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Green Ships

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1.Introduction

The theme of TechSAMUDRA 2012 is “Design, Construction and Operation of Marine Vehicles, Platforms, Systems and Technologies for Sustainable Development”. Sustainable development, which is related to the “Green Economy”, has been defined as Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

An addition to this definition is :

The perfect green economy would deliver equitable improvement in living standards without eroding environmental assets.

At the Green Ship Conference at Copenhagen in March this year, Dr. Stefan Micallef, Director, Marine Environment Division, IMO stated in his keynote address [1] that : The credentials of shipping as the cleanest and most energy efficient mode of transport carrying an overwhelming volume of world trade are long established. This makes shipping integral to civil society’s transition to a ‘green economy’ based on sustainable development.

When one considers shipping in relation to sustainable development, it is necessary to consider the complete “life cycle” of a ship : ship design, shipbuilding, ship operation and ship recycling. In this paper, the focus is on ship design and ship operation. Shipbuilding and ship recycling are considered briefly in the next section.

2.Shipbuilding And Ship Recycling

- Shipbuilding has been characterized (somewhat harshly) by Hong He-Ping of Guangzhou Shipyard [2] as an industry with high energy consumption, high material consumption and high pollution. To reduce pollution, he advocates improving production efficiency and saving resources, labour and all kinds of capital by “high and new technology” and modern management. He recommends a policy of three Rs - Reduce, Recycle and Reuse – to minimize waste and reduce pollution.

  Efficiency conscious shipyards strive to improve production efficiency, save resources and adopt modern management practices for sound economic reasons; any benefits to the environment are probably incidental. Quite often, labour is saved by employing capital to acquire this high and new technology which is frequently energy intensive and therefore may be more polluting. Whether the use of high and new technology to save labour (human power) in regions of the world where people are unemployed is sustainable development is questionable.

- Ship recycling, according to an IMO document of 2003 [3], is without question a "green" industry. Virtually nothing goes to waste and materials and equipment are reused. As an example, the new steel made from recycled steel requires only one-third of the energy required to make steel from iron ore. However, it is necessary to control the working conditions and environmental problems at ship recycling locations.

  Ships have on-board substances that may be environmentally hazardous when the ship is broken. When this hazard was recognized, ships were required to carry what was known as a "Green Passport". This has been replaced by the more prosaic Inventory of Hazardous Materials, which is specific to each ship and lists the hazardous substances that the ship carries, although classification societies still give a "green passport" [4]. Table 1 gives a list of prohibited or restricted materials.

Asbestos
Polychlorinated Biphenyls (PCBs)
Ozone depleting substances such as chlorofluorocarbons (CFCs)
Organo-Tin compounds such as Tri-Butyl-Tin (TBT)
Cadmium and its compounds
Hexavalent Chromium and its compounds
Lead and lead compounds
Mercury and its compounds
Polybrominated Biphenyls
Polybrominated Diphenyl Ethers
Polychloronaphthalenes
Radioactive substances
Certain short chain chlorinated paraffins

Table 1: Prohibited or Restricted Materials

In addition when the ship goes for recycling, items that are not normally regarded as hazardous become a matter of concern. Table 2 lists some of these items.

Household appliances such as refrigerators
IT and telecom equipment
Consumer equipment such as TVs and video cameras
Lighting equipment such as fluorescent lamps
Electrical and electronic goods
Leisure and sports equipment
Furniture and furnishings
Bathroom installations
Toys

Table 2 :Some Items that may be Hazardous during Ship Recycling

There are also operational wastes and stores that may be hazardous during ship recycling. A few of these are listed in Table 3.

Lubricating oil
Paints, solvents, thinners and stabilizers
Flammable gases such as acetylene and propane
Greenhouse gases
Grease
Waste oil (sludge)
Bunkers
Ballast water
Sewage
Garbage

Table 3 :Some Operational Wastes and Stores that may be Hazardous during Ship Recycling

The International Convention for the Safe and Environmentally Sound Recycling of Ships 2009 (Hong Kong Convention) provides a mechanism to ensure green ship recycling. Environmental activists, however, regard the Hong Kong Convention a move backwards from the Basel Convention (1992) that in effect prohibits ships containing hazardous wastes to move across international boundaries.

3. Pollution From Ships

Ships in operation can pollute the environment in many ways and there are national and international regulations dealing with pollution due to ships. Table 4 lists the main ways in which ships can pollute the sea and the relevant IMO instruments dealing with the prevention of pollution.

Oil	MARPOL[1] Annex I
Noxious Liquid Substances	MARPOL Annex II
Harmful Substances in Packaged Form	MARPOL Annex III
Sewage	MARPOL Annex IV
Garbage	MARPOL Annex V
Air Pollution	MARPOL Annex VI
Water Ballast	Ballast Water Convention[2]
Anti-fouling Paints	Anti-fouling Convention[3]

Table 4: Pollution of the Sea from Ships

1 : International Convention for the Prevention of Pollution from Ships.
2 : International Convention on the Control of Harmful Anti-fouling Systems on Ships, 2001.
3 : International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004.

Another mechanism of pollution by ships is noise : the noise generated by ships in their passage through the seas is hampering communication between whales and causing their population to decline. Ships also cause pollution on land when pollutants from ships are transferred to land for treatment and disposal.

In recent years, the focus has been on air pollution because of its role in climate change. Although ships are not among the major polluters of air, it is accepted that emissions from ships must be controlled and minimized as far as possible. Among the important pollutants emitted into the atmosphere by ships are ozone depleting substances, sulphur oxides (SOx), nitrogen oxides (NOx), particulate matter, volatile organic compounds (VOCs) and greenhouse gases (GHGs).

Table 5 gives a list of some ozone depleting substances that are now prohibited in new installations in ships. New installations containing hydrochlorofluorocarbons (HCFCs) are permitted up to 1st January 2020.

Halon 1211	Bromochlorodifluoromethane
Halon 1301	Bromotrifluoromethane
Halon 2402 (Halon 114B2)	1,2-Dibromo-1,1,2,2-tetrafluoroethane
CFC-11	Trichlorofluoromethane
CFC-12	Dichlorodifluoromethane
CFC-113	1,1,2-Trichloro-1,2,2-trifluoroethane
CFC-114	1,2-Dichloro-1,1,2,2-tetrafluoroethane
CFC-115	Chloropentafluoroethane

Table 5: Ozone Depleting Substances

SOx causes acid rain. Among the methods to reduce SOx emissions from ships are the use of low Sulphur fuels, particularly in sensitive areas, and the use of dual fuel engines that can burn normal fuel on the high seas and liquefied natural gas (LNG) in sensitive areas. The use of exhaust gas scrubbers allows normal heavy fuel oils to be used while reducing SOx emission levels to values that would be obtained from low sulphur fuels. The exhaust gases are cooled in an economizer, treated with a spray of fresh water to remove soot particles, scrubbed with sea water or fresh water with caustic soda, heated to prevent condensation and corrosion and then discharged through the funnel. Tests show that 98-100 per cent SOx and 80 per cent particulate matter are removed by this process.

NOx also causes acid rain. Many measures have been taken to reduce NOx emissions from marine diesel engines. The design of engines has been improved to ensure a more uniform distribution of temperature in the cylinder and avoidance of local hot spots during fuel combustion by multi-point fuel injection, better mixing of air and fuel, improved design of cylinder head and piston crown and other measures. Compared to the older generation of marine diesel engines, engines with electronic and hydraulic components and computer controls ("intelligent" engines) have many improved characteristics, including greatly reduced NOx emissions. There are many other methods that are used to reduce NOx emissions from marine diesel engines, and some of these are listed in Table 6.

Miller Cycle
Humid Air Motor
Exhaust Gas Recirculation
Emulsified Fuels
Selective Catalytic Reduction

Table 6 :Methods to Reduce NOx Emissions

Particulate matter in the exhaust gases from ships may be dealt with by particulate filters, cyclone separators or electrostatic precipitators. Reduction technology is being developed for black carbon and particulates in the exhaust gases. Particulate matter may also be reduced by exhaust gas recirculation to reduce NOx and by exhaust gas scrubbing used to eliminate SOx.

VOCs include hydrocarbons such as methane, propane, benzene and toluene, oxidized hydrocarbons such as methyl tertiary butyl ether (MTBE) and chlorinated hydrocarbons such as chloroform. Methane being lighter than air may be emitted to the atmosphere and contribute to global warming. The other components, non-methane volatile organic compounds (NVOCs), are heavier than air. Some of them are quite harmful : benzene, toluene and xylene are carcinogenic. VOCs are produced during the loading of crude oil in tankers and during crude oil washing operations as well as during the voyage. VOC emissions from tankers during loading may be controlled by providing a vapour emission control system in which the inert gas piping collects vapour from the cargo tanks and delivers it to the shore for treatment and disposal. There are many other systems for dealing with VOC emissions from tankers, including :

- Reducing volatility of cargo oil before loading,
- Vapour balancing
- Thermal oxidation
- Absorption
- Adsorption
- Membrane separation

- Cryogenic condensation.

In some shuttle tankers, VOCs are collected and treated for use as fuel in specially adapted diesel engines.

Greenhouse gases (GHGs) cause global warming and contribute to climate change. A list of greenhouse gases is given in Table 6. The main concern is Carbon dioxide. International shipping carries 90 per cent of world trade but produces 870 million tonnes of CO_2 per year. Although this is only 2.7 per cent of the total CO_2 emissions of the world total, it is essential to control CO_2 emissions from ships since this figure for emissions, already slightly out of date, is expected to double by 2050 if substantial improvements in ship design, ship machinery and ship operation are not achieve

Carbon dioxide CO_2
Methane CH_4
Nitrous oxide N_2O
Sulphur hexafluoride SF_6
Nitrogen trifluoride NF_3
Chlorofluorocarbons such as CCl_2F_2 (CFC-12)
Hydrochlorofluorocarbons such as $CHCl_2F_2$ (HCFC-22)
Perfluorocarbons such as hexafluoroethane C_2F_6 (Water vapour H_2O)

Table 6 :Greenhouse Gases

There are various approaches to reducing CO_2 emissions from ships, such as :

- More efficient use of energy obtained from fuels that produce CO_2
- Use of fuels that produce less CO_2 per unit of fuel
- Use of energy sources that provide energy without producing CO_2
- CO_2 capture and storage.

Some of the methods that are being adopted or considered to reduce CO_2 emissions from ships are described briefly in what follows.

4. Ship Design

The most effective way of reducing CO_2 emissions from ships is to reduce their speeds : a 10 per cent decrease in speed will cause a reduction in propulsion power of about 27 per cent and a corresponding decrease in fuel consumption and CO_2 emissions. This has been done in the past when there was a sharp increase in the price of fuel. However, there are economic considerations that may not permit this in many cases. Other approaches to reduce CO_2 emissions are therefore necessary.

More efficient use of energy can be achieved by improvements in Ship Hydrodynamics, and some of the areas of interest are :

- Improved hull forms for reduced resistance and better ship handling, bulbous bows optimized for different loading conditions, stern shapes for improved flow to propellers.
- Lubrication of the hull surface to reduce friction between the hull and water, an old idea that has reappeared recently, for example, as the Mitsubishi Air Lubrication System. This is being fitted to three 95000 dwt grain carriers to be built in Japan for U.S. owners.
- Improved propulsion devices : conventional propellers with advanced blade sections, unconventional propulsion devices such as controllable pitch propellers, ducted propellers, contra-rotating propellers, contracted and loaded tip (CLT) propellers, propeller boss cap fin (PBCF) propellers, podded and azimuthing propellers, vane wheel propellers and many others.
- Improved appendages :
    - Appendages with lower resistance.
    - Appendages that produce forward thrusts such as the Sumitomo fin, the IHI fin and the Hyundai thrust fin.
    - Appendages that improve the flow to the propeller such as vortex generators, Grothues spoilers, the Schneekluth wake equalizing duct, the Hitachi-Zosen or superstream duct (SSD), the semi-circular duct system (SDS), the Sumitomo integrated Lammeren duct (SILD), the Mitsui integrated duct and the Mewis duct.
    - Appendages that eliminate rotation of the propeller slipstream, i.e. radial fins fitted ahead or astern of the propeller (pre-swirl and post-swirl stators), such as the Mitsui reaction fin system.

- Twin skeg ships instead of twin screw ships for improved propulsive efficiency.
- Improved rudders such as rudders with twisted leading edges to match the rotation of the propeller slipstream, high lift rudders and integrated rudder-propeller designs such as the Rolls Royce Promas, as well as advanced auto-pilots that minimize sailing “off track” resulting in significant savings in fuel consumption.
- Improved seakeeping qualities in ships and improved motion stabilization devices that permit ships to maintain their course and speed in higher sea states.

Some attention is being given to the aerodynamics of the above water part of a ship to minimize air resistance by proper design and arrangement of deckhouses. Consideration could also be given to the above water profile of a ship so that in cross winds the centre of wind pressure and the centre of lateral resistance are in the same longitudinal location. This would reduce yaw and the associated increase in resistance.

Improvement in the propulsive efficiency of ships has been an important goal of ship design since ships began to be mechanically propelled over two hundred years ago, i.e. much before the current focus on minimizing CO_2 emissions. Ships have therefore already achieved propulsive efficiencies that are close to the limit of what is possible. Many of the improvements in Ship Hydrodynamics that have been mentioned in the foregoing can lead only to modest gains in efficiency and in reduction of CO_2 emissions.

An arrangement that may lead to significant improvements is the contra-rotating pod (CRP) propeller. It is claimed that such an arrangement is up to 20 per cent more efficient than a conventional arrangement. The distribution of power between the main propeller and the contra-rotating pod propeller, the distance between the two propellers and the ratio of their diameters are important considerations. This arrangement has been fitted to two fast ropax vessels in Finland after a research project in which the Finnish government, ABB, the Kvaerner-Masa shipyard and Wartsila participated [5]. The vessels have a speed of 29 knots with the power for the main controllable pitch propeller being 33.6 MW and for the CRP propeller 10 MW. A similar arrangement has been adopted for two fast ferries in Japan.

Another area that requires more attention is ship performance in a seaway. Considerable attention has been given to developing hull forms for minimum resistance in calm water.

Now, attention must be given to hull forms that have minimum performance degradation in heavy seas, e.g. minimum added resistance in waves.

Improvements in ship structural design can also contribute to the reduction of CO_2 emissions from ships. Among the areas that are being considered are :

- Better materials of higher strength-weight ratio and minimum corrosion in marine conditions.
- Optimization of hull structure for minimum weight.
- Optimum distribution of hull weight to obtain favourable trims in different operating conditions.

5.Marine Machinery And Systems Design

A significant reduction in CO_2 emissions from ships can be achieved through improvements in the design of marine machinery and systems, and considerable work has been carried out and is in progress to make ship machinery and systems more efficient. Some of the important areas are :

- Main engines, mainly large, low speed diesel engines : Apart from changes to minimize NOx formation and reduce specific fuel consumption through improvements in cylinder and piston design, improvements in the fuel injection system and more efficient turbo-chargers, perhaps the most significant change has been the replacement of some mechanical components by hydraulic and electronic components ("mechatronics") with computer control, resulting in engines that can optimize their performance automatically in a wide range of operating conditions as well as protect themselves when something goes wrong. Among the parameters that can be controlled are fuel injection timing, amount and profile and exhaust valve actuation. This allows the engine to run with optimum efficiency over a wide range of powers and rpms. This is particularly important in modern times when a ship may be required to operate at lower speeds than the design speed for prolonged periods.
- Variable turbine geometry turbo-chargers have been developed that allow the scavenge air pressure to be increased at part loads and continuously controlled. This is not possible with conventional turbo-chargers. Variable geometry turbo-chargers are particularly useful today when many ships

operate at lower than design speeds. Such turbo-chargers also reduce smoke and soot at part loads and improve the acceleration characteristics of the engine.

- Another approach that is being adopted for part load operation is to cut out a turbo-charger in installations with multiple turbo-chargers. This approach is said to be more efficient than part load operation under computer control in "intelligent" engines. Turning a turbo-charger off and closing a throttle allows the speed, fuel consumption and CO_2 emissions to be reduced in an efficient manner. This method was tried out in the 8000 TEU *Maersk Salalah* which has an MAN-B&W 12K98ME engine rated at 68650 kW at 104 rpm [6]. The ship speed was reduced from 24 k to 22 k, the power dropped from 77 per cent of MCR to 56 per cent and the CO_2 was reduced by 28 per cent.
- Waste heat recovery systems : Significant improvements in energy efficiency can be achieved by making use of the heat that would otherwise be lost in the exhaust gases from the main engine and auxiliary engines. Some of the exhaust gases from the main engine are made to by-pass the turbo-chargers and used to produce steam in an exhaust gas boiler for a steam turbine to produce additional power. Alternatively, the exhaust gases are used to drive a gas turbine to produce power. A diesel engine with a "power recovery turbine" can have an efficiency of just over 60 per cent. The exhaust gases after producing steam in the boiler are used to heat the boiler feed water, and then added to the scavenge air for heating and exhaust gas recirculation. Heat from the jacket cooling water may also be used to heat boiler feed water and the scavenge air. Waste heat from the main engine (exhaust gases and cooling water) may also be used to provide heat to the cargo tanks, fuel oil tanks and accommodation spaces, so that the auxiliary boiler need not be operated when the main engine is running . In one case, 8 t of fuel corresponding to 24 t of CO_2 was saved by adopting such a waste heat recovery system. It is, of course, necessary to provide new piping, heat exchangers and pumps, and the pipes have to be insulated. Heat from auxiliary engines may be similarly recovered.
- Engine cooling and lubricating systems : Considerable improvements in the efficiency of these systems are possible using appropriate computer software.

Bigger coolers with larger pressure drops across them allow smaller pumps to be used resulting in a reduction in CO_2 emissions. In one case, it is claimed that this allowed a 90 per cent saving in the energy used by the pumps resulting in a reduction of 160 t of CO_2 per year. Similarly, the proper choice of pump type and size resulted in CO_2 emissions being reduced by 110 t per year. Another approach to improve the efficiency of engine cooling systems is to use variable speed drives for the pumps. Pumps driven at constant speed use more energy than necessary and require complex hydraulic circuits to ensure the correct amount of cooling. Variable speed pump drives eliminate the need for complex hydraulic circuits and offer a large saving in energy. A cooling system with variable speed pump drives requires smart control algorithms with fault tolerant robust control and self-optimization. Such a system installed on the 7000 TEU *Gudrun Maersk* resulted in the saving of 235 t of fuel per year, corresponding to 731 t of CO_2 [6].

- Gas turbines : When gas turbines are used for ship propulsion, their efficiency can be increased by adopting refinements such as recuperation, reheat and intercooling, but at the cost of increased weight and space. These refinements have not been generally adopted in gas turbines for ship propulsion till now, but may require consideration for limiting CO_2 emissions. Gas turbines are often used for ship propulsion in combination with other types of engines such as diesel engines and steam turbines and even other gas turbines, usually in combination with electric propulsion. Multiple engines for propulsion allow the engines to operate under near optimum conditions over a wide range of power by cutting off one or more engines from the system when the power demand is low and can be met by the remaining engines operating at their design power. The addition or removal of engines in a multiple engine installation can be computer controlled for optimum performance.
- Electric propulsion : Among the many advantages of electric propulsion are the ability to use multiple engines of different types efficiently and the ability of electric propulsion motors to provide a wide range of torque and rpm in both directions efficiently, thereby eliminating the need for controllable pitch propellers. There is, however, the disadvantage of losses in the energy

conversions that are involved. In ships that have a large energy requirement for purposes other than propulsion, it is advantageous to adopt the "power station concept" in which electrical power is generated centrally and distributed to the different consumers including propulsion. The total system can be made highly efficient even when the power demand varies widely and the overall CO_2 emissions from the ship can be reduced.

- Other ship systems : Attempts to reduce CO_2 emissions are also being made by examining other ship systems such as heating, ventilation and air conditioning, lighting, navigation systems, steering gear and cargo handling systems to see if there is scope for reducing their energy consumption by increasing efficiency or other means.

6. Alternative Fuels, Energy Sources And Technologies

Liquid fossil fuels are used in most ships, but the need to minimize emissions of all kinds and to use renewable sources of energy have led to a search for alternatives such as :

- Liquefied natural gas (LNG) : LNG has been used for many years as a fuel for the propulsion of LNG tankers using steam propulsion plant as this is the most effective way to deal with the boil-off gas except in the largest LNG tankers. As a fuel, natural gas has many advantages over conventional liquid fuels – more energy per unit mass, lower CO_2 emissions per unit of energy, negligible other emissions, a density lower than air and a high auto-ignition temperature. Therefore, the use of LNG as a fuel in ships of other types is growing, despite the need for liquefying the gas and the difficulty of doing so.
- Bio-fuels : Bio-fuels are fuels obtained from agricultural produce. Various types of bio-fuels are being considered for use in ships – biodiesel and di-methyl ether (DME) to replace marine diesel oil (MDO) and marine gas oil (MGO), straight vegetable oil (SVO) to replace heavy fuel oil (HFO), bio-methane for use in gas engines and bio-ethanol for use in high speed engines. Bio-fuels obtained from algae in the sea are also considered promising. A blend of 20 per cent bio-diesel with MDO/MGO is often recommended, but 100 per cent biodiesel is being used on some vessels operating on the Great Lakes [7]. With bio-fuels, harmful

emissions decrease, oil spills are less damaging, engine performance and life are improved, maintenance is reduced because of the cleaning properties of bio-fuels, and there are less dangerous substances and offensive odours. On the other hand, bio-fuels have a lower energy content per unit mass and a lower mass density, so that the amount of bio-fuel required to be carried is more than the amount of petroleum fuel. The burning of bio-fuel also produces CO_2 in an amount comparable to that produced from conventional fuels, but it is argued that the CO_2 produced from bio-fuels does not cause an increase in the amount of CO_2 in the atmosphere because it was captured from the atmosphere for growing the agricultural crop.

- Fuel cells : Fuel cells may be used as a source of power in addition to the mechanical power generation equipment in a ship. In a fuel cell, the fuel is converted into energy not by combustion but by an electro-chemical process. There are many types of fuel cells such as the proton exchange membrane or polymer electrolyte membrane (PEM) fuel cell, the solid oxide (SO) fuel cell and the molten carbonate (MC) fuel cell. The fuel ideally is hydrogen, but methane, propane and butane may used with a reformer inside the fuel cell to convert these fuels into hydrogen. Methanol, ethanol and even diesel oil may be used as fuels, but in that case a reformer outside the cell is required. If hydrogen is used as the fuel, the only waste product is water; if a hydrocarbon is used as the fuel, water and CO_2 are the waste products. A fuel cell produces a limited amount of voltage and current, and it is necessary to stack fuel cells in series to get high voltage and in series to get high currents. The efficiency of a fuel cell is comparable to that of a diesel engine, but the space and weight required are considerably higher. The first ship to be fitted with fuel cells is the *Viking Lady*, a 5900 t supply vessel with an LNG fueled gas engine electric propulsion plant, which has 320 kW molten carbonate fuel cell.
- Wind energy : Wind energy may be used in various ways to assist the main propulsion plant in a ship – soft sails, rigid aerofoils or “wingsails”, rotating cylinders (Flettner rotors), kites and wind turbines. Soft sails are

widely used in traditional sailing vessels, but may be used in modern ships with technology that has been developed for the operation of sails without additional crew. Rigid sails can be computer controlled to give the best propulsion performance in the prevailing wind conditions (relative wind speed and direction) including feathering or folding when the wind is not favourable and automatically reducing engine power when the wind thrust increases. Flettner rotors were first used for wind-assisted ship propulsion in the 1920s and have been now revived as the need for reducing fuel consumption and CO_2 emissions has become more important. A recently built rotor ship is the 10500 dwt *E-Ship 1* that entered service in 2010. This ship has two propellers each driven by a 3500 kW diesel engine and an exhaust gas boiler and turbo-generator system to drive four deck mounted rotors 27 m tall and 4 m in diameter. A kite as used for ship propulsion is a sail flying high in the sky where the wind speed is much higher than at the surface, the kite being attached to the ship by a tow rope. A ship with kite assisted propulsion is the 140 m multipurpose heavy cargo vessel, *Beluga* Skysails. Wind turbines for wind assisted ship propulsion are mounted on the deck, and may have horizontal or vertical axes.

- Solar energy : Energy obtained from solar cells on the deck will reduce fuel consumption and CO_2 emissions. NYK's car carrier *Auriga Leader* (18700 t deadweight, 6200 cars) has solar cells mounted on rigid sails on deck to obtain wind and solar energy simultaneously. The 328 solar cells produce 40 kW power.
- Nuclear energy : Nuclear energy is used in some warships and has been used in a small number of non-military vessels. Nuclear energy has several advantages including zero air pollution, but the cost, weight and complexity of the system and the catastrophic consequences of an accident are deterrents to the use of nuclear energy in ships.
- Battery power : If energy can be produced much more cheaply and cleanly on land than on a ship, one may consider using power from storage batteries carried on board ships.

- Magnetohydrodynamic (MHD) propulsion : MHD is an alternative technology for ship propulsion that has been tried out, e.g. the ship Yamoto I built by Mitsubishi in 1991, but has so far not been successful compared to conventional methods of ship propulsion.
- Superconducting motors : Electrical equipment with "high temperature superconductors" (HTS) which have a very low electrical resistance is an alternative technology that appears to be promising. The U.S. Navy has been at the forefront in developing superconducting motors for ship propulsion and has successfully tested a 36.5 MW superconducting motor intended for use in aircraft carriers.

7. Energy Efficiency Design Index

Concern for global warming and climate change led the International Maritime Organization (IMO) to cooperate with the United Nations Framework Convention on Climate Change (UNFCCC) to develop measures to control greenhouse gas (GHG) emissions from international shipping through the (a) establishment of a GHG emission baseline, (b) development of a methodology to develop a GHG emission index, (c) development of guidelines for applying the GHG emission index and (d) evaluation of technical, operational and market-based solutions. The Marine Environment Protection Committee (MEPC) of IMO has developed rules, regulations and guidelines in this regard [8]. A new Chapter 4 has been added to MARPOL Annex VI, and this is expected to enter into force on 1st January 2013.

The technical means to reduce GHG emissions (CO_2 emissions) are measures to be taken during the design and construction of a ship and involve an attained "Energy Efficiency Design Index" (EEDI) that must be below a specified baseline. EEDI will apply to all new ships over 400 gross tons but is not applicable at present to ships with diesel-electric, turbine or hybrid propulsion systems. A simplified definition of EEDI is :

$$\text{EEDI}\left(\frac{\text{grams}}{\text{tonne-nautical mile}}\right)=\frac{\text{Fuel Consumption}\left(\frac{\text{grams}}{\text{hour}}\right)\times\text{Carbon Emission Conversion Factor}}{\text{Carrying Capacity}\left(\text{tonnes}\right)\times\text{Ship Speed}\left(\text{knots}\right)}$$

The actual formula for EEDI is much more complicated.

It is necessary to consider all the engines that consume fuel and to take into account power take-offs and power take-ins. Different engines may consume different fuels, and each fuel has its own carbon emission factor. The fuel consumption in g/hr is equal to the power in kW multiplied by the specific fuel consumption in g/kW hr. For main engines, the power is taken as 75 per cent of the maximum continuous rating (MCR). The specific fuel consumption must be corrected to a standard heating value. The power of the auxiliary engines for use in the formula is to be calculated from the power of the main engine(s). There are corrections for the use of "innovative mechanical energy efficient technology". There is also a factor for the availability of each energy efficient technology. The power of the main and auxiliary engines must be corrected for ship specific design elements.

The carbon emission conversion factor C_F is the ratio of the mass of CO_2 generated to the mass of fuel consumed and depends on the type of fuel as given in Table 7.

Fuel	**Reference**	**Carbon Content**	**C_F t-CO_2 / t-fuel**
Diesel/Gas Oil	ISO8217 DMX to DMC	0.8744	3.206
Light Fuel Oil	ISO8217 RMA to RMD	0.8594	3.151
Heavy Fuel Oil	ISO8217	0.8493	3.114
LPG	Propane Butane	0.8182	3.000
LNG		0.7500	2.750

Table 7:Carbon Emission Conversion Factor

The carrying capacity is deadweight in tonnes for most ships and gross tonnage for passenger ships and ro-pax vessels. For container ships, the carrying capacity for use in the EEDI formula is 70 per cent of the deadweight. There is a correction factor to be applied for any regulatory or technical limitation on carrying capacity, e.g. ice class. There is also a cubic capacity correction factor for certain ship types such as chemical tankers and LNG tankers with direct drive diesel propulsion plant.

The ship speed in knots is the speed in deep water at a draught corresponding to the summer load line at 75 per cent MCR of the main engine(s) in calm water (no wind, no waves). There is a correction factor speed loss in waves.

The Energy Efficiency Design Index is to be determined at the ship design stage using data obtained from model experiments and engine and equipment manufacturers. The value of EEDI is then to be verified during the sea trials of the ship.

The "attained" EEDI must not be more than the "required" EEDI. There are different base lines for the required EEDI for different types of ships, viz. passenger ships, ro-ro passenger ships, ro-ro ships (divided into vehicle carriers, volume carriers and weight carriers), bulk carriers, gas carriers, tankers, container ships, general cargo ships, refrigerated cargo carriers, and combination carriers. These base lines are given by a formula of the type :

Base line value = $a \times b^{-c}$

The values of *a* and *c* are given for the different ship types (except passenger ships and ro-ro ships of all types) in Table 8, *b* being the deadweight in tonnes.

Ship Type	*a*	*c*
Bulk carrier	961.79	0.477
Gas carrier	1120.00	0.456
Tanker	1218.80	0.488
Container ship	174.20	0.201
General cargo ship	107.48	0.216
Refrigerated cargo carrier	227.01	0.244
Combination carrier	1219.00	0.488

Table 8:Reference Values of Required EEDI

$$Base\ line\ value = a \times b^{-c}$$

The values of the required EEDI calculated from Table 8 are for Phase 0, which is from 1st January 2013 to 31st December 2014. These values are to be reduced by 10 per cent in Phase 1 (1st January 2015 to 31st December 2019), a further 10 per cent in Phase 2 (1st

January 2020 to 31st December 2024) and a further 10 per cent in Phase 3 (1st January 2025 onwards).

Ships complying with the EEDI requirements will receive an International Energy Efficiency Certificate.

8. Ship Operation

Reduction in CO_2 emissions requires not only improvements in ship and marine engineering design but also improvements in ship operation. Among the methods by which ship operation can contribute to the reduction of CO_2 emissions are :

- Reduced speed operation : For a voyage of a given length, the fuel consumption is approximately proportional to the square of the speed, so that reducing speed is a very effective way of reducing fuel consumption and the resulting CO_2 emissions. However, unduly low speeds may result in problems such as vibration, soot and smoke. There may also be limitations due to charter agreements. The operation of an engine at powers lower than the design power may cause problems with the permitted level of NOx emissions.
- Improved voyage planning and fleet management : The voyages of a ship can be planned so that the fuel consumed for a given amount of transportation is minimized by the optimum sequencing of ports of call, for example. With improved fleet management, it should be possible to avoid or minimize long ballast voyages.
- Just in time arrival : The speed of a ship on a voyage should be so adjusted that the ship arrives at the destination port just in time for a berth to be available. This requires good communication between the ship and the port.
- Slow changes in ship speed : Important economies in fuel consumption can be achieved by making only gradual changes in ship speed when leaving or entering harbours.
- Constant engine rpm : Avoiding frequent changes in engine rpm manually to ensure a particular ship speed improves fuel economy. Alternatively, an automated engine management system may be used.

- Route optimization : The route followed by a ship must be optimized for minimum fuel consumption taking into account the weather, shallow water and adverse currents on the route. Computer programs are available which use accurate information on sea currents, weather and shallow water areas along with a mathematical model of the ship's propulsion system to determine the most fuel efficient route between two ports at a given time. Up-to-date weather forecasts are obtained, currents due to tides and wind are calculated, shallow water stretches along the route are determined from a detailed bathymetric model and the mathematical model of the ship takes into account resistance components in a seaway, propeller characteristics, effects of wind, waves, currents and shallow water and fuel consumption. The computer program receives updated weather forecasts at the start of the voyage and several alternative routes are evaluated with respect to safe navigation and fuel consumption, and a route is selected. Continuous re-calculation for the remaining part of the voyage is carried out to guide the navigator and the actual route is tracked through a global positioning system.
- Optimum trim : The optimum trim of a ship is a function of the speed and displacement. The optimum trim may change continuously during the voyage. A computer based tool is available that calculates the optimum trim for a ship based on model tests. However, design and safety factors may limit the trim that can be used.
- Optimum ballast : Water ballast distribution in the ship affect trim and this may affect steering and auto-pilot settings. Optimum ballast distribution may be achieved by good cargo planning, but may be limited by the ballast water management plan of the ship.
- Hull maintenance : Proper hull and propeller maintenance by in-water inspections, correct dry-docking intervals, ensuring a smooth hull by timely replacement of underwater coating systems and the use of modern coating systems, and periodic propeller cleaning and polishing are important for energy efficient ship operation.
- Machinery operation and maintenance : Operation of the machinery and scheduled maintenance according to the manufacturer's instructions, the

use of engine condition monitoring systems, fuel additives, adjustment of cylinder lubrication according to operating conditions and fuel quality and similar measures ensure that the machinery in the ship works at the highest efficiency, consumes minimum fuel and has minimum emissions. Many of these measures are programmed into the operation of "intelligent" engines.

- Shore power in port : The use of electric power from the shore instead of power from the ship's own generators when in port also reduces pollution by the ship.
- Continuous and automatic engine tuning : Manual tuning of engines can only be carried out at intervals and can only ensure that the engine runs between recommended operating limits. Automatic tuning continuously tunes the engine for optimum performance based on on-line measurements of cylinder pressures and temperatures, comparison with reference values and automatic adjustment of fuel injection to minimize deviations between the measured and the reference values. Apart from minimizing fuel consumption and CO_2 emissions, automatic tuning reduces maintenance and minimizes risk of damage.
- Mathematical modeling : The machinery system in a ship is very complex and has many inter-connected elements that mutually influence each other. An advanced mathematical model has been developed in which all the relevant parameters are measured and recorded, special sensors being used if necessary. The data are then fed into software which analyzes and correlates the data to determine the combination of parameters that give the optimum performance.

9. Energy Efficiency Management In Ship Operation

In addition to designing energy efficient ships that minimize CO_2 emissions, it is necessary to operate ships in an energy efficient manner. For this, it is necessary to have a parameter to measure the energy efficiency of a ship in operation and to have a system by which this energy efficiency is continuously improved. Two measures have been introduced by IMO in this regard [8].

The first measure is the Energy Efficiency Operational Indicator, EEOI, which indicates how efficiently the operation of a ship is managed in terms of minimizing CO_2 emissions.

$$EEOI = \frac{\text{Fuel consumption on a voyage} \times \text{Carbon emission conversion factor}}{\text{Capacity} \times \text{Voyage distance}}$$

The different types of fuel consumed must be considered since each fuel has a different carbon emission conversion factor (Table 7). The capacity may be expressed in terms of the cargo carried in tonnes, or the number of containers in TEUs, or the number of passengers. For passenger ships, one may also use gross tonnage as a measure of capacity. Depending upon the units for the different terms involved, EEOI may have units such as grams CO_2 per tonne-nautical mile or tonnes CO_2 per TEU-nautical mile etc. EEOI is calculated for each voyage and an average EEOI for a suitable time period or number of voyages (six to ten) is determined. A rolling average is maintained as the ship continues to operate, and this gives an indication whether the energy efficiency of the ship is increasing or decreasing over time.

The second measure is the Ship Energy Efficiency Management Plan (SEEMP), which will be mandatory for all ships of 400 GT and more from 2013. The main features of SEEMP are :

- SEEMP is a ship specific document but linked to the shipping company.
- The aim of SEEMP is to improve the ship's energy efficiency and involves four steps – planning, implementation, monitoring and self-evaluation.
- Planning starts with determining the current status of energy usage in the ship, identifying areas for possible improvement and drawing up an effective plan for implementation. The shipping company must have an energy management plan, but this may involve other stakeholders such as ports, charterers, cargo owners and ship repairers. The plan must include human resource development involving creating awareness of and providing training in efficient energy management. Finally, there must be internal goals to be achieved during the plan period such as a target value of annual fuel consumption or EEOI.

- Implementation involves executing the planned measures, assigning tasks and identifying the persons responsible, and keeping records for later self-evaluation.

- Monitoring requires a continuous assessment of energy efficiency by the EEOI rolling average or some other means. Consistent and continuous collection of data must be carried out, preferably by the shore staff from records and log-books maintained in the ship.
- Self-evaluation measures the effectiveness of the plan, identifies measures that were unsuccessful and the measures to be adopted in subsequent plans. Self-evaluation requires procedures for assessing improvements in energy efficiency management.

10.Miscellaneous Considerations

Apart from ship design, ship machinery and ship operation, there are many other areas which affect energy efficiency in ships directly or indirectly. Three such areas are described briefly in the following.

Underwater hull paints that give a very smooth surface, prevent bio-fouling and maintain hull smoothness for a long time can reduce the resistance of the ship and lead to significant fuel savings over a period of time. Self-polishing co-polymer coatings have these features but contain powerful biocides that permanently harm marine organisms. Modern anti-fouling coatings based on silicone do not contain biocides such as TBT or copper oxide. The main feature of these paints is a hydrogel consisting of a network of polymer chains insoluble in water that provides an invisible barrier which prevents organisms from attaching themselves to the hull. These new anti-fouling paints can contribute to reducing CO_2 emissions up to 5 per cent.

A system has been developed that can analyze fuel oil, lubricating oil and exhaust gases automatically on the ship, enabling the engineers on board to optimize fuel oil treatment and cylinder lubrication, thereby reducing operating costs and minimizing emissions.

A group of shipping companies, marine equipment manufacturers and educational institutions believe that "without a green consciousness, there can be no Green Ship and no quality shipping." The focus is on the education and training of the next generation of engineers and ship operators so that they automatically take the environment into account in all that they do. While obtaining their professional degrees, students undergo training on board a ship and are continuously exposed to environmental concerns, collecting relevant data for research or product development. The combination of theory and practice enables these students to gain an insight into research, equips them to apply the results of research in industry effectively and to contribute to further development. Collaboration between industry and the university helps these students to become the "world's best maritime leaders".

11. Research And Development

That the various measures that have been adopted for decreasing pollution from ships described earlier are the result of research and development is obvious. However, it is necessary to understand how this research and development has come about. The following two examples are illustrative.

Lloyd's Register China and Bestway Marine Engineering Design, a leading marine design group in China, have signed a memorandum of understanding to collaborate on jointly developing a new fuel-efficient bulk carrier incorporating some of the methods described in the earlier sections [9]. The work will be in two parts : (i) research in measures to increase energy efficiency, and (ii) technical approval and implementation of the proposed solutions. This project is part of the initiatives being taken by Lloyd's Register Strategic Research Group.

The Danish Maritime Cluster has adopted the aim to make the green ship a reality [6]. The Danish Maritime Cluster consists of the leading maritime companies in Denmark such as Aalborg Industries, A.P. Moller-Maersk, Hempel Paints, MAN Diesel and Odense Steel Shipyard, as well as companies from neighbouring countries such as Finland. There are also research institutions such as Force Technology and educational institutions such as the Denmark Technical University. The primary object of this Cluster is to develop and demonstrate green technologies in shipping and shipbuilding, reducing CO_2 emissions by 30 per cent and SOx and NOx emissions by 90 per cent for both new and existing ships. Many of the methods described earlier for creating environmentally friendly ships have in fact been developed by companies in the Danish Maritime Cluster working in close collaboration.

Many of the measures for increasing the energy efficiency of ships and reducing their emissions have been described in References [6, 9, 10, 11, 12, 13].

12.Conclusion

The importance of preventing pollution from ships has long been realized. The current focus is on CO_2 emissions, which are difficult to reduce so long as energy is produced from the burning of fuels. CO_2 emissions may be reduced by increasing the energy efficiency of ships, but the goal of producing energy efficient ships has been pursued for a long time and measures such as improving hull forms or designing better engines are unlikely to produce striking improvements. It is also important to ensure that reduction of pollution from ships is not obtained at the cost of worse pollution elsewhere. Innovative technologies will therefore be required to meet the goal of reducing CO_2 emissions from ships by 30 per cent in the next 10-15 years.

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