Exhaust Emissions from Ship Engines
Significance, Regulations, Control Technologies

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presentation for MLAANZ Annual Conference, Queenstown, New Zealand, September 2009

Overview

- Shipping is the most fuel efficient means of moving freight, more than 70% of global freight task
- Powered by diesel engines – the most fuel efficient engines
- Generally use low quality fuel – low cost, high sulphur content
- Emissions of oxides of nitrogen (NOx), oxides of sulphur (SOx) and particulate matter (PM) are significant
- Ship NOx about 18% of global emissions from fossil fuel combustion, around 40% of global transport NOx emissions
- 70% of ship emissions occur within 400km of land
- Impact of ship emissions on terrestrial air quality under focus
- Terrestrial air emission controls outpacing controls on ship emissions

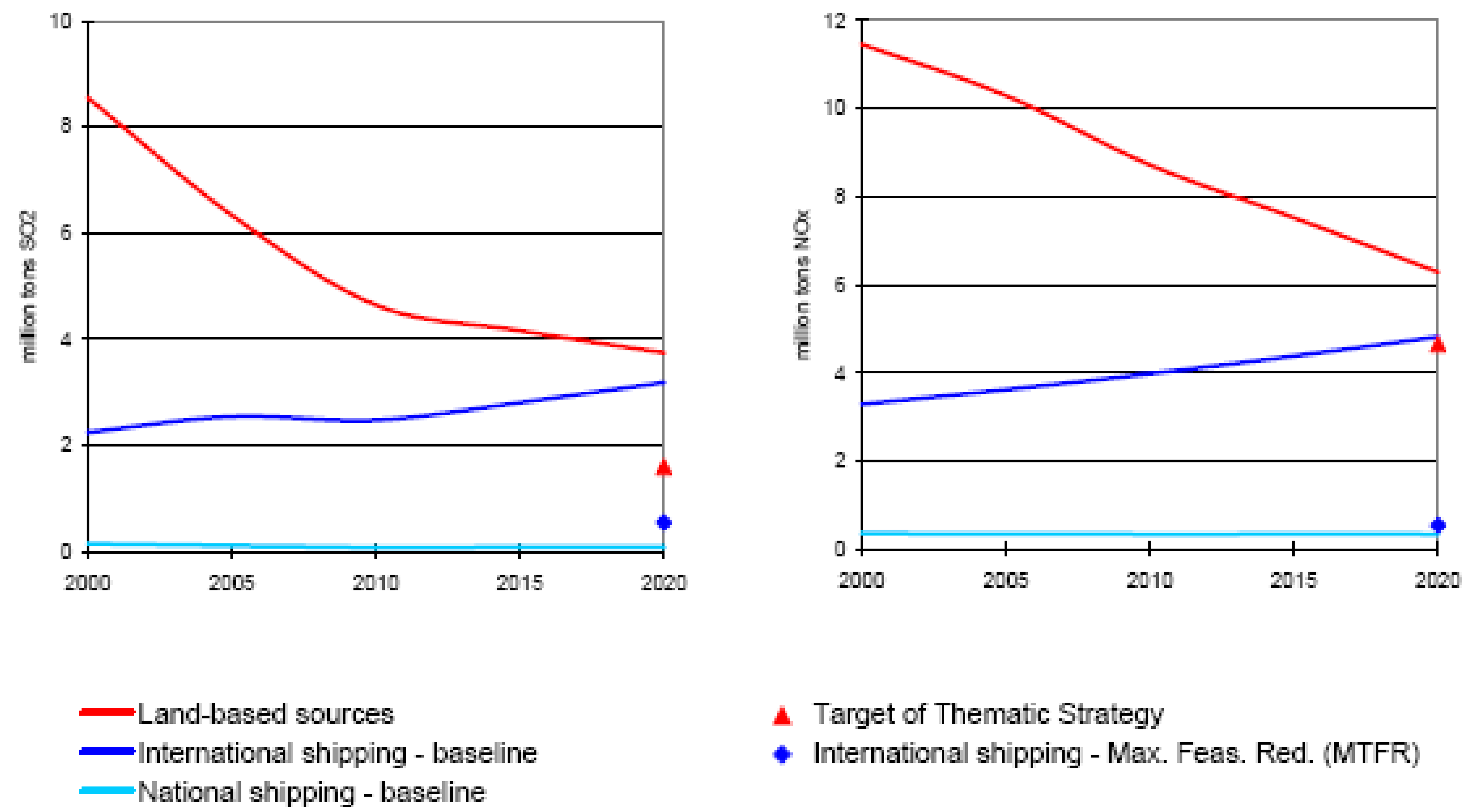

Figure 4.2: Emissions of sulphur dioxide (left panel) and nitrogen oxides (right panel) from shipping (baseline scenario) compared with the emissions from land-based sources in the EU25, million tons.

Analysis of Policy Measures to Reduce Ship Emissions in the Context of the Revision of the National Emissions Ceilings Directive Final Report
Janusz Cofala, Markus Amann, Chris Heyes, Fabian Wagner, Zbigniew Klimont, Max Posch, Wolfgang Schöpp Leonor Tarasson, Jan Eiof Jonson, Chris Whall, Andrianna Stavrakaki
Submitted to the European Commission, DG Environment, Unit ENV/C1 Contract No 070501/2005/419589/MAR/C1

IMO MARPOL Annex VI 2008

- 2005 Tier1 NOx for new engines post 2000
- 2010 ECA fuel sulphur 1% (currently 1.5%)
- 2011 global Tier2 NOx for new engines (IMO Tier 1 less 15 to 20%) (engine tuning)
- 2012 global fuel sulphur 3.5% (currently 4.5%)
- 2015 ECA fuel sulphur 0.1%
- 2016 ECA Tier3 NOx for new engines (IMO Tier 1 less 80%) (exhaust gas aftertreatment)
- 2020 global fuel sulphur 0.5% - if refineries can produce it, review in 2018
- Tier 1 NOx for engines >5MW installed 1990 to 2000 (conversion kits)

Exhaust gas scrubbers can be used as an alternative to low sulphur fuel

Reduced sulphur content will reduce particulate emissions significantly

IMO: International Maritime Organisation
MARPOL: International Convention for Prevention of Pollution from Ships
Annex VI: Air Pollution
ECA: designated emissions control area (relevant countries make application to IMO)

Colombo Express – large modern container ship, length 335m, power 68.6MW, 8749TEU, cruise speed 25 knots
(from www.hapag-lloyd.com/en/press_and_media/overview_photo_library.html)

Other Limits

- 2010 fuel sulphur 0.1% at berth in European Union
- 2009 distillate fuel, fuel sulphur 1.5%/0.5% depending on fuel aromaticity, in Californian waters
- 2012 distillate fuel, fuel sulphur 0.1%, in Californian waters
- USA/Canada application for IMO Emission Control Area (ECA) covering the Pacific coast, the Atlantic/Gulf coast and the eight main Hawaiian Islands, 200 nautical miles

CARB fuel switching regulations 2009

Fuel Requirement	Effective Date	Fuel
Phase I	July 1, 2009*	Marine gas oil (DMA) at or below 1.5% sulfur; or Marine diesel oil (DMB) at or below 0.5% sulfur
Phase II	January 1, 2012	Marine gas oil (DMA) or marine diesel oil (DMB) at or below 0.1% sulfur

US EPA statement on new ship engine emission controls (primarily IMO ECA plus HC and CO reductions): “By 2030, the coordinated strategy is expected to yield significant health and welfare benefits, annually preventing between 13,000 and 33,000 premature deaths, 1,500,000 work days lost, and 10,000,000 minor restricted activity days.
The monetized health benefits are projected to range from \$110 billion to \$280 billion... These estimated benefits exceed the projected costs by a ratio of at least 30:1”, EPA-420-F09-029, June 2009

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Emissions taxes and incentives

- Norwegian NOx tax on all industries including domestic shipping to meet Gothenburg Protocol* obligations - continuous measurement or calculation based on default indices tax (NOK = 15 x kg NOx emitted in Norwegian territory)
- Sweden differentiated harbour dues – NOx, fuel sulphur
- Vancouver differentiated harbour dues – fuel sulphur
- Environmental Indices for NOx, SOx and CO_2 – allow selection of ships according to environmental performance
- DNV Clean Design certification – NOx, SOx, refrigerants…

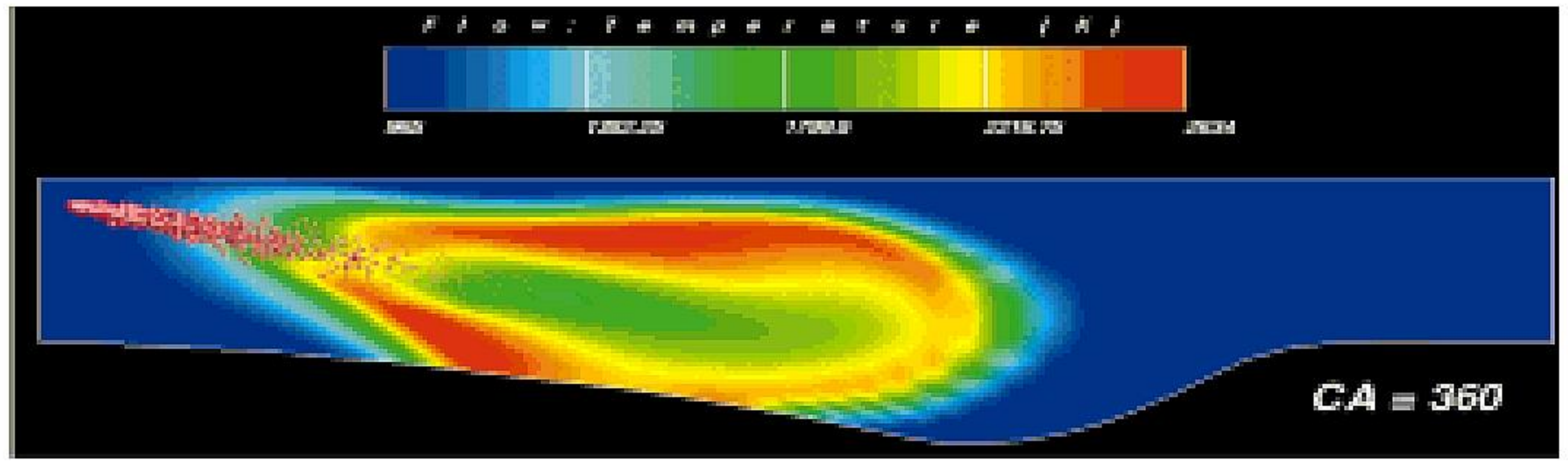
"Marinox" Marine Diesel Emissions Monitoring System logs NOx emissions against vessel location

*Gothenburg Protocol – Europe/USA/Canada, reduction of acidification, eutrophication and ground level ozone to agreed levels by 2010 – sulphur, NOx, VOC, ammonia – part of Convention on Long Range Transboundary Air Pollution

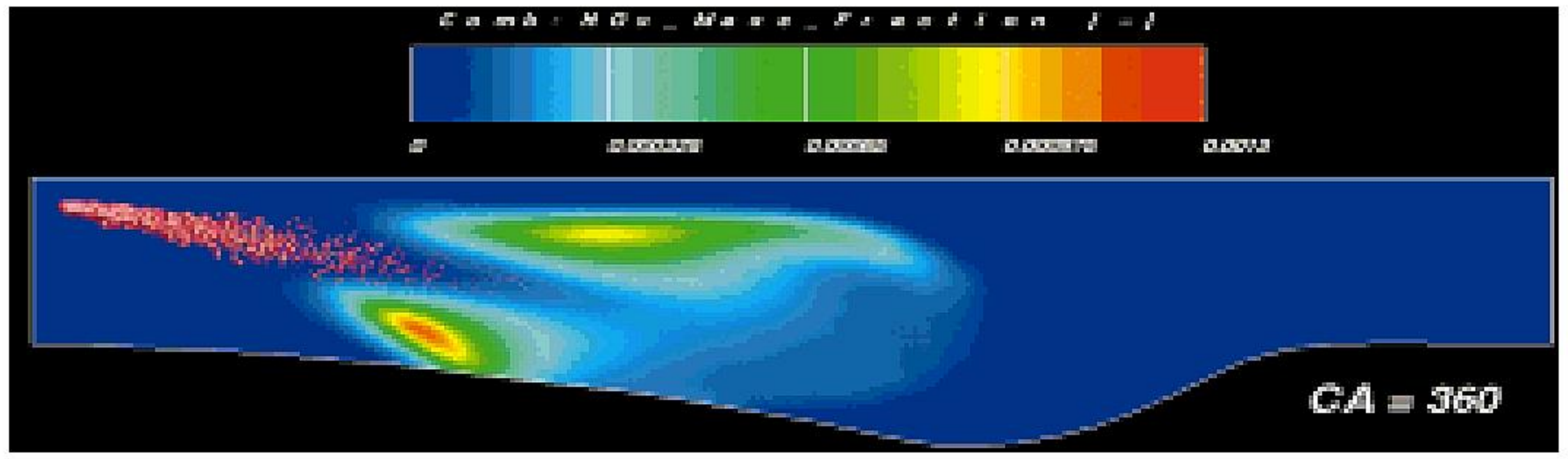
Oxides of Nitrogen

- NOx emissions inherently high due to engine size and thus slow rotational speed – more time for NOx to form around the burning fuel spray and less heat transfer to surroundings
- Shipping about 18% of global NOx emissions from fossil fuel
- New engines meet the IMO Tier 2 limits, possibly with a small fuel consumption increase (up to 3%)
- Tier 2 achieved by combustion process optimization – fuel injection timing and pressure, exhaust valve timing and compression ratio
- electronically controlled high pressure fuel injection best for combustion optimisation, especially at low loads

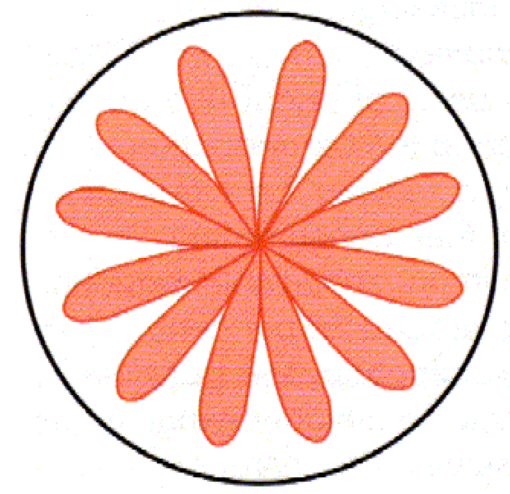
Combustion temperature and fuel droplets

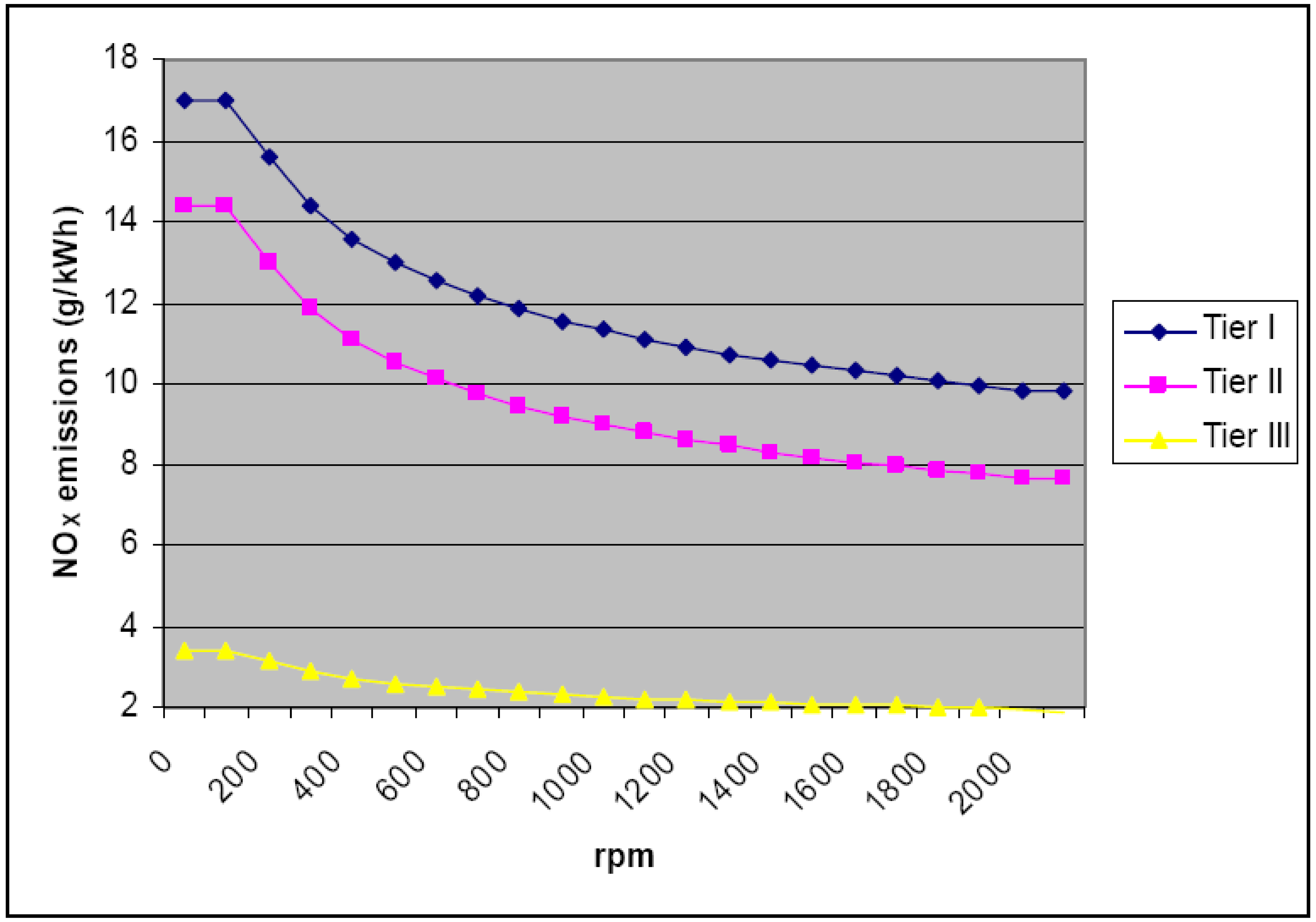


NO_x mass fraction and fuel droplets



Computer simulation of temperature and NOx in a burning fuel spray for a Wartsila medium speed engine at TDC (vertical plane through a single spray)



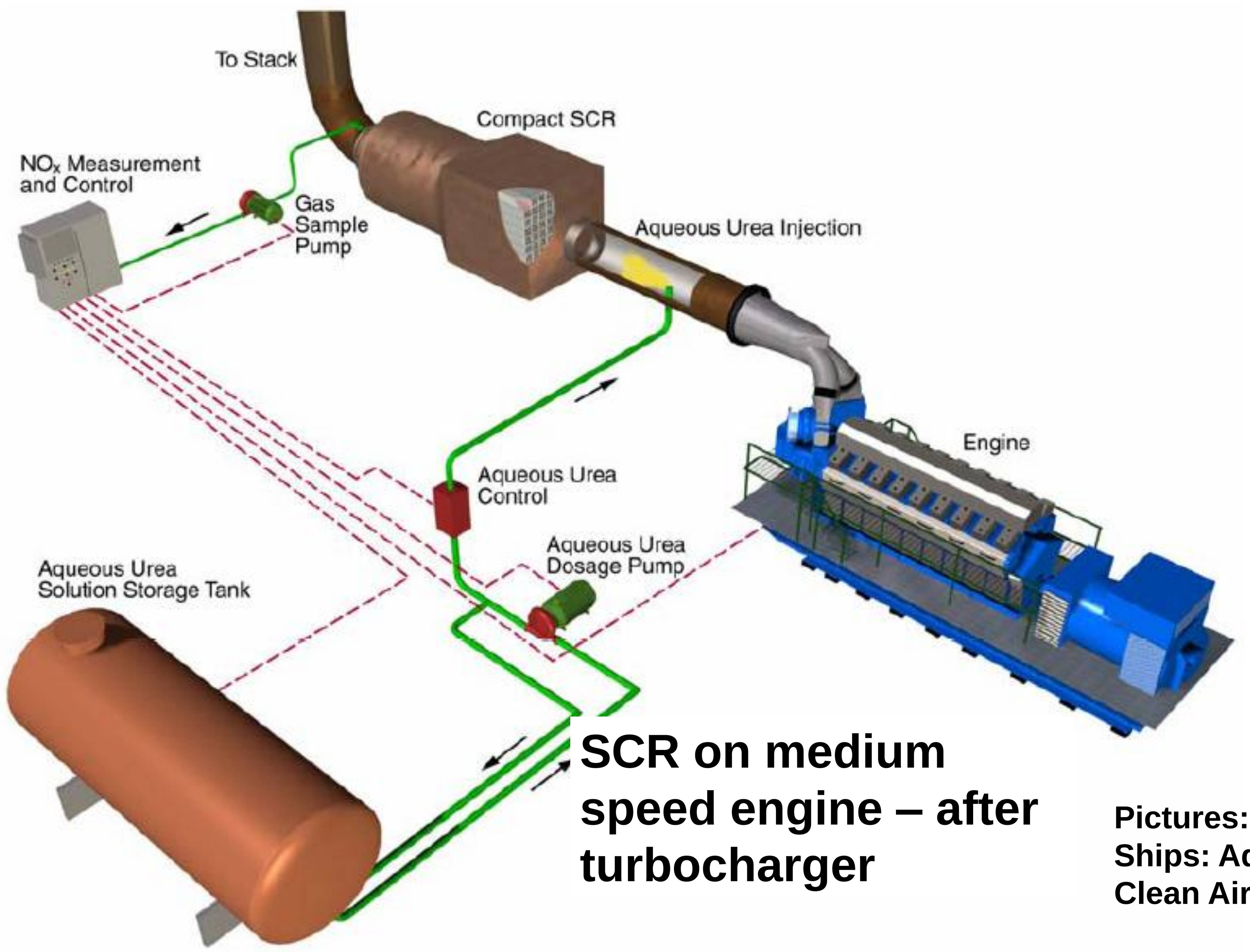


IMO limits are a function of engine size (speed)

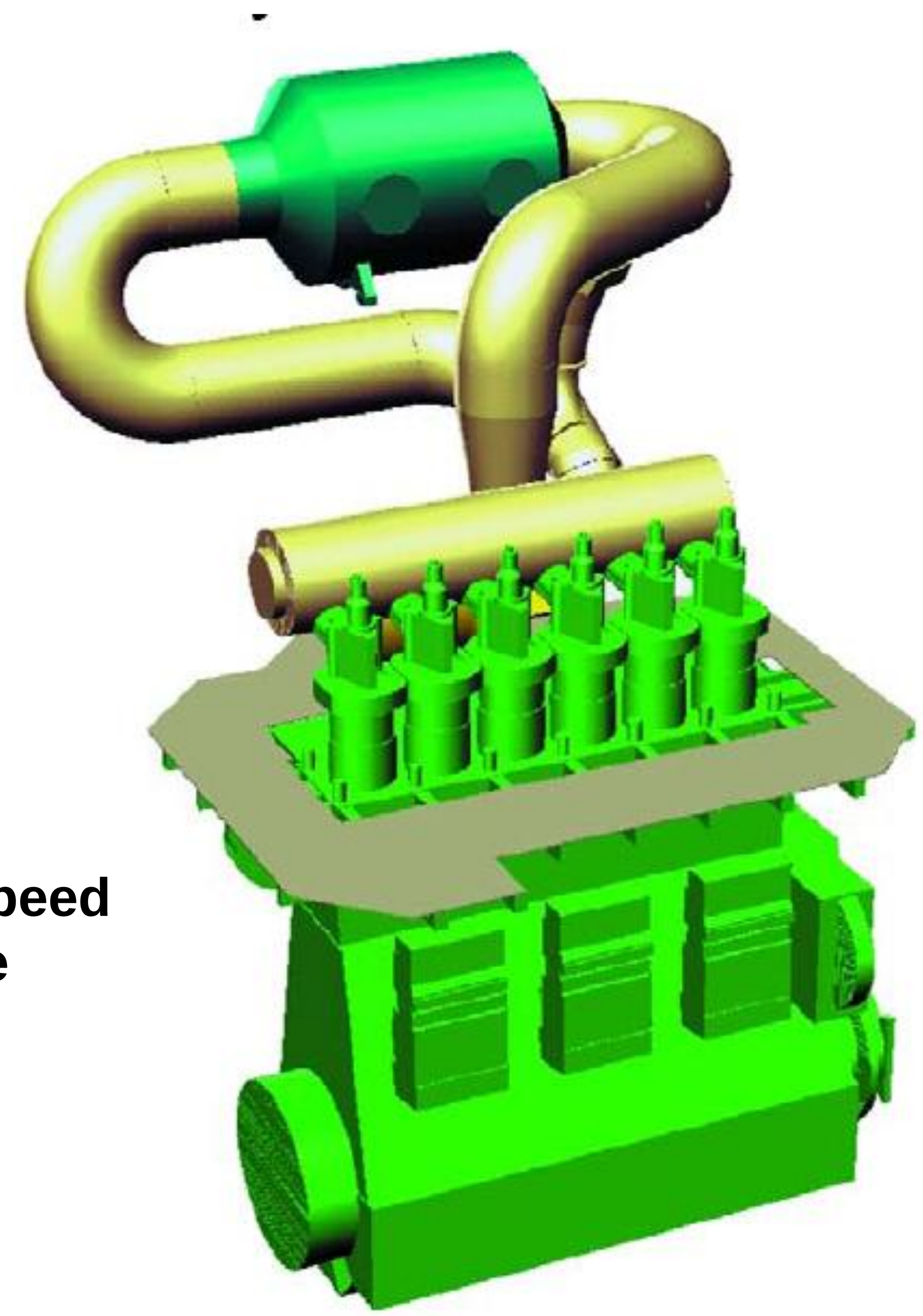
Oxides of Nitrogen – achieving next levels of reduction

- Engine Tuning
- Fuel water emulsions or direct water injection - 20% to 50% reduction
- Air humidification - up to 70% reduction on 4 stroke engines
- Exhaust Gas Recirculation (EGR) – up to 75% reduction with small fuel consumption penalty around 2%
- Selective Catalytic Reduction (SCR) - up to 95% reduction – more difficult on slow speed diesels due to lower exhaust gas temperature – allows engine to be tuned for minimum fuel consumption
- Reduced fuel sulphur will make SCR and EGR easier
- Liquefied Natural Gas (LNG) can achieve Tier 3 levels without aftertreatment

Wartsila combined water and fuel nozzle for medium speed engines



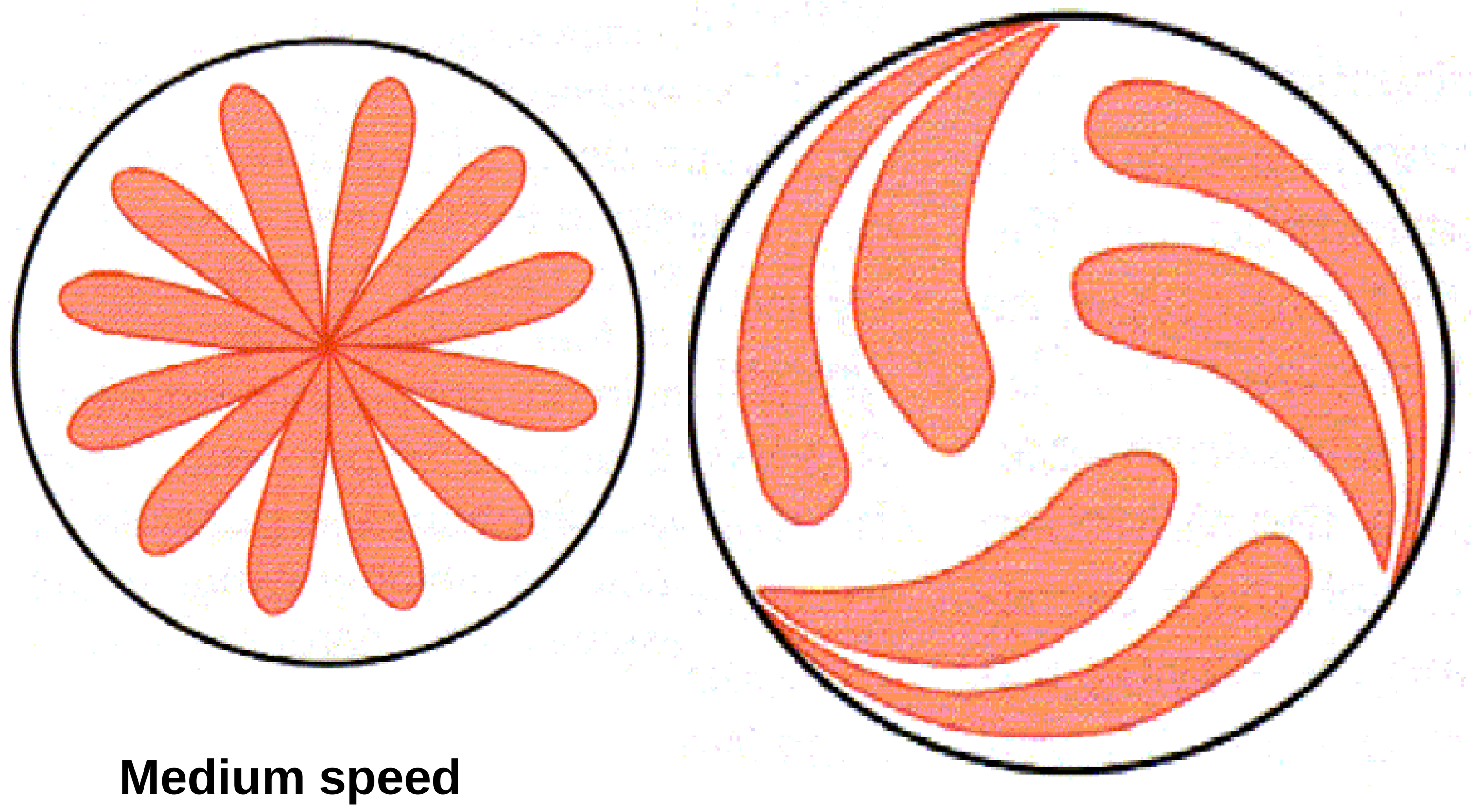
SCR on medium speed engine – after turbocharger



SCR on slow speed engine – before turbocharger

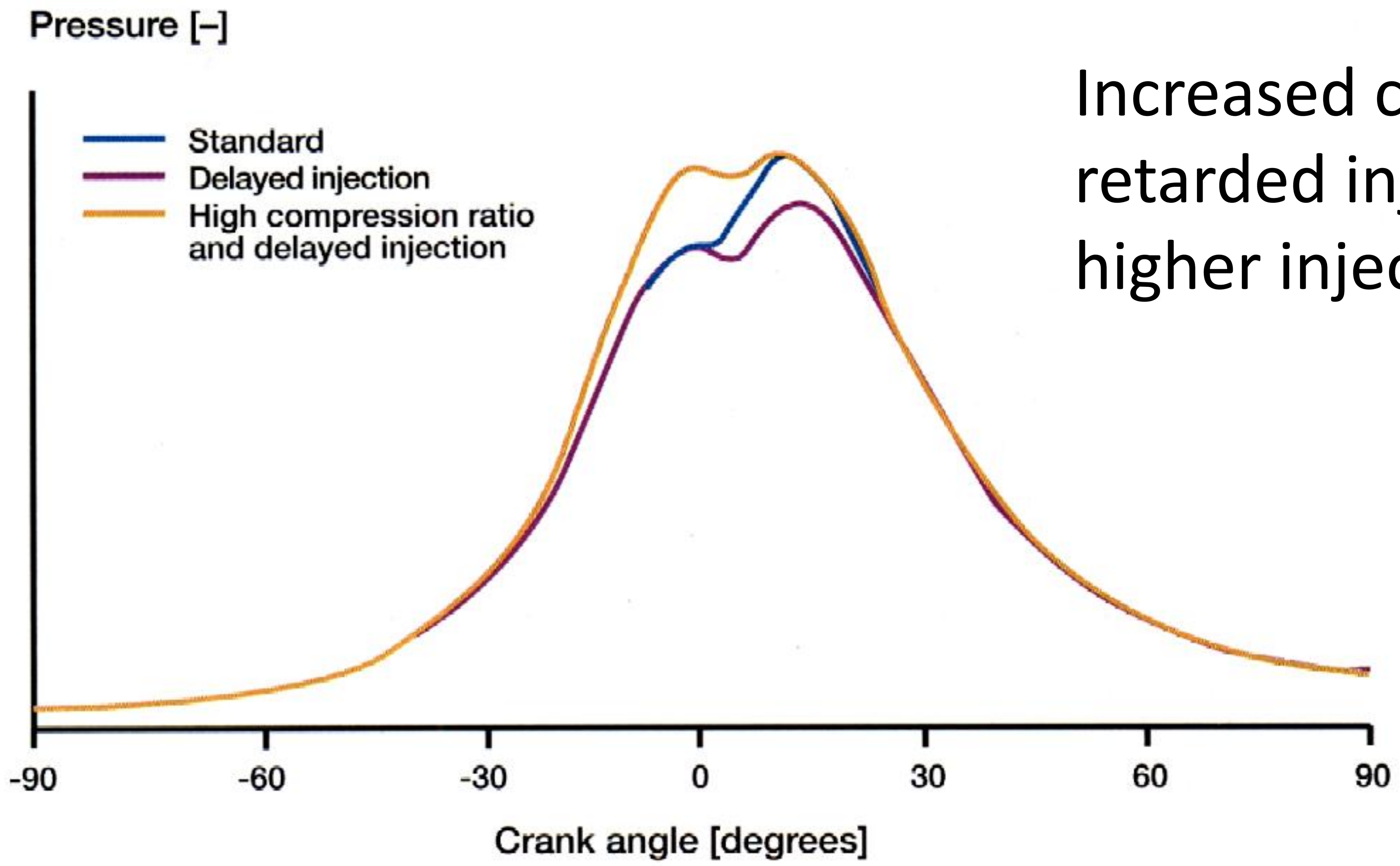
Pictures: Weisser, Wartsila, Clean Ships: Advanced technology for Clean Air 2007

Low NOx Tuning



Medium speed engine: central injector, no swirl

Slow speed engine: peripheral injectors, high swirl

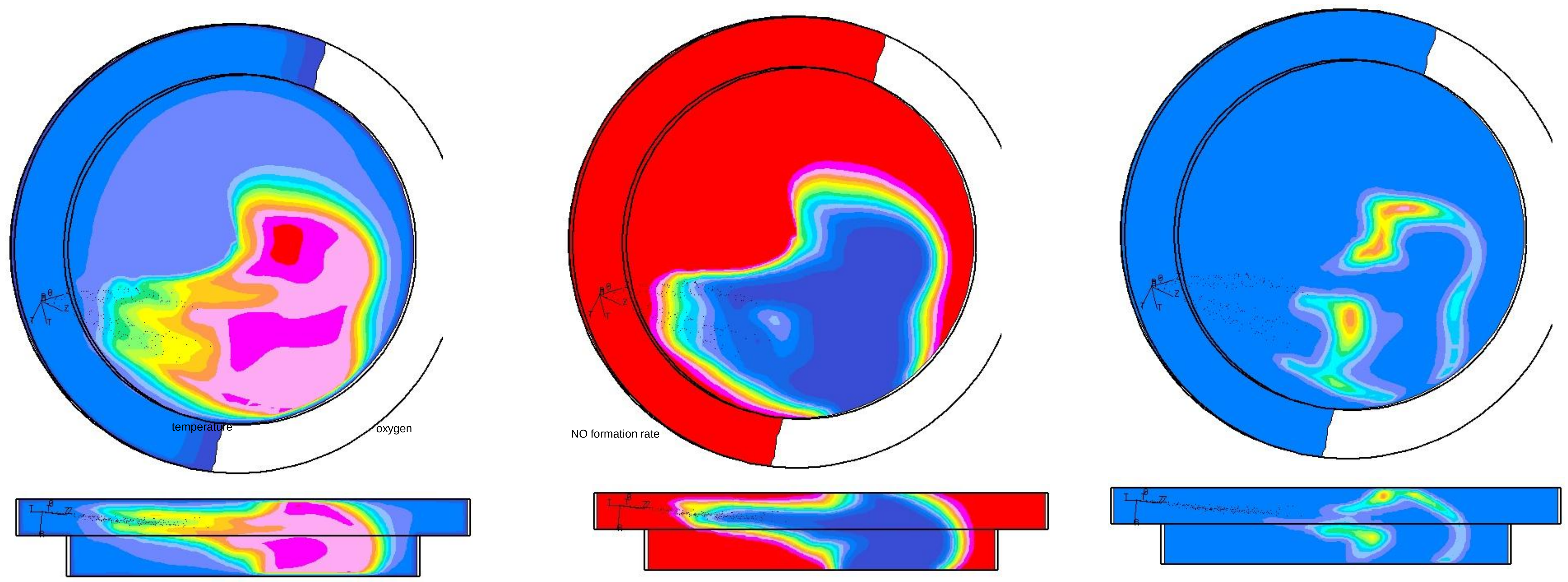


Increased compression ratio + retarded injection timing + higher injection rate

NOx kinetically controlled – highly temperature dependent – mostly formed in burnt gas surrounding flame

Optimised combustion chamber and injector layout – combustion temperature, oxygen available to burnt gases, temperature of burnt gases

Orientation and size of injector nozzles – spatial relationship between individual sprays and between sprays and combustion chamber walls (cylinder head, piston crown)



temperature

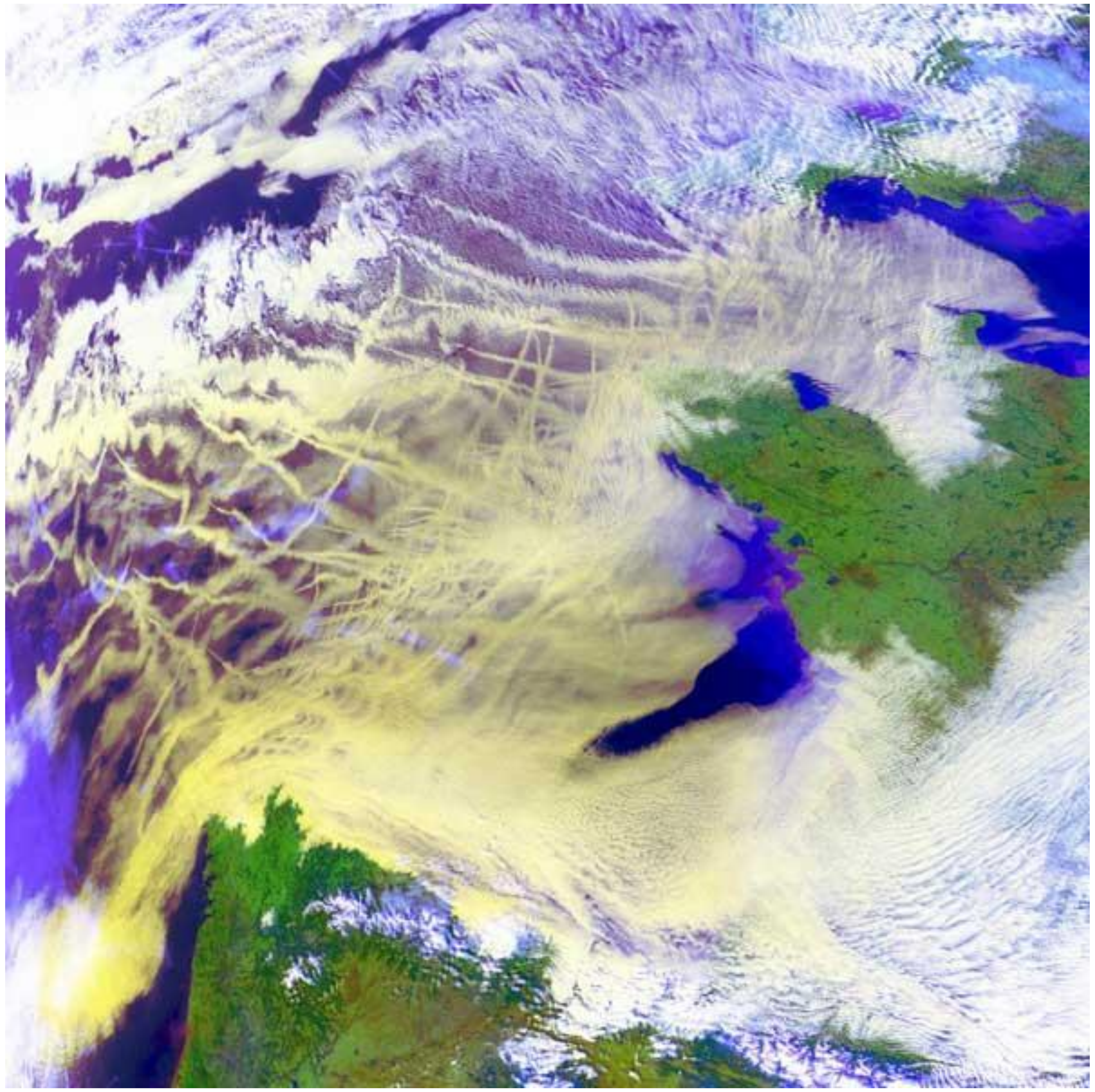
oxygen

NOx formation rate

NOx/soot/fuel consumption tradeoff
High combustion rate gives low fuel consumption, but high flame temperature
High flame temperature gives more complete soot burnout but increased NOx

Oxides of Sulphur

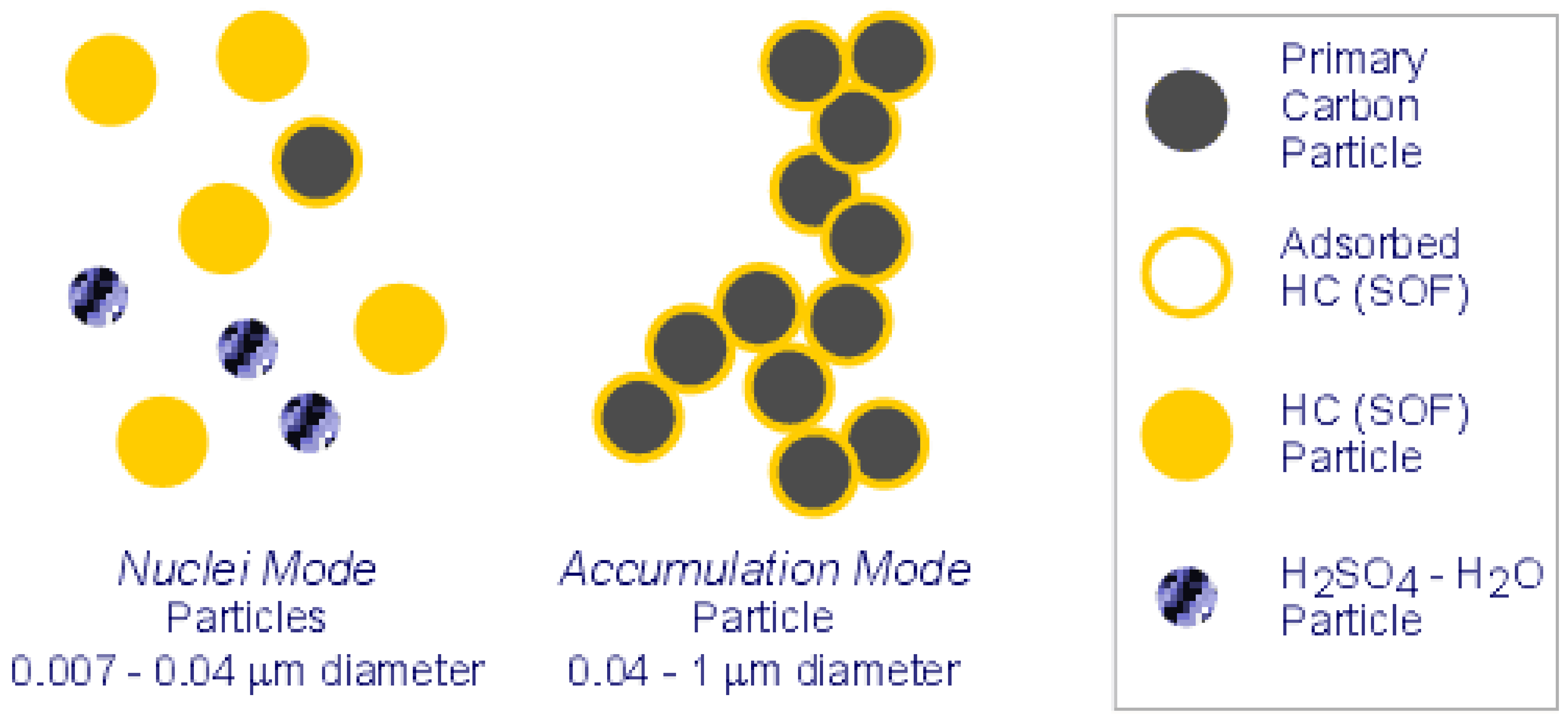
- Sulphur in fuel converted to oxides of sulphur – acid rain, particulate emissions, atmospheric haze
- Shipping about 60% of global transport emissions of SO_2
- Current world average fuel sulphur content for shipping around 2.7% by mass
- Sulphur levels for land transport very low - 10ppm or 0.0010% by mass
- IMO SO_X Emission Control Areas (Baltic Sea (2006), North Sea (2007)
    - Low sulphur fuels or equivalent treatment of exhaust gases
    - Some operational problems with switching between fuels
- Uncertain refinery capacity for low sulphur heavy fuel oil for IMO global 0.5% sulphur limit in 2020
- Global switch to distillate?
    - On-board fuel handling simpler
    - Around 10% NOx reduction, reduced particulates
    - Reduced fuel spill hazard
    - More expensive
- Seawater scrubbers can clean SOx emissions and soluble particulates from the exhaust gas
    - Development well advanced
    - Allow use of low cost high sulphur heavy fuel oil
    - Possible issues with disposal of contaminated scrubber water in confined waters
    - Scrubbers also remove particulate matter



Ship tracks north of Spain and west of France – water condenses on sulphate particles

Mathias Schreier , University of Bremen, New Scientist September 2007

Particulates – smoke, haze



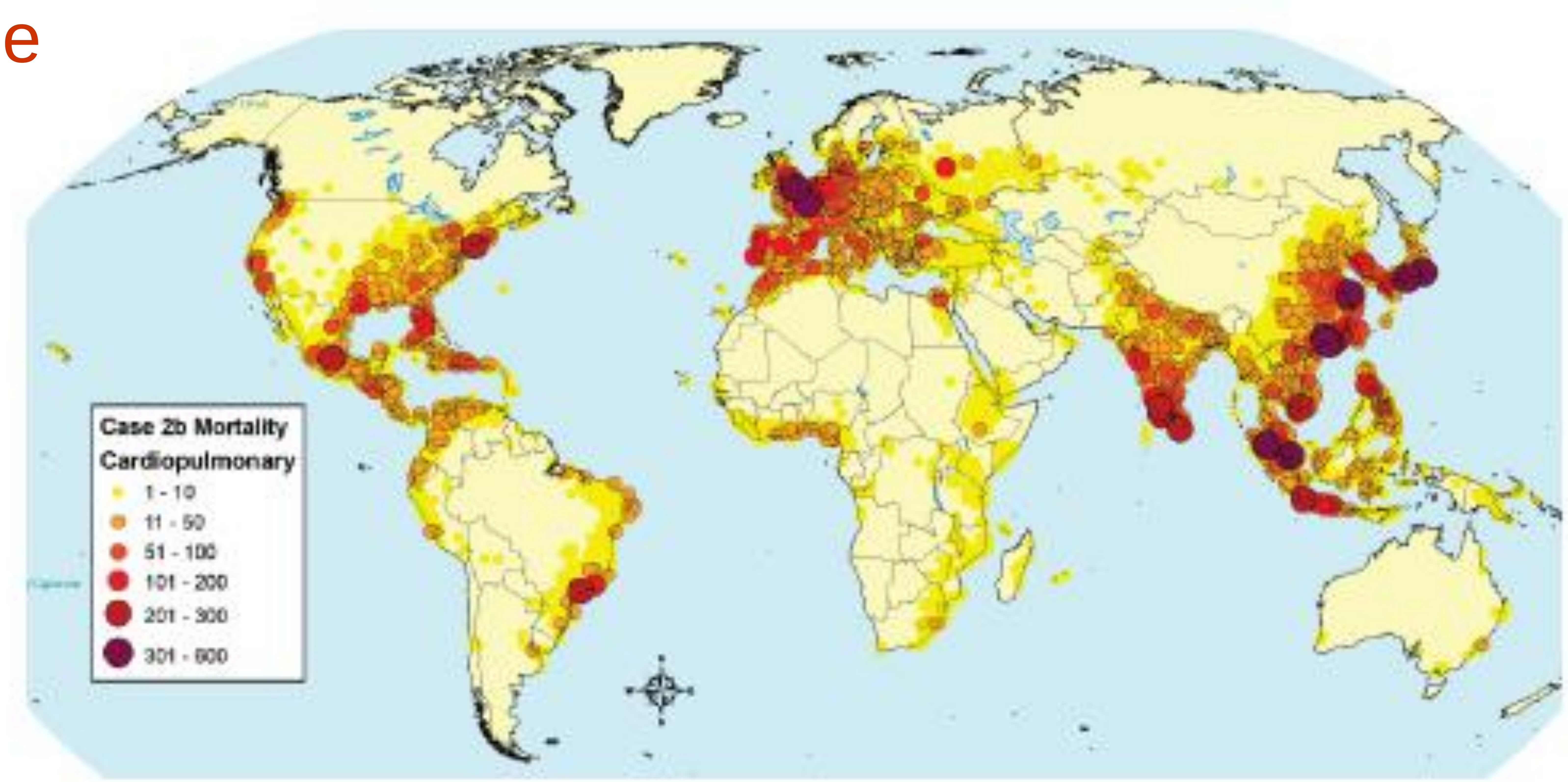


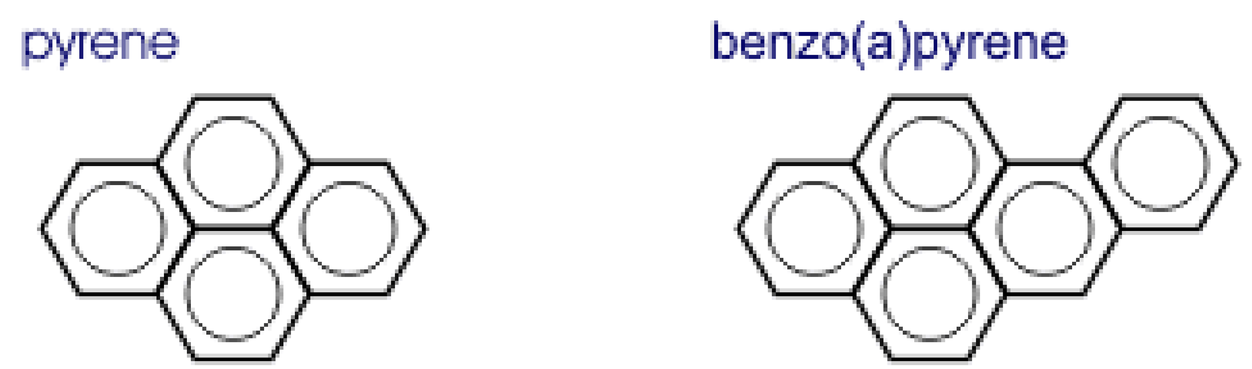
FIGURE 2. Cardiopulmonary mortality attributable to ship $PM_{2.5}$ emissions worldwide, Case 2b.

From Corbett et al, Environmental Science and Technology, Vol 41, No 24, 2007
Case 2b world fleet including auxiliary engines, all PM constituents
(particulate organic matter, sulphates, black carbon)

Nuclei mode particles are primarily volatile
-consist mainly of hydrocarbon (SOF) and hydrated sulphuric acid condensates
- formed from gaseous precursors as temperature decreases in the exhaust system and after mixing with cold air

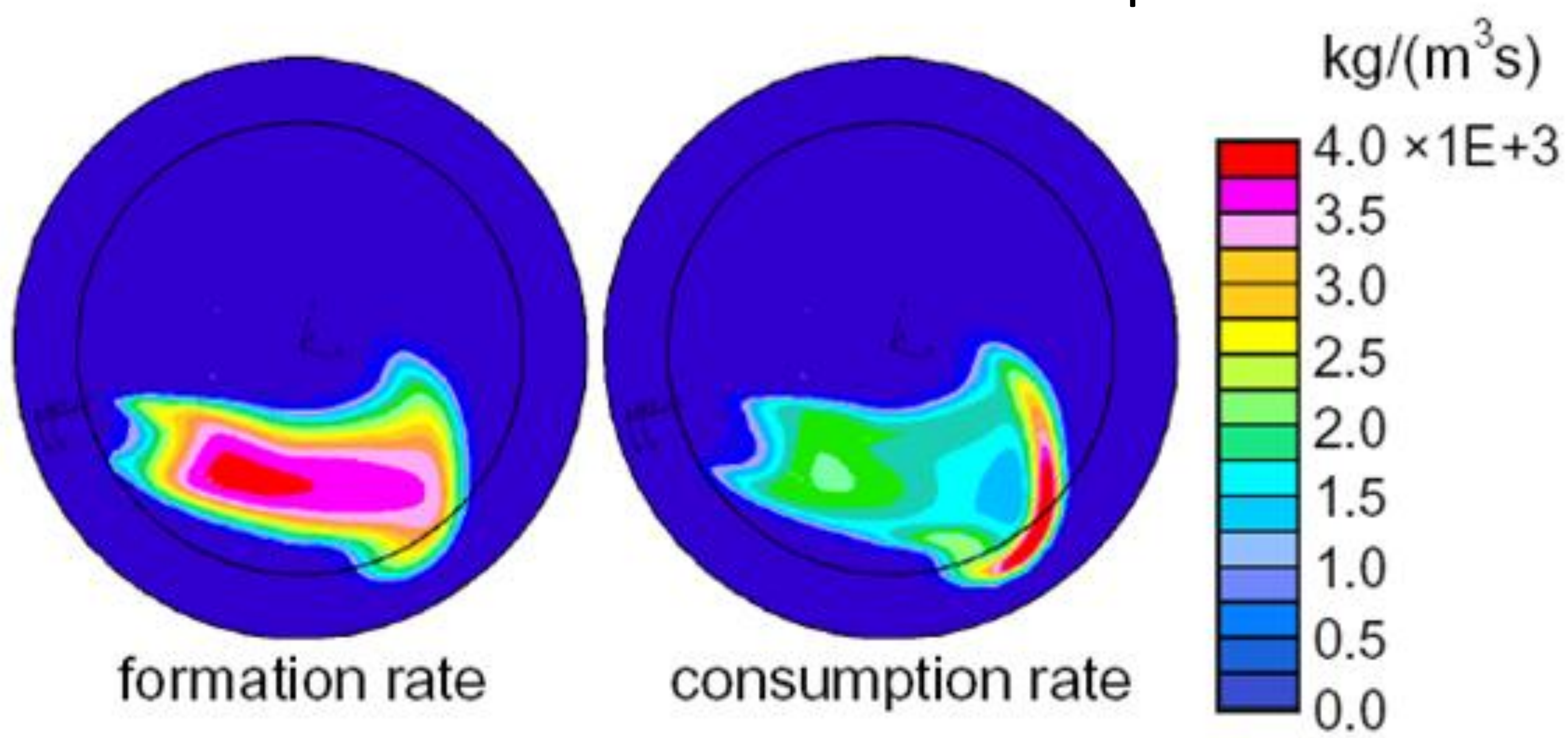
Accumulation mode particulates (black carbon + SOF)
-formed during combustion by agglomeration of primary carbonaceous particles (99% C by mass) and other solid materials
-plus adsorption of gases and condensation of vapours

Soluble Organic Fraction (SOF) contains most of the mobile polycyclic aromatic hydrocarbons (PAH) and nitro-PAHs emitted with diesel exhaust gases (air toxics)



From: Majewski, Diesel Particulate Matter, DieselNet 2002 and Borman and Ragland, Combustion Engineering, McGraw Hill 1998

Final accumulation mode particle concentration is a balance between soot formation rate and soot consumption rate



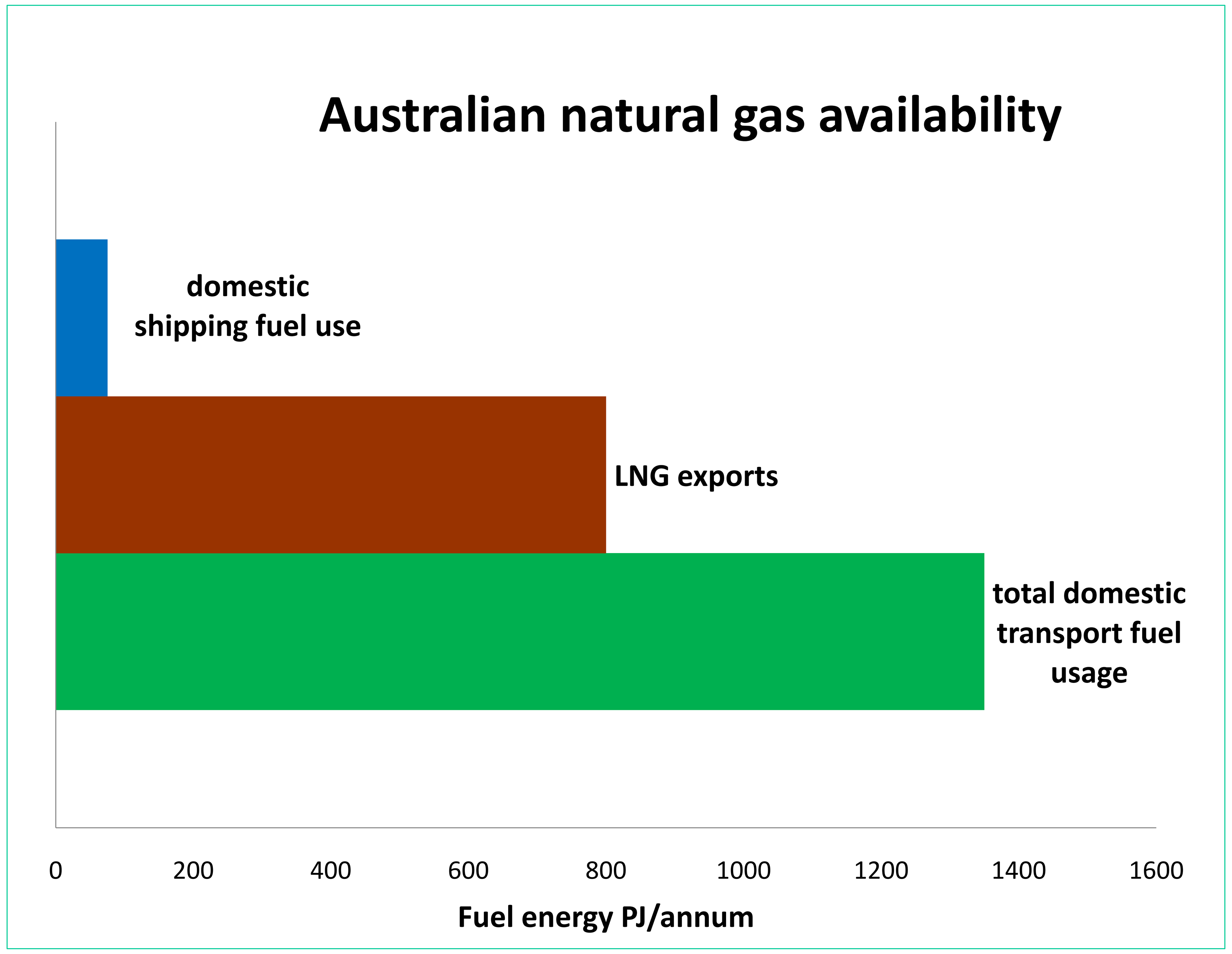
From H.Tajima, Koji Takasaki, L.Goldsworthy, T. Takaishi, A. Strom, R. Masuda, **Diagnosis of Combustion with Water Injection using High Speed Visualisation and CFD**, THIESEL International Conference on Thermo- and Fluid Dynamic Processes in Diesel Engines, Spain (2004).

Emissions at berth (hotelling)

- Diesel generators make electricity for hotelling loads, cargo handling
- Oil fired boilers to heat fuel, cargo, steam for steam driven cargo pumps, hot water
- Generally close to urban areas
- Cruise ships have high hotelling loads
- **Fuel switching** – low sulphur fuel at berth, proposals for LNG to also reduce NOx
- **Shore power** (alternative maritime power, cold ironing) – electricity supplied from land grid – shift air quality emissions away from port – gain depends on shore power source – diesel engines more efficient but more NOx – shore power doesn't replace boilers so SOx reduction not necessarily as big as fuel switching – problems with connection standards

Shore Power
From: Presentation to ENO Transportation November 2008
Geraldine Knatz, Executive Director, Port of Los Angeles

Natural gas

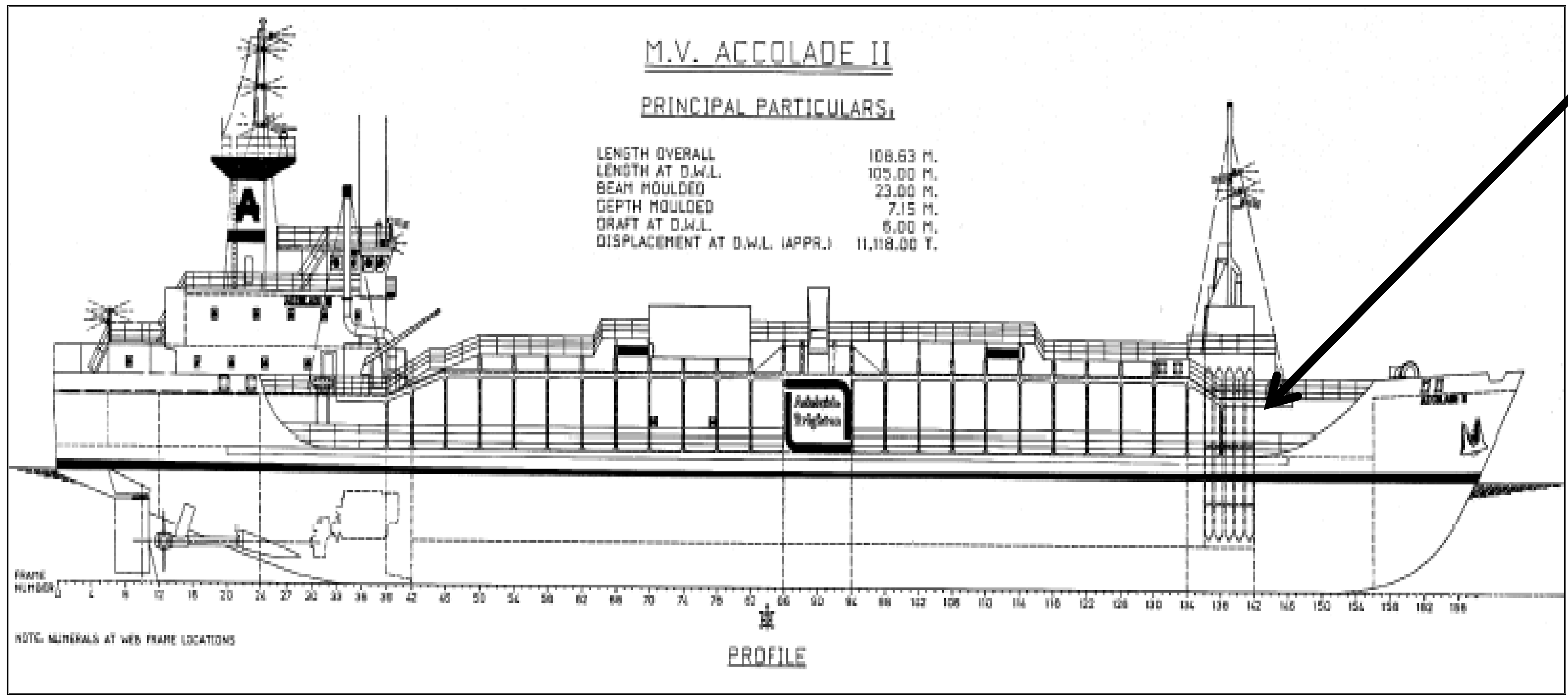


Dual fuel diesel engines

- well developed technology
- 80% to 99% of fuel energy from gas
- 25% greenhouse reduction if no methane emissions
- reduce NOx, SOx and particulates by more than 80%
- emissions meet IMO Tier3 ECA <u>without aftertreatment</u>

MV Accolade operating successfully out of Adelaide on compressed natural gas for about 20 years

MV Accolade Cement Carrier, Adelaide



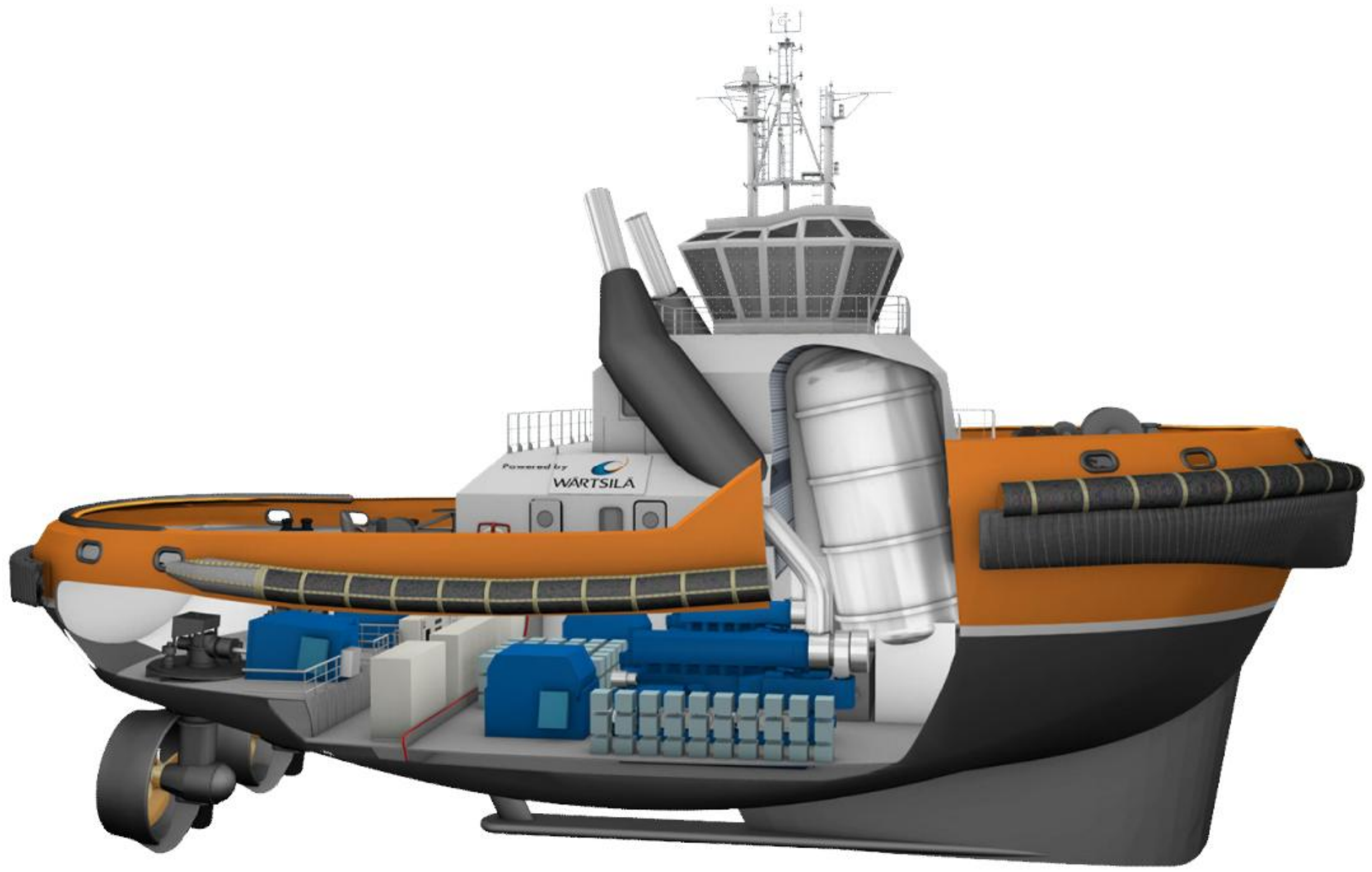
gas cylinders

Liquefied Natural Gas (LNG)

- Liquefied Natural Gas allows greater fuel quantities than compressed natural gas
- Stored in highly insulated tanks
- Norway establishing LNG infrastructure for domestic shipping

LNG powered ferry

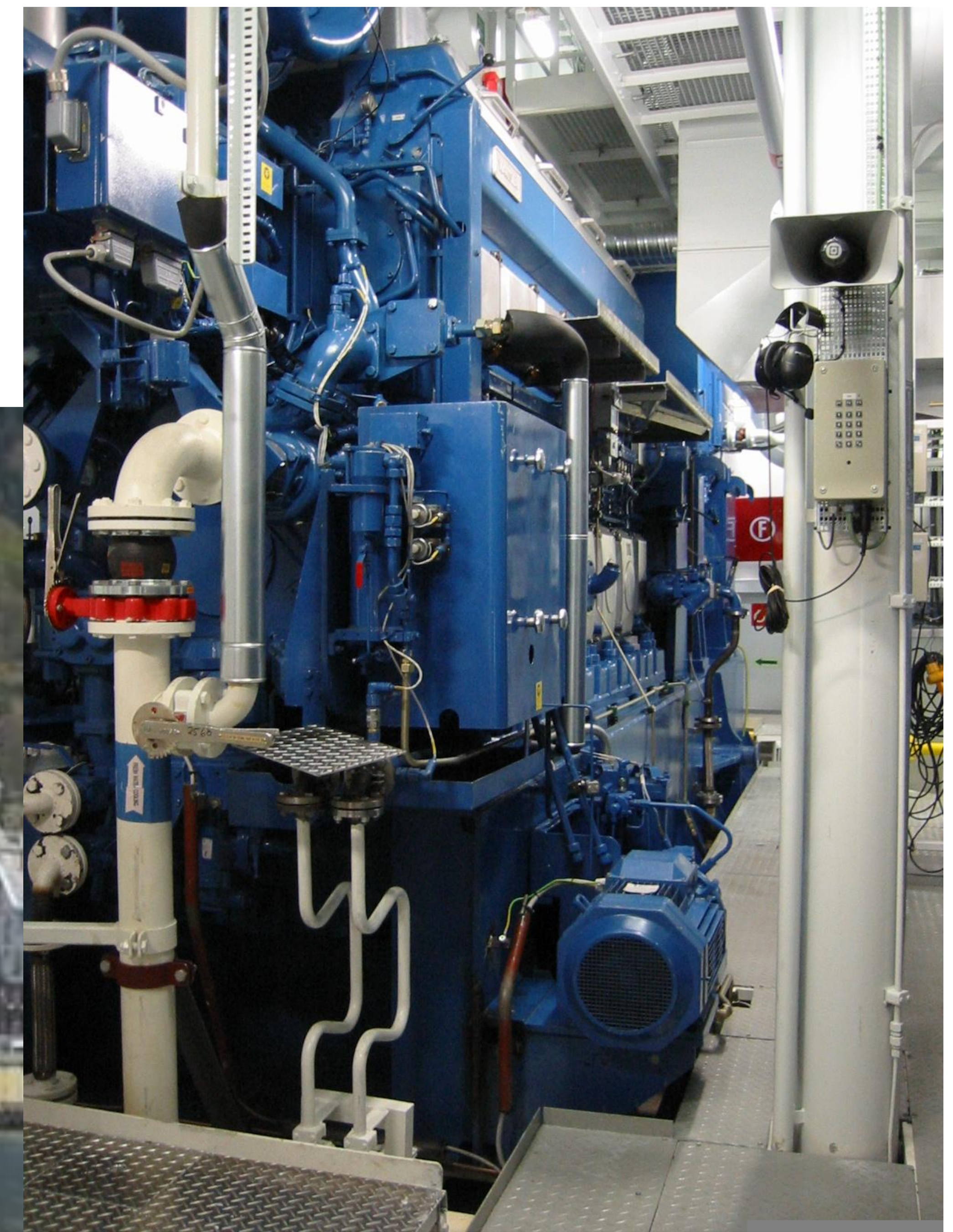
Pioneer Knutsen coastal LNG tanker



LNG dual fuel diesel/electric/battery hybrid tug concept

From http://marine.wartsila.com/,en,productsservices,productdetail,product,B1FD4AD3-083F-4474-8AA0-6717B818244D,D8F9646A-F4D0-464C-8A7E-3B892D2A0E23,,8003.htm Accessed May 2009

Viking Energy offshore supply vessel



Wartsila 6L32DF lean burn natural gas engine

Photos from a Statoil presentation at
ENGVA 10th ANNUAL EUROPEAN NGV CONFERENCE, Graz 2004

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Other Measures

- Speed reduction – 10% speed reduction gives about 20% reduction in fuel consumption over the same distance – can de-rate engines to optimise operation at reduced speeds
  - De-rating by increasing compression ratio to recover optimum cylinder pressures when less fuel is used per cycle
- New IMO NOx limits apply to new engines only – need to improve older engines
  - Engine upgrading to reduce NOx and soot – new turbocharger to increase charge air pressure, new pistons to increase compression ratio, new fuel pumps to increase injection rate, delayed injection timing
- New aftertreatment technologies
  - Eg CSNOx by Ecospec - promoted to remove 93% of SOx, 82% of NOx and 74% of CO_2 from exhaust – not yet proven

Conclusion

- Need to quantify significance of impact of ship emissions on air quality in Australia (and New Zealand)
- Inform government policy
  - shipping offers a relatively low greenhouse gas option for domestic transport compared with road or rail
  - incentives for uptake of alternative fuels such as low sulphur distillate or LNG
- For the shipping industry, provide a sound basis for arguing the benefits of shipping and for investment planning
- Also quantify greenhouse gas emissions

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