Emission Fundamentals;
Formation, Reduction, & Control

Canadian Institute of Marine Engineering
Mari-Tech 2010
June 9 – 11, 2010
Montreal, Quebec, Canada

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Agenda

- **Current Legislation**
- **Exhaust Components**
- **Overview Formation, Reduction, Control**
- **Leading Engine Technologies**
  - **Primary Wet / Dry Means**
  - **Secondary Wet / Dry Means**
- **Value Mapping Analysis**
- **Why Clean Natural Gas**
- **Summary**

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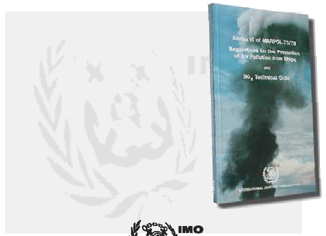
IMO & EU



IMO •19 May 2004
Ratification of IMO Annex VI

IMO •19 May 2005
Entry into force of IMO Annex VI
Global limit 4,5%S

IMO •19 May 2006
SECA Baltic sea
1,5% Sulphur max.
or exhaust cleaning
to 6 g/kWh

1,5%S

IMO •22 Nov. 2007
SECA North Sea
and English Channel
1,5% Sulphur max.
or exhaust cleaning
to 6 g/kWh

IMO
SECA next sulphur step ?

?

2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010

EU •14 April 2005
EU Parliament passes Sulphur Directive 1999/32/EC

EU •22 July 2005
Publication of Sulphur Directive 2005/33/EC

EU •11 August 2006
EU directive enters into force:

- 1,5%S max in Baltic
- 1.5%S max for passenger ship and EU territorial seas in regular service to or from EU ports
- Alternatively exhaust cleaning to 6 g/kWk

1,5%S

EU •August 2007
SECA North Sea
and English Channel
1,5% Sulphur max.
or exhaust cleaning
to 6 g/kWh

EU •in 2008
EU review on further proposal for:
- new SECAs
- 0,5%S max.
- alternative measures including trading

possibly
[redacted]

EU •01 January 2010
0,1% Sulphur max.
On all marine fuel
in EU ports and inland vessels
Alternatively exhaust cleaning to 0.4 g/kWh

0,1%S

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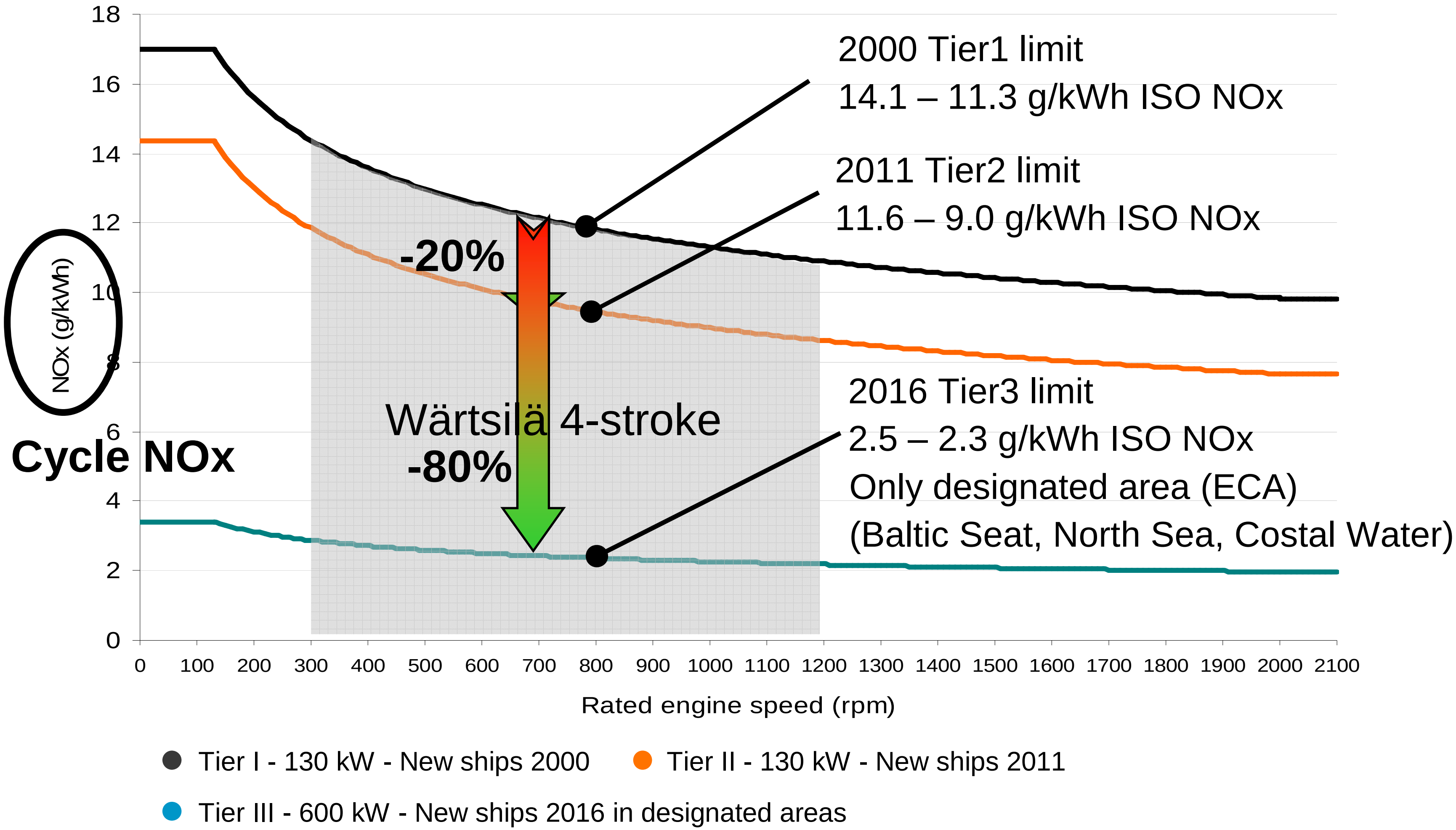
Current Legislation

Revised Marpol Annex VI (9.10.2008)



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 SOx

1st Baltic Sea enforced May 2005

2nd North Sea November 2006

Greenhouse Gas

CO_2 emission reduction

Reduce power demand

- Ship and propulsion design
- Operation profile

Improve efficiency

- Propulsion optimisation
- Engine technology
- Waste energy recovery

Use alternative fuels

- Lower carbon content fuels = LNG

Fundamental shifts in vessels; why, what, how

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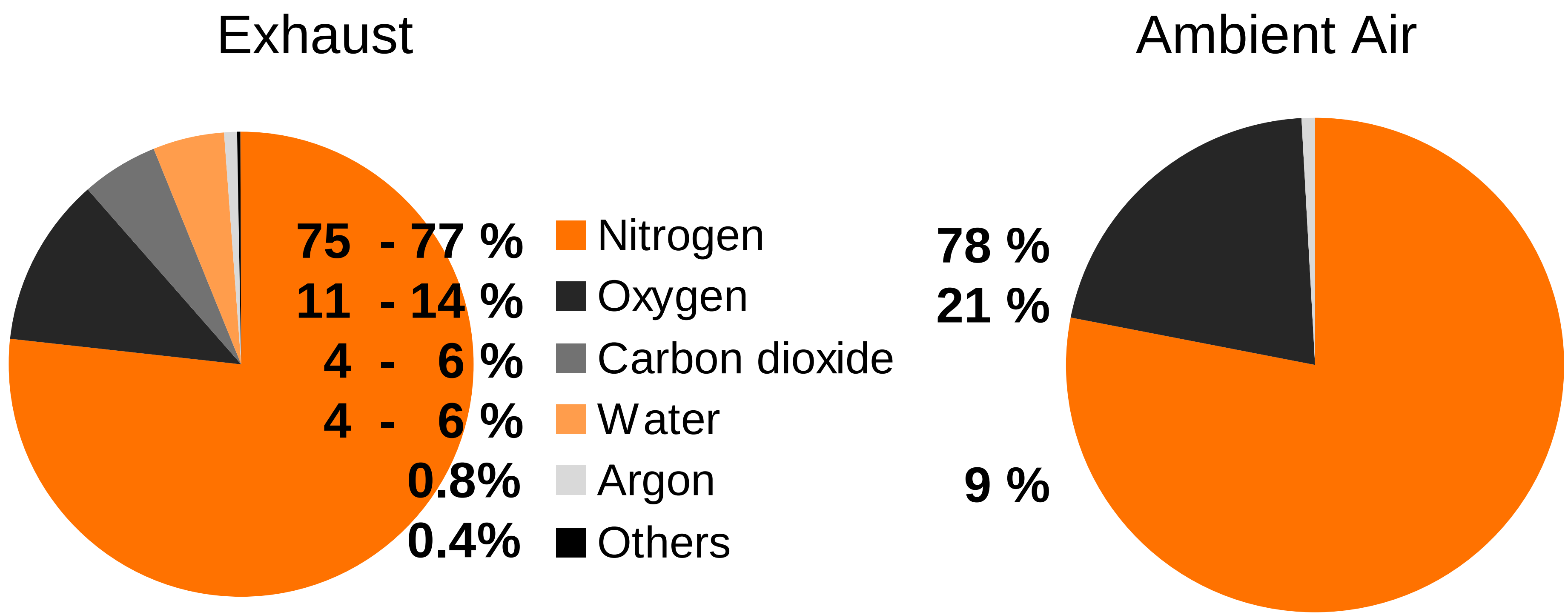
Gas Volumetric Composition



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 "NO_2"	Nitrogen and oxygen dissociation react forming nitric oxide.	Combustion zone dissociation reactions form Nitric Oxide NO. Flame region reactions yield Nitrogen Dioxide NO_2	Exponentially temperature dependent, also dependent on residence time	Lower peak combustion temperature. Reduce combustion time duration. Inhibit dissociation.
Particulate Matter, Soot "PM"	Carbon soot mixture plus some volatile organic and sulfate compounds.	Later combustion oxidizes most carbon particles. Organic fraction from unburned fuel and lube oil consumption. Sulfate dependent upon sulfur proportion in fuel.	Temperature, combustion residency time, and oxidation availability. After-cooling and exhaust air dilution foster sulfate PM and volatile organic	Improve mixing. Reduce fuel sulfur content. Exhaust catalyst treatment. Shorten ignition delay. Remove crevices.
Hydrocarbon "HC"	Fuel and trapped lubricant.	Crevice traps in top ring land and injector sac promote incomplete combustion mixing. Excessive swirling promote fuel related overmixing during ignition delay.	Cold start white smoke.	Exhaust catalyst treatment. Shorten ignition delay. Remove crevices. Reduce sac volume. Eliminate secondary injections.

Emission engineering first principle fundamentals form root basis

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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

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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 NOX 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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Emissions Control Technologies

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

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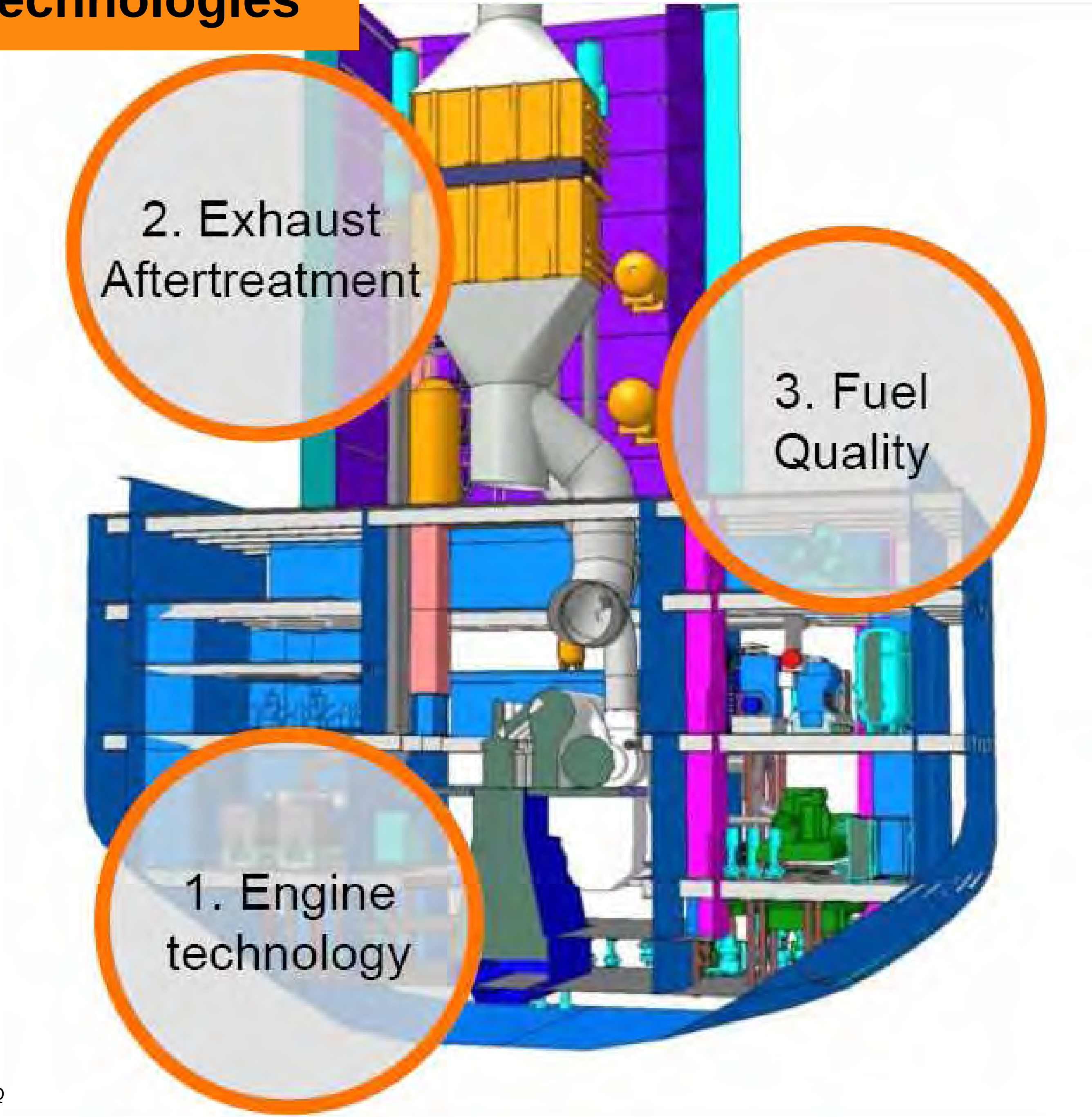
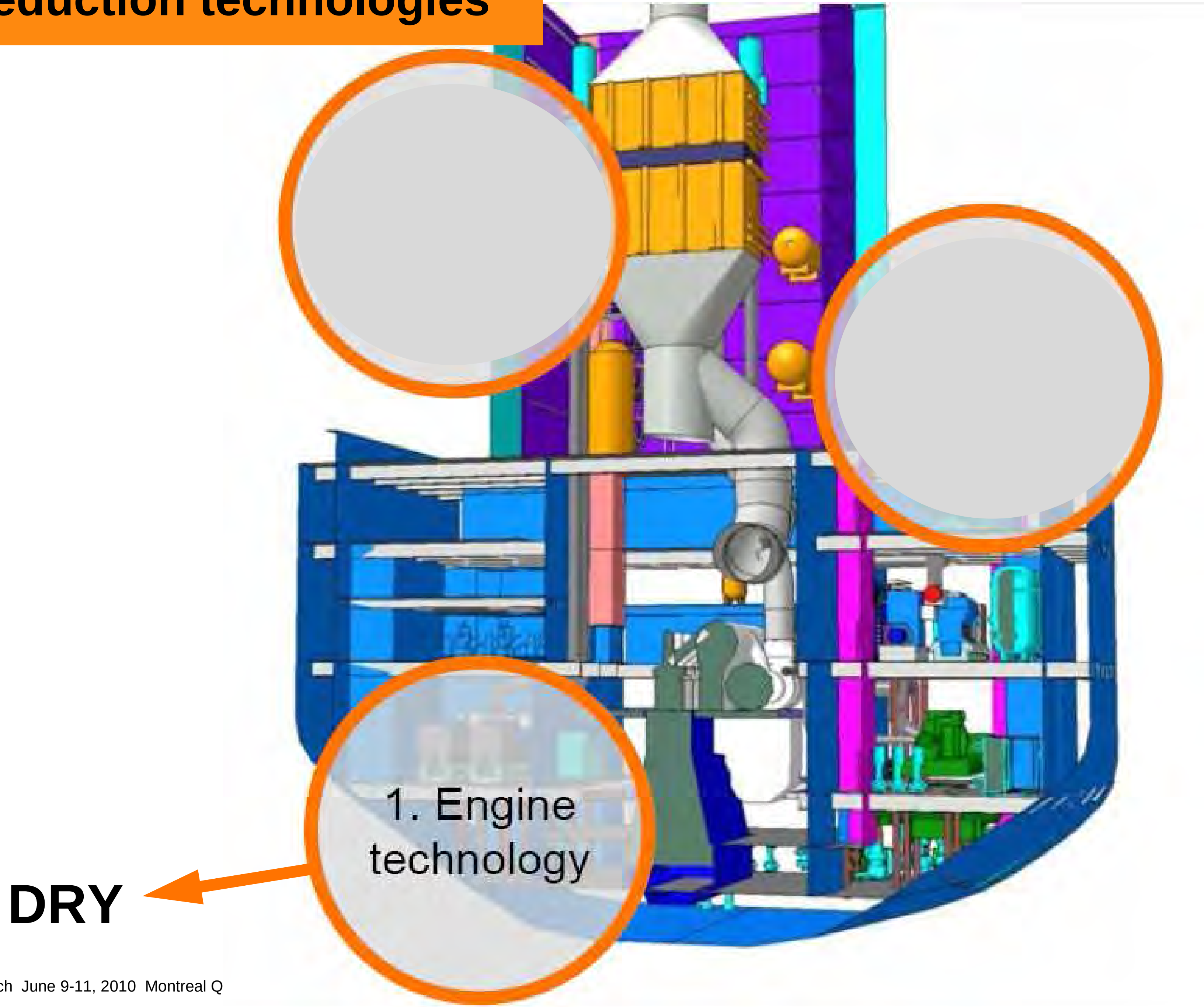
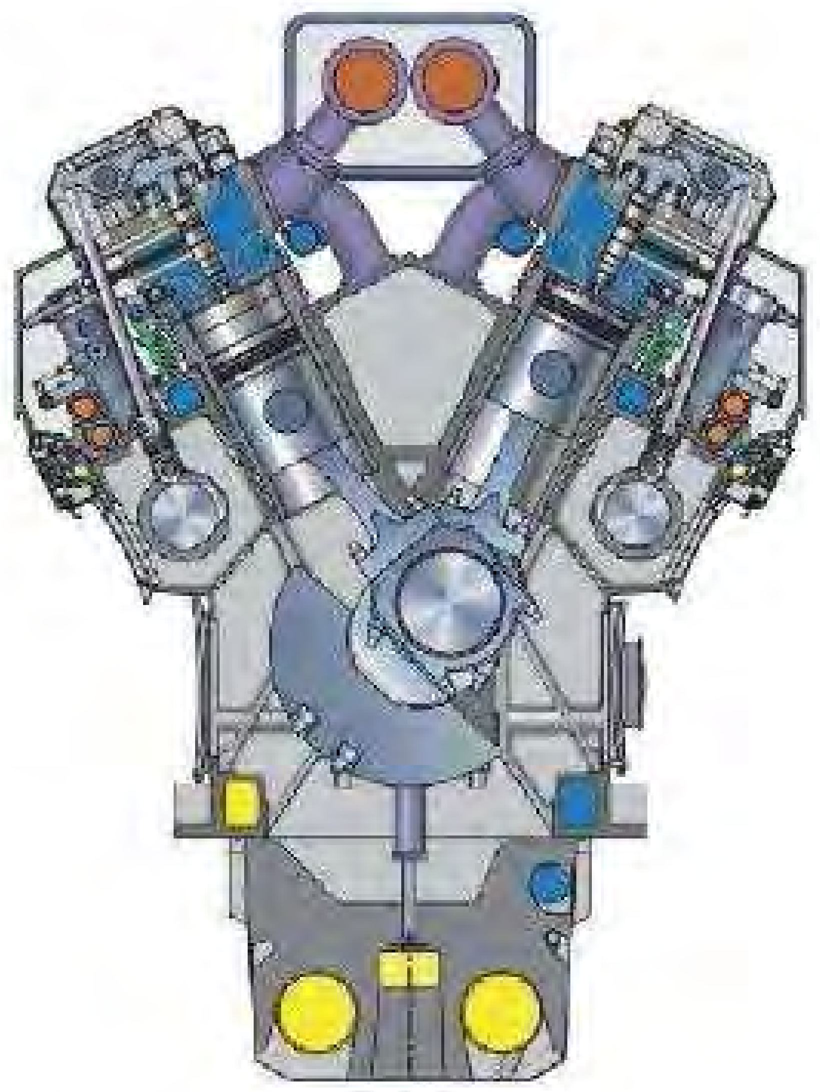
NOx reduction technologies



NOx reduction technologies





Low NOx Technology

Later fuel injection start

High compression ratio

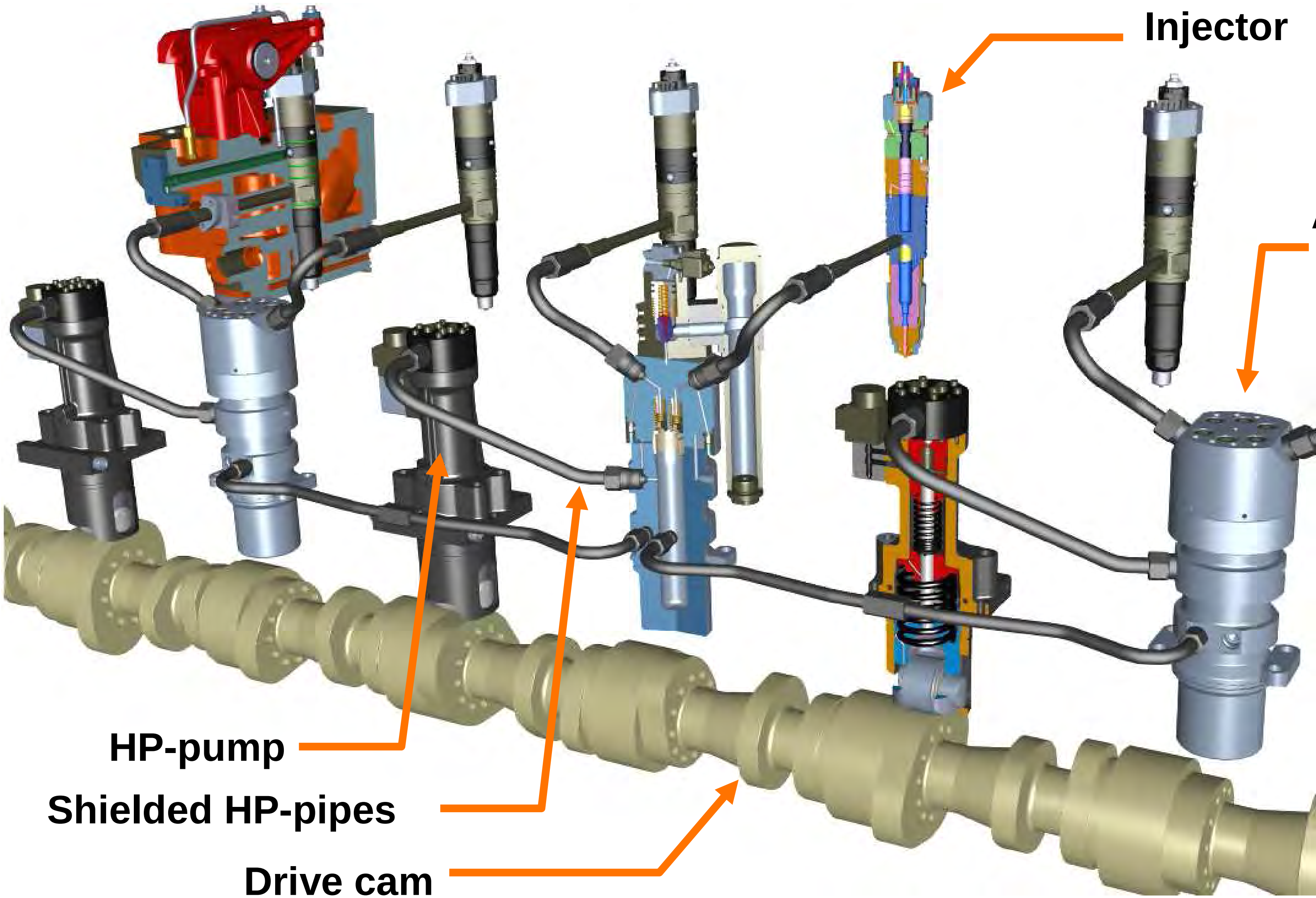
Optimized combustion chamber

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)**

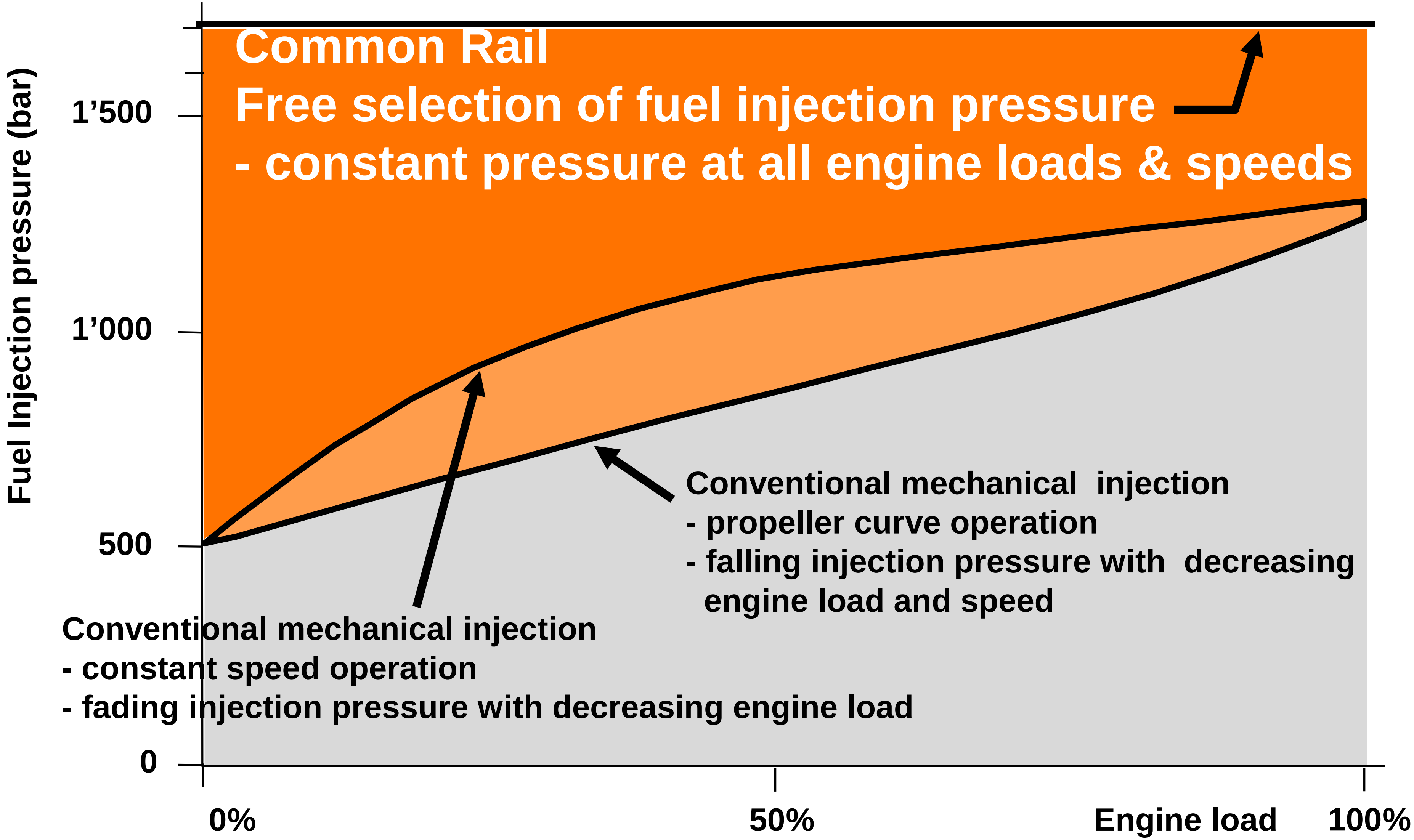
Common Rail, 4-stroke

NOx	SOx	PM	Smoke
☆☆		☆	☆☆☆☆



Fuel Injection

NOx	SOx	PM	Smoke
★★		★	★★★★



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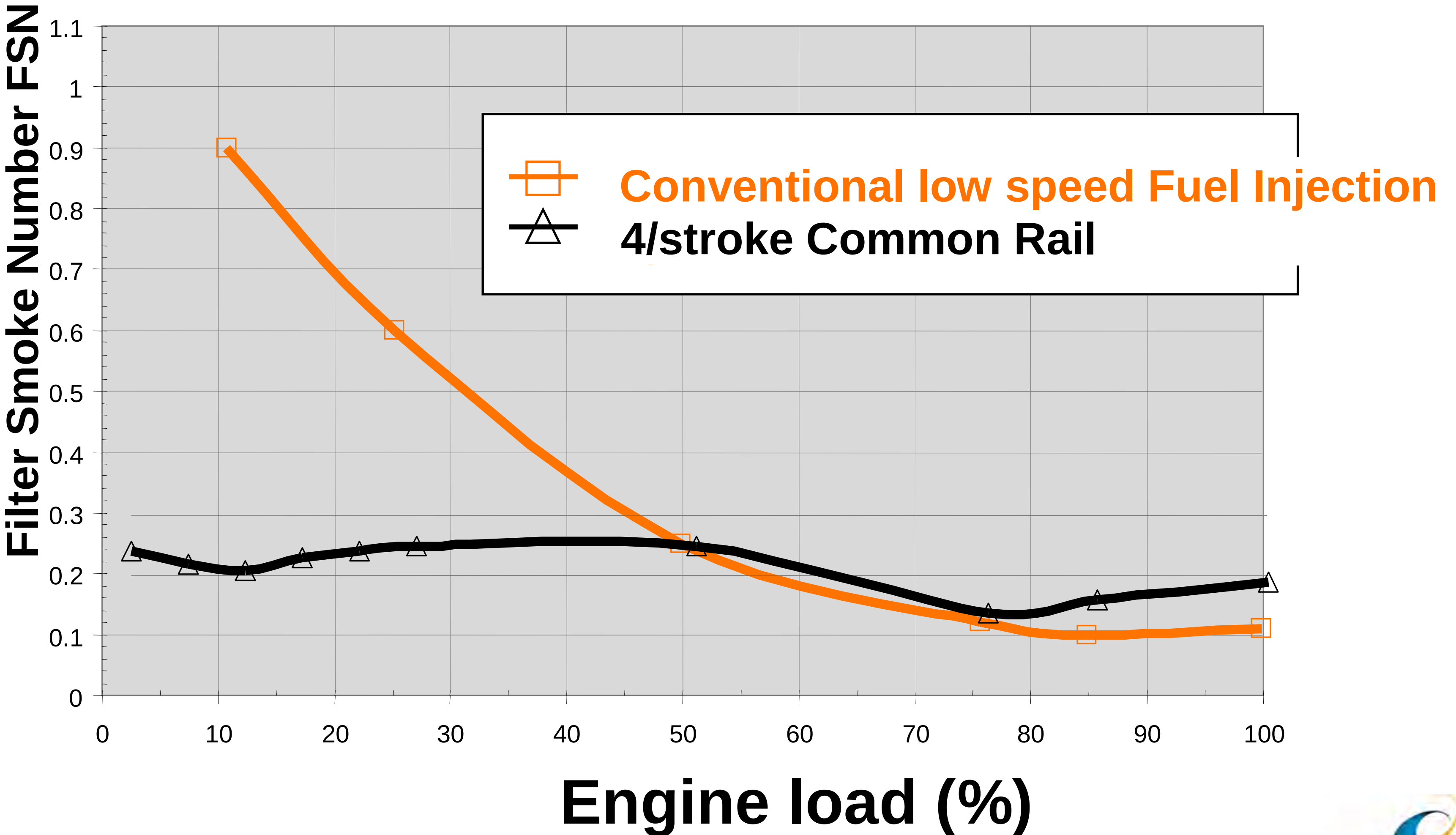
Common Rail 4-stroke

NOx	SOx	PM	Smoke
★★		★	★★★★

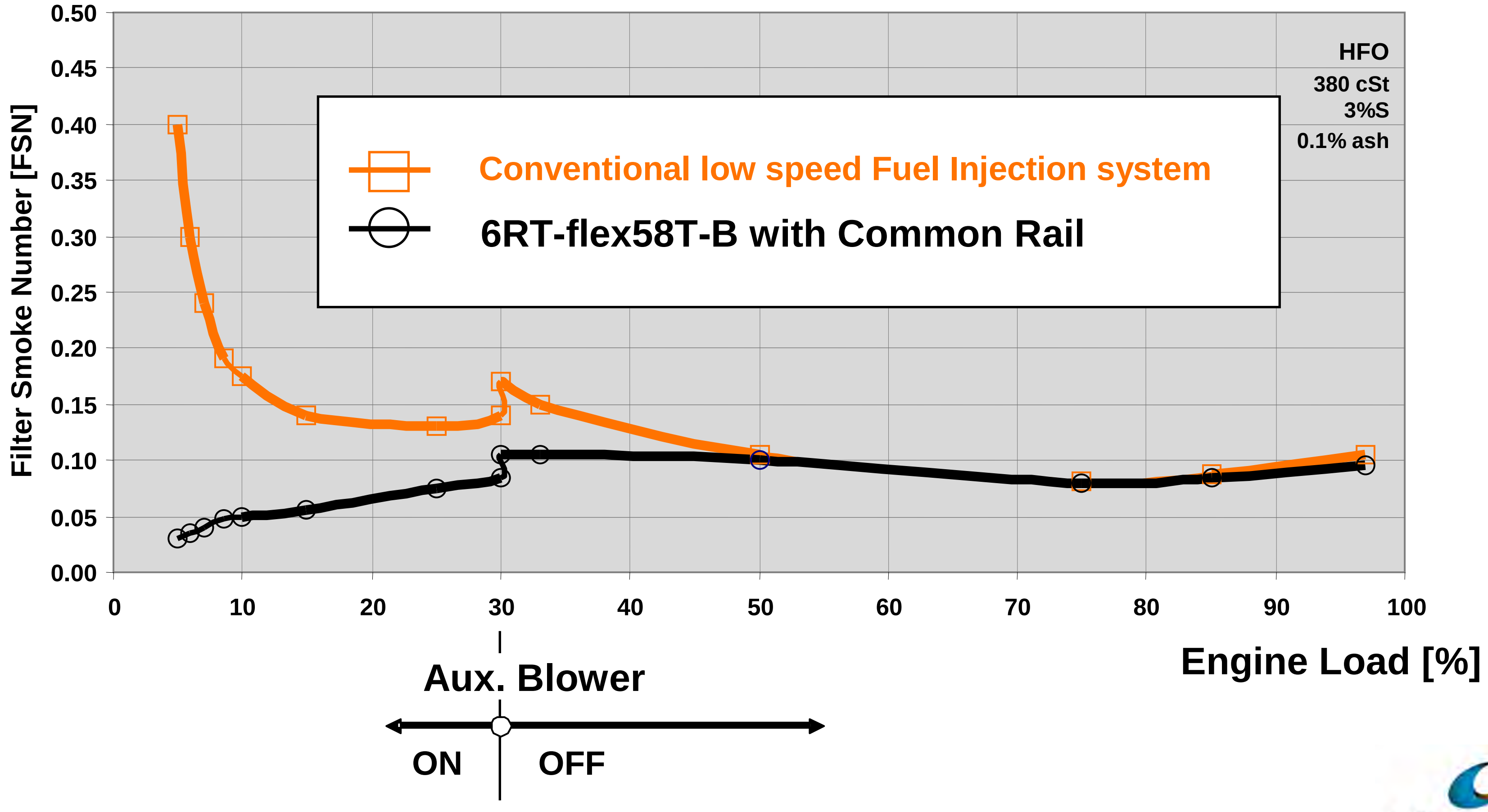


Common Rail, 2-stroke

NOx	SOx	PM	Smoke
★★		★	★★★★

Near Smokeless operation throughout the load range

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



  Mari-Tech June 9-11, 2010 Montreal, Quebec John Hatley Americas VP Ship Power

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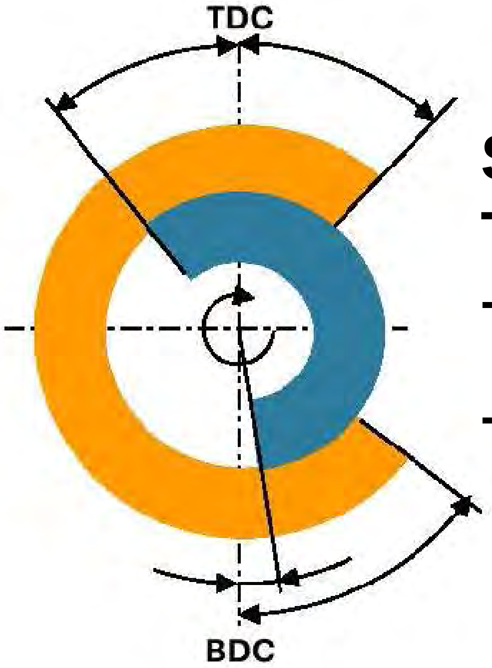
Variable Inlet Valve Closing "VIC"

NOx	SOx	PM	Smoke
★		★	★★

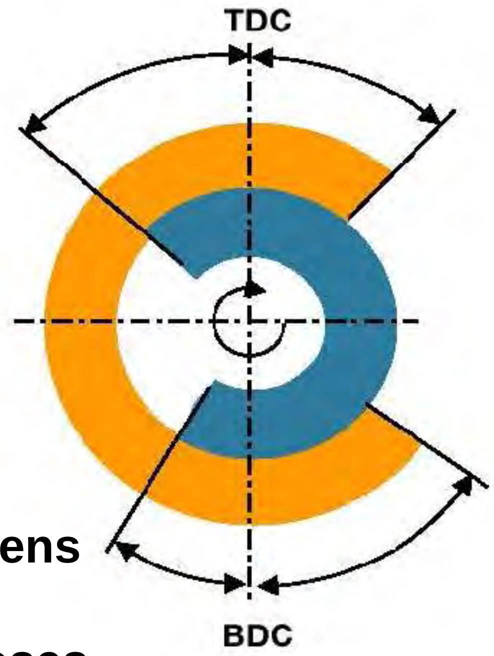


Standard Miller Timing

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

VIC Timing

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

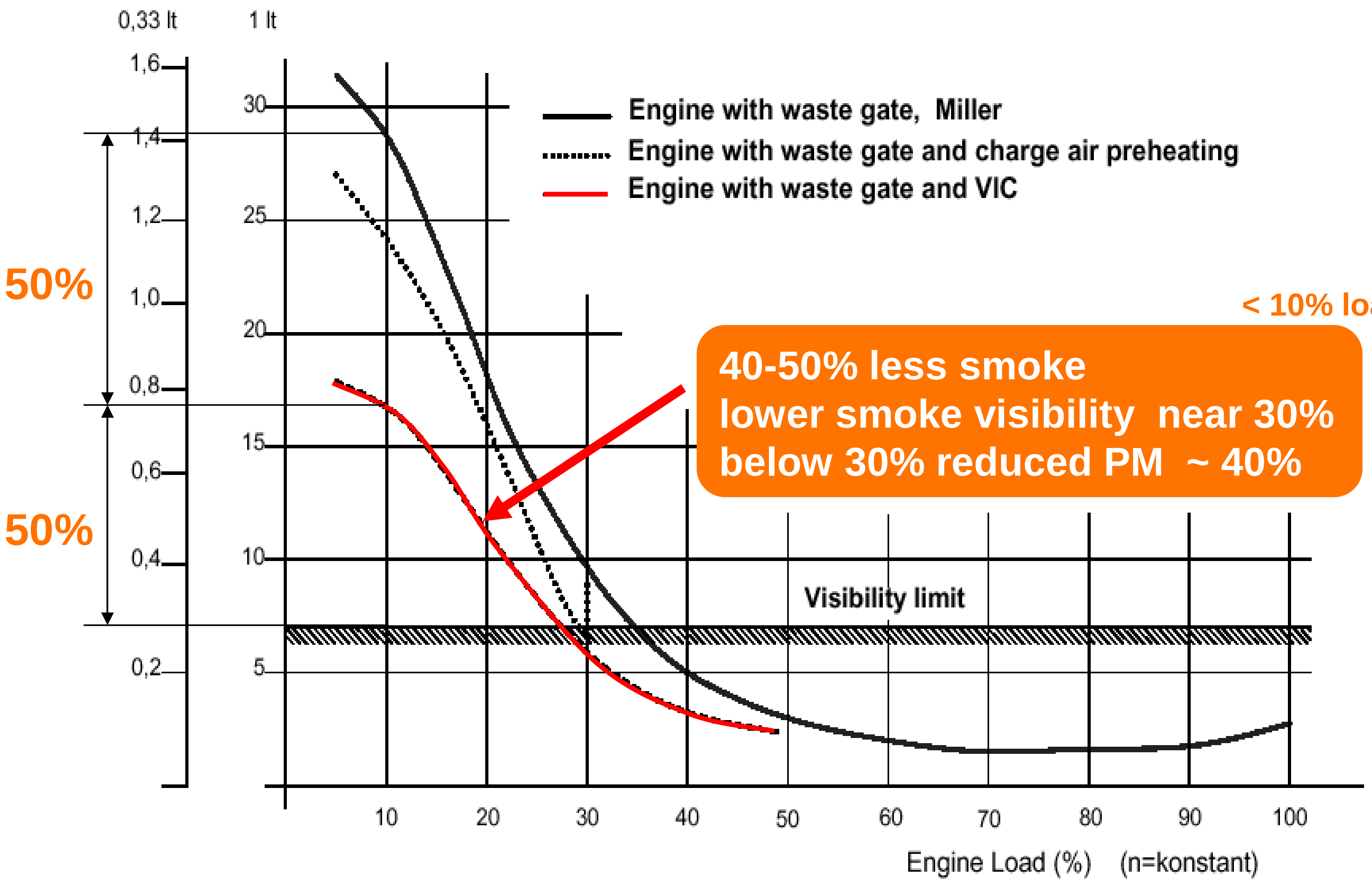


Delay in Inlet Valve Closing → **Increase on air quantity & compression pressure** → **Better combustion process** = **LESS SMOKE**

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
★		★	★★



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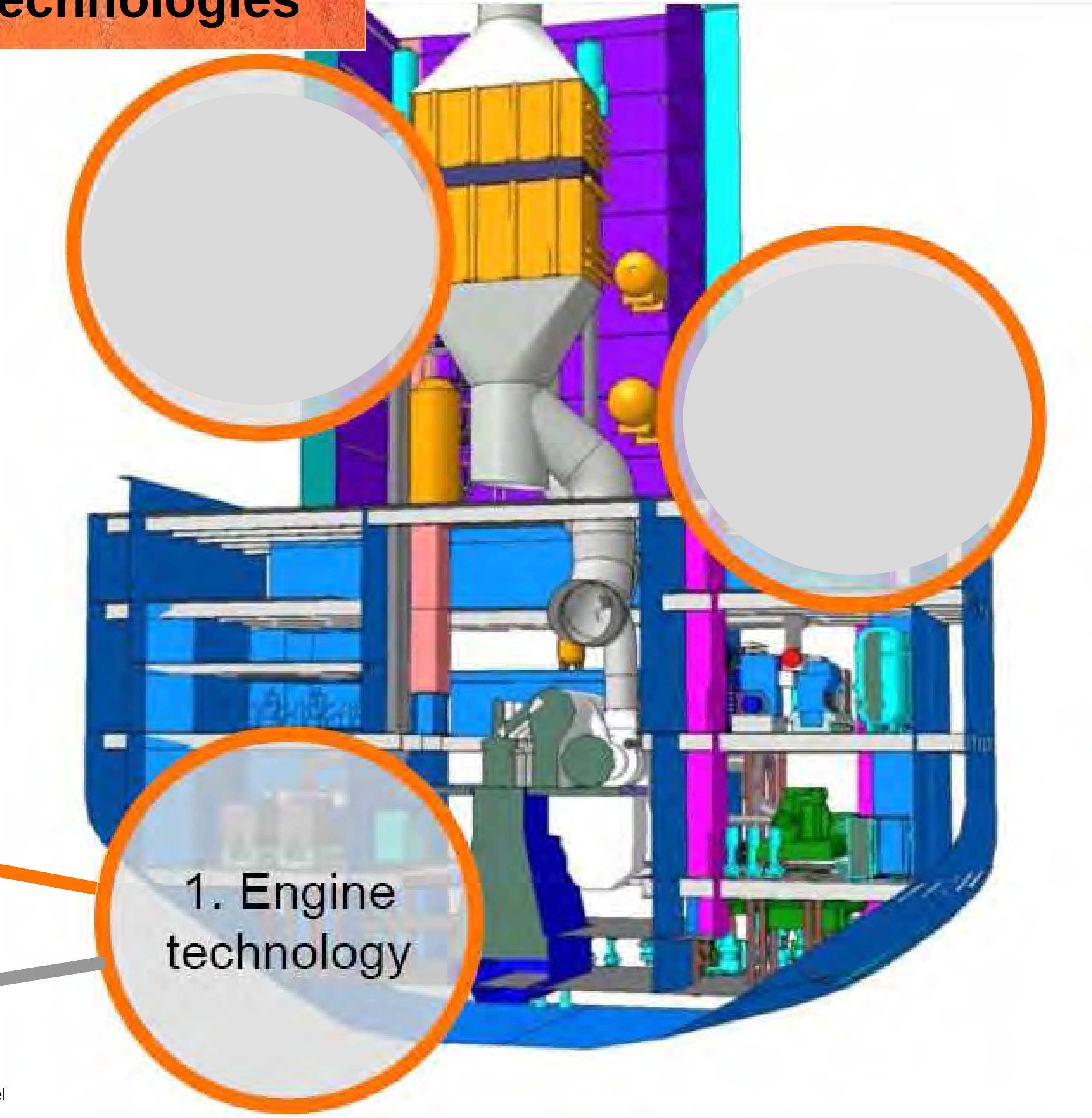
NOx reduction technologies

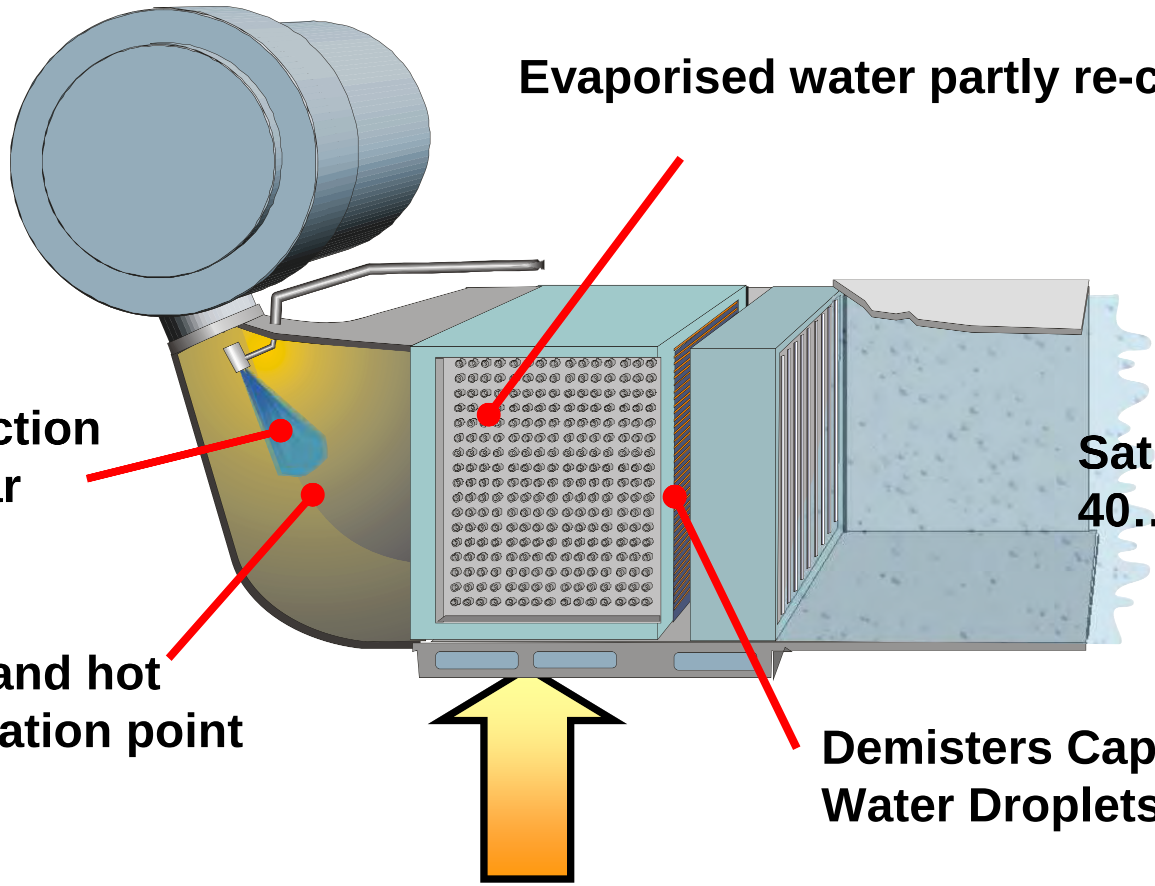


WET

DRY

Air Humidification

NOx	SOx	PM	Smoke
★★★		★	



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Direct Water Injection

NOx	SOx	PM	Smoke
★★		★	

Combined Water Fuel Nozzle

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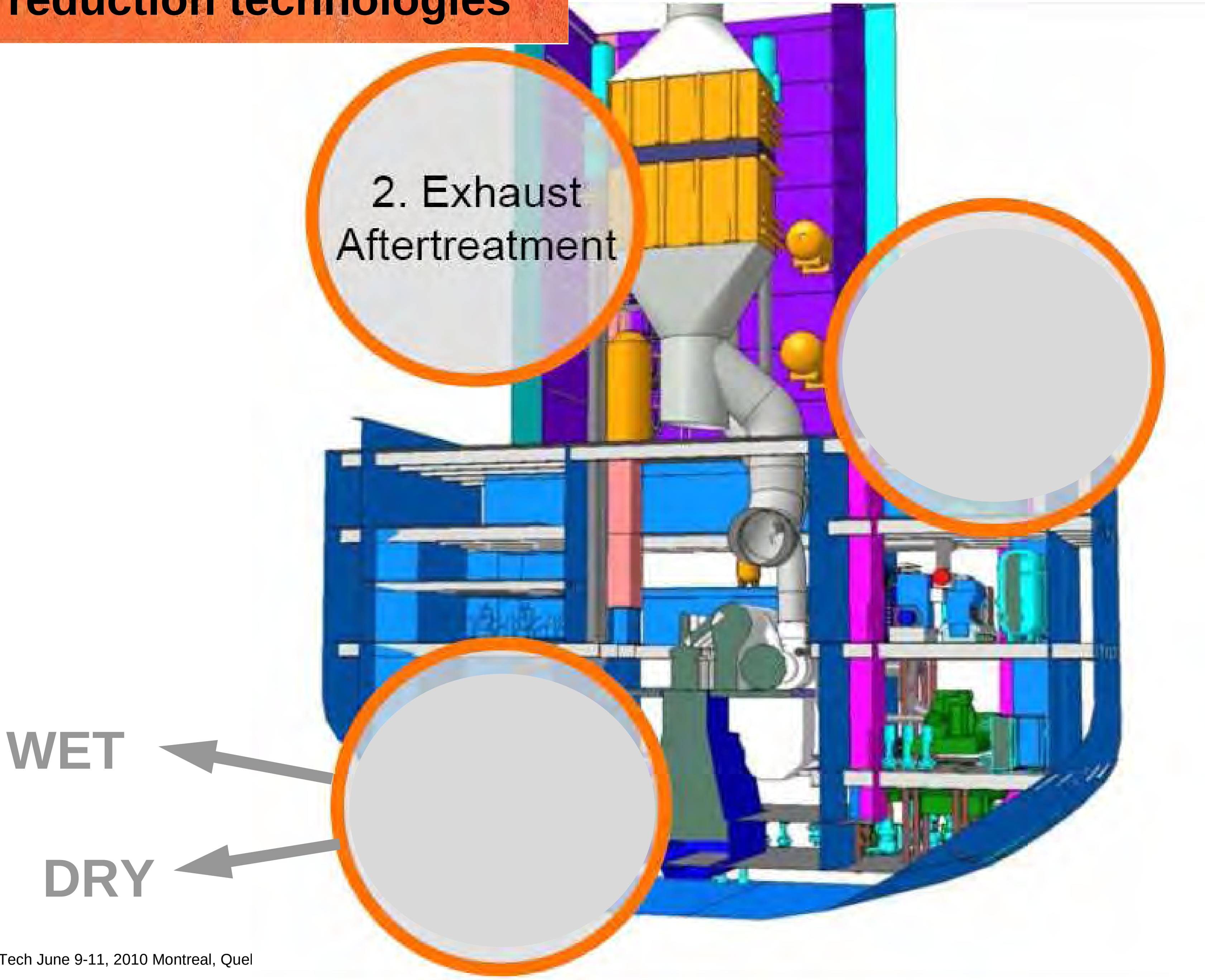
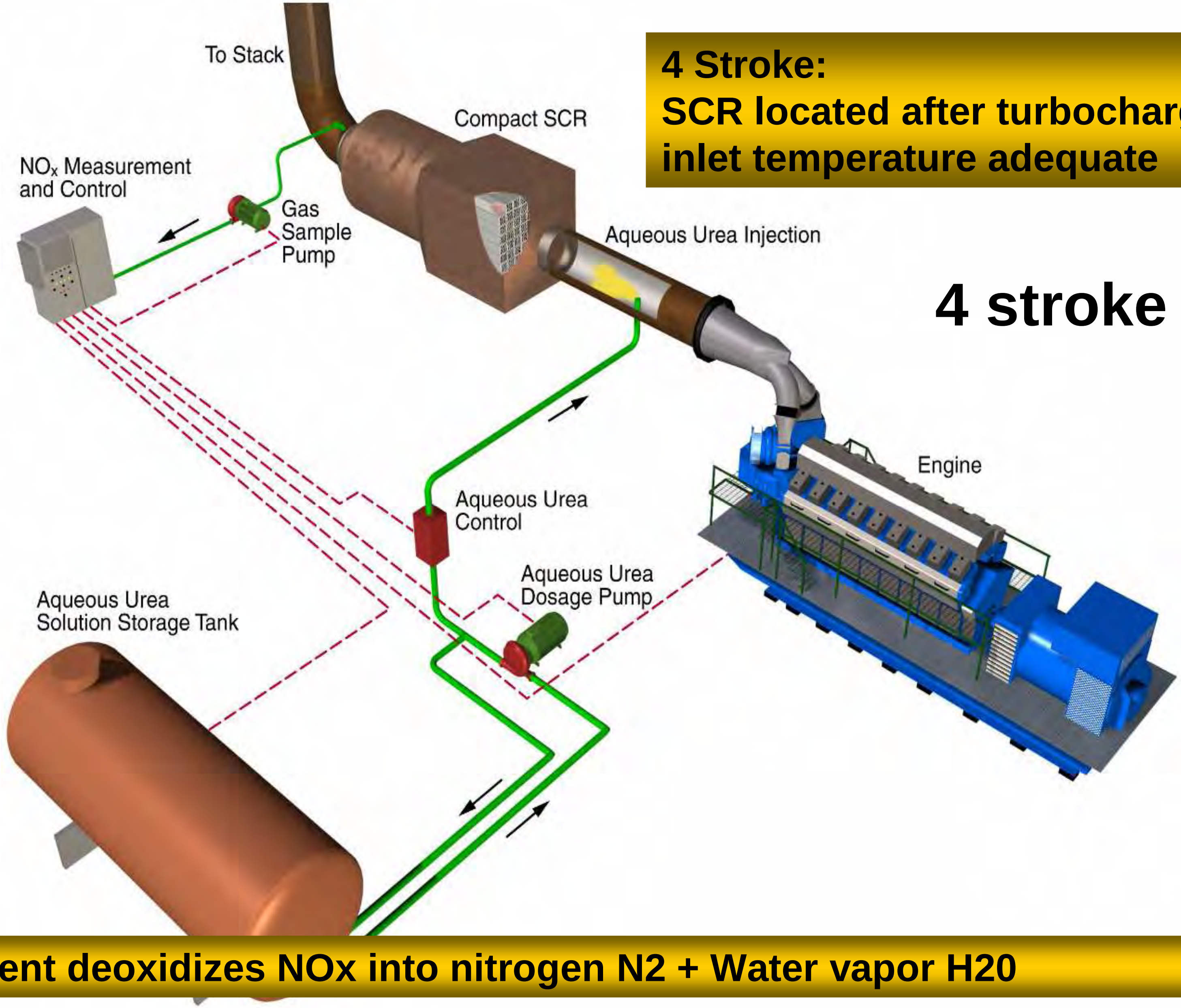
NOx reduction technologies



Selective Catalytic Reducer "SCR"

NOx	SOx	PM	Smoke
★★★★		★	

4 Stroke:
SCR located after turbocharger inlet temperature adequate

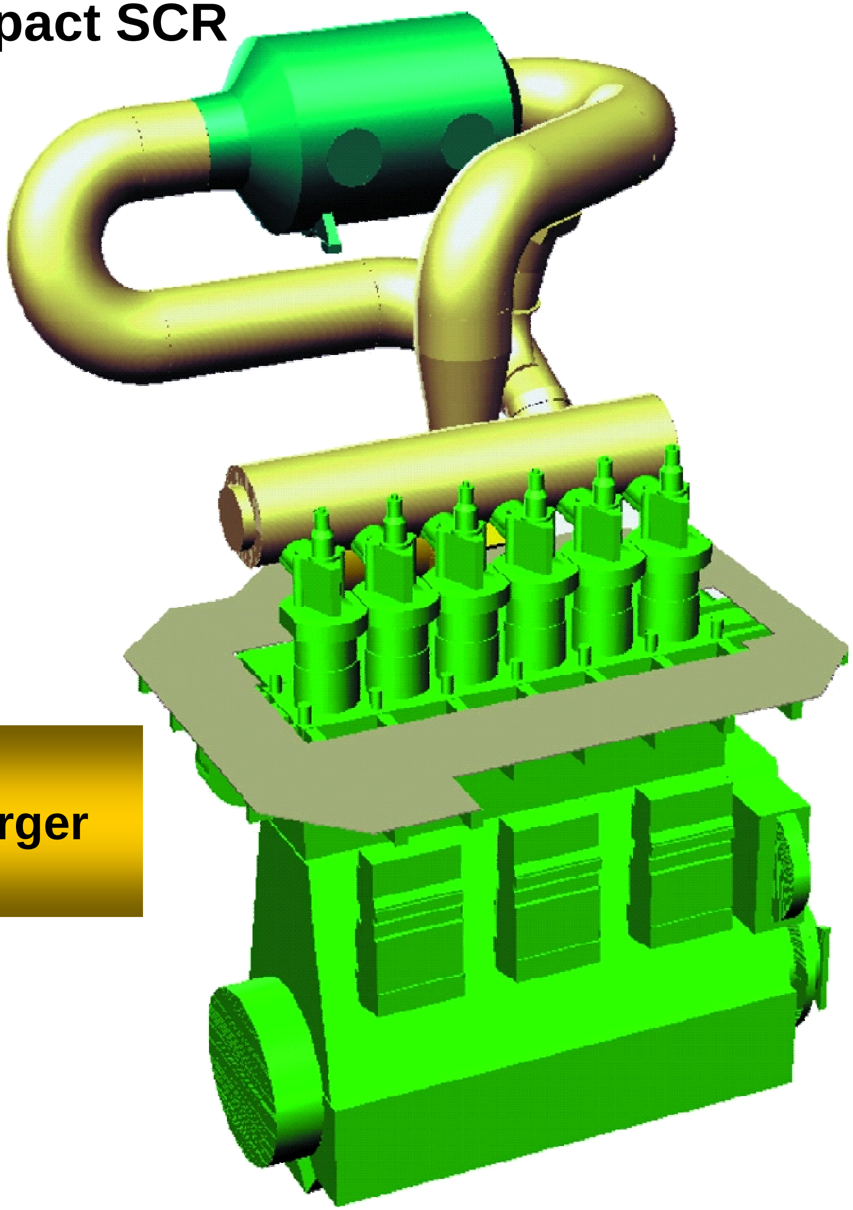


4 stroke

Agent deoxidizes NOx into nitrogen N2 + Water vapor H20

Selective Catalytic Reducer "SCR"

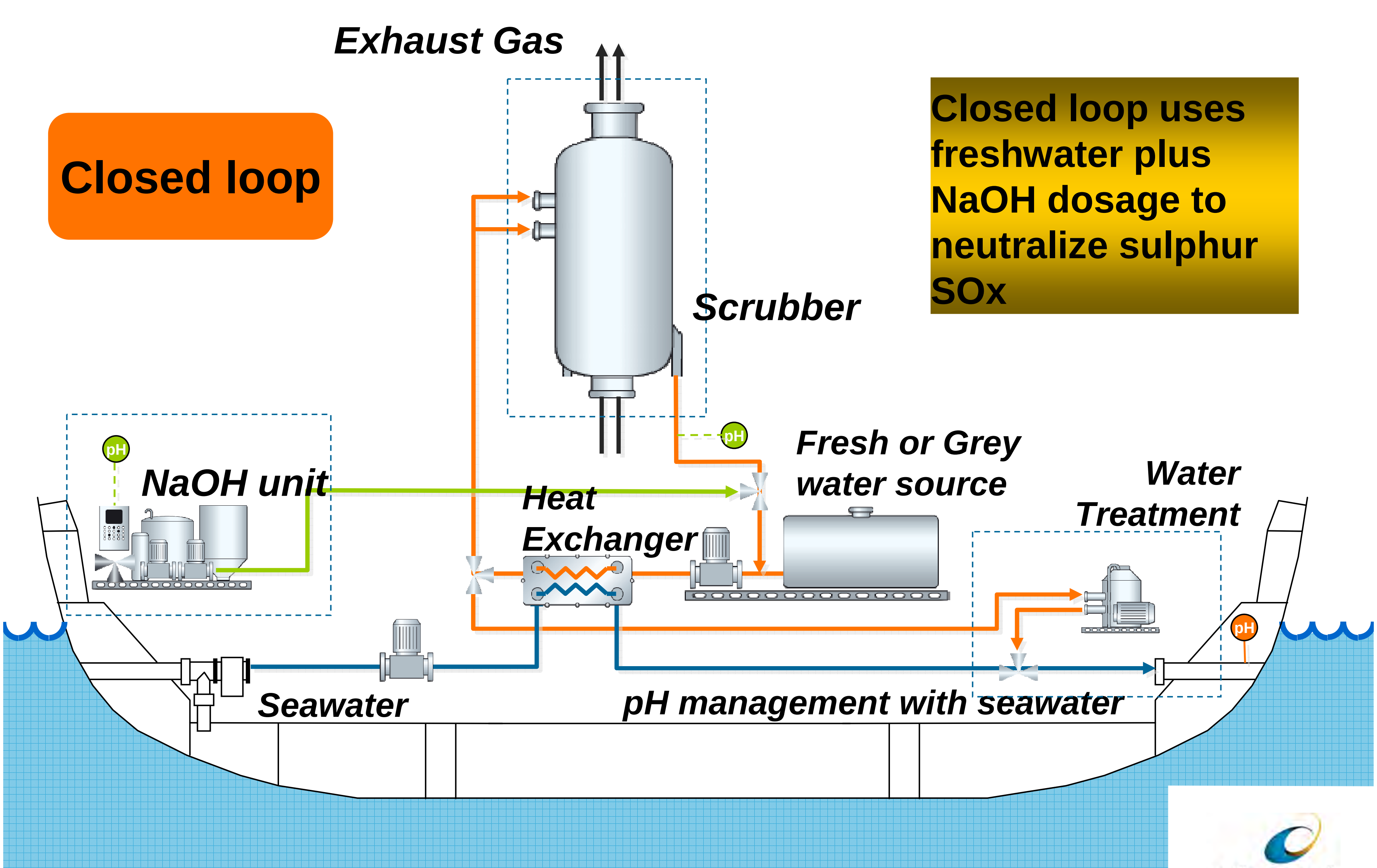
NOx	SOx	PM	Smoke
★★★★		★	



2 Stroke:
SCR located before turbocharger maintains inlet temperature

Fresh Water Scrubber (FWS)

NOx	SOx	PM	Smoke
★	★★★★	★	



Closed loop uses freshwater plus NaOH dosage to neutralize sulphur SOx

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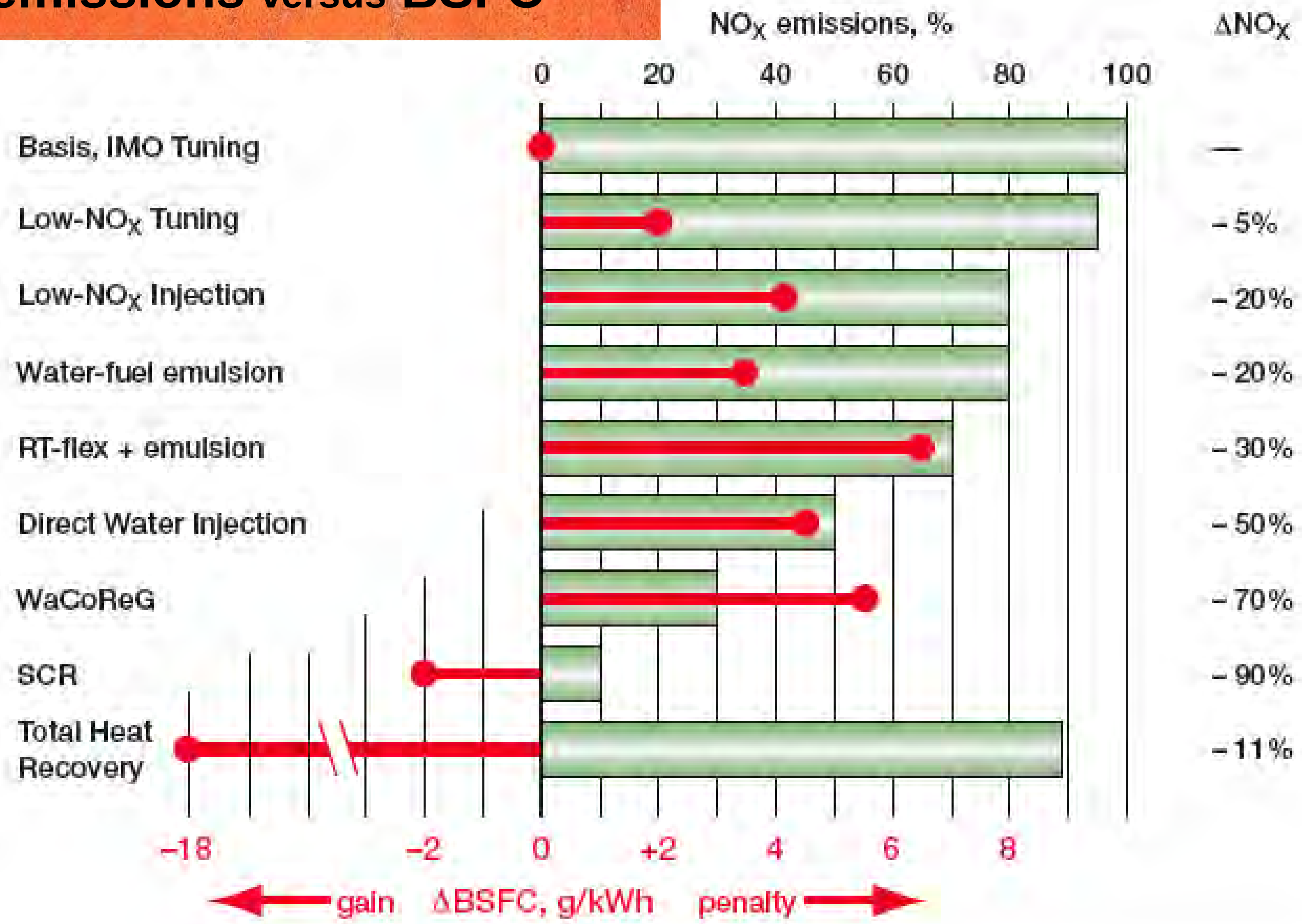
NO_X emissions versus BSFC



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

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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.

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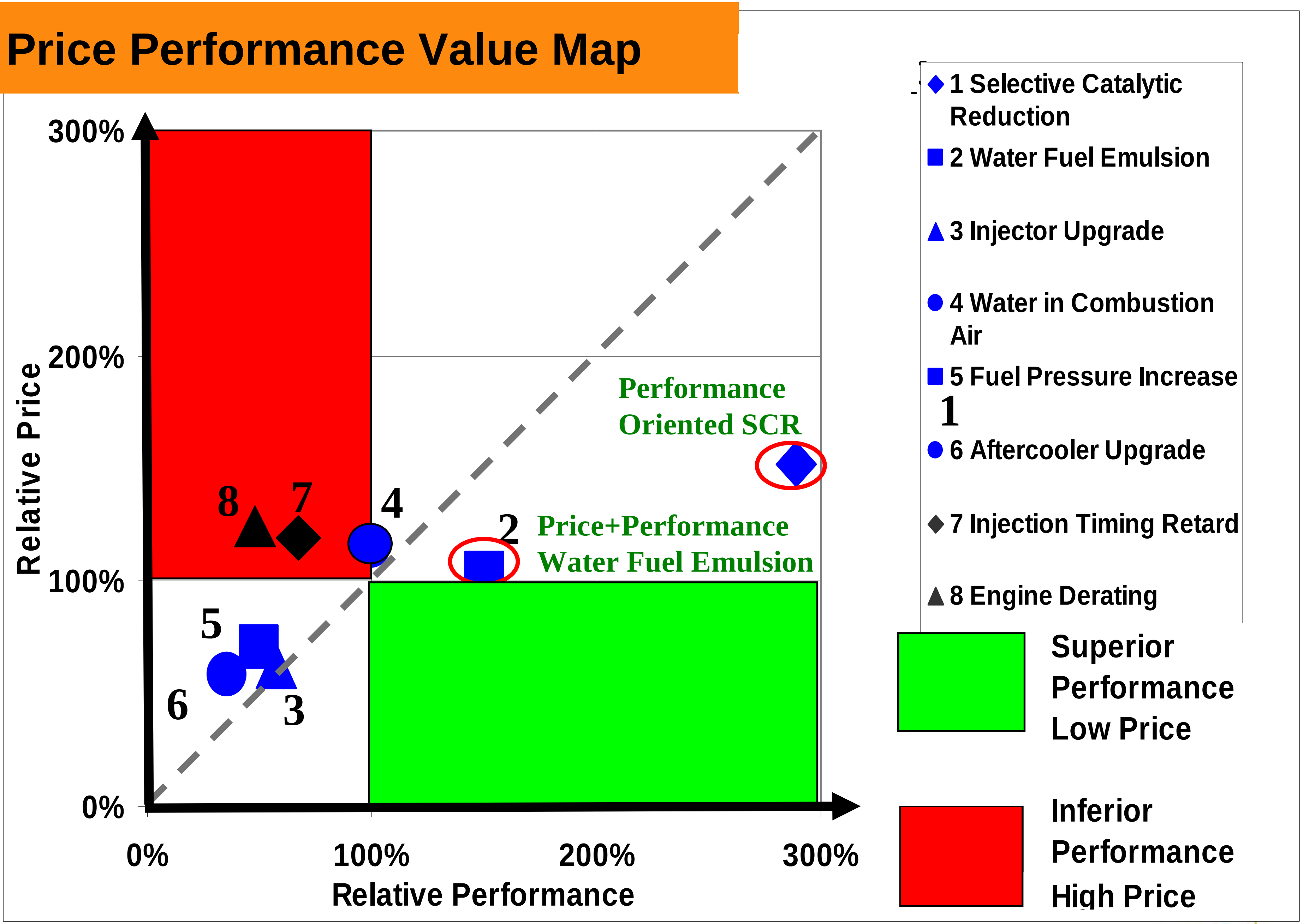
Price Performance Value Map



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

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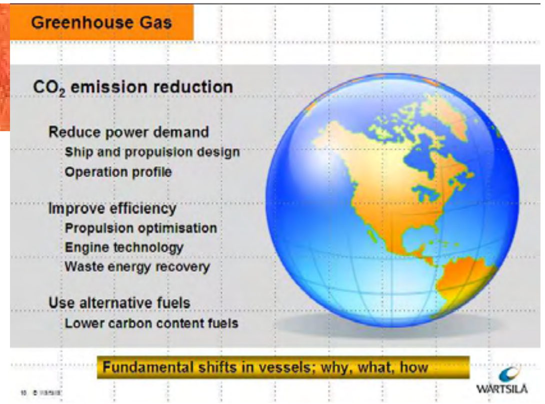
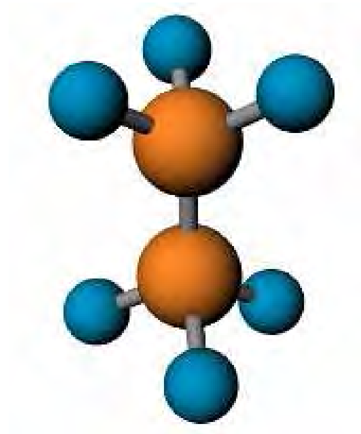
What is natural gas?



Natural gas … mostly methane (CH_4)

Methane has highest hydrogen content energy of any fossil fuel

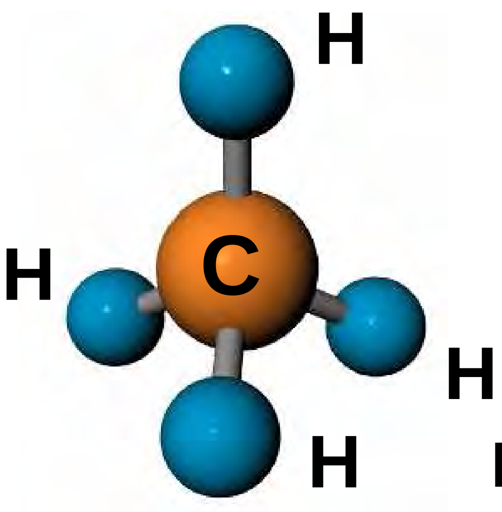
Carbon to hydrogen ratio 1 / 4 (gasoline: 1 / 2,25)



Ethane (C_2H_6)

Natural gas is:

- Non-toxic
- Colourless
- Odourless
- Lighter than air



Methane (CH_4)

Natural Gas has least Carbon content = Low CO2 Emissions

Low Natural Gas Emissions

25-30% lower CO_2

Low Carbon to Hydrogen ratio of fuel

85% lower NO_X

Lean burn concept (high air-fuel ratio)

No SO_X emissions

Sulphur is removed from fuel when liquefied

50% lower PM Particulates

Particulates vary across operating range

No visible smoke

No sludge deposits extends engine life and time between overhauls achieving maintenance savings

ULTRA CLEAN COMBUSTION

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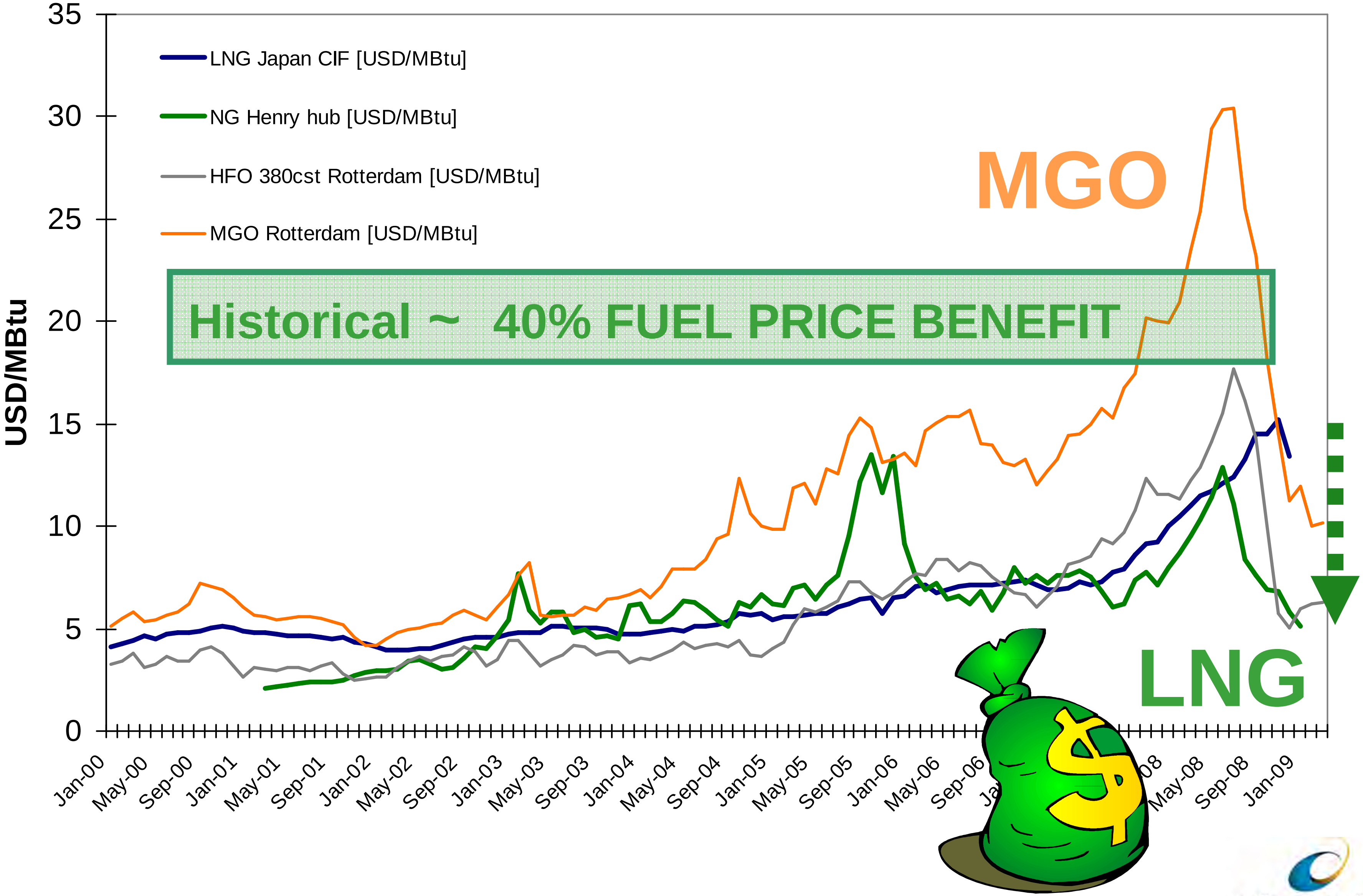
Win Win : Emissions Reduction & OPEX Savings



Sources: www.lngoneworld.com, www.bunkerworld.com, LR Fairplay

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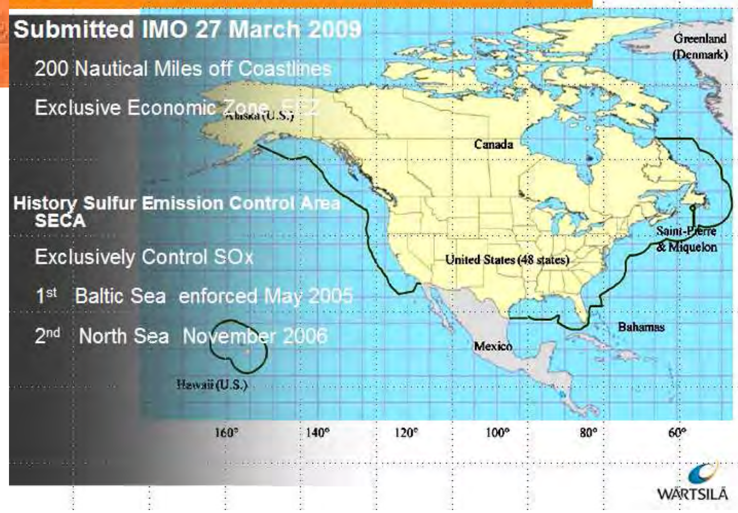
Natural Gas Tug Engine

US / Canada Emission Control Area " ECA "



<u>Main data</u>:

Cylinder bore......................200 mm
Piston stroke.......................280 mm
Cylinder output.................. 146/176 kW/cyl
Engine speed......................1000 1200 rpm
Mean effective pressure .....20.0 bar

NEWLY RELEASED: WARTSILA 20DF

1056 KW (1415 HP) TO 1584 KW (2123 HP)

20DF Natural Gas Category 2 Engine targets emissions sensitive port and coastal vessels operating in restrictive Emission Control Area "ECA"

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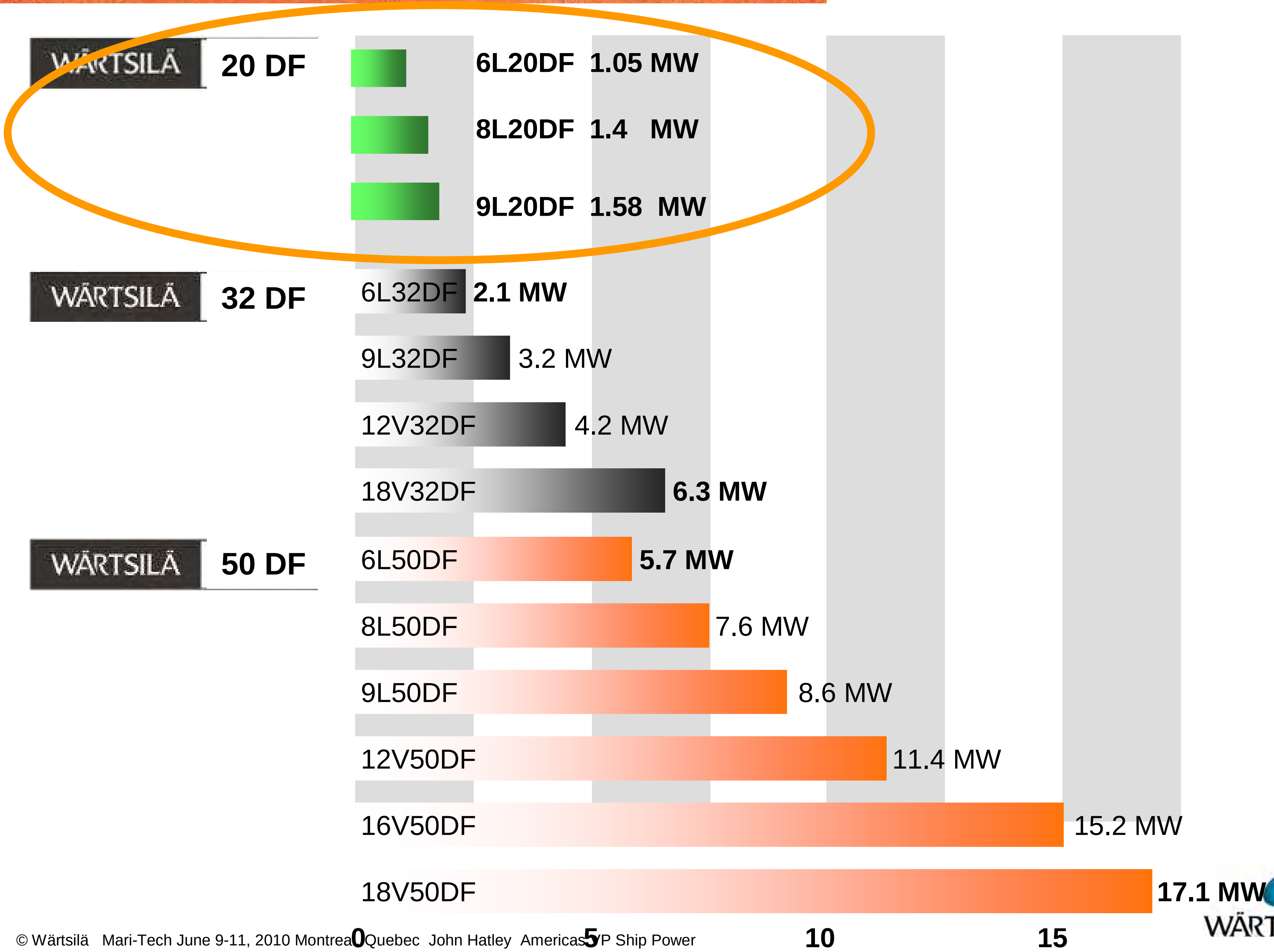
Expanded Dual-fuel Power Range



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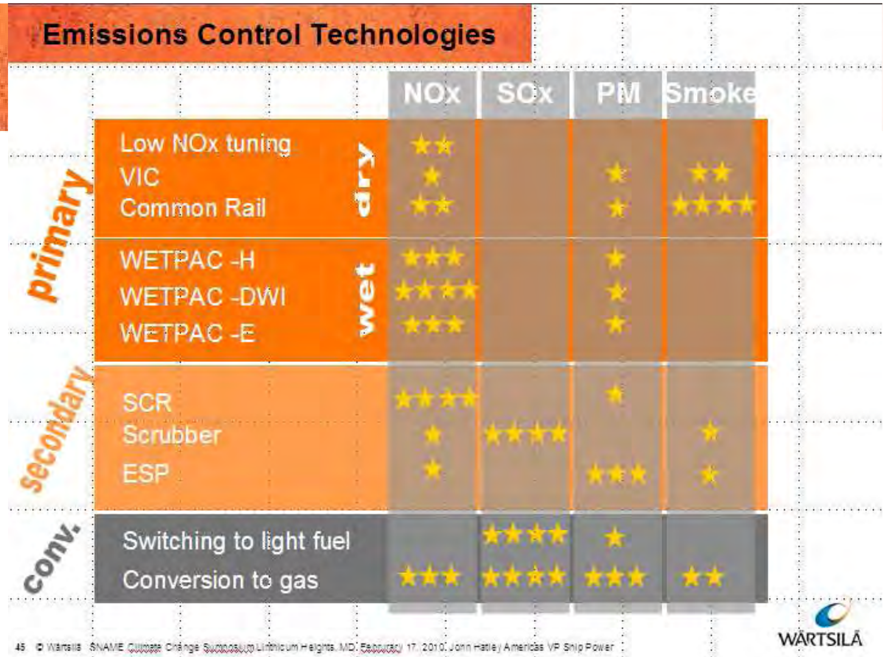
Conclusion



Emissions Control Technologies

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

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Emission Control

Operation Flexibility

Adopting to different Emission Control Areas "ECA" is key

Scarcity of light compliant fuel for ECA likely imposes significant increase in operating costs … scrubbers deal with existing fuel or industry adopts LNG for Emissions reduction and OPEX savings

LNG = ULTRA CLEAN COMBUSTION **&**

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Appendix

Comments

- Emission reduction regulations ultimate goal is to reduce Air Emissions, especially along sea shore where community leaves, 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.

Sources: SEAaT studies and Lloyd's Register Fairplay Event London 2005

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.

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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.

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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.

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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.

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