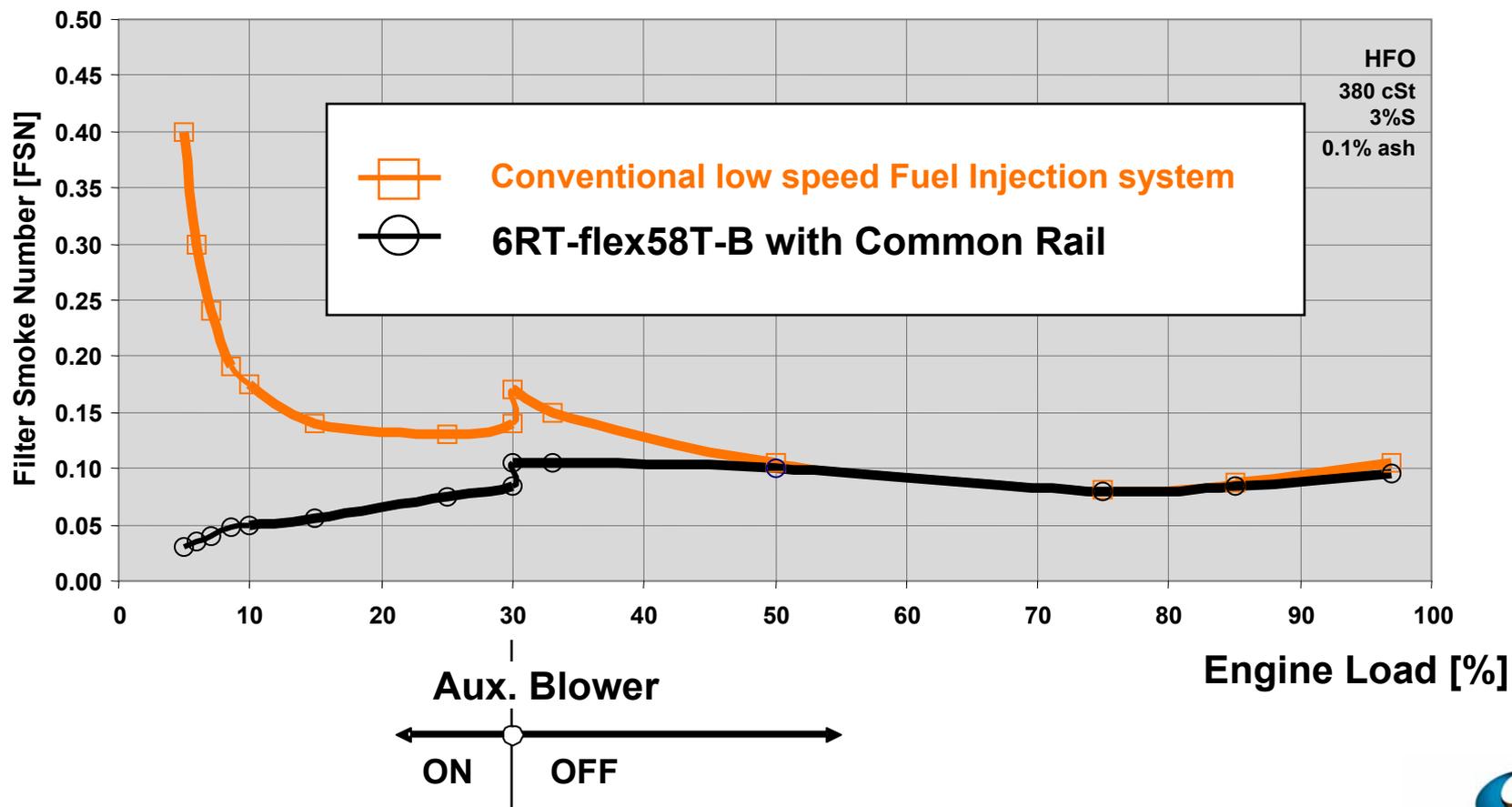
SOx

PM
☆

Smoke
☆☆☆☆

Near Smokeless operation throughout the load range

Sulzer 6 RT-flex58T-B M/V Gypsum Centennial



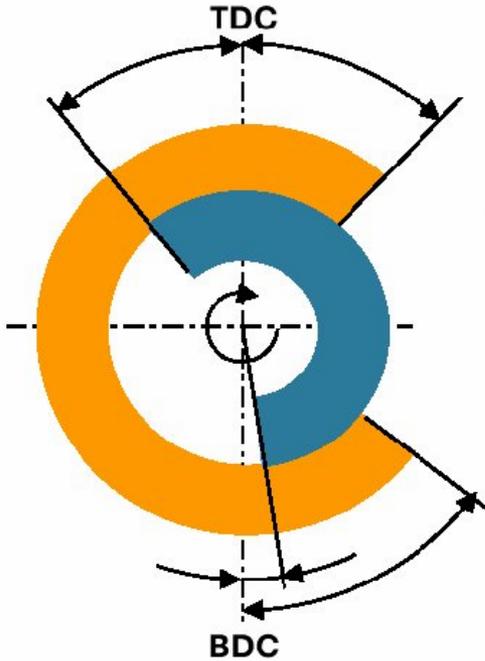
Variable Inlet Valve Closing "VIC"

NOx
★

SOx

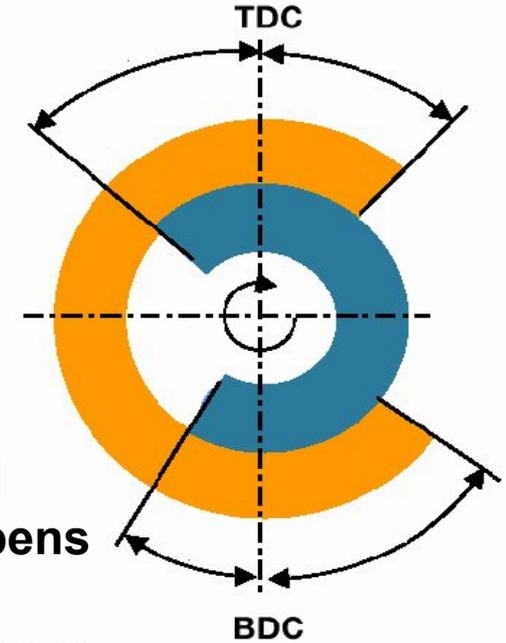
PM
★

Smoke
★★



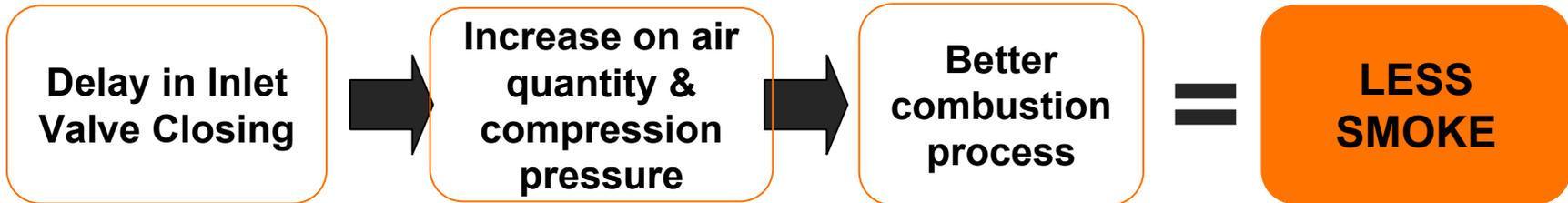
Standard Miller Timing

- Inlet Valve opens @ 35° bTDC
- Inlet Valve closes @ 16°±1 bBDC



VIC Timing

- Inlet Valve opens @ 35° bTDC
- Inlet Valve closes @ 16°±1 aBDC



Delayed timing is actuated only below 50%load
Over 50% the system returns to standard Miller Timing

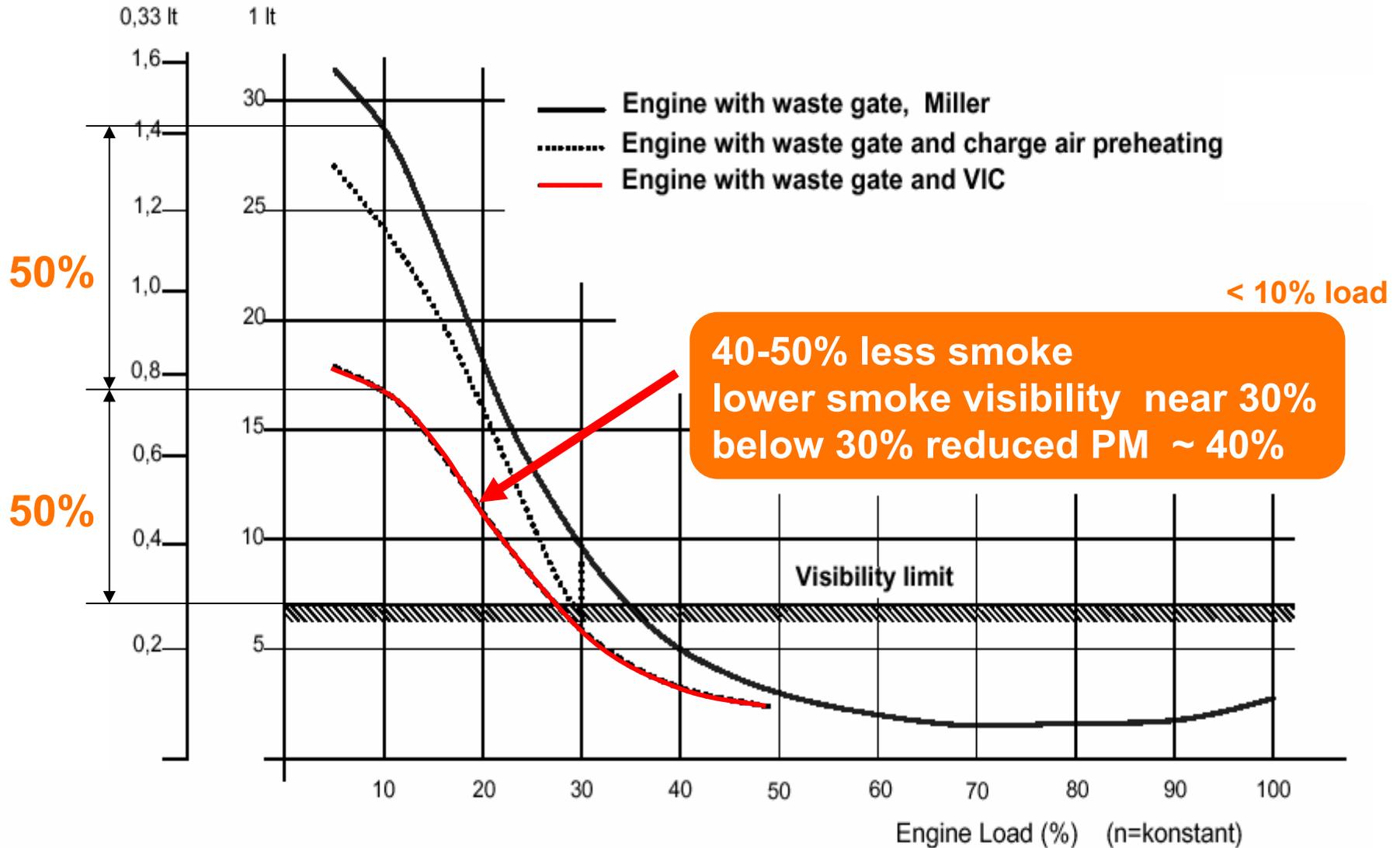
Variable Inlet Valve Closing

NOx
★

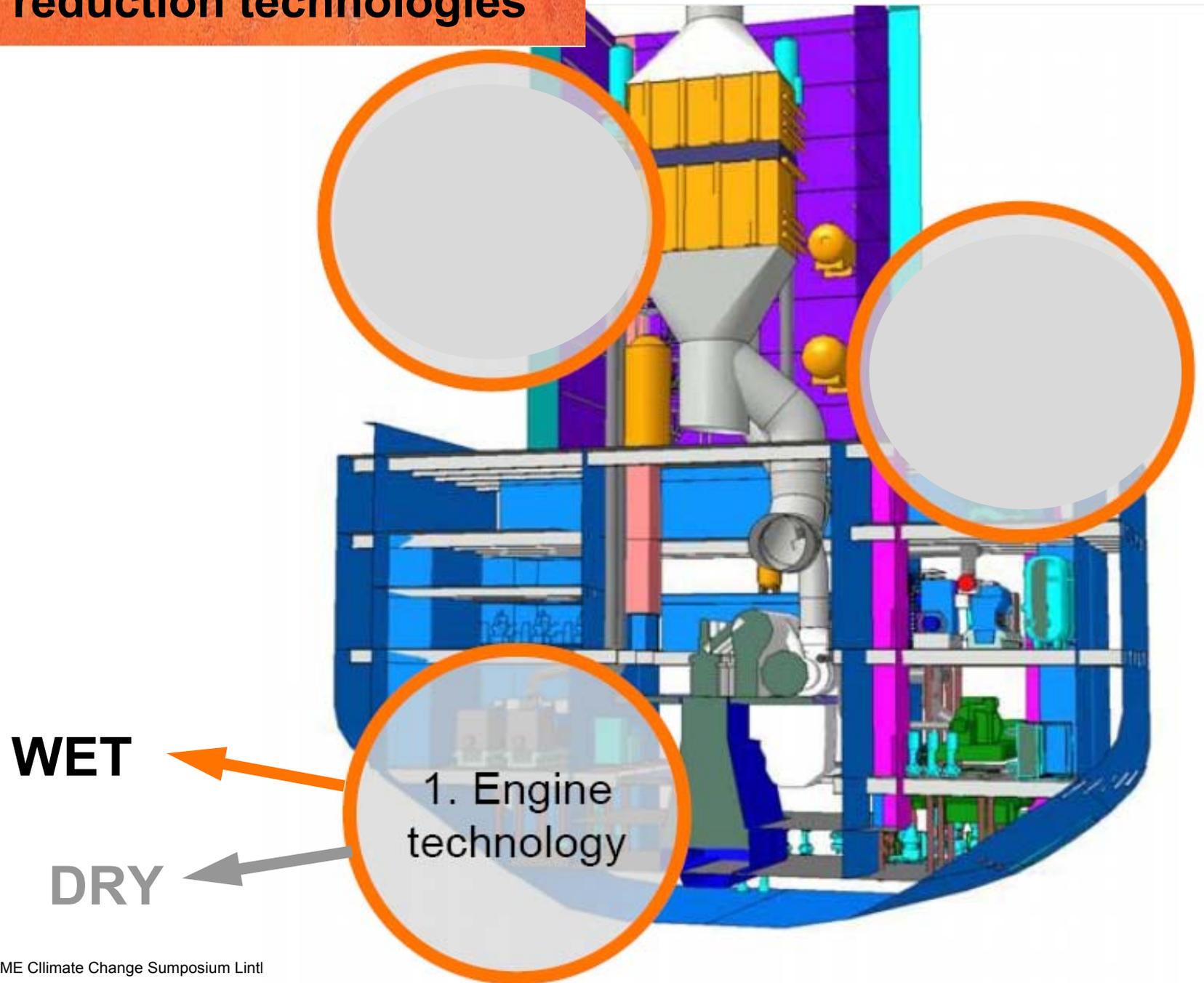
SOx

PM
★

Smoke
★★



NOx reduction technologies



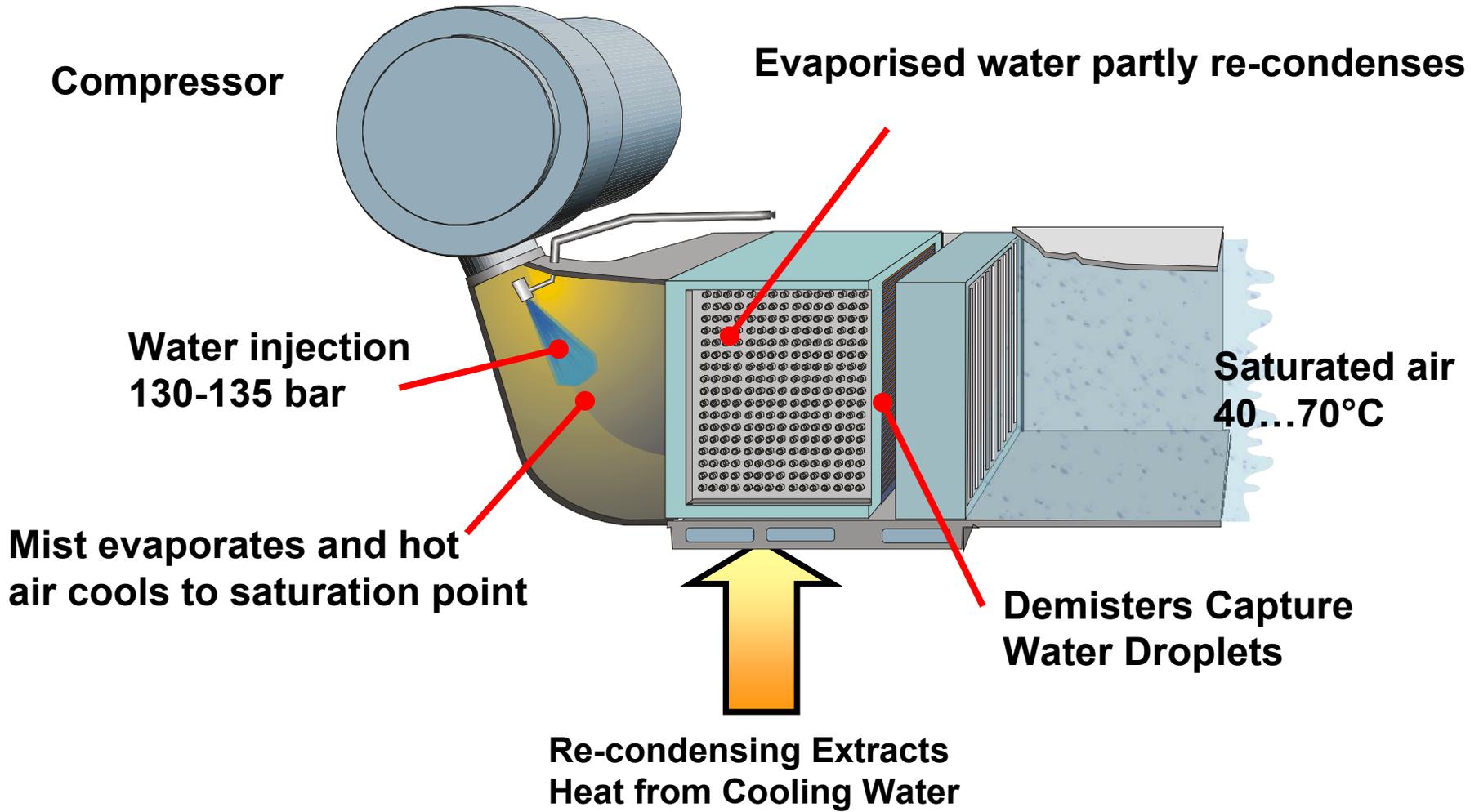
Air Humidification

NOx
★ ★ ★

SOx

PM
★

Smoke



Direct Water Injection

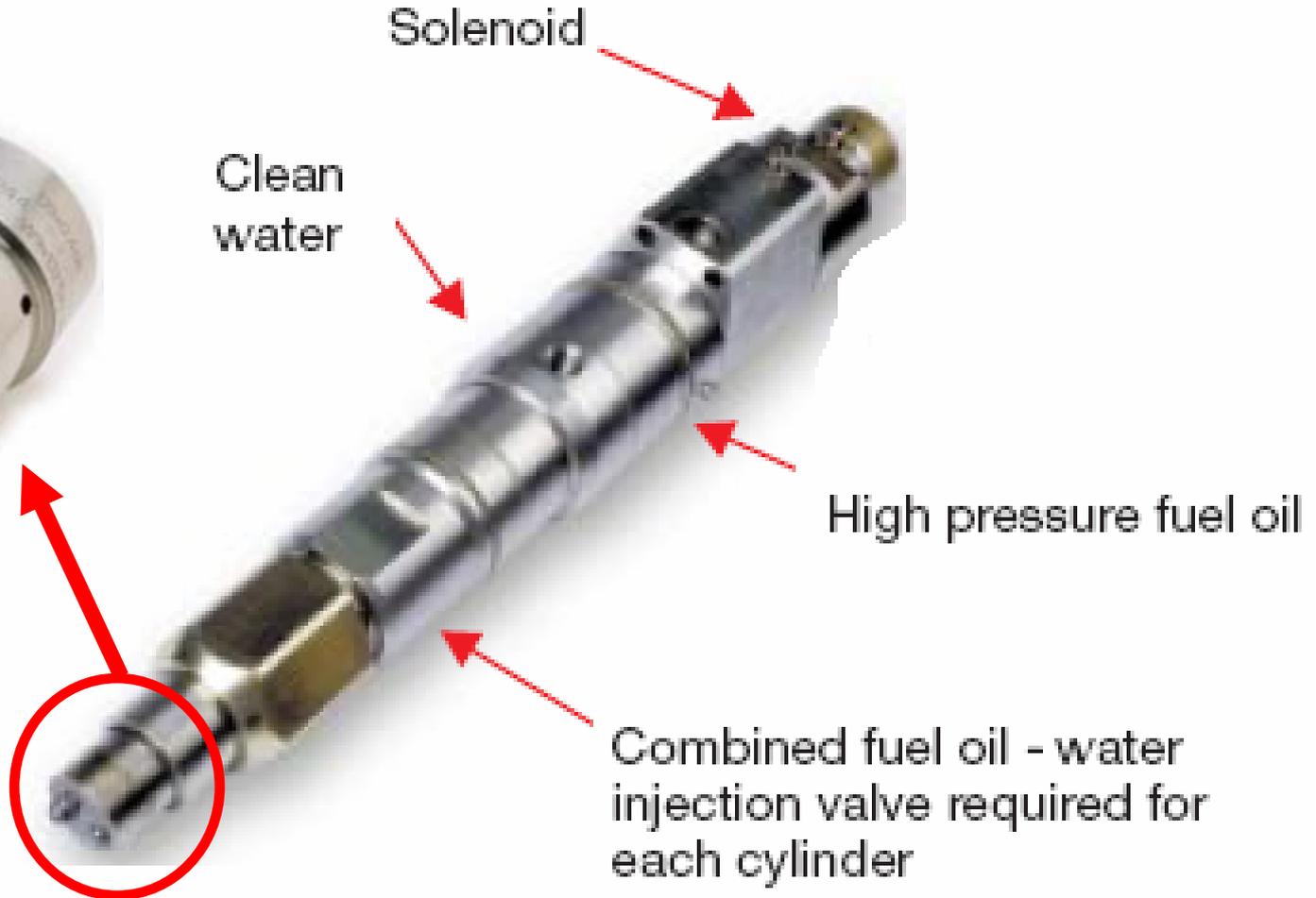
NOx
★ ★

SOx

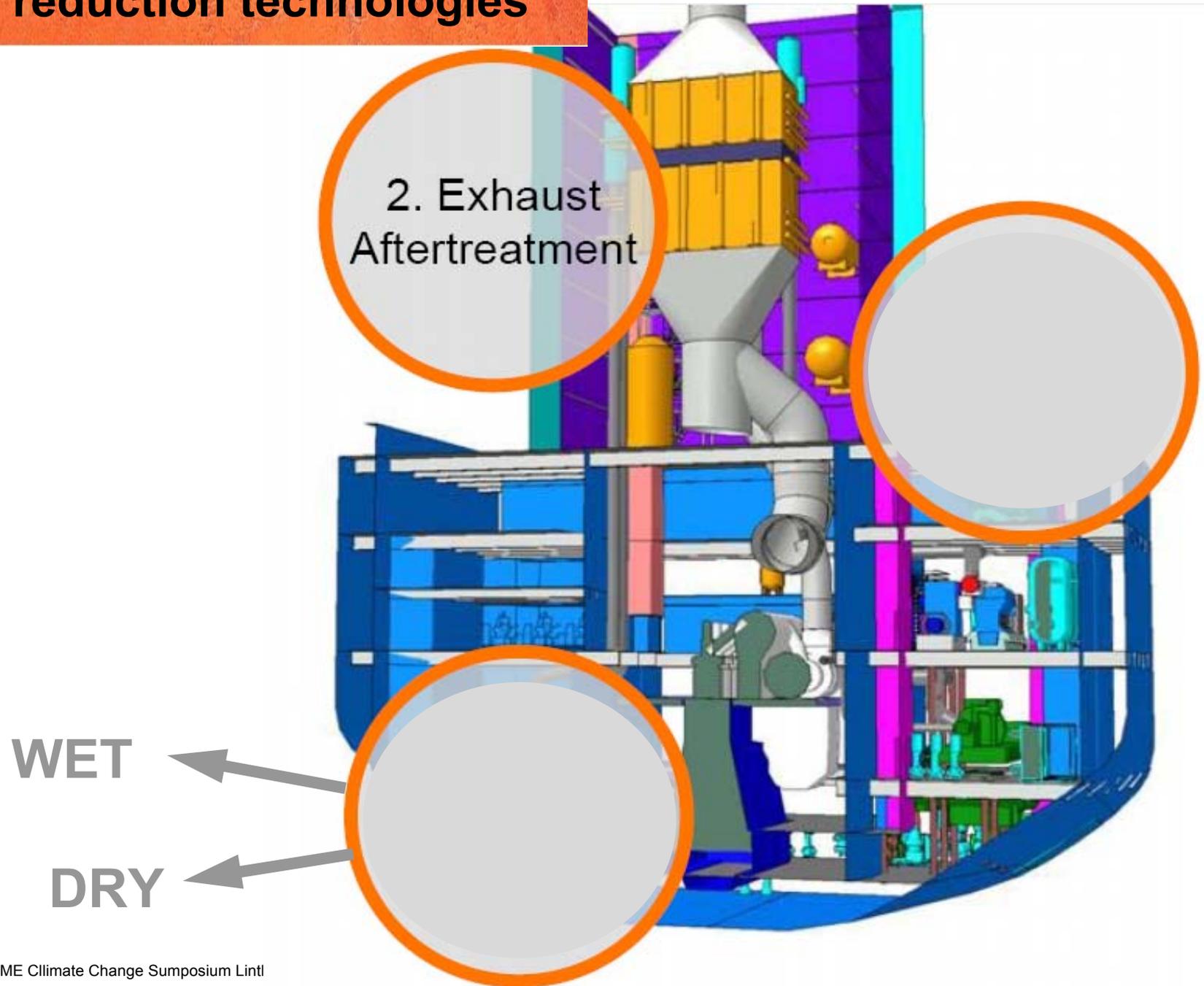
PM
★

Smoke

Combined Water Fuel Nozzle



NOx reduction technologies



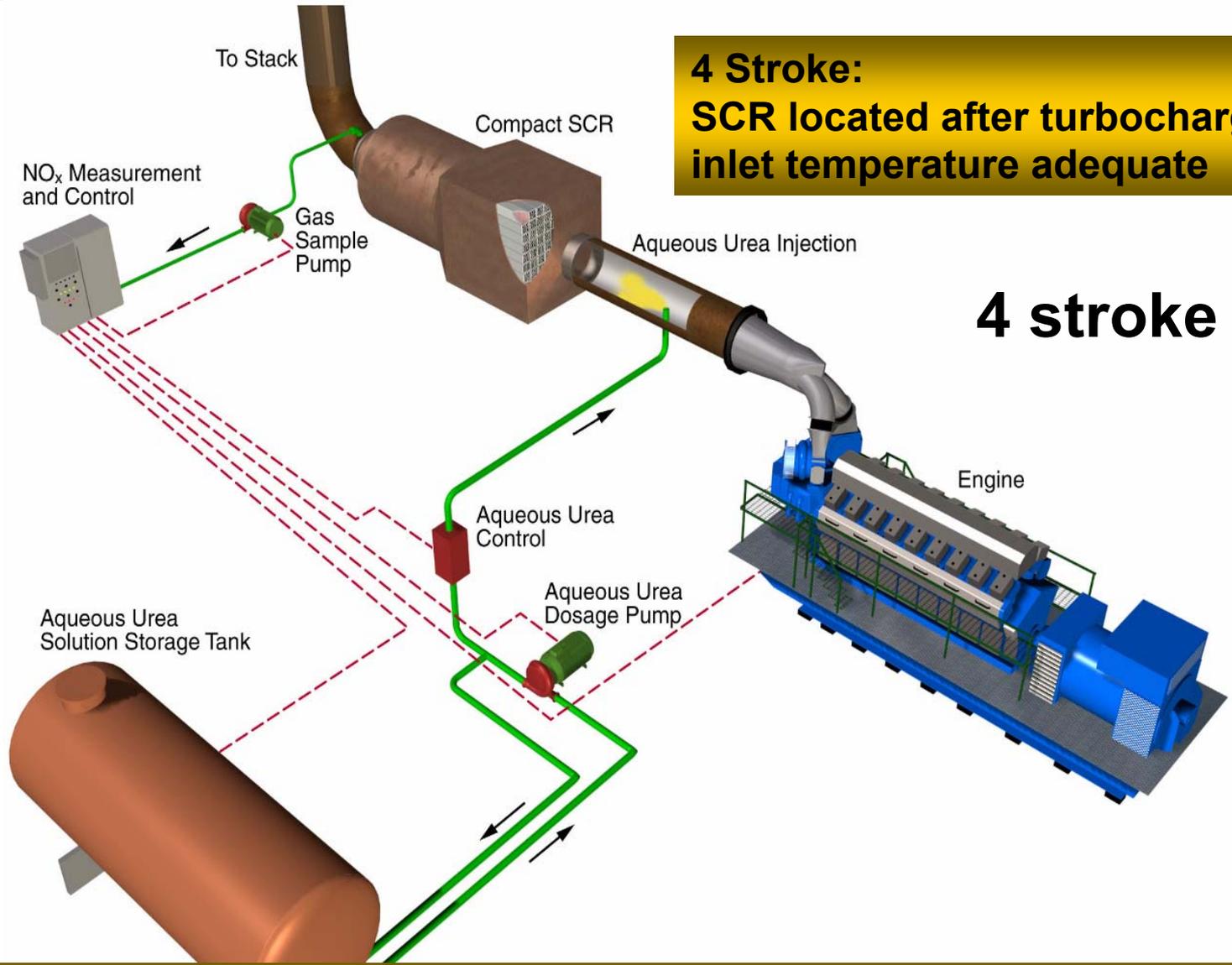
Selective Catalytic Reducer "SCR"

NOx
★★★★

SOx

PM
★

Smoke



**4 Stroke:
SCR located after turbocharger
inlet temperature adequate**

Agent deoxidizes NOx into nitrogen N₂ + Water vapor H₂O



Selective Catalytic Reducer "SCR"

NOx
★★★★

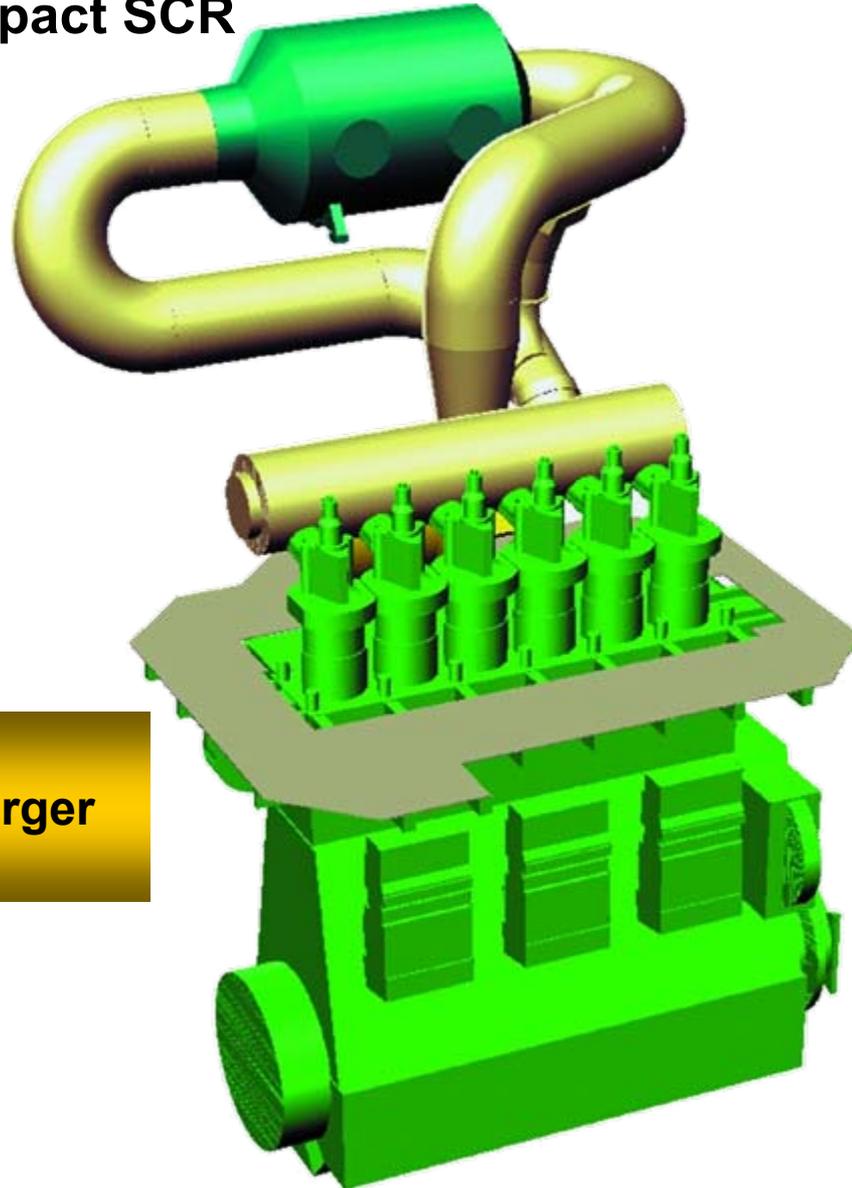
SOx

PM
★

Smoke

Compact SCR

2 stroke



**2 Stroke:
SCR located before turbocharger
maintains inlet temperature**

Seawater Scrubber "SWS"

NOx
★

SOx
★★★★

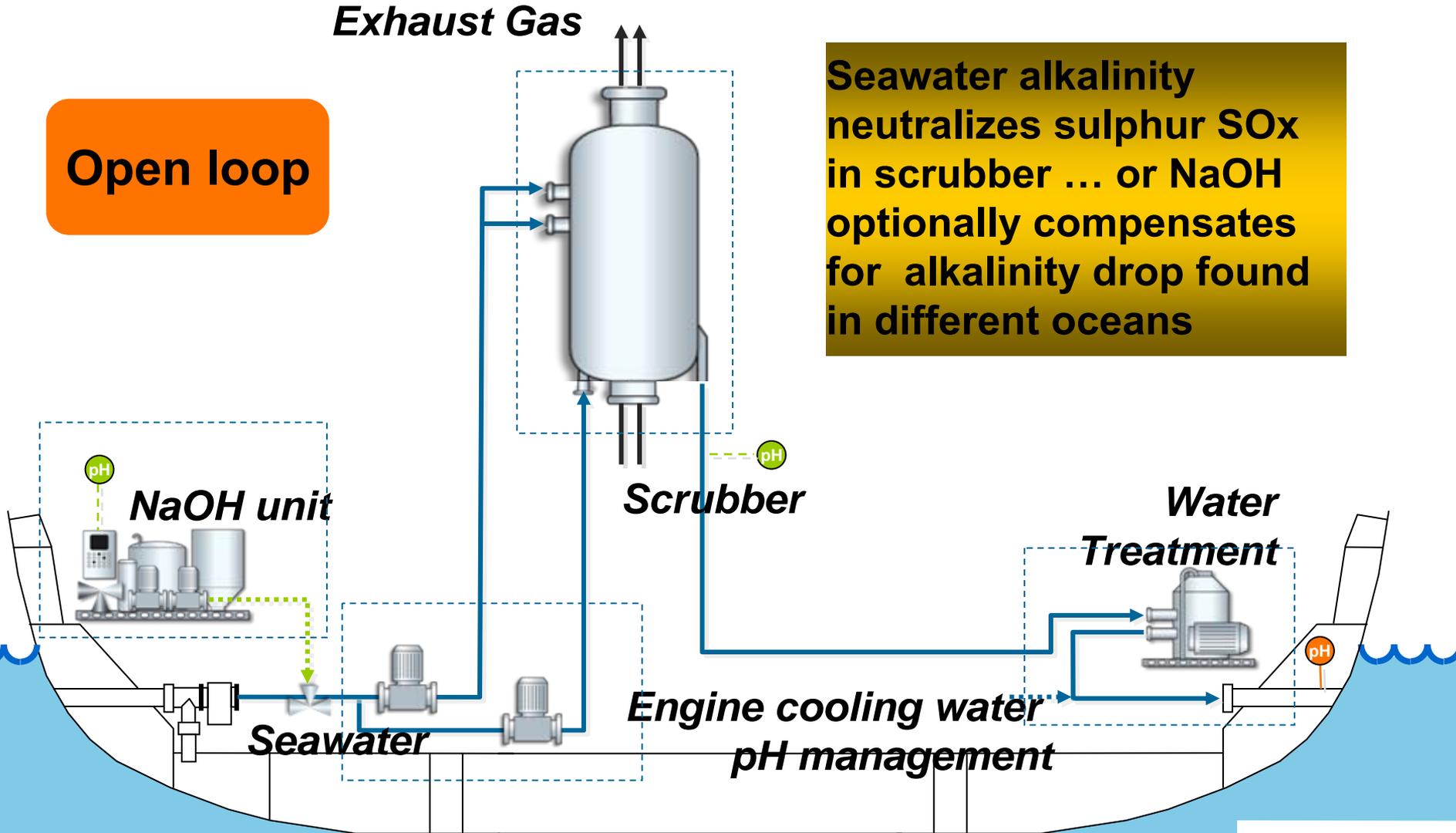
PM
★

Smoke

Seawater alkalinity neutralizes sulphur SOx in scrubber ... or NaOH optionally compensates for alkalinity drop found in different oceans

Open loop

Exhaust Gas



Fresh Water Scrubber (FWS)

NOx
★

SOx
★★★★

PM
★

Smoke

Closed loop

Exhaust Gas

Closed loop uses freshwater plus NaOH dosage to neutralize sulphur SOx

Scrubber

Fresh or Grey water source

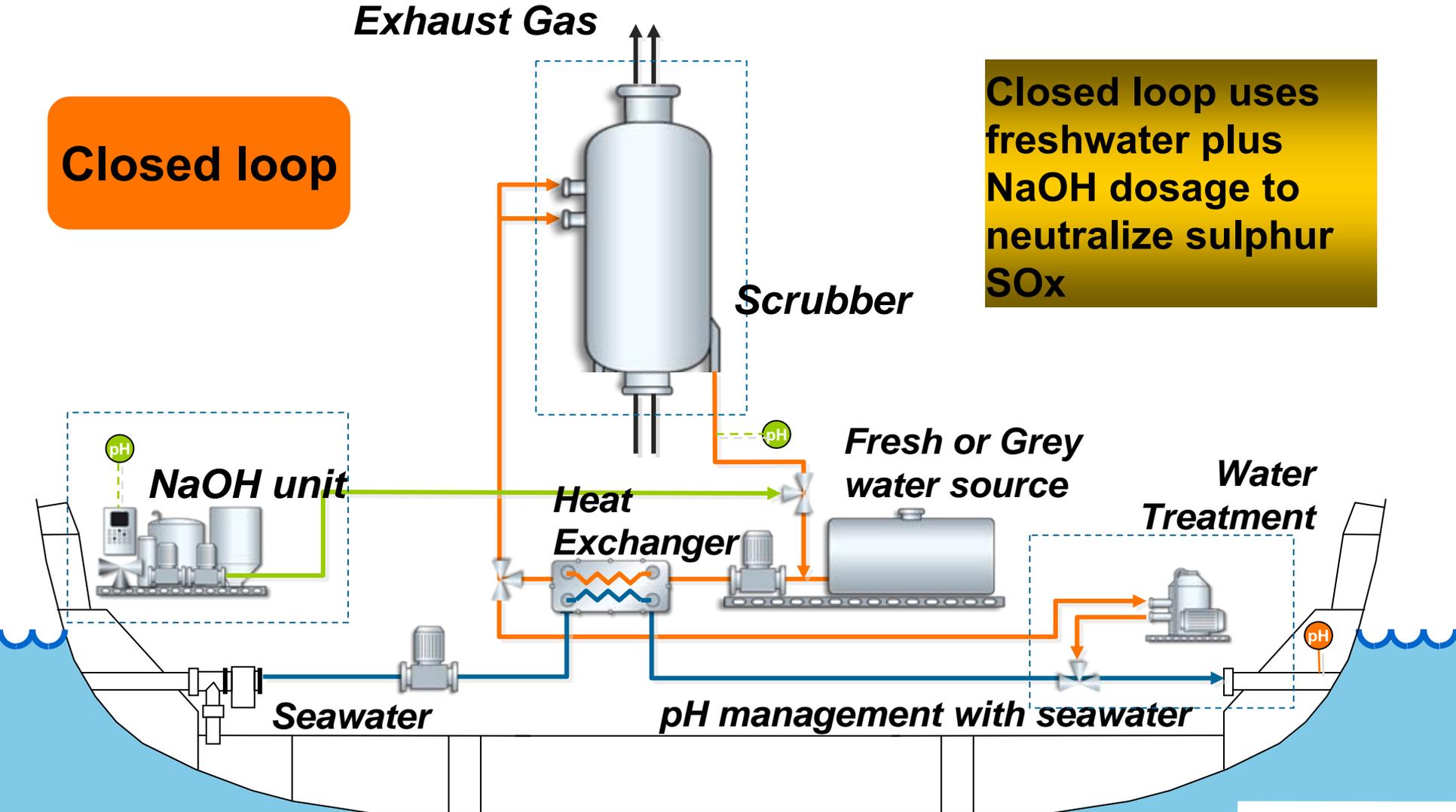
Water Treatment

NaOH unit

Heat Exchanger

Seawater

pH management with seawater



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Emissions Case Study

Case Study Basis

4 Stroke Engine

Light Sulfur Fuel LSF

25 Year Life

Emissions Control Area ECA

Emissions IMO Tier 3

Crude oil = 90 \$/bbl

Conservative may spike if "crunch" between higher demand versus limited supply

HSFO = 485 USD / Mt €

≈ 350 € / Mt

Correlated to crude oil

LSF = 1.3 x HSFO price

(0.5% S) Correlated to HSFO

MGO = 1.8 x HSFO price

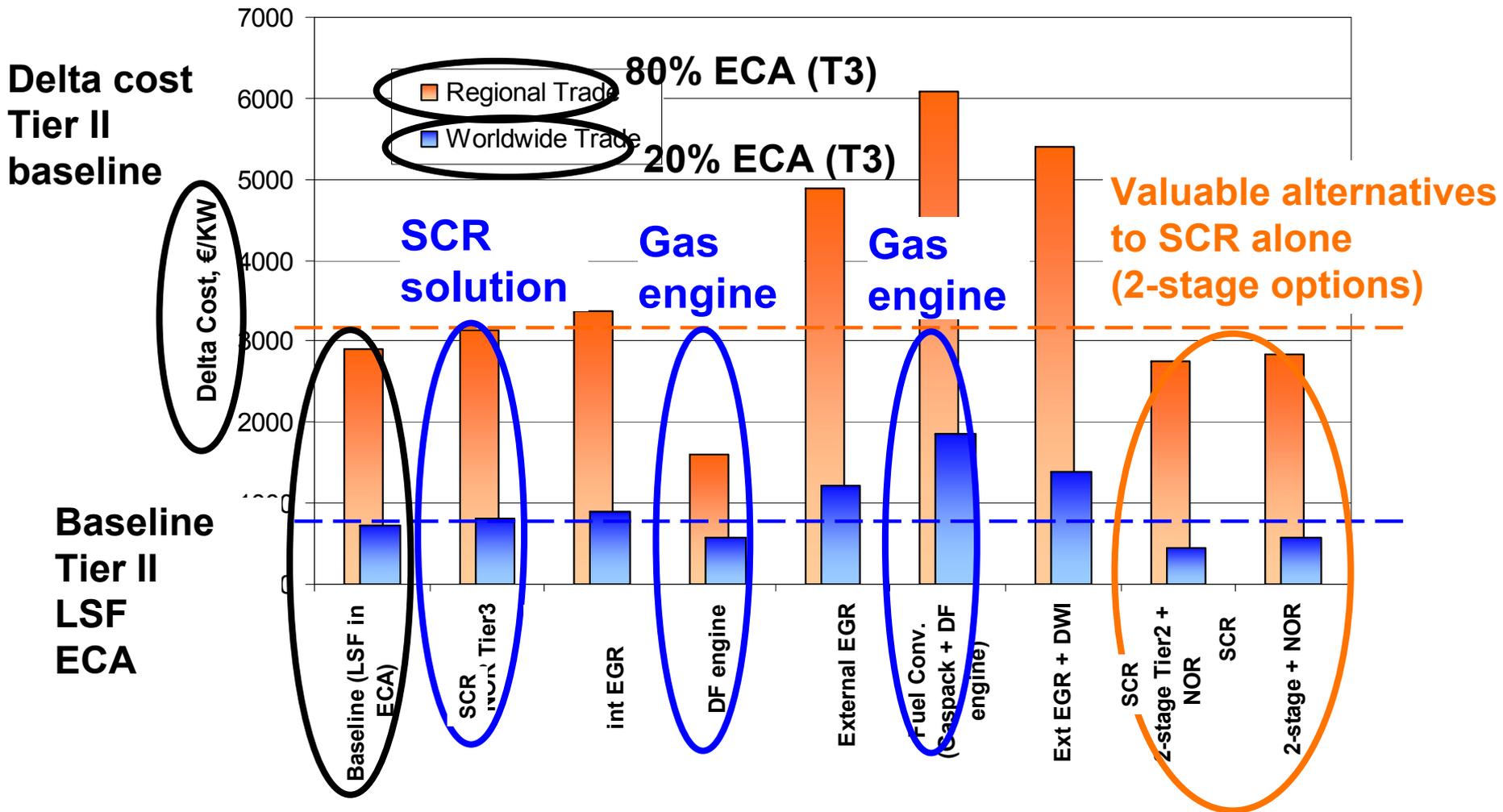
Correlated to HSFO

LNG = 1.4 x HSFO price

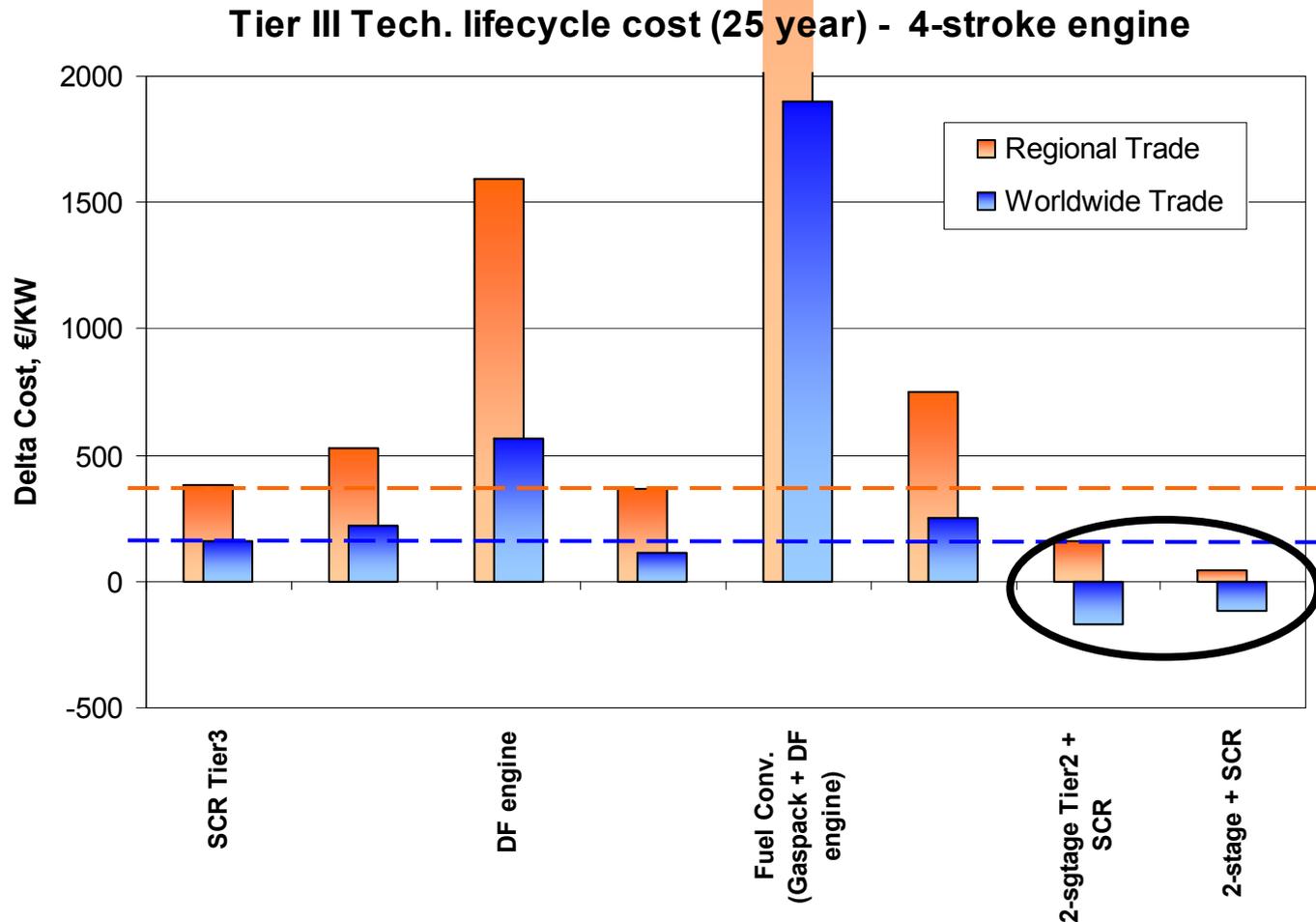
Correlated to crude oil and HSFO

Baseline price multiple normalizes different energy content of fuels

Case Study Results: Regional + Worldwide Trade



Tier 3 Lifecycle cost (25 y) – 4-S solutions / Scrubber + HFO in ECA

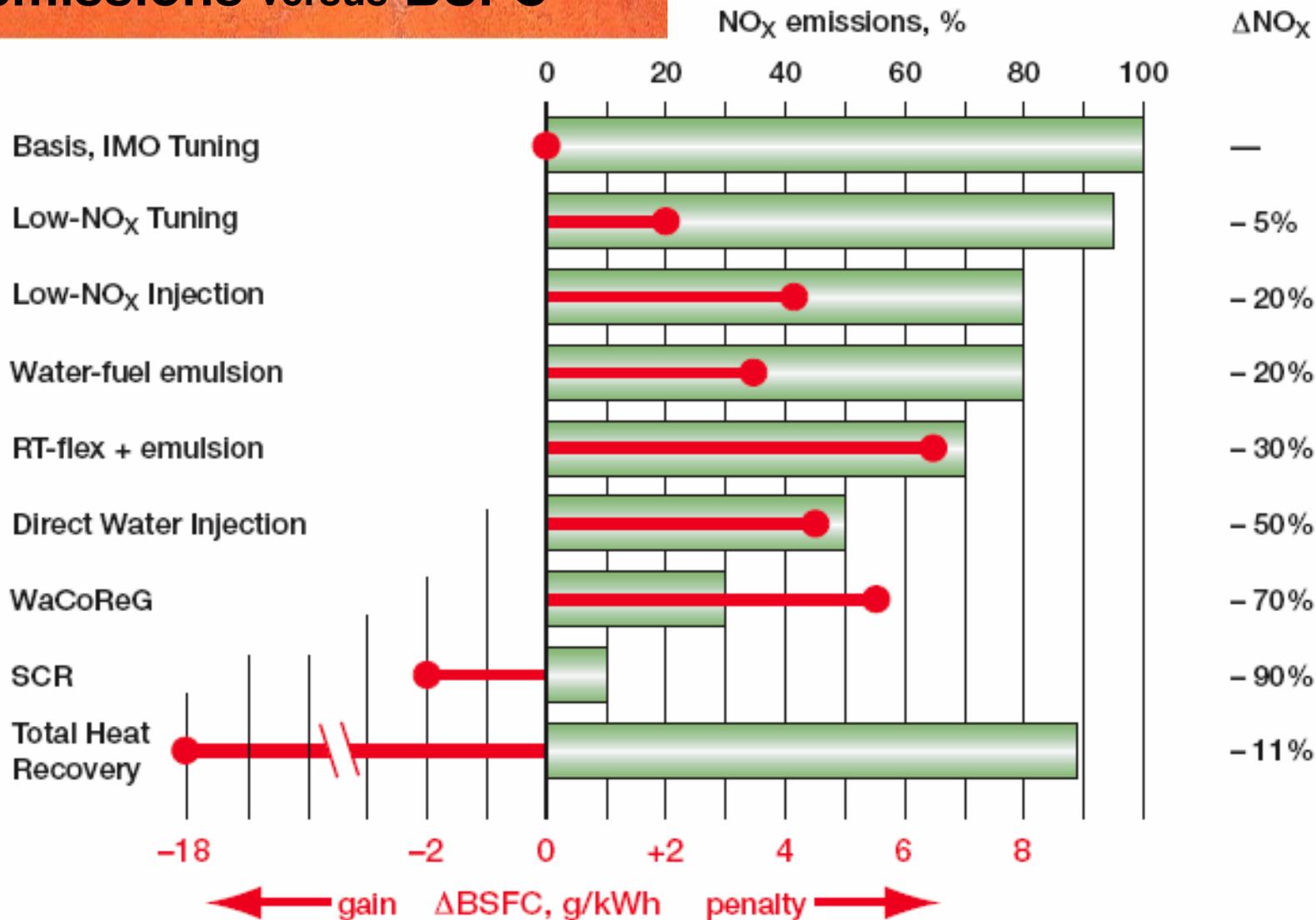


Lifecycle cost estimation is very sensitive to fuel and urea market price scenario. No option at this stage can be easily dropped out

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NO_x emissions versus BSFC



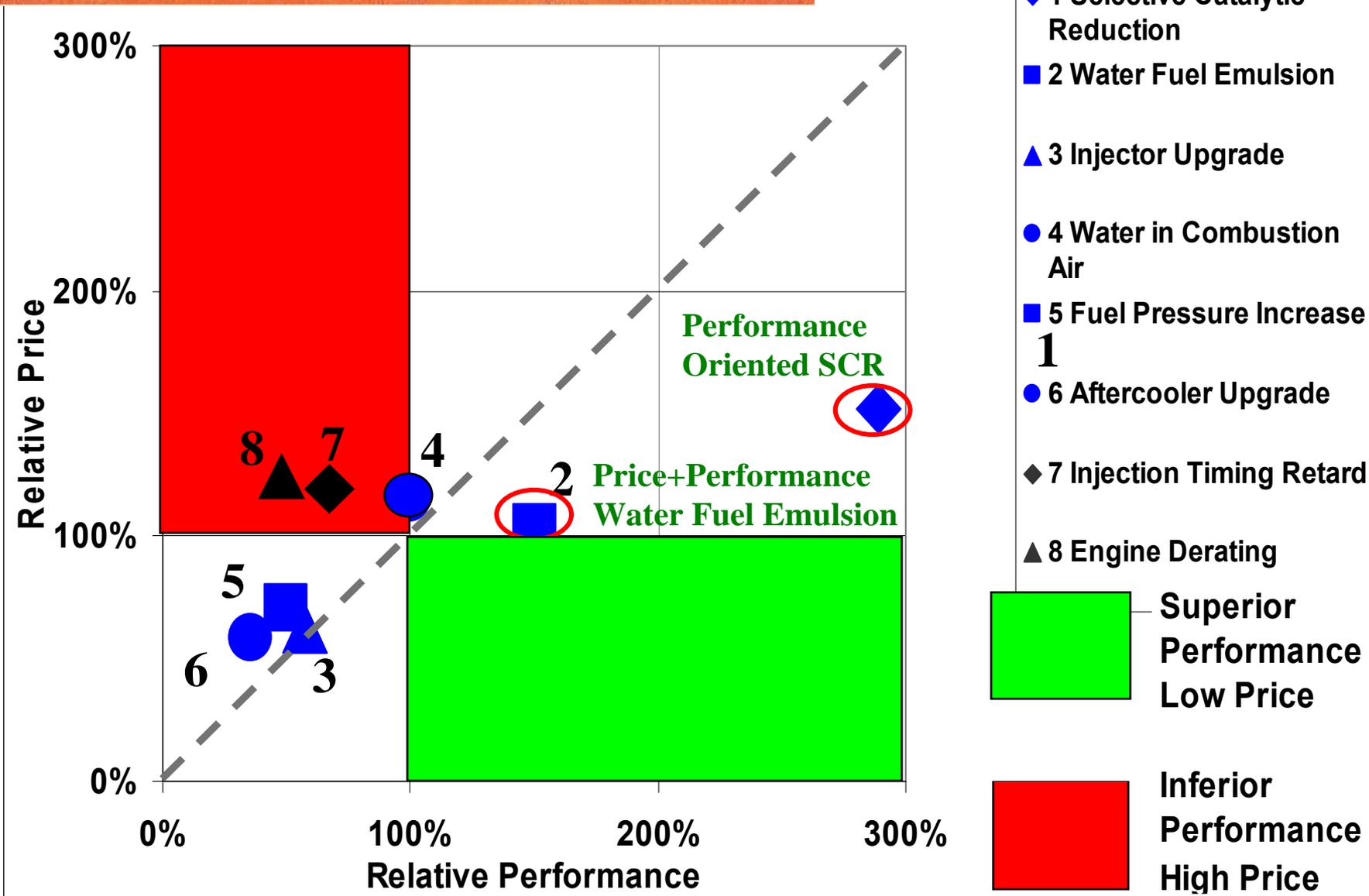
Many NO_x reduction measures increase fuel consumption and particulates. Emissions optimization must balance several factors

EMISSIONS NET PRESENT VALUE

	Technology	% NOx Reduction	NPV CAPEX & Operating \$
1	SCR	81	\$477,000
2	Water Fuel Emulsion	42	\$324,000
3	Injector Upgrade	16	\$195,000
4	Water in Combustion Air	28	\$364,000
5	Fuel Pressure Increase	14	\$222,000
6	Aftercooler Upgrade	10	\$185,000
7	Injection Timing Retard	19	\$365,000
8	Engine Derating	14	\$386,000

Spreadsheet Source: MARAD: Energy & Emissions Program, Daniel Gore, DEER Workshop August 26, 2002. NPV costs at 15% over 23 years.

Price Performance Value Map



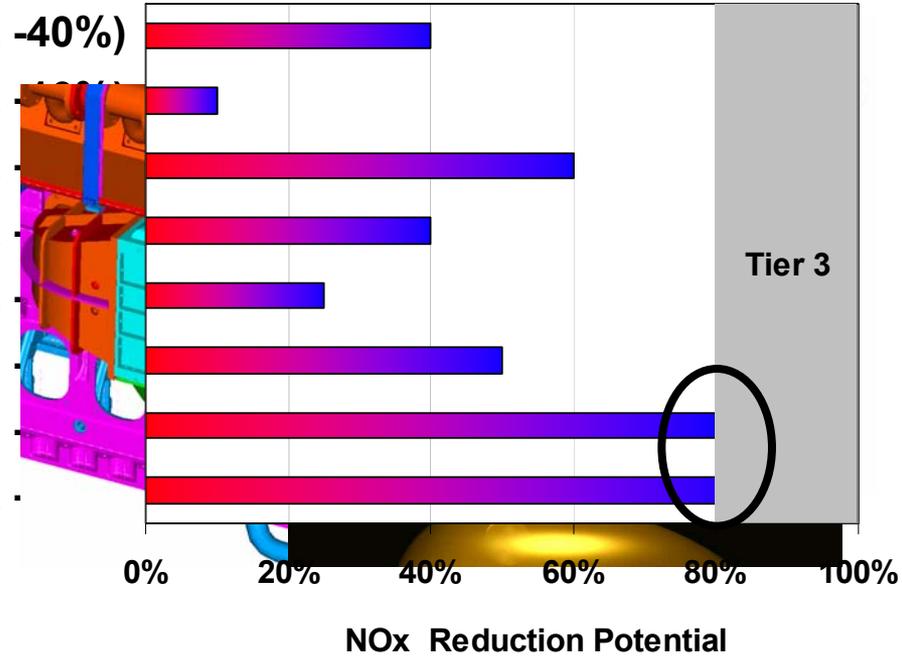
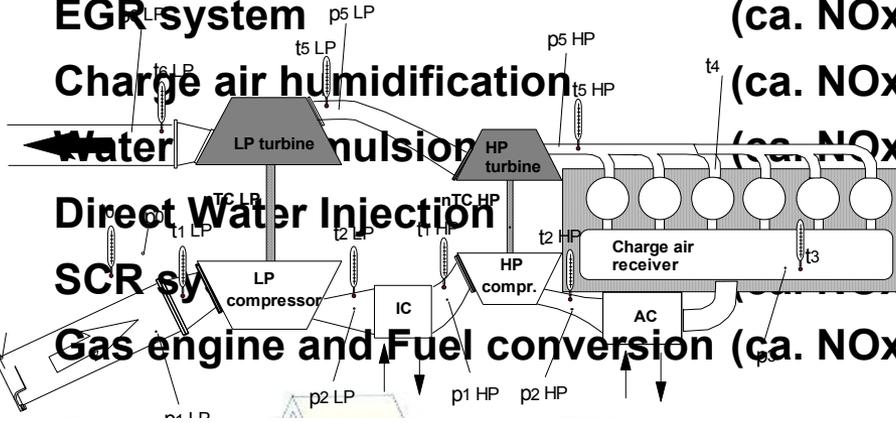
SCR = Superior Price for Performance vs. Space and reductant complexity
 Water Fuel Emulsion = Price + Performance: vs. Quantity water consumed.

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NOx reduction technologies

- ❑ High pressure TC sys. (2-stage) (ca. NOx -40%)
- ❑ Low NOx combustion tuning (ca. NOx -10%)
- ❑ EGR system (ca. NOx -10%)
- ❑ Charge air humidification (ca. NOx -10%)
- ❑ Water emulsion (ca. NOx -10%)
- ❑ Direct Water Injection (ca. NOx -10%)
- ❑ SCR system (ca. NOx -80%)
- ❑ Gas engine and Fuel conversion (ca. NOx -80%)



Emissions Control Technologies

			NOx	SOx	PM	Smoke
<i>primary</i>	dry	Low NOx tuning	□ □			
		VIC	□		□	□ □
		Common Rail	□ □		□	□ □ □ □
	wet	WETPAC -H	□ □ □		□	
		WETPAC -DWI	□ □ □ □		□	
		WETPAC -E	□ □ □		□	
<i>secondary</i>	SCR	□ □ □ □		□		
	Scrubber	□	□ □ □ □	□	□	
	ESP	□		□ □ □	□	
<i>conv.</i>	Switching to light fuel		□ □ □ □	□		
	Conversion to gas	□ □ □ □	□ □ □ □	□ □	□ □	



Summary and conclusions



3 principal control technologies

- Engine technologies

- After treatment

- Fuels i.e. Gas

- Operation flexibility adapting to different emission areas will be a key future engine success

- Required fuel quality and quantity in ECA area will probably affect significantly lifecycle costs for operators, ushers in scrubber technology

Appendix

Comments

- Emission reduction regulations ultimate goal is to reduce Air Emissions, especially along sea shore where community lives, but not to limit technologies to achieve the required levels.
- Regulating fuel isn't a holistic approach as:
 - § it will increase carbon foot print from land base production facilities and logistics chains
 - § it only solves SO_x while having low or no effect on PM, and other harmful particulates
- Primary & Secondary technologies combination can achieve high emission reduction, also on non-regulated particulates, while minimising investment on land base infrastructure and having no negative impact on carbon foot print
- Emission trading, already in force for CO (Nordic countries) and NOX (US land base facilities) is an enabler with proven effect on global emission reduction.

Nitrogen Oxides (NO_x)

- The formation of NO_x emissions in an engine is thermal; the primary source of nitrogen is the nitrogen in the combustion air
- The combustion temperature, the degree of fuel/air premixing and the duration of the fuel in the cylinder all strongly affect the formation of NO_x . It is highest with a high combustion temperature, low degree of premixing and long fuel duration
- NO_x formation in an engine is an extremely complex process comprising hundreds of different chemical reactions and many intermediate products
- The typical NO/NO_x ratio in a diesel engine's exhaust gases is 0.95
- The typical NO_2/NO_x ratio in a diesel engine's exhaust gases is 0.05
- After being released as exhaust into the atmosphere NO oxidizes into NO_2 typically within a few hours.

Reducing Nitrogen Oxides (NO_x)

- **Delayed fuel injection and ignition**, which reduces the in-cylinder duration of the combustion gases at high temperatures
- In a diesel engine, **lowering the fuel injection pressure** reduces the formation of droplets and also the combustion efficiency and temperature
- Raising the degree of premixing, and in a gas engine increasing the **amount of air**
- Advancing the **closing time of the inlet valve** to lower the final combustion temperature (“Miller valve timing”)
- Reducing the temperature and pressure of the **combustion air**
- Optimizing the **geometry** of the combustion space
- Optimizing the **compression ratio**
- In a diesel engine, optimizing the **fuel injection method**
- Introducing **water** to the combustion space to reduce the temperature, e.g. using a water-fuel emulsion or saturating the intake air
- A Selective Catalytic Reduction (SCR) **catalytic converter**.

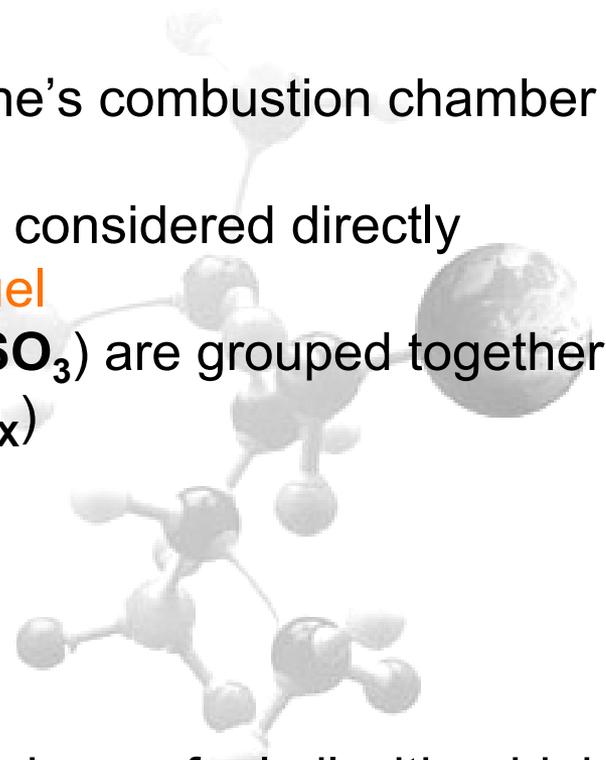
Sulphur Oxides (SO_x) and Reduction methods

Formation in engines

- The sulphur in the fuel oxidizes in the engine's combustion chamber into SO_x .
- Hence, the emissions levels of SO_x can be considered directly **proportional to the sulphur content of the fuel**
- Sulphur oxide (SO_2) and sulphur trioxide (SO_3) are grouped together under the general term sulphur oxides (SO_x)
- The typical ratio of SO_2 to SO_x is 0.95
- The typical ratio of SO_3 to SO_x is 0.05.

Emissions reduction methods in engines

- **Using low-sulphur fuels**, e.g. changing from heavy fuel oil with a high-sulphur content to low-sulphur heavy or light fuel oil.
- Secondary technology such as **scrubbers**
- Changing from fuel oil to **natural gas**.



Particulate Matters (PM) and Smoke

Particles form in the combustion space as a result of locally low quantities of excess air. Some of the particles do not have time to burn completely but pass out into the atmosphere in the exhaust gases.

The amount of particles in the exhaust depends on the amount of hydrocarbons in the fuel and lubricating oil and on the amount of sulphur and ash in the fuel.

- When using heavy fuel oil, typically more than 50% of particles in the exhaust come from the ash and sulphur components in the fuel
- When using light fuel oil, most of the particles consist of carbon or hydrocarbons and only a very small proportion comes from the ash and sulphur components in the fuel
- Particles smaller than about 0.4 μm are considered to be invisible. A proportion of the particles produced by an engine fall below this size.
- Gas engines have very low levels of particle emissions.

Reducing Particulate Matters (PM) and Smoke

Primary technologies

- In diesel engines, **raising the fuel injection pressure** as this improves droplet formation and combustion efficiency
- Raising the temperature of the intake air
- Optimizing the **geometry** of the combustion space
- Optimizing the **compression ratio**, and the **fuel injection method**

Many measures taken to reduce particle emissions also tend to increase NO_x emissions.

High PM reduction with secondary technologies

Of the commercial technologies available today, only the electrostatic precipitator is suitable for diesel engine power plants but its investment costs are high.

Sometimes, in conjunction with desulphurization equipment, bag filters are used to reduce particle emissions.

