Marine Emission Fundamentals: Formation, Reduction, & Control

SNAME
Texas Section
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CAUTIONARY STATEMENT

The opinions expressed herein are solely those of the authors and are not necessarily representative of Wartsila North America, Inc, Wartsila Finland, Wartsila Lips, or Wartsila Corporation.

Agenda

- Emissions Inventory
- Combustion Process
- Formation & Reduction
- Control Technologies
- Regulatory Standards

Agenda

- **Emissions Inventory**
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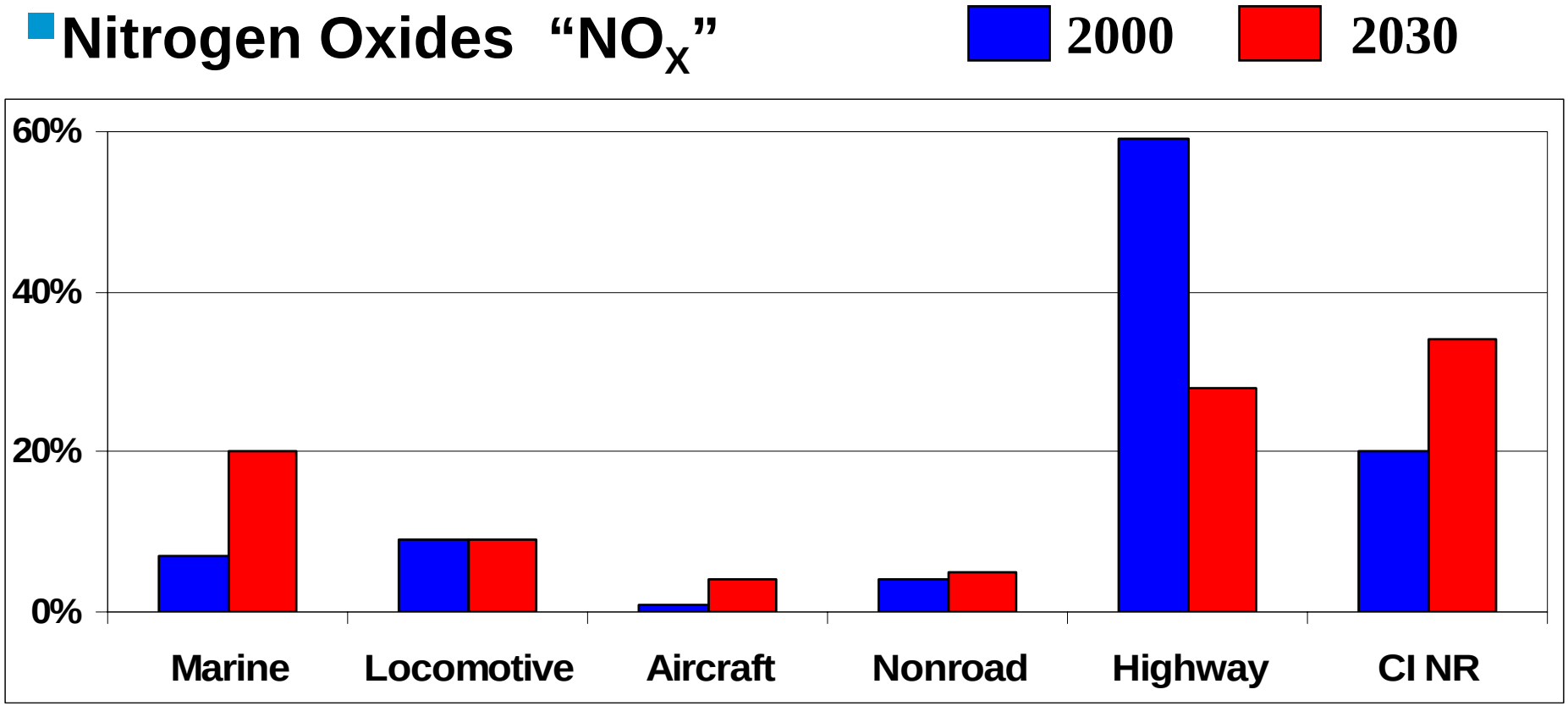
Diesel Emission Inventory

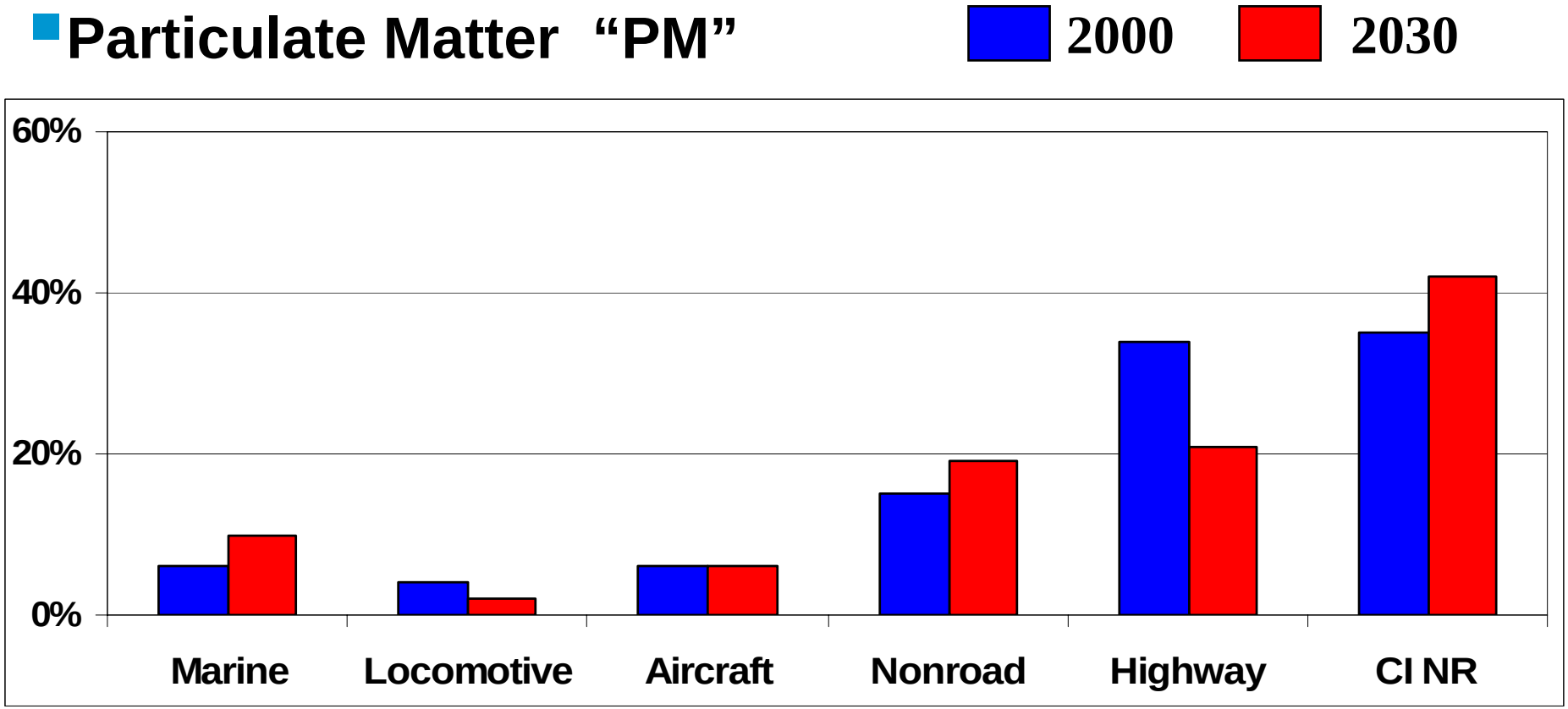
Nitrogen Oxides "NO_X"



Data Source: C3 Marine FRM, 68 FR 40, page 9755 (Feb 28, 2003)

Diesel Emission Inventory

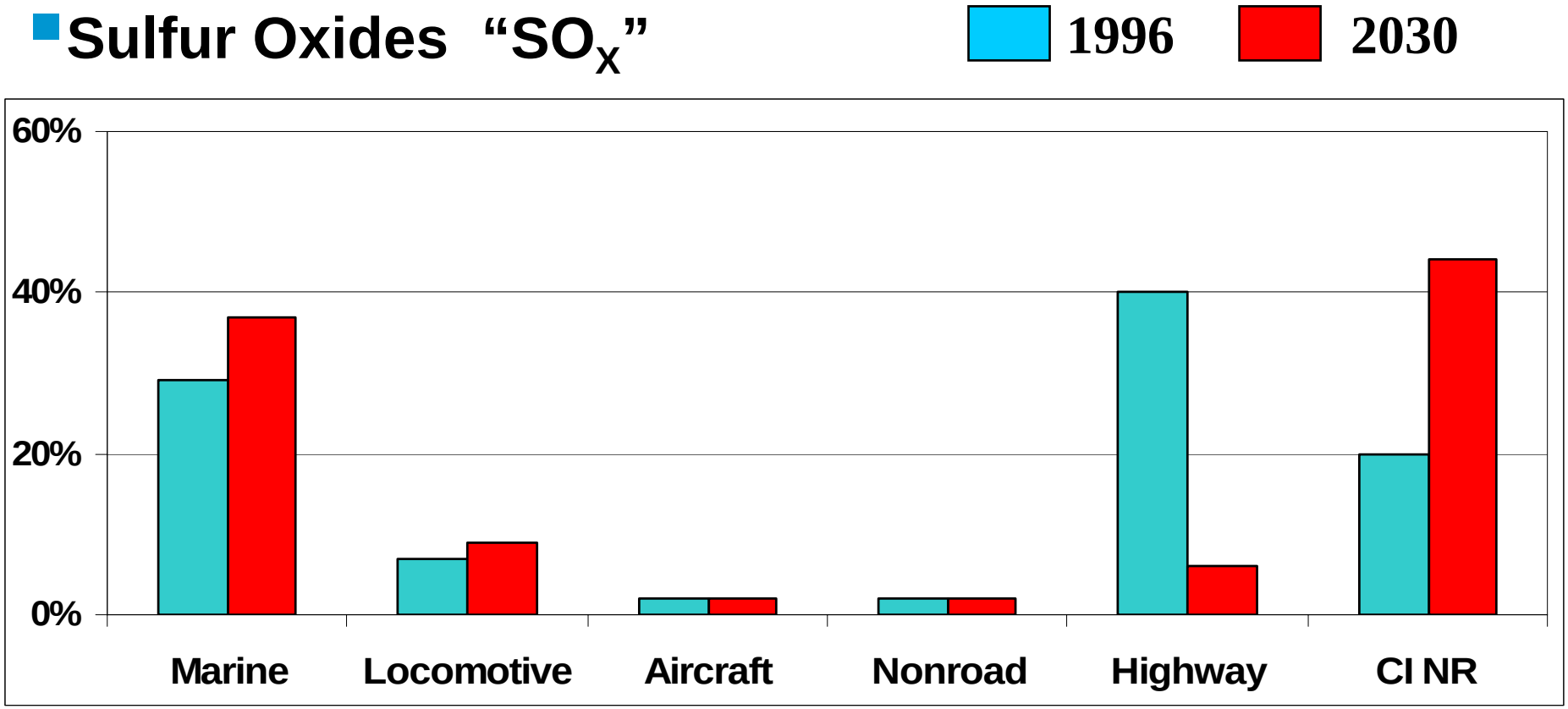
- Particulate Matter "PM"



Data Source: C3 Marine FRM, 68 FR 40, page 9755 (Feb 28, 2003)

Diesel Emissions Inventory

- Sulfur Oxides "SO_x"



Data Source: Non-road NPRM Draft Regulatory Impact Analysis, EPA420-R-03-008, April 2003

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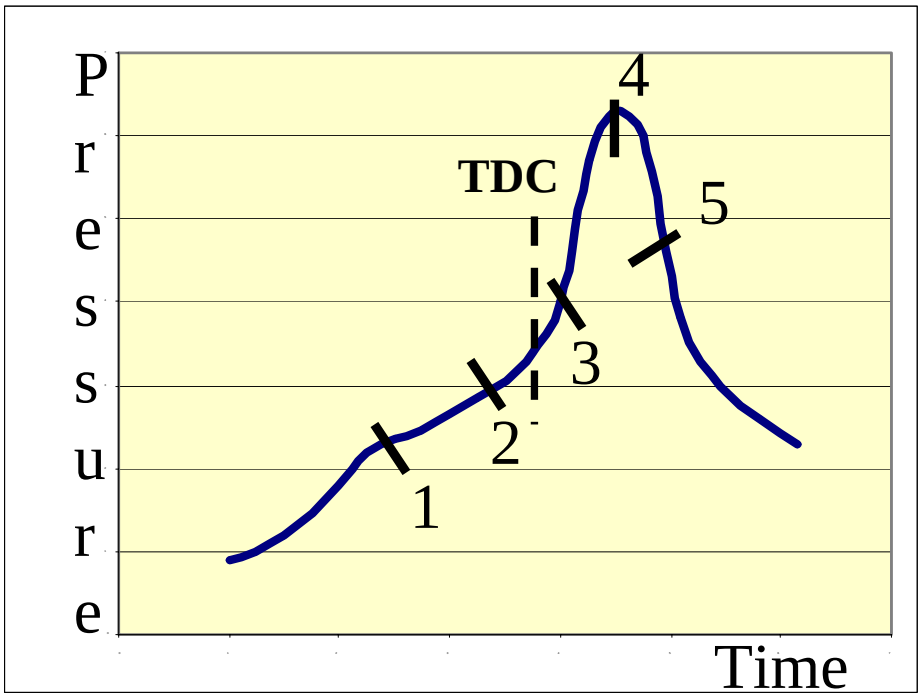
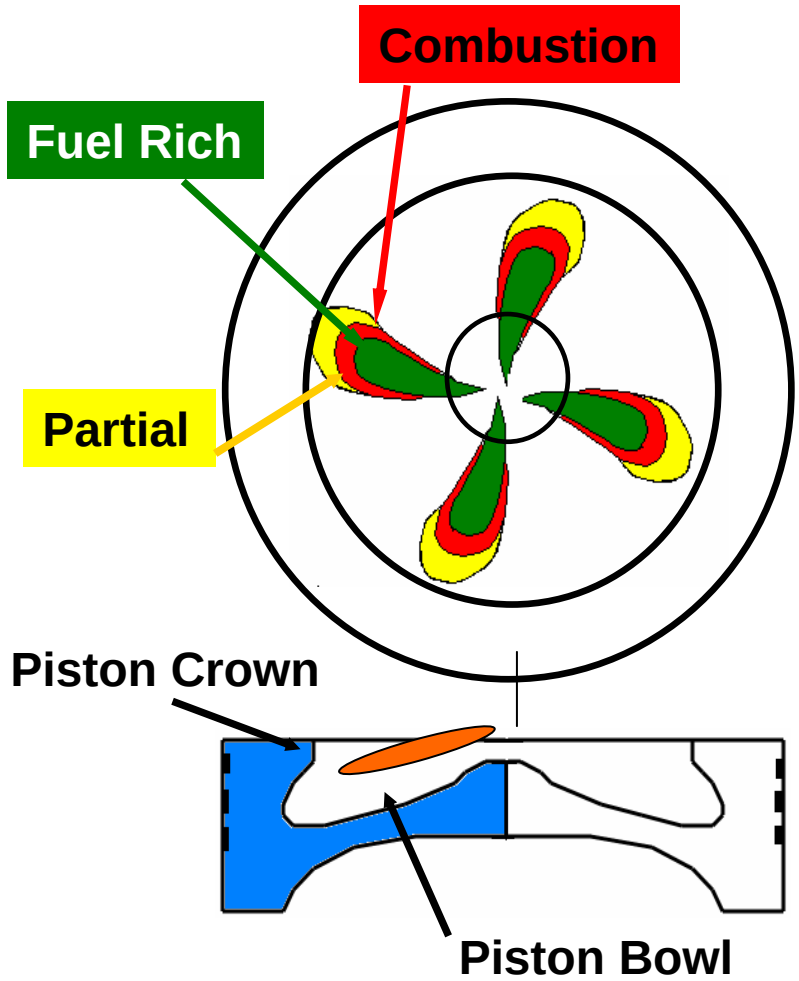
Combustion Process





1 Injection Begins
2 Combustion Starts
4 Injection Ends
5 Combustion Ends

1-2 Delay
2-3 Rapid Combustion
3-4 Controlled Combustion
4-5 After Burn

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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. 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.**
"PM"		**Organic fraction from unburned fuel and lube oil consumption. Sulfate dependent upon sulfur proportion in fuel.**		
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.**		

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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.**		

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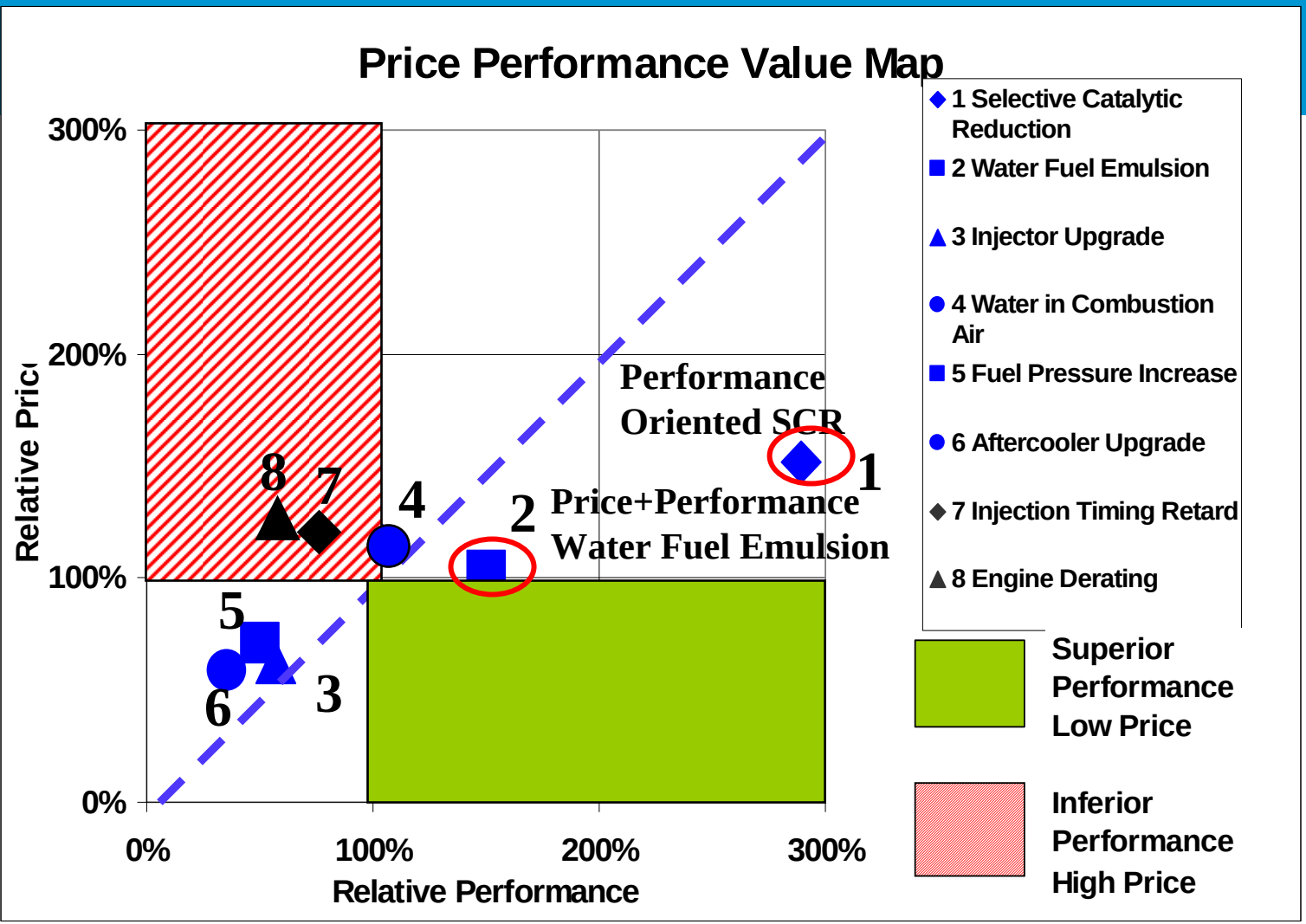
Control Technologies

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.**		

What Reduces Marine NO_X Best ?



SCR Pro & Con

Added infrastructure, space requirements, and operating reductant bring complexities.

	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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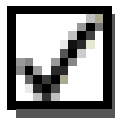
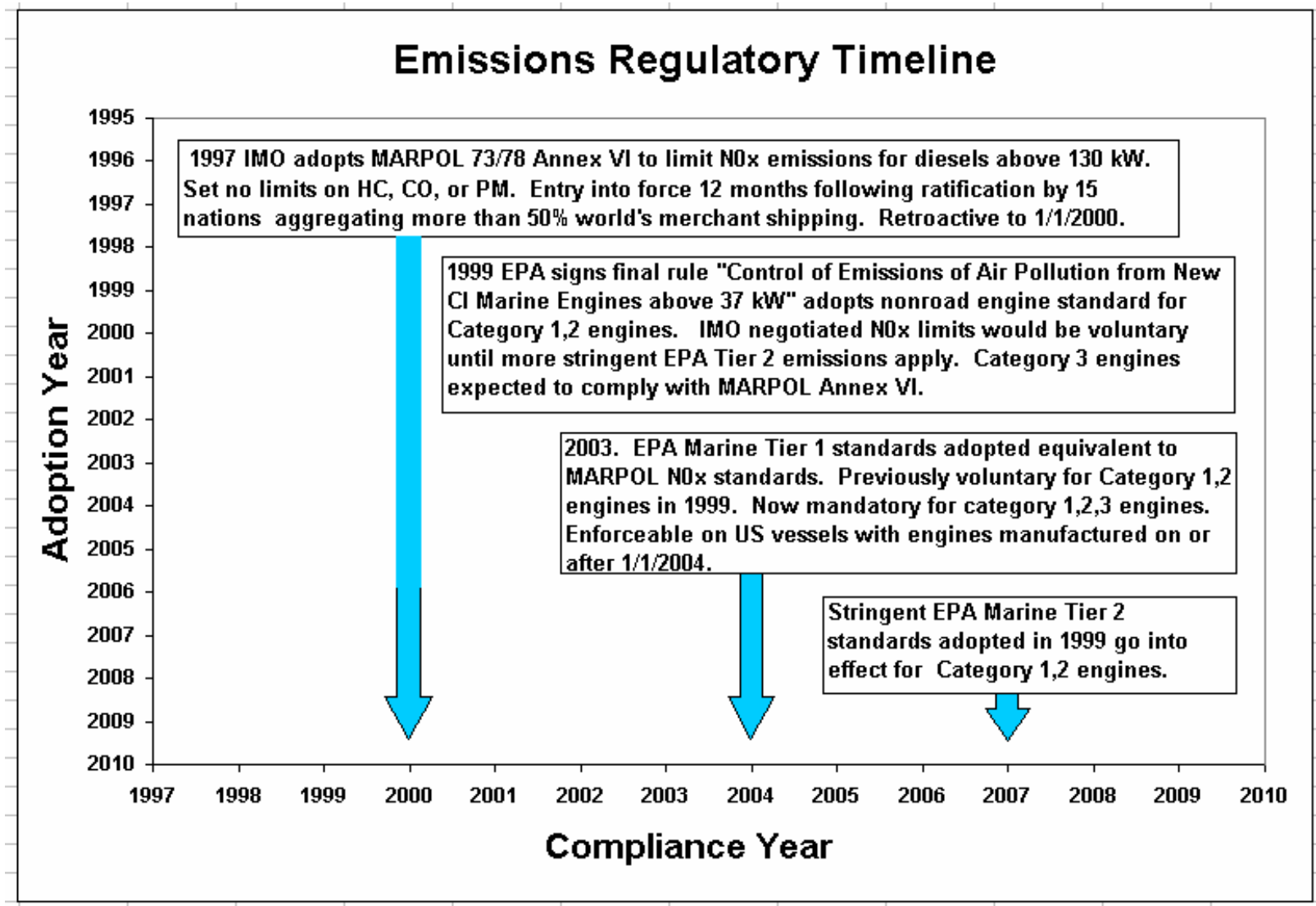
- Control Technologies 
- **Regulatory Standards**

Regulatory Standards

	Year											Limits			
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	N0x	THC	PM	CO
Foreign Flag	IMO MARPOL Annex VI											☑			
US Flag	IMO MARPOL Annex VI											☑			
					EPA Marine Tier 1 = Mandatory Annex VI							☑			
								EPA Marine Tier 2				☑	☑	☑	☑

Regulatory Timelines

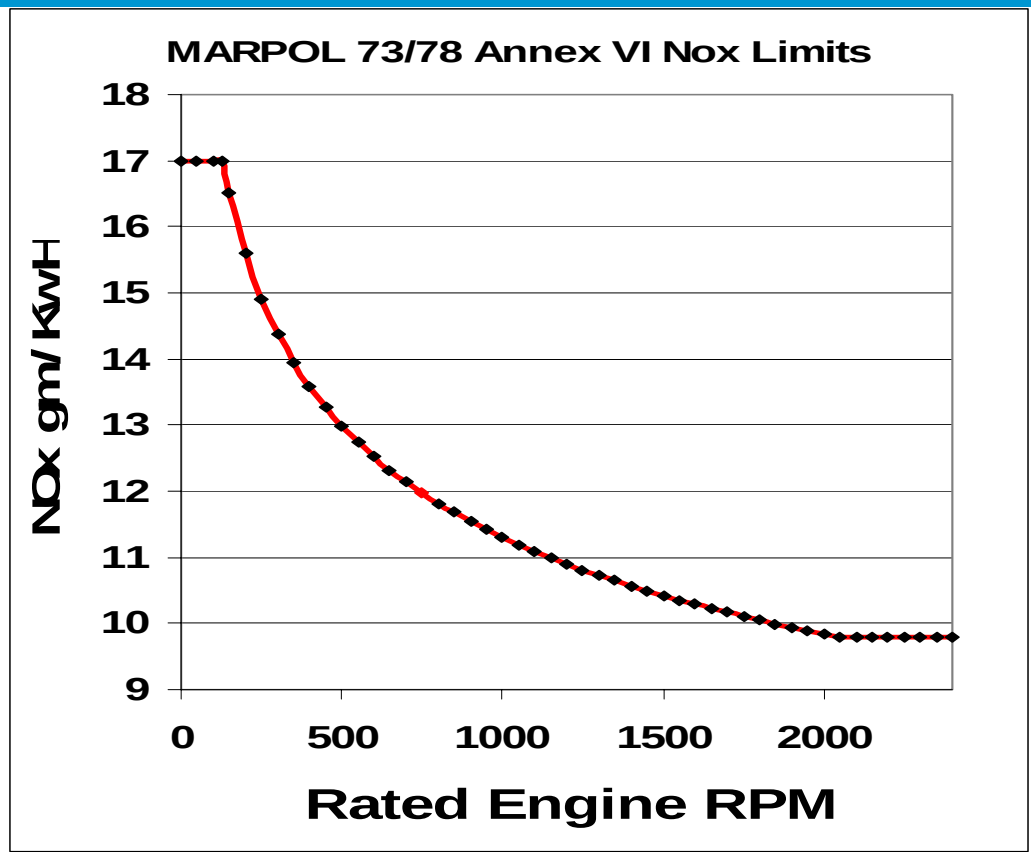


Regulatory Criteria

MARPOL Annex VI

2004 EPA Marine Tier 1

MARPOL Annex VI Limits	
Engine RPM	N0x g/ kW hr
n < 130	17.0
130 < n < 2000	45 x n $^{(-0.2)}$
n >= 2000	9.8



RPM Characteristic Basis

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Regulatory Criteria

2007 US EPA Marine Tier 2

EPA Marine Tier 2 Emissions Standards and Dates					
Category	Displacement liters / cylinder	Starting Date	N0x + THC g / kW hr	PM g / kW hr	CO g / kW hr
1	below 0.9 and power above 37 kW	2005	7.5	0.40	5.0
	greater than or equal to 0.9 less than 1.2	2004	7.2	0.30	5.0
	greater than or equal to 1.2 less than 2.5	2004	7.2	0.20	5.0
	greater than or equal to 2.5 less than 5	2007	7.2	0.20	5.0
2	greater than or equal to 5 less than 15	2007	7.8	0.27	5.0
	greater than or equal to 15 less than 20 and power below 3300 kW	2007	8.7	0.50	5.0
	greater than or equal to 15 less than 20 and power at or above 3300 kW	2007	9.8	0.50	5.0
	greater than or equal to 20 and less than 25	2007	9.8	0.50	5.0
	greater than or equal to 25 and less than 30	2007	11.0	0.50	5.0

EPA Engine Category Definitions	
Category	Displacement Per Cyclinder
1	below 5 liters and power equal to or above 37 kW
2	equal or above 5 liters and less than 30 liters
3	equal or above 30 liters

Displacement Characteristic Basis

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Questions ?

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- **Regulatory Standards … Slide 18, 19, 20**