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GUIDE to DIESEL EXHAUST EMISSIONS CONTROL of NO_x, SO_x, PARTICULATES, SMOKE and CO_2

SEAGOING SHIPS and LARGE STATIONARY DIESEL POWER PLANTS

The International Council on Combustion Engines

Conseil International des Machines à Combustion

CIMAC was founded in Paris in 1951 where the first Congress took place. Originally CIMAC was organized as an industry event to discuss new ideas and developments within the engine and components industry together with institutes and universities.

It is supported by engine manufacturers, engine users, technical universitites, research institutes, component suppliers, fuel and lubricating oil suppliers and several other interested parties.

The National Member Associations (NMAs), National Member Groups (NMGs) and Corporate Members (CMs) as well as previous CIMAC Recommendations are listed in the back of this publication.

This document has been elaborated by the CIMAC Working Group “Exhaust Emissions Control“
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FOREWORD BY THE PRESIDENT

Several exhaust emission regulations have recently entered or are about to enter into force for seagoing ships as well as big stationary diesel power plants. In order to cope with the requirements applicable potential emission abatement technologies are currently being evaluated by the industry.

Many of the emission control technologies that are developed for on-road and off-road high speed diesel and gasoline engines and other types of industrial sources cannot be applied directly to big medium and slow speed diesel engines which do not operate on automotive quality diesel fuel. Only methods that are adapted to the big engine environment as well as fuel qualities used can be applied.

This CIMAC 'Guide to Diesel Exhaust Emissions Control of NO_x, SO_x, Particulates, Smoke and CO_2 – Seagoing Ships and Big Stationary Diesel Power Plants' gives some background information on diesel exhaust gas components and their environmental impact along with a short overview of the most important existing and upcoming regulation and various existing and future potential emission abatement technologies. The technologies are evaluated from the applicability point of view – both applicable and rejected technologies are discussed.

The guide was developed by the CIMAC Working Group No 5 "Exhaust Emissions Control", chaired by G. Hellen/ Wärtsilä. I would like to express my appreciation to the WG for integrating the results of their discussion into this condensed CIMAC recommendation.

K. Wojik, CIMAC President
October 2008

Content

1. TYPICAL DIESEL EXHAUST GAS COMPOSITION

Component		Typical Component Concentration Range in Diesel Exhaust Gas	Component Concentration in Natural Dry Ambient Air
Nitrogen	N_2	75 – 77 %-vol	78.08 %-vol
Oxygen	O_2	11.5 – 15.5 %-vol	20.95 %-vol
Carbon dioxide	CO_2	4 – 6.5 %-vol	0.038 %-vol
Water	H_2O	4 – 6 %-vol	
Argon	Ar	0.8 %-vol	0.934 %-vol
Totally		> 99.7 %-vol	

%-vol: Concentration, percentage, volume basis

ppm-vol: Concentration, parts per million, volume basis

Additional components found in diesel exhaust – typical concentration range (steady state, high load, residual and distillate fuel oil):

Nitrogen oxides	NO_x:	1000 - 1500 ppm-vol
Sulphur oxides	SO_x	30 - 900 ppm-vol: Fuel composition related
Carbon monoxide	CO	20 - 150 ppm-vol
Total Hydrocarbons	THC (as CH_4)	20 - 100 ppm-vol
Volatile org.comp.	VOC (as CH_4)	20 - 100 ppm-vol
Particulates *)	PM	20 - 100 mg/Nm^3, dry, 15% O_2: Fuel composition related

Smoke: Related to low load (<50% load), start-up and fast load increase

*) Measurement method: ISO 9096 or other principally similar method

2. NO_x – NITROGEN OXIDES

2.1 Definitions

- Nitrogen monoxide (NO) and nitrogen dioxide (NO_2) are collectively referred to as nitrogen oxides (NO_x)
- N_2O (nitrous oxide, “laughing gas”) is not regarded as a NO_x component. N_2O is considered as a “strong” green house gas. Additionally it has a detrimental effect on the ozone layer in upper atmosphere
- NO is a colourless gas, oxidizes fast to NO_2 in the ambient air within some hours
- NO_2 is a reddish-brown gas (gas form) and yellow-brown when it starts to condensate
- NO_2 is a toxic gas
- The regulator requires NO_x-mass emissions e.g. mg/Nm^3, g/kWh, etc., to be calculated as NO_2 (i.e. 100% of NO_x is calculated as NO_2)

2.2 Environmental Impact

- Acid rain – acidification
- Over-fertilization of lakes and soil etc.
- Ozone/smog formation in the lower atmosphere especially in urban highly polluted areas - potential damage on vegetation and human health
- Contributes to formation of small size particulates – part of NO_x is forming nitrates

2.3 Recommended Measurement Standards and Methods - quote from reference 1)

- Recommended methods:
  - ISO 8178-1 Chapter 7.4.3.6: *Oxides of nitrogen (NO_x) analysis*
  - EPA Method 7E (USA): *Determination of nitrogen oxides from stationary sources (Instrumental analyser procedure)*.
  - VDI 2456 Blatt 5 and 7 (Germany)
- Recommendation:
- Methods based on chemiluminescense are recommended
- Non-Dispersive InfraRed (NDIR) absorption methods can be used for measurement of the NO part of NO_x. The NO_2 part of NO_x cannot be measured with NDIR since NO_2 is soluble in water and the sample must be supplied cold and dry
- Methods based on Zirconia sensors can be used at on-board measurements provided that good correlation with the chemiluminescense method can be documented
- Warning:
  - Electrochemical cells are sometimes used for measuring NO_x emissions after diesel engines. Electrochemical sensor technology can be prone to cross interference, noise, short term drift at low concentrations, and overloading or saturation at high concentrations (reference 2) Experience from the field indicates that electrochemical cells should be avoided

2.4 Diesel Process

- N_2O emissions are typically very low from diesel engines i.e. negligible
- NO_x emissions:
  - relatively high from diesel engines due to high local combustion temperatures
  - NO_x formation is thermal, the main nitrogen source is the combustion air
  - NO_x formation has a strong exponential temperature influence i.e. high temperature results in high NO_x formation. NO_x formation in diesel engines is thus mainly thermal, the main nitrogen source is the combustion air.
  - NO_x formation process is extremely complex including hundreds of different chemical reactions
  - Typical NO / NO_x ratio is 0.9…0.95

- Typical NO_2 / NO_x ratio is 0.05..0.1

2.5 Some Important NO_x Regulations

2.5.1 Marine Sector

IMO – International Maritime Organization

- Current Tier I: – speed (n) dependent:
  - n<130 rpm = 17 g/kWh; n>=2000 rpm = 9.8 g/kWh; 130 =<n<2000 rpm limit = $45*n^{-0.2}$
- Future: proposed Tier II for new ships from 2011:
  - n<130 rpm = 14.4 g/kWh; n>=2000 rpm = 7.7 g/kWh; 130 =<n<2000 rpm limit = $44*n^{-0.23}$
- Future: proposed Tier III for new ships from 2016:
  - n<130 rpm = 3.4 g/kWh; n>=2000 rpm = 2.0 g/kWh; 130 =<n<2000 rpm limit = $9*n^{-0.2}$
  - Applied to designated sensitive water areas only
- Future: proposed modification of existing ships:
  - Modification to IMO Tier I level
  - Engines covered: installed on ships constructed on or after 1 January 1990 but prior to 1 January 2000
  - Cylinder displacement at or above 90 litres/cyl and power >5000 kW
  - Application to those engines where an update kit is commercially available (if no kit there are no requirements)
- Final adoption of the proposed future regulations is supposed to be taken by IMO in October 2008

European Union

- as IMO plus other "local" more restrictive regulations (e.g. River Rhein, Bodensee)
- Inland waterways and engines with a per cylinder displacement <30 liters/cylinder
  - Tier IIIA = 7.2 to 11 g/kWh depending on engine size

USA

- as IMO for engines with a per cylinder displacement >=30 liters/cylinder
- Engines with a per cylinder displacement <30 liters/cylinder
  - Tier 2: 7.2 to 11 g/kWh depending on engine size
  - Tier 3: 5 to 11 g/kWh depending on engine size
  - Tier 4: 1.8 g/kWh

Norway

- Globally: Environmentally differentiated tonnage tax system
- Norwegian waters: NO_x fee system
    - 15 NOK / kg emitted NO_x for engines exceeding 750 kW

Sweden

- Differentiated fairway and harbour fee system

Voluntary Emission Control Programs

- DNV: Clean Design
- Lloyd´s Register: “N” character
- RINA: “Clean Air”
- US-EPA: “Blue Sky”
- ABS: Environmental Safety (ES) Notation

2.5.2 Stationary Power Plant

International regulation – World Bank Guidelines

Regulation in force:

- Liquid fuel diesel plants in a resultant non-degraded air-shed:
    - Plants 3…50 MWth (General EHS Guidelines)
        - NO_x: 1460 … 1600 mg/Nm^3, dry, 15% O_2 for engine bore below 400 mm
        - NO_x: 1850 mg/Nm^3, dry, 15% O_2 for engine bore at or exceeding 400 mm
        - Gas diesel engine plants: 1600 mg/Nm^3, dry, 15% O_2 (other gas engine types have other ruling)
    - Plants >50 MWth: 2000 mg/Nm^3, dry, 15% O_2 (Thermal Power guideline for new plants 1998)
- Lower emission levels are required in degraded air-sheds or close to sensitive areas

New regulation (Thermal Power Plants Guidelines) proposed by World Bank (final decision is not taken):

- Diesel plants exceeding 50 MWth
    - Liquid fuel plants 50<MWth<300
    - 1460 mg/Nm^3, dry, 15% O_2 for engine bore below 400 mm
        - 1850 mg/Nm^3, dry, 15% O_2 for engine bore at or exceeding 400mm
    - Liquid fuel plants >300 MWth and regardless of engine bore
        - 740 mg/Nm^3, dry, 15% O_2

    - Gas diesel engine plants: 1600 mg/Nm^3, dry, 15% O_2 (other gas engine types have other ruling)

- Lower emission levels are required in degraded air-sheds or close to sensitive areas

India ("Emission standards for diesel engines (engine rating more than 0.8 MW (800 kW) for power plant, generator set applications and other requirements", issued July 2002)

- Diesel engine plants (oil)
    - 710 ppm, dry, 15%O_2 (up to 75 MWe plant in big city or up to 150 MWe plant in "other areas")
    - 360 ppm, dry, 15%O_2 (more than 75 MWe plant in big city or more than 150 MWe plant in "other areas")

Japan ("Nation wide general limits", >50 l/h fuel oil, outside big cities):

- Diesel engine plants
    - Engine bore <400mm: 950 ppm, dry, 13% O_2 (710 ppm, dry, 15% O_2)
    - Engine bore >400mm: 1200 ppm, dry, 13% O_2 (900 ppm, dry, 15% O_2)

2.6 NO_x Abatement Technologies

2.6.1 Dry Low NO_x Technologies

- Combination of one or several of following elements: Late Fuel Injection Timing, High Compression Ratio, Combustion Chamber optimization, Miller Cycle, Variable Valve Timing, Electronic & Common Rail FIE, Turbocharger improvement, 2-stage turbocharging, etc
- NO_x reduction potential and status of development:
    - Marine 2-stroke: 15% below IMO Tier I level
        - Status: Well advanced, available now or within 2-3 years
    - 4-stroke:
        - Marine: 20% below IMO Tier I level
        - Power Plant:
            - <400mm bore: 1460 ... 1600 mg/Nm^3, dry, 15% O_2
            - Bore equal or greater than 400mm: 1850 mg/Nm^3, dry, 15% O_2
        - Status: Well advanced, available now or within 2-3 years
    - 4-stroke marine: 40% below IMO Tier I level with 2-stage turbocharging
        - Status: First tests started up, available after 4-8 years
- Impact on fuel consumption: Moderate
- Fuel quality requirements: Unchanged
- Estimated additional engine costs (engine type and output dependent figures)

    - 0-3% for 15-20% NO_x reduction
    - Up to 10% for 40% NO_x reduction
- Estimated additional operating costs: Moderate
- High efficiency and high pressure ratio turbochargers are required
- Advanced control system required
- Variable Valve Timing may be required
- Applicability:
    - Difficulties with retrofit to existing engines is limiting scope for implementation
    - No limitations for new engines

2.6.2 Wet Low NO_x Technologies

- Introduction of water into the combustion process. NO_x reduction is a result of lower peak combustion temperatures. Water can be introduced into the engine in several ways
- Availability depending on engine type and manufacturer

2.6.2.1 Intake Air Humidification

- “Fogging” and/or saturation of the intake air
- NO_x reduction potential:
    - Marine: 30-60% depending on engine type and calculated as a ISO 8178 test cycle result
    - Power Plant: 20-60% depending on the engine type and at steady state high load conditions
- Status of development: Systems available for some engine types
- Impact on fuel consumption: Low
- Water quality requirements dependent on principle:
    - Water injection after T/C and before air cooler: high quality necessary
    - Humidification in a separate vessel without air cooler: low quality (sea water) sometimes sufficient
- Water-to-fuel ratio: 1.3-2.5
- Fuel quality requirements: Unchanged
- Estimated additional engine & plant costs: 5-30% of the engine price depending on the principle and engine type
- Estimated additional operating costs: Moderate (dependent on water consumption and quality needs)

- Applicability:
    - Retrofit to existing 4-stroke engines is often possible, but reliability and durability shall be considered

2.6.2.2 Direct Water Injection

- Water is injected directly into cylinder
- NO_x reduction potential: 40-50% calculated as a ISO 8178 test cycle result
- Status of development: Systems available now
- Impact on fuel consumption: 1-2.5%
- Water quality requirements: Moderate
- Water-to-fuel ratio: 0.5-1
- Fuel quality requirements: Unchanged but preference for sulphur <1.5%
- Estimated additional engine costs: about 10%
- Estimated additional operating costs: 3% (cost for producing fresh water can differ)
- Comments: Higher NO_x reduction levels are possible in principle, but the level has to be restricted otherwise tendency to increased smoke and fuel consumption
- Applicability:
    - 2-stroke and 4-stroke engines
    - Retrofit to existing engines is often possible (if the technology developed for the engine type), but reliability and durability shall be considered
    - No limitations for new engines (if the technology developed for the engine type)

2.6.2.3 Water-in-Fuel Emulsions

- In-line emulsification of water into fuel
- NO_x reduction potential: typically up to 20%
- Status of development: Systems available
- Impact on fuel consumption: Low
- Water quality requirements: Moderate
- Water-to-fuel ratio: 0.2-0.3
- Fuel quality requirements: Unchanged
- Emulsifier might be needed for distillate fuel
- Estimated additional engine costs: about 5%
- Estimated additional operating costs: Low

- Comments: Tendency to decreased smoke at low load with conventional fuel injection system
- Applicability:
    - Capacity of the FIE needs to be high enough to handle the increased volume flow rates when operating with fuel/water emulsions
    - 2-stroke and 4-stroke engines
    - Retrofit to existing engines is often possible
    - Often no limitations for new engines

2.6.3 SCR - Selective Catalytic Reduction

- Reduces NO_x to N_2,CO_2 and water by addition of typically 40%-weight aqueous urea (marine and power plant applications) or alternatively 25%-weight ammonia solution (power plant applications only) in presence of catalyst
- NO_x reduction potential: typically up to 80-90%
    - Status of development: Systems available now
    - Impact on fuel consumption: No
    - Fuel quality requirements: sulphur content - max. 1-1.5% depending on application
    - Estimated additional engine & plant costs: 15-20% of the engine price
    - Estimated additional operating costs: 10% (highly dependent on reagent price)
- Comments:
    - Requires a reagent: often a good quality 40% urea in water solution (or alternatively 25% ammonia solution)
    - Operating temperature window is crucial – can cause some limitations in operation of the system
    - To avoid ammonia slip is crucial to avoid fouling of equipment such as exhaust boiler, etc and to avoid smell
    - The engine can sometimes be optimized for lower fuel consumption
    - 2-stroke engines: The catalyst is installed in the exhaust system before the turbocharger turbine
    - 4-stroke engines: The catalyst is typically installed in the exhaust system after the engine (turbocharger turbine)
- Applicability:
    - 2- stroke and 4-stroke engines
    - Retrofit to existing engines is often impossible due to space constraints (SCR is a big size system)
    - Often no limitations for new installations
    - An infrastructure for supply of reagent is required

2.6.4 EGR - Exhaust Gas Recirculation

- A part of the exhaust gas stream is taken out and mixed back with the intake air.
- NO_x reduction due to lower peak temperatures as a result of high specific heat of recirculated CO_2 and H_2O.
- Additional NO_x reduction due to lower oxygen partial pressure
- NOx reduction potential: up to 50-70%
- Fuel quality restriction:
    - Distillate fuel quality (only) with very low sulphur and ash content
    - Maximum sulphur content: 0.05% (500 ppm)
- Comments:
    - EGR is an efficient NO_x reduction method used in truck engines but cannot be used together with current marine/power plant fuel qualities without efficient cleaning of the recirculated exhaust gas
- Applicability:
    - Currently not for marine nor power plant use together with today´s and anticipated residual, distillate and emulsified fuel qualities

2.6.5 Scrubber Technology

- Reduces the NO_2 part of NO_x
- NO_x reduction potential: 5-10%
    - Status of development: Marine systems under development
    - Impact on fuel consumption: No
    - Fuel quality requirements: Unchanged
- Comments:
    - Scrubber technology is used for reducing SO_2 emissions
    - NO_x reduction is very low
- Applicability:
    - Not aimed for NO_x reduction

2.6.6 Non Thermal Plasma Technology

- Reduces NO_x to N_2 and H_2O by use of Plasma and catalyst
- NO_x reduction potential: unclear
- Status of development: Systems under development
- Fuel quality restriction:

- Distillate fuel quality (only) with very low sulphur content otherwise deactivation of the catalyst
- Maximum sulphur content: ~0.005% (50 ppm)

- Comments:
  - Precious metal catalyst is a part of the system. Consequently the system is very sensitive for deactivation by sulphur in fuel

- Applicability:
  - Not for marine nor power plant use together with today´s and anticipated residual and emulsified fuel oil qualities

2.6.7 Fuel Additives

- Combustion and/or catalyst performance enhanced additives
- NO_x reduction potential: Negligible effect on NO_x has been noticed when tested under controlled conditions

3. SO_x – SULPHUR OXIDES

3.1 Definitions

- Sulphur dioxide (SO_2) and sulphur trioxide (SO_3) are collectively referred to as sulphur oxides (SO_x)

3.2 Environmental Impact

- Acid rain, acidification
- Contributes to formation of small size particulates – part of SO_x is forming SO_3 and sulphates condensing to particulates
- Potential detrimental effect on vegetation, human health and buildings

3.3 Recommended Measurement Standards and Methods – quote from reference 1)

Sulphur dioxide (SO_2) after engine

Recommended method:

- ISO 8178-1 Chapter 7.4.3.7: *Sulphur Dioxide (SO_2) analysis.*
  - According to ISO 8178-1, the SO_2 concentration shall be calculated from the sulphur content of the fuel, since experience has shown that using direct measurement method for SO_2 does not give more precise results. It is further noted that SO_2 measurement is a difficult task and has not been fully demonstrated for exhaust measurements.

Sulphur dioxide (SO_2) after flue gas desulphurisation (FGD)

Recommended method:

- EPA Method 6C (USA): *Determination of sulphur dioxide emissions from stationary sources (Instrumental analyser method)*

Recommendations for both methods above:

- SO_x is to be measured, calculated and reported as sulphur dioxide (SO_2). Typically only about 2-4% of SO_x is SO_3 after the engine and after the FGD the percentage is even lower. Consequently, the contribution of SO_3 to SO_x can be disregarded.

3.4 Diesel Process

- All sulphur entering the engine combustion chamber is oxidized forming SO_x, which is emitted to the atmosphere with the exhaust gases. As the sulphur absorbed by the alkaline lubricant is negligible in this respect, the SO_x emissions from the engine are practically directly proportional to the fuel sulphur content and fuel consumption
- Due to the superior fuel efficiency of the diesel process among prime movers, also the SO_x emissions are lowest when comparing operation to other prime mover technologies on the same fuel quality
- Typical SO_2 / SO_x ratio is 0.95
- Typical SO_3 / SO_x ratio is 0.05

3.5 Some Important SO_x Regulations

3.5.1 Marine Sector

IMO – International Maritime Organization

- Current: 4.5%-m fuel S global cap with 1.5%-m S fuel limit when in SO_x Emissions Controlled Areas (SECAs)
- Future: proposed for global application:
    - Max. fuel S content from 1 January 2012: 3.5%-m
    - Max. fuel S content from 1 January 2020: 0.5%-m
        - IMO review in 2018 for the availability of required fuel quality in 2020. If necessary postponement to 2025.
- Future: proposed for SECA areas:
    - Max. fuel S content from 1 March 2010: 1.0%-m
    - Max. fuel S content from 1 January 2015: 0.1%-m
- No restrictions in the use of heavy fuel oil. However, the consequence of the 0.1% and 0.5% sulphur caps will be distillate fuel in SECA areas from 2015 and globally from 2020 (some residual fuels may still be used)
- Abatement technologies including scrubbers are allowed as alternatives under certain conditions
- Final adoption of the proposed future regulations is supposed to be taken by IMO in October 2008

European Union

- Current: 1.5%-m fuel S cap in SECA areas and all passenger ships in regular service to/from EU ports
- Future: 0.1%-m fuel S cap (or equivalent by exhaust cleaning) from 2010 for ships on berth and for operation in inland waterways
- Exhaust gas cleaning is an alternative to achieve same levels

USA

- Current: as IMO for engines with a per cylinder displacement >30 liters/cylinder
- Current: Maximum 500 ppm S in distillate marine fuels
- Proposal for 2012: Maximum 15 ppm S in distillate marine fuels

USA – California

- Mandatory use of low sulphur marine distillate fuel in all engines (and boilers) on ocean-going ships within 24 nautical miles of the California coastline:
    - From 2009:
        - Maximum 1.5% sulphur in Marine Gas oil (MGO)
        - Maximum 0.5% sulphur in Marine Diesel Oil (MDO)
    - From 2012:
        - Maximum 0.1% sulphur in MGO and MDO

Norway

- Globally: Environmentally differentiated tonnage tax system

Voluntary Emission Control Programs

- Bureau Veritas: Cleanship and Cleanship Super
- Det Norske Veritas: Clean and Clean Design
- Germanischer Lloyd: Environmental Passport
- Lloyd´s Register: Supplementary “N” and “S” Character
- RINA: Clean Air
- American Bureau of Shipping: Environmental Safety
- US-EPA: Blue Sky

3.5.2 Stationary Power Plant

International regulation – World Bank Guidelines

Regulation in force:

- Liquid fuel diesel plants in resultant non-degraded air-sheds:
  - Plants 3…50MWth (General EHS Guidelines)
    - 1.5…3 %-weight S in fuel
  - Plants >50 MWth
    - 0.2 ton (metric) per day/MW(electric) (Thermal power – Guidelines for new plants 1998)
- Lower sulphur levels are required in degraded air-sheds or close to sensitive areas

New regulation proposed by World Bank (Thermal Power Plants Guidelines) (final decision is not taken):

- Plants 50<MWth<300
  - 2 %-weight S in fuel
- Plants >300 MWth
  - 1 %-weight S in fuel
- Lower sulphur levels are required in degraded air-sheds or close to sensitive areas
- Abatement technologies are allowed

India (“Emission standards for diesel engines (engine rating more than 0.8 MW (800 kW) for power plant, generator set applications and other requirements”, issued July 2002)

- Diesel engine plants
  - Max. 2%-m S in fuel in big cities (> 5 MWe plants)
  - Max. 4%-m S in fuel in “other areas”

Japan (“Nation wide general limits”, > 50 l/h fuel oil, outside big cities):

- Diesel engine plants
  - The allowed SO_x level is regulated locally by a total quantity approach (max. SO_2 quantity per time unit (Nm^3/h)) – varying from area to area

Europe

- EU Directive 1999/32/EC
  - Max. 1%-m S in HFO
  - Max. 0.1%-m S in gas oil
  - Alternatively a FGD is to be applied

3.6 SO_x Abatement Technologies

3.6.1 Switch to Low Sulphur Fuel

- Operation on low sulphur residual fuel or distillate fuel or natural gas (LNG)
- Comments:
  - We will see more of:
    - Several fuel qualities on board
    - Fuel switching on board
      - Correct switching procedure is crucial – instructions required from engine manufacturers
    - Low sulphur and low viscosity fuel qualities on board
      - Marine engines are often designed to cope with “industrial quality” of distillate fuel (sulphur content 0.05-2%)
      - Operation on “automotive quality” of distillate fuel (Ultra Low Sulphur Fuel) is not always straight forward due to low fuel viscosity challenges

3.6.2 Sea Water Scrubber

- Reduces SO_x by dissolving it and neutralizing it in sea water
- SO_2 reduction potential: typically 80-90%
- Status of development: Systems under development
- Impact on fuel consumption: No
- Fuel quality requirements: Unchanged
- Estimated additional engine costs: 200 USD/kW
- Estimated additional operating costs:
  - Parasitic power (pumping): 2% of engine MCR
- Comments:
  - Sea water scrubber exploits the natural alkalinity of water to neutralize the dissolved sulphur dioxide from the exhaust gas
  - High alkalinity improves the neutralization and simultaneously the water can stand the process better without collapse in pH
  - Water areas with high alkalinity are beneficial for sea water scrubbing
  - Variation in alkalinity between sea water areas and in port. Consequently the use of sea water scrubbing can be problematic in some areas/ports
- Challenges:
  - Waste water treatment

- IMO is currently developing discharge criteria for scrubber waste waters
- Cold exhaust plume => risk of visibility and poor buoyancy => exhaust reheating may be needed

- Applicability:
  - Feasible system for installing on board
  - No stationary diesel engine plant exist so far

3.6.3 Caustic Soda Scrubber

- Reduces SO_x in a closed loop system with fresh water, to which Sodium Hydroxide (NaOH) or Carbonate (Na_2CO_3) is added for the neutralization of SO_x
- SO_2 reduction potential: up to 80-90%. Even higher SO_2 reduction levels can be achieved corresponding to a SO_2-level equivalent to 0.1% sulphur in fuel.
- Status of development:
  - Marine systems under development
  - Stationary power plant systems in commercial use
- Impact on fuel consumption: No
- Fuel quality requirements: Unchanged
- Estimated additional engine costs: typically 200 USD/kW depending on plant size
- Estimated additional operating costs:
  - Parasitic power (pumping): <1% of engine MCR
  - NaOH cost: typically 0.5 – 4% of HFO price
- Comments:
  - Closed loop = zero discharge in enclosed area by use of a holding tank (ship application)
  - Advantages compared to sea water scrubbing alternative:
    - Works anywhere
    - Smaller water flow than sea water scrubber
    - Lower Pumping power
    - Corrosion and scaling issues easier

        - Only small amount of fresh water required

        - Small amounts of bleed-off

        - Zero effluent discharge mode possible, if end product can be stored, transported and disposed elsewhere

    - Challenges:

        - Reagent, fresh water and electricity are needed

        - Cold exhaust plume => risk of visibility and poor buoyancy => exhaust reheating may be needed

        - Power plant: Liquid effluent regulations varies greatly around the world

- Applicability:

    - Marine and power plant: Suitable system for small/medium size plants

4. PARTICULATE MATTER (PM) AND SMOKE

4.1 Definitions

- Diesel particulate matter (PM) is a complex mixture of solid and carbonaceous material, unburned hydrocarbons and inorganic compounds. The amount of absorbed and condensed matter strongly depends on the cooling conditions: temperature, cooling rate, residence time in the conditioning and sampling devices, etc

- Exhaust particulate matter (PM) composition of residual fuel diesel operation can be summarized by following fractions:

    - PM = Soot + SOF + IF

    - Where Soluble Organic Fraction (SOF) refers to organic material and IF (Inorganic Fraction) to volatile, semi-volatile and non-volatile compounds like sulphates and nitrates, metals and water.

- Particulate emissions (PM) are defined by the measurement method and the understanding and knowledge of used methods are essential. The methods are many and based on measuring various physical/chemical characteristics of the particle at different temperatures and pressures. The measurement results differ a lot for the methods – the results are not comparable and the establishment of correlations between results is often impossible. Emission regulations are based on different measurement methods (i.e. regulators are defining particulates in different ways).

- By definition smoke is visible (white, grey, blue, black, brown and yellow)

- See annex 1 for typical diesel particulate composition

4.2 Environmental Impact

- Small particles are considered detrimental to human health. They are considered penetrating down into the human lung.
- Large particles are of less concern to human health because they are effectively removed by the pulmonary system
- As fine particulates can easily be transported by air currents, their detrimental effects can be encountered at far distance from the exhaust plume
- Visual impact – smoke

4.3 Recommended Measurement Standards and Methods – partly quoted from reference 1)

4.3.1 Measurement of Total Mass Concentration of Particulates

- Particulate Matter from marine sources can be measured according to two different measurement methods i.e. the dilution method and the direct measurement method (dry dust method).
- Warning and recommendation!
  - The dilution method should only be used with low sulphur fuels (S<0.8% as indicated in the ISO 8178 standard) whereas the direct measurement method (dry dust method) can be used when operating on any fuel quality (no restrictions in the standard)
  - The particulate measurement results differ a lot for the two measurement methods – the results are not comparable. The root cause of the difference in results is the behaviour of sulphur compounds in sampled exhaust gas. Simultaneous measurements from the same engine exhaust duct with both measurement methods have shown that the fuel sulphur content is resulting in big difference in results between the methods, since dilution promotes spontaneous condensation of water soluble compounds (e.g. sulphuric acid)
  - The direct measurement method is used for measuring particulates from land based stationary sources.
- Note – for all particulate measurements:
  - Quartz fibre filter material should be used.
  - Glass fibre filter material may react with acidic compounds in the exhaust gas originating from sulphur compounds present in fuel and lube oil, leading to an increase of the filter mass 3) – the use of glass fibre filter paper material should be avoided
  - Teflon coated glass fibre filter material can be used together with the dilution method (ISO 8178)

4.3.1.1 Dilution Method – Marine Engines only - Maximum Fuel Sulphur Content is 0.8% %-weight

Recommended method:

- ISO 8178: *Reciprocating internal combustion engines – Exhaust emission measurement (reference 3)*
- Note:

  The ISO 8178-1 states that the maximum fuel sulphur content with this method is 0.8%-weight.

See the explanation above.

4.3.1.2 Direct Measurement Method – All Fuel Qualities

Measurement after engine and before heat recovery boiler, before flue gas cleaning system, etc - Recommended methods:

- ISO 9096: 2003: *Stationary source emissions – Manual determination of mass concentration of particulate matter.* In-stack filtration

- EN 13284-1: *Stationary source emissions – Determination of low range mass concentration of dust – Part 1: Manual Gravimetric method.* In-stack filtration.

- VDI 2066 Blatt 1 (Germany): *Particulate matter measurement. Measuring of particulate matter in flowing gases. Gravimetric determination of dust load.*

- EPA Method 17 (USA): *Determination of particulate emissions from stationary sources*

- JIS Z8808 (Japan): *Methods of measuring dust concentration in flue gases*

- Note:

  Particulate matter is a function of temperature and pressure. Many direct emission measurement methods (dry dust) specify a sampling temperature, which for a diesel engine means that the exhaust gas has to be cooled very dramatically. The cooling of the exhaust gas cannot be considered a controlled process and will not yield reproducible sampling. The main reason for this is the uncontrolled condensation of semi-volatile components from the exhaust gas on the cold surfaces needed to cool the gas. According to ISO 9096 (reference 4) and EN 13284-1 (reference 5), more reproducible results are achieved if volatile compounds are not trapped during sampling or further evaporated during sample drying. Considering the above issues it is concluded that to yield repeatable particulate matter measurement data from the hot exhaust gas of a diesel engine, the particulate sampling has to be performed at exhaust gas temperature, i.e. using in-stack sampling.

Measurement after heat recovery boiler in stack (flue gas temperature <160℃) or low temperature flue gas cleaning system (flue gas temperature <160℃) - Recommended methods:

- ISO 9096:2003: *Stationary source emissions – Manual determination of mass concentration of particulate matter.* Out-stack filtration
- EN 13284-1: *Stationary source emissions – Determination of low range mass concentration of dust – Part 1: Manual Gravimetric method.* Out-stack filtration.
- EPA Method 5B (USA): *Determination of nonsulfuric acid particulate matter emissions from stationary sources.*
- JIS Z8808 (Japan): *Methods of measuring dust concentration in exhaust gases*

- Note:

  The out-stack filtration is recommended, because this arrangement enables heating of the filter holder to a temperature close to 160ºC for avoiding any risk of condensation and absorption of sulphur compounds, water, etc on the sampling filter. If the temperature of the exhaust gas is high enough (close to 160ºC) for ensuring that no condensation or absorption could take place then the in-stack filtration can be used

4.3.2 Measurement of Smoke

4.3.2.1 Filter Smoke Number

Recommended methods:

- ISO 8178-3: *Reciprocating internal combustion engines –exhaust emission measurement, method 2: Smoke measurement by a filter-type smoke meter*

- ISO 10054: *Internal combustion compression ignition engines – measurement apparatus for smoke from engines operating under steady-state conditions – filter type smoke meter*

Warning!

- Simultaneous measurements from the same engine exhaust duct with several different smoke meter types and configurations, all in line with the requirements in the FSN measurement standards above, have shown big differences in Filter Smoke Number, especially when operating on high sulphur and high ash fuel qualities. Consequently, the precise smoke meter configuration is affecting the Filter Smoke Number result and has to be taken into account when evaluating FSN test results.

Requirements for achieving reproducible Filter Smoke Number results

- Although the used smoke meter type and configuration are fulfilling the measurement standards ISO 10054 and ISO 8178-3 the following additional requirements must be met in order to achieve reproducible FSN smoke results and enabling comparison of FSN results between engines:

  - Exact the same type of sample probe has to be used

  - Exact the same type and length of sample tube has to be used

  - Same type of instrument has to be used

    - If the results from a "heated system" is intended to be compared to results received with a "non-heated system" the heating has to be switched off (instrument and sample line)

  - Same sampling volume and same sampling time are to be used

  - Same filter paper quality is to be used

Requirements for achieving comparable results to the "one stroke Bosch scale"

- In case a "heated system" is used the heating should be switched off (instrument and sample line)

- "Bosch hand pump" type of sample probe with cap screwed on has to be used

- Sample line type to be used: Viton material, Unheated Non-insulated tube
- Sample line length is to be minimized
- Standard filter paper has to be used
- Reference sample volume is 0.33 litre/ stroke and the number of strokes is 1.

Comparison of the FSN smoke value to the "one stroke Bosch value" is not possible to do, unless these requirements (above) are met. The FSN corresponds to approximately 1:1 to the "one stroke Bosch value" provided that the requirements above are fulfilled.

Bacharach

Bacharach method should be avoided due to low reproducibility of results

4.3.2.2 Smoke Density

Recommended methods for Smoke Density (Opacity):

- ISO 8178-3: *Reciprocating internal combustion engines – exhaust emission measurement, method 1: Smoke measurement by an opacimeter*
- ISO 11614: *Reciprocating internal combustion compression ignition engines – apparatus for measurement of the opacity and for determination of the light absorption coefficient of the exhaust gas*

Ringelmann

- Ringelmann is a smoke measurement method based on visual assessment of the smoke appearance. Visual Ringelmann testing should be avoided, because many uncontrollable factors will affect the subjective smoke appearance value, such as weather conditions (cloudy, bright day, etc), position of sun, number of stacks, stack diameter, etc
- ASTM D3211-79 "Standard Test Method for Relative Density of Black Smoke (Ringelmann Method) can be used for specifying the relationship between Ringelmann Number and Smoke density (Opacity). Opacity of 20% corresponds to Ringelmann 1, etc.

4.4 Some Important Particulate Regulations

4.4.1 Marine Sector

IMO – International Maritime Organization

- Current: no limits
- Future:
    - Proposal not to include any stipulated limits on particulates
    - The proposal is to control particulate emissions indirectly by reducing the fuel sulphur content
    - Final adoption of the proposed future regulations is supposed to be taken by IMO in October 2008

European Union

- Current – Some “local” regulations e.g. River Rhine and Bodensee
- Current - Inland waterways and engine bore size <30 liters/cylinder
  - Tier IIIA = 0.2 to 0.5 g/kWh depending on engine size. Particulates defined according to the ISO 8178 measurement method

USA

- Current – US flagged ships and engine bore size <30 liters/cylinder
  - Tier 2 = 0.2 to 0.5 g/kWh depending on engine size. Particulates defined according to the ISO 8178 measurement method

Smoke restrictions:

- Alaska: Strict visible smoke regulations
- Smoke emissions regulated “Memorandum of Understanding” in Florida, California and Hawaii
- Smoke restrictions also in ports of Rotterdam and Hamburg

4.4.2 Stationary Power Plant

International regulation – World Bank Guidelines

Regulation in force

- Diesel plants in resultant non-degraded air-shed:
  - Plants 3…50 MWth (General EHS Guidelines)
    - 50…100 mg/Nm^3, dry, 15% O_2
  - Plants >50 MWth (Thermal Power – guidelines for new plants 1998)
    - 50.. 150 mg/Nm^3, dry, 15% O_2

New regulation proposed by World Bank (Thermal Power Plant) (final decision is not taken)

- Diesel engine plants:
  - Plants >50 MWth
    - 50 mg/Nm^3, dry, 15% O_2

General

- Measurement method: ISO 9096
- Lower particulate levels are required in degraded air-sheds or close to sensitive areas
- Abatement technologies are allowed

India ("Emission standards for diesel engines (engine rating more than 0.8 MW (800 kW) for power plant, generator set applications and other requirements", issued July 2002)

- Diesel engine plants
  - 75 mg/Nm^3, dry,15 % O_2 with High-speed diesel and light diesel oil
  - 100 mg/Nm^3, dry, 15 % O_2 with Furnace oil-Low Sulphur Heavy Stock

Japan ("Nation wide general limits", > 50 l/h fuel oil, outside big cities):

- Diesel engine plants
  - 75 mg/Nm^3, dry,15 % O_2 (all areas)
  - 60 mg/Nm^3 , dry, 15 % O_2 (special areas)

4.5 Diesel Process

- Soot is produced during incomplete combustion. Ash originates from fuel and lube oil (additives, impurities) as well as engine wear and corrosion products. Volatile species are accumulated on the particles as exhaust gas cool down during the travel through the exhaust duct and measurement system. In addition to the change of particulate composition and mass, the volatile matter buildup affects the physical properties of the particle.
- All liquid & gas fuel operated combustion processes generates small size particulates - the diesel engine is not unique in this respect

4.6 PM and Smoke Abatement Technologies

4.6.1 Primary Technologies

Reduction of particulate soot fraction – combination of

- Increased fuel injection pressure and advanced fuel injection timing
- Increased boost pressure
- Increased charge air temperature
- Optimized combustion chamber – swirl, squish
- Optimized fuel injection system - nozzle
- Split injection / Multiple injection (post injection)
- Electronic & Common Rail fuel injection system
- Variable valve timing
- Variable turbine area
- Soot reduction potential at residual fuel operation:
  - High load: Typically low potential
  - Low load: Significant potential.

Reduction of Soluble Organic Fraction (SOF)

- Reduction of leakages from turbocharger turbine seal, exhaust valve guides and fuel injection nozzles
- Faster rate of injection pressure decay at end of fuel injection
- Reduced aromatic and asphaltene content of residual fuel
- Reduction of lubricating oil consumption

Reduction of Inorganic Fraction (IF)

- Reduction of particulate sulphuric acid/water fraction
  - Reduced fuel sulphur content
  - Reduced lube oil sulphur content
  - Reduced lube oil consumption
- Reduction of particulate ash fraction
  - Reduced fuel ash content
  - Reduced lube oil additives (containing ash components)
- IF reduction potential at residual fuel operation
  - High by reducing fuel sulphur and ash content due to the fact that the contribution of fuel sulphur and ash to total particulate emissions is typically 40-80% at high load

4.6.2 Water-in-Fuel Emulsions

- In-line emulsification of water into fuel
- Smoke/particulate reduction potential at low load with engines equipped with conventional fuel injection system: Noteworthy
- Smoke/particulate reduction potential at high load: Low
- Status of development: Systems available
- Impact on fuel consumption: Low
- Water quality requirements: Moderate
- Water-to-fuel ratio: 0.2-0.3
- Fuel quality requirements: Unchanged
- Estimated additional engine costs: about 5%
- Estimated additional operating costs: Low
- Applicability:
  - Capacity of the FIE need to be high enough for unchanged power output
  - 2-stroke and 4-stroke engines

- Retrofit to existing engines often possible
- Often no limitations for new engines

4.6.3 Scrubber Technology

- See also 2.6.5 and 3.6.2 and 3.6.3
- Particulate reduction potential: 0-20%
- Status of development:
  - Marine systems under development
  - Stationary power plant systems in commercial use
- Comments:
  - Scrubber technology is used for reducing SO_x emissions
  - Particulates and NO_x reduction are very low

4.6.4 Non Thermal Plasma Technology

- See also 2.6.6
- Reduces particulates by use of Plasma and catalyst
- Particulate reduction potential: >50%
- Comments:
  - Sulphur from the fuel has a negative impact on the electrodes generating the plasma and also particulate matter coats the electrodes, which in consequence have to be regularly maintained and/or plasma power has to be continuously increased
- Applicability:
  - Not for marine nor stationary power plant use together with anticipated residual, distillate and emulsion fuel qualities

4.6.5 Particulate Traps and Oxidation Catalysts

- Particulate traps are (will be) used in many diesel cars and trucks running on clean diesel fuel for filtering off particulates/soot
- The trap has to regenerate on a regular basis, i.e. the trapped soot must be burnt out. Precious metal catalyst are often used for regeneration
- Oxidation catalysts are sometimes (will be) used on diesels equipped with EGR for oxidation of CO, HC and Soot
- Both systems are based on precious metal catalysts – fast deactivation and clogging would occur with marine/power plant fuel qualities

4.6.6 Bag Filters and Electrostatic Precipitators

- Efficient reduction methods for particulates/soot
- The methods are used in large land-based industrial sources, coal-fired power plants, etc
- The systems are extremely bulky
- Limited experience exits with diesels
- These are not viable methods for marine applications

4.6.7 Fuel Additives

- Combustion enhanced additives
- Particulate/soot reduction potential: No significant reduction has been noticed when tested under controlled conditions
- Risk for increased particulate emissions due to compounds in the additive

5. CO_2 – CARBON DIOXIDE

5.1 Definitions

- CO_2 is a colourless and odourless gas
- CO_2 is non-toxic gas in concentrations below 5%
- CO_2 is the main end product of combustion of carbonaceous fuels (fuel oils, etc)
- CO_2 is a product of normal human respiration
- CO_2 is a natural constituent of the air

5.2 Environmental Impact

- Makes up 0.03-0.04% of the earth atmosphere
- CO_2 is a major player in the carbon cycle on earth
- Organic carbon is in general transformed into CO_2 either through burning or metabolism of dead organic material
- Concentration of CO_2 is increasing in the atmosphere as the result of human activity
- CO_2 is acting as a “greenhouse gas” trapping infrared radiation from the surface of the earth and contributing to global warming.
- Most important greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), some hydroflorocarbons and sulphur hexafluoride.
    - These have different Global Warming Potentials (GWP) (Reference 6)

5.3 Recommended Measurement Standards and Methods

- ISO 8178-1 section 7.5 (NDIR – Non-Dispersive InfraRed)
- Calculation from fuel carbon content and fuel consumption

5.4 Diesel Process

- Practically all carbon entering the engine combustion chamber is oxidized to form CO_2 which is emitted into the atmosphere with the exhaust gas. As the carbon from the lubricant oxidation is negligible in this respect, the CO_2 emissions from the engine are practically directly proportional to the fuel carbon content and the fuel consumption
- Due to the superior fuel-to-shaft energy efficiency of the diesel process among prime movers, also the CO_2 specific emissions are lowest when comparing operation on the same fuel quality

5.5 Some important CO_2 Regulations and Aspects

- CO_2 is a major "greenhouse gas"
- Main regulations and trading markets are based on:
  - The Kyoto protocol/mechanism
  - The EU Emission Trading Scheme (EU ETS)
- The Kyoto mechanism includes the Joint Implementation (JI) and Clean Development (CDM) mechanisms allowing industrial countries with an emission limitation commitment to earn emission reduction units from an emission reduction project in other countries
- EU ETS is for time being affecting big combustion plants >20 MWth and some other activities such as production of ferrous metals, mineral industry and pulp and paper industry
- Other trading markets:
  - Chicago Climate Exchange (CXX), World Bank Community Development Carbon Fund (CDCF), World Bank Prototype Carbon Fund (PCF), etc
- IMO is committed in developing GHG reduction strategies and mechanisms for international shipping in co-operation with UNFCCC (United Nations Framework Convention on Climate Change). Completion of work is set to July 2009

5.6 CO_2 Abatement Technologies

- Limitation of the use of fossil fuels for energy production
- Switch to fuels containing less carbon (Reference 7)
- More use of biofuels and other renewables such as wind and water power, sun, etc
- Improvement of fuel-to-energy efficiency
- Nuclear power
- Use of carbon capture and storage (CCS) techniques. These are currently under development and are expected to play an important role in the future CO_2 reduction measure palette. Cost and energy demand for currently available CCS technologies are very high.

6. REFERENCES

1) CIMAC Recommendation Number 23/2005. " Standards and methods for sampling and analysing emission components in non-automotive diesel and gas engine exhaust gases – marine and land based power plant sources" – Appendix 1

2) EPA CTM-022: Determination of nitric oxide, nitrogen dioxide and NO_x emissions from stationary combustion sources by electrochemical analyser.

3) ISO 8178: Reciprocating internal combustion engines – Exhaust emission measurement

4) ISO 9096: Stationary source emissions: Manual determination of mass concentration of particulate matter

5) ISO 13284-1: Stationary source emissions – Determination of low range mass concentration of dust – Part 1: Manual gravimetric method

6) UN IPCC Global Warming Potential

7) 2006 UN IPCC Guidelines for National Greenhouse Gas Inventories.

7. ACKNOWLEDGEMENT

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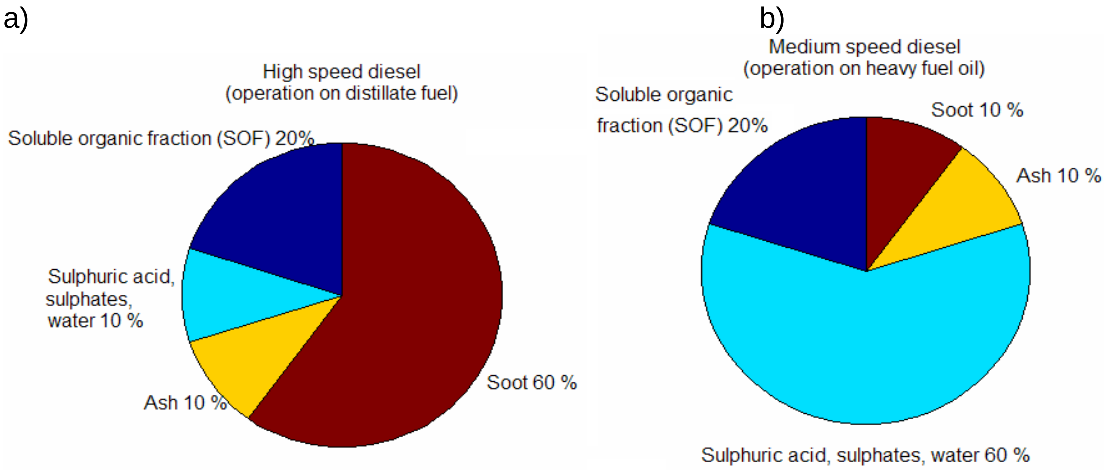
8. ANNEX 1: EXAMPLE OF TYPICAL EXHAUST PARTICUALTE COMPOSITION AT HIGH ENGINE LOADS



Example of typical exhaust particulate composition at high engine loads – ISO 8178 measurement method. a) High speed diesel operating on distillate fuel b) Medium speed engine operating on residual (heavy) fuel oil

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(available in the CIMAC Technical Paper Database)

No. 1 Recommendations for Diesel Engine Acceptance Tests, 1968

No. 2 Recommendations for Gas Turbine Acceptance Test, 1968

No. 3 Recommendations of Measurement for the Overall Noise of Reciprocating Engines, 1970

No. 4 Recommendations for SI Units for Diesel Engines and Gas Turbines, 1975

No. 5 Recommendations for Supercharged Diesel Engines, 1971
Part I: Engine De-rating on Account of Ambient Conditions
Part II: Engine Acceptance Tests

No. 6 Lexicon on Combustion Engines, Technical Terms of the IC Engine and Gas Turbine Industries, 1977

No. 7 Recommendations regarding Liability – Assured Properties, Publications and Fuels for Diesel Engines, 1985

No. 8 Recommendations regarding Requirements for Heavy Fuels for Diesel Engines, 1986 (superseded by No. 11)

No. 9 Recommendations concerning the Design of Heavy Fuel Treatment Plants for Diesel Engines, 1987 (superseded by No. 25)

No. 10 Recommendations regarding Liability - Assured Properties, Publications and Fuels for Gas Turbines, 1985

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No. 27 Turbocharging efficiencies - Definitions and guidelines for measurement and calculation, 2007

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