1997

Engineering triggers for the development of design and evolution of marine propulsion systems

Daniel Hurmingson Dickson Maikalanga
WMU

WORLD MARITIME UNIVERSITY

Malmö, Sweden

ENGINEERING TRIGGERS FOR THE DEVELOPMENT OF DESIGN AND EVOLUTION OF MARINE PROPULSION SYSTEMS

by

DANIEL HURMINGSON DICKSON MAIKALANGA

Malawi

A dissertation submitted to the *WORLD MARITIME UNIVERSITY* in partial

fulfilment of the requirements for the award of the degree of

MASTER OF SCIENCE

in

MARITIME EDUCATION AND TRAINING

(Engineering)

1997

Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me. The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

....

Daniel H.D. MAIKALANGA

10th October 1997

Supervised by

....

Name : **Takeshi NAKAZAWA**

Office: *Associate Professor (MET-E)*

World Maritime University

Assessed by

....

Name:.....................................Eiichi NISHIKAWA

Office: .... *Visiting Professor - World Maritime University*

Institution/organisation: Kobe University of Mercantile Marine - Japan

Co- assessed by

....

Name: ....Patrick M. ALDERTON

Office: ....*Retired Professor - World Maritime University*

Institution/organisation: Residence - United Kingdom

DEDICATION

Dedicated to my wife Joanna and daughter Mwadala.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to IMO organisation for funding the scholarship making my study possible at the World Maritime University.

Special thanks go to Associate Professor Takeshi Nakazawa, for supervising, proof reading through, this document during the time of its inception.

Many thanks go to Professor P. Muirhead Course Professor for MET, and all the staff of WMU for the guidance and support they rendered while I was pursuing this course.

My gratitude are also to all individuals and organisations that helped me in one way or another during my study and stay at WMU in Sweden.

Lastly I'm deeply indebted to my wife, Joanna for being patient, supportive and kindly typing this work when it was still in its infant stage.

ABSTRACT

This study looks into the history of development of Marine Propulsion systems. It is set to determine and analyse the engineering triggers that made it possible for the evolution and development of propulsion systems. In the last 200 years, propulsion machinery systems have undergone several technological changes. Demand for more efficient modes of transport and requirement for larger sizes of vessels for cargo, have led to development of faster and more reliable ships. In order to meet these demands, Naval architects and shipbuilders, together with engine manufacturers have worked hard at designing and improving the propulsion systems. When the first marine steam engine was built and put into service, it had a big impact on the shipping industry as a whole. This resulted in more experiments and changes in the powering of ships.

In this dissertation, factors that affected these changes have been identified. The development of the diesel engine as a dominant technology of today's ship propulsion has been studied These elements constitute a change in time and have forced a progression of development in the overall ship technology and the concept of propulsion. It is seen that steam engine ships were popular until early this century. At the moment in time, the diesel engine has completely taken over.

Lastly, it is well known that most cargo is transported over long distances by and on ships. With the discovery of more trading areas and more cargo to be transported, demand for more efficient and reliable ships increased. This led to several successful changes and developments in the field of propulsion machinery, port and cargo handling facilities, shipbuilding and economics of trade. Several changes have occurred, from paddle wheels to screw propulsion, from steam engines to diesel engines, resulting in more cost effective and efficient propulsion systems as demanded.

CONTENTS page

LIST OF TABLES

LIST OF FIGURES. *page*

LIST OF ABBREVIATIONS

AD	Anno Domini
BC	Before Christ
BDC	Bottom Dead Centre
BHP	Brake Horse Power
IMO	International Maritime Organisation
MEP	Mean Effective Pressure
MET	Maritime Education and Training
MIP	Indicated Mean Pressure
MV	Motor Vessel
NHP	Nominal Horse Power
NO_X	Nitrogen Oxide, (NO_2 and NO_3)
SI	Systemé Internationalé
SS	Steam Ship
TDC	Top Dead Centre
USA	United States of America
VLCC	Very Large Crude Carriers

SYMBOLS and TERMS

ft	foot, feet
hp	horse power
in	inch, inches
kg	kilogram
kW	kilo Watt
m	metre
mi	mile
psi	pounds per square inch
rpm	revolutions per minute
η	Efficiency

CONVERSIONS USED

Imperial	Unit	SI Standards
1 psi	lb. f/in^2	= $6.895 * 10^3$ Pa
1 horse power	hp	= $7.457 * 10^2$ W
		= 0.7457 kW
1 standard atmosphere	atm	= $1.01325 * 10^5$ Pa
1 pound mass	lb.	= 0.454 Kg
1 ton	ton	= 1.016 * 103 Kg
		= 1.016 tonne
1 inch	in	= $2.54 * 10^{-2}$ m
1 foot	ft	= 0.3048 m
1 mile	mi.	= $1.609 * 10^3$ m
area	1 in^2	= $1.638 * 10^{-5}$ m^2

CHAPTER ONE

INTRODUCTION

1.1 Introduction

The economical environment for propulsion systems consists of a considerable number of factors. The dynamics and relative importance of such factors vary considerably with time. Some of the factors are sighted below as:

a) technical developments of the ship and propulsion systems

b) service demands and profile of ships in various trade routes

   - flexibility of operation in various freight market and interaction between load and ship
   - availability, quality and price of energy

c) economically oriented, thus the development of the sea borne trade

d) improvement of transport systems

   - increase of fleet and
   - developments in the new-building requirements

e) sociological and educational aspects of sea going personnel and the interface between man and machinery.

Looking at ship propulsion machinery, one sees a tremendous improvement than what was there 200 years ago. Development of sea transport and world trade over the past century can be followed closely with intriguing results. When it started, it was developing through human power, sail and wind. Eventually steam and the paddle wheel were being invented by the late 18th century, followed by modern propulsion systems of compression/heat engines and the screw propeller.

The factors and elements that caused these technological and historic changes, form the basis of this dissertation and they shall be considered. It is of popular belief that as the world history changed, thus discovery of the Americas and colonies in the late 17th century and discovery of the route to the East by Vasco Da Gama, laid out the first real *Maritime Sea Trade.*

Trading Colonies and Empires were established by the British and other European countries in search of new land for settlement in the case of Canada, South America and Australia in the Far East. Also, commodities were highly sought after, especially spices, tea and gold discoveries. With all the opportunities emerging, the countries started trading with these far lands. Desire and requirement for quick turn around time emerged. Larger sailing ships were required to carry more cargo and supplies. Another phenomenon that came with trade that could be defined as greed was war. The war introduced by the British through pilating when they were attacking the Spanish, (which resulted in Spanish Armada war), prompted introduction of legislation and protectionist laws. To fulfil these quests for speed, cargo capacity and monopolistic ideas, competition for the development of the maritime vessel started.

The competition was being led by the Americas, followed by the British, then, the rest of the world joined in by late 18th century. It is seen that the development of maritime craft shifted from wooden ships propelled by wind/sail arrangement to that of iron ships being propelled by Steam Engines, eventually, Diesel Engines and the screw propeller, then Turbines entered to change the fate of the steam engine. Other forms of propulsion systems had emerged but the dominant technologies were those of the steam engine and paddle wheel arrangement, these being dominant in the 19th century and the diesel engine and screw propeller being dominant in the 20th century. Which is the dominant technology of the 21st century?

This dissertation attempts to answer this question. Supremacy and reliability of Diesel Engines installation will be challenged and seen if they can survive the arrival of the Gas Engines, and the screw propeller with water jet installations. Also Chemical/Nuclear sources of energy are a threat to the dominant Diesel technology.

Chapter Two discusses the historical nature of the steam engine and the problems associated with the early technologies as they were being introduced into the Maritime Trade. This discussion is continued in Chapter three when the diesel engine is introduced at the time of its inception. While knowingly that the diesel engine is the dominant technology of today shipping transport, the *pros'* and *cons'* of its survival are looked at in terms of its design factors and elements of its suitability as a prime mover. Historical development of Steam and Diesel propulsion systems installations are discussed in these Chapters Two and Three, with Economical and Social Triggers that resulted in Supply and Demand of World Sea-borne Trade. These are discussed in Chapter Four. Chapter five concentrates on the design factors of the dominant diesel engine installation, and its relationship with today's technology coupled with its existence in the future say the next 100 years. A concise and brief historical background of marine propulsion systems is given below, and it is within these context that the discussion to follow will centre. A conclusion is drawn based upon the areas found to be most effective on the changes. These have been grouped in the form of functions of energy for transport performance.

Some of the factors involved and looked at are:

- sea-borne trade and improvement of propulsion systems
- technical development of ships and their propulsion systems coupled
- with the sociological and educational aspects of sea-going engineers
- and the interface between them and machinery.

1.2 Historical Background Information

a) Propulsion Machinery Systems

At the end of the 19th century all ships had sails, thus they used wind for their propulsion. This tradition was popular particularly in the earliest part of the 18th century as the American ships became very popular in the crossing of the Atlantic Ocean. The former navigators also, had their ships propelled by wind. With the coming of steam, many experiment on board, became more popular as were done in the mining industry. Most people joined the race and other forms of propulsion were developed. The trend of technological development was as follows:

1. development of ships propelled by steam engines driving paddle wheels
2. development of the screw propeller to replace the paddle wheel driven by the steam engine
3. development of diesel engine to replace the steam engine
4. development of the steam turbine in order to achieve the higher rotative speeds.

Although, the above gives the developments in point form it is not a chronological representation of the actual developments. Different engineers or researchers were experimenting in different places, yet, at the same time. Some became successful while others failed, but the combined effort resulted in successful, and what is now the most popular form of propulsion ***'THE SCREW PROPELLER'***.

b) Crossing the Oceans with SAIL SHIPS (1800 - 1900's)

The merchant ships within this era were all constructed with sail rigs. The Maritime community and architects were used to this tradition of ship building. The drawback with the sail ships was that as the ships became larger, the sail area also, became larger and so did the handling equipment. Then, this became cumbersome and problems arose in reliability and maintainability of the sail and its equipment.

Therefore research into other forms of propulsion was encouraged in order to discover areas of reliability in order to move the ship efficiently and effectively.

c) Enter the 'PADDLE WHEELS.'

Paddles came onto the scene with the discovery of properties of steam and the developments in the Newcomen Engine. These were driven by the steam engine, and were largely made up of wooden spirals/planks riveted around a large wheel mounted on the sides of the ship. Initially the paddles were a series of oars, which were arranged around on a framework and worked by a mechanism to give them the to - and -fro movement. Obviously this was not very affective and the oars took up most the space in the engine room. The development of rotary paddles mounted on the side of vessel came as an improvement as it allowed larger and multiple engined cylinders to be used. Some of the early vessels had the paddles placed at the stern with the engine on deck, or 'quarter-wheels' (one on each side of stern), with the engine and boiler in the hold.

It should be noted that most of the ships were designed as sailing ships. The paddle and their engines were only for assistance if the wind failed. So it was common practice and knowledge that the engine wasn't run continuously. The only exception was a popular belief that, the paddle ships had to continue running their engines in a storm as it improved the ship's stability and sea keeping capabilities.

d) The ' SCREW PROPELLER.'

The screw propeller was not very well known in the first half of the ninetieth century. The first scientist seen to be popular with the propeller, was Colonel John Stevens - an American, who designed a screw driven ship in 1804. The race for this new innovation continued and several ships were fitted and driven by the screw propeller.

Problems associated with the screw propeller were:

- Rotational speed which was very slow due to low pressures from the boilers. In order to achieve high speed it required high pressure steam and this was achieved by 1860
- No propeller gearing equipment to upgrade the speed from that of low steam engine
- The absorbing of the propeller thrust into the ships hull 'thrust bloc' by then, was not yet developed
- With direct drive coupling the propeller shaft to the intermediate shaft resulted in transmission to the crankshaft bearing, resulting in overheating and problems of lubrication
- Finding a suitable means of providing an underwater fitting in the ships hull for the main shaft 'stern tube'. The solution was the development of the stern tube with lignum bush (material) in 1854

The success story of the screw propeller came in later years. Starting with the Archimedes experiments and Brunel adoption of the ideas, as employed on the Great Britain and the Great Eastern. The screw propeller had found its mark, and it was there to stay.

Other developments in the screw propeller were:

- fitting of twin screw propulsion
- gearing to adopt various speed requirements
- optimisation of number of blades and
- improvements of the underwater fitting arrangements

As the ship size increased, the size of the propeller became also larger, in order to absorb the new power requirements.

CHAPTER TWO

2 MARINE STEAM ENGINES

2.1 The First Marine Steam Engine

The first marine steam engine to be successfully employed was a steam engine installed on a cross Atlantic Liner the Great Western of the American Steamer Liners Corporation. The engine was developed by Brunel early in 1838. This engine was as a result of further development of the Newcomen engine which had shown success in the oil and coal mining industry and the locomotive trade. It operated on low boiler pressure of 5 psi with the engine developing 450 NHP (Nominal Horse Power). The concept was further developed to accommodate the use of propellers and the pioneer in this area was the SS Sirius. Brunel then saw the opportunity and ordered that they change the paddle driving arrangement to that of the up and coming screw propeller drive. Thus was born the *first marine engine* with screw propulsion fitted on a cross Atlantic Liner the *SS GREAT BRITAIN,* a 3, 600 gross tons cargo/passenger vessel.

> 'The engine was of vertical type cylinder arrangement with the crankshaft directly above the cylinder and driving a big wheel which further drove a small wheel driving the propeller shaft. This engine was built with four vertical cylinder arranged in vee - formation to facilitate fitting in the engine.'

Figure 2.1 illustrates and shows this fitting.

The basic dimensions were as follows:

Parts	Specifications	S.I. units
• No of cylinders	4	
• Diameter of cylinder	bore 88"	2.235 m
	stroke 72"	1.829 m
• Horse power per cylinder	1,600 hp	
• Engine speed	18 rpm	
• Boiler steam pressure	5 psi	$3.45 * 10^3$ Pa
• Gear ratio	2.95 : 1	
• Propeller revolution	53 rpm	

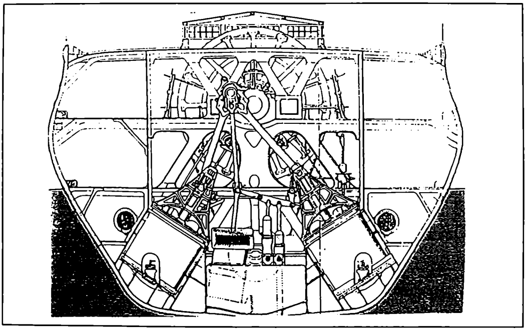


Figure 2 - 1: Steam Engine as installed in the Great Britain.

Source: Buchanaan, (1996) page 29

The life of the engine came to an abrupt stop when the ship the 'Great Britain' ran aground, on its maiden voyage. It got stranded in Dundrum Bay in Northern island in 1846. But the principle of screw propulsion was transferred to other vessels.

2.1.1 Basic Forms of Steam Engine Arrangement

1) Block Arrangement:

The first marine engine design had the following basic block layout:

A. The side lever arrangement which was popular for paddle wheel steamers.

B. The trunk engine which was chosen for its versatility due to introduction of the screw propeller, and lastly

C. The double cylinder side trunk layout.

The diagrams show the basic arrangements as they were perceived.

a) side lever arrangement

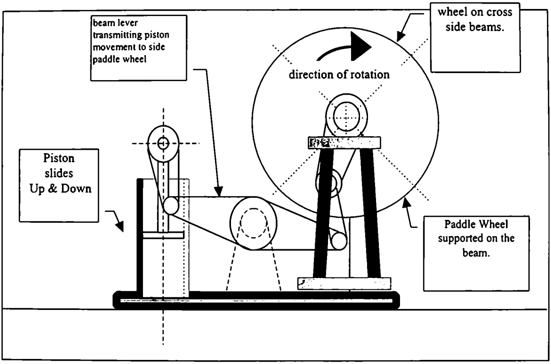


Figure 2 - 2: Side Lever Arrangement

Source: Buchanaan, (1996) page 29

This was reliable but a disadvantage was that it occupied a larger space and it was not light and compact.

b) trunk engine layout:

This had several layout arrangements but the main three arrangements are shown as :

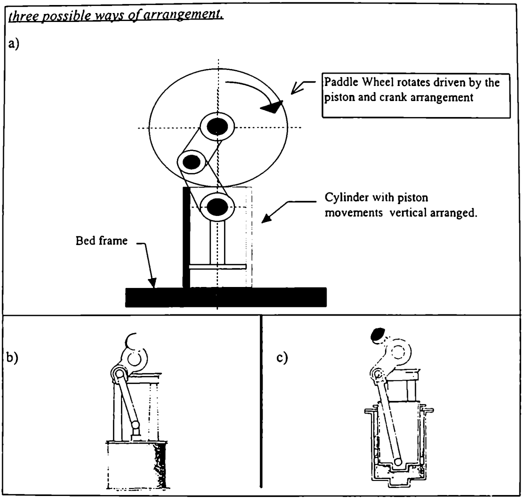


Figure 2 - 3: Trunk Overhead Layout

Source: Buchanaan, (1996), Pg. 29

This arrangement did away with the cumbersome side arrangement and the wheel was directly arranged on top of the cylinder directly driving the crank. This was possible for engines arranged astern of the vessel.

c) **double cylinder side trunk layout.**

This was another layout which did not become successful due to its cumbersome arrangement and weight of the parts. The crank for this arrangement is also shown showing the right angled connections in the figure .

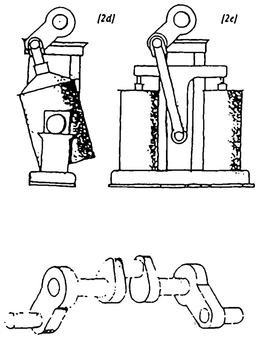


Figure 2 - 4: Double Cylinder Side Trunk Layout.

Source: Buchanaan, (1996), page 29

2.2 Marine Steam Engine (1800 - 1900's)

Marine steam engine of 1800's were of the reciprocating type. The actual historical engine details are scanty as most of the details were lost or were not properly recorded, but, most of the information can be found in various maritime museums where such information has been stored in the form of drawings, sketches and artistic impressions. , the table shows details of engines when and where, they were first used:

Table 2- 1: The First Steam Engines Employed in Marine Services (1780 - 1860)

Year	Vessel Name	Owner and Service Record
1787	unknown	Fitz (USA) - boat with oars driven by steam
1801	Dundas	W. Simington UK Charlotte
1807	R. Fulton	First steamships seen on Clyde
1812	Comet	Europe Commercial Ship Paddle wheel
1818	Rob Roy	90 ton boat powered by a 30 hp steam engine.
1819	The savannah	Auxiliary steamer crosses Atlantic
	The Vulcan	First iron steam engined craft registered with Lloyds Register
1837	Great Western & SS Sirius	Regular Trans-Atlantic ferries using paddle wheels for propulsion
1844	Great Britain	The first screw propelled ship to cross the Atlantic with a 1,000 horse power engine.
1858	Great Eastern	An improved version of the Great Britain fitted both with paddle wheels and screw propeller

All of these vessels were fitted with steam engines.

2.2.1 Increase in Ship Sizes and Types

Advancement and increase of ship sizes and ship types occurred in the first half of ninetieth century. The main reasons for the advancement and increase of the ships sizes and ships types were:

- Trans- Atlantic passenger traffic increase
- Technical expertise /superiority which was being served by the USA with fast sailing ships which had the technical ability and business ability to organise them better, hence requirement to compete with such established liners
- Requirement to carry large quantity of fuel required for long journeys and still have sufficient capacity for earning
- Simplicity of the two stroke bore engine to the steam engine. This resulted in low maintenance and low specific fuel oil consumption.

2.1.2 Problems of the First Engine

Problems with the first steam engine were :

- lack of compactness hence large engine room space was required.
- most materials used were heavy cast iron
- difficulties on the connection between piston and crank as technology on bearing materials and properties was still not yet discovered.
- problems on take off drive from the crankshaft - horizontal vertical motion transmission
- the air pump and means of driving it
- parallel motion arrangements and
- overall slow speed due to low boiler pressures.

2.3 The Birth of the Steam Engine

2.3.1 Savery Steam Pump

The story of the marine engine goes back 150 years. It is most attributed to the development of steam and its physical properties. The founder of the steam engine 'Thomas SAVERY, (1698), was the first to develop the first machinery (pump that worked continuously pumping water from a mine sump and delivering it from 80 feet (24.4 m).

Operation of the pump was by admitting steam to one side of the cylinder. The steam would force the water in the cylinder out through the discharge chamber. The steam would then be shut off. Upon condensation a vacuum would be created and water would enter the chamber through the valves from the well to replace the already discharged steam. Then, when the steam is admitted, the water would be forced out through the valve chest thus repeating the cycle. The other side of the cylinder is operated in the same way hence duplicating the amount of water discharged. Thus the arrangement is a double pump.

Setbacks of the pump was in its operation that it required an attendant to operate the steam valve with careful manipulation. The steam drums were very hot so the water level could not be judged correctly. Obviously the skills of the operator were required to:

i. determine length and duration of stroke for the most efficient delivery
ii. minimise the steam intake per stroke and
iii. ascertain the quantity of steam being discharged together with water.

The Savery Pump was extensively popular for use in the mines and was the most required tool sometimes known as the friend of the miner. Fuel consumption was about 30 lb. (13.6 kg) coal per hp).

The outline of the Savery's pump is given in figure 2-5:

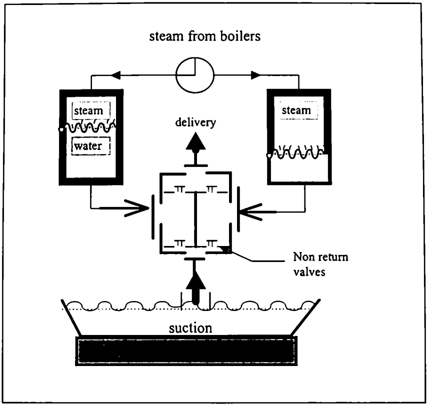


Figure 2 - 5: Thomas Savery Engine (1698)

Source: Guthrie, (1971), page 22

The diagram above shows the Savery pump arranged with twin cylinders for more water to be pumped. The steam is directed from the boiler through the two way valves into the cylinder. The diagram gives the position of the cylinder, the two way valves and the position of the non return valves in the valve chamber.

2.3.2 Newcomen Engine

Thomas Newcomen developed the Thomas SAVERY idea and built what was known as the fire engine in 1712 . This raised the depth of water to be pumped and, pump itself was made to be self acting. The depth of pumping water to the surface was increased from 80 feet to 500 feet (24m - 154 m) almost over 600 % increase. Despite the success achieved in the depth of the mines drawbacks still existed:

- It was operating on atmospheric boiler steam pressure which was too low
- working pressure had to be brought from cold loosing thermal heat in the process (solution was to condense the steam separately without cooling the main cylinder.)

The PICKLEPOT arrangement is shown the figure 2-6:

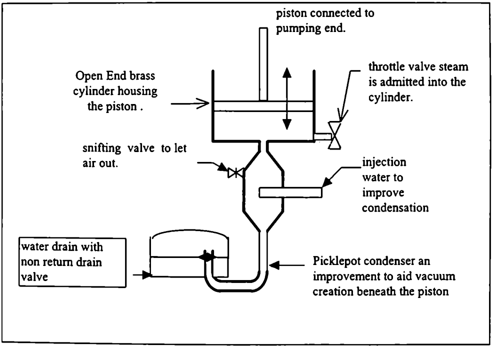


Figure 2 - 6: Picklepot Condenser for Newcomen Engine (Fire Engine)
Source: Guthrie, (1971), page 22

To achieve the above Newcomen developed the Thomas SAVERY idea and came up with the PICKLEPOT condenser in 1705 which became operational in 1712 as the Newcomen engine. This was achieved by having the steam and pump ends separately thus, the engine could operate at higher temperatures.

2.3.3 James Watt Engine

James watt studied the Newcomen engine and recognised the causes of high fuel consumption. He adopted the idea and made an improvement to the idea and developed what was known as the steam condenser engine which was introduced in 1765. Further development of the engine was a device called the 'PICKLEPOT' which was an opening into the main steam cylinder and draining into a non-return water trap. A snifting valve and a condensing spray cock were incorporated to let air be expelled through the valve and water drained on the working cycle. The PICKLEPOT was replaced later by the common jet condenser in around 1800.

Newcomen engines became successful with each improvement and one of the largest had the following dimensions and characters.

Cylinder	Description
• Bore diameter	82 inches (24 m)
• Stroke	11 feet (3.35 m)
• Weigh	6.5 tons (6.6 tonne)
• Number of condensing jets	3
• Mine depth	570 feet (174 m)

with 3 boilers to work with, and the most significant points were:

- the fuel used was un-sellable coal and free of maintenance,
- longest period of operation 1775 - 1931. 150 years.

Limitations and draw backs of the Newcomen engine, as discovered and improved by James Watt were:

- high fuel consumption, in which the cure was designing a separate condenser, air pump and lagged cylinder.
- use of steam in a cylinder to push the piston and
- create a vacuum underneath the piston.

The various developments continued and these led to what was known as the Cornish engine. The figure 2-7 illustrates the James Watt engine showing the steam admission and the position of the valves.

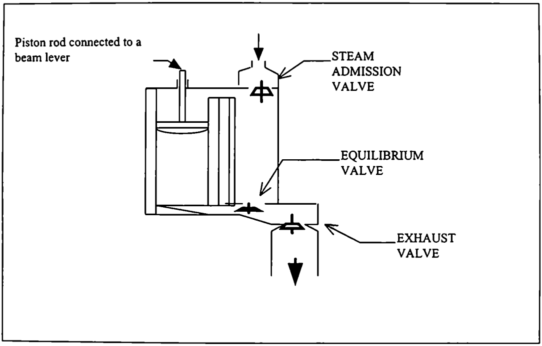


Figure 2 - 7: James Watt Engine Pumping Cylinder Arrangement.

Source: Guthrie, (1971), page 28

The success of the watt engine in mining industry led to the idea that such an engine could be used in other industries. Therefore the idea was adopted and in 1781 a single acting rotative beam engine was developed and in 1783 a double acting beam engine as an improvement of the same proto-type was developed. The crank arrangement was developed as an improvement to change the reciprocating motion of the piston to that of rotation for the crank and shaft 'crankshaft'.

Fitting The Watt Engine On The Ship.

The success story of the industrial engine meant that the ship owners also wanted to use the same idea on board the ship. This was done to replace the laborious work involved with the sails, and also trying to cut the time taken to sail on a voyage. Obviously, the main drawback of the engine was the cumbersome and crude, heavy parts of the beam and brick-wall furnaces and the boiler parts, so the engine could not be used as it was. Hence refinement had to be done in order to ascertain the fitting and use of such a structure on board the ship.

Another design, an adaptation of the same steam engine was developed. This was driving a piston inside a cylinder by steam and having the engine movement more direct drive and more of a compact shape. In such developments room for the cargo was of vital importance as it was already established that the purpose for the voyage was for transportation of cargo or people.

The marine engine experiments continued for a long time starting with the paddle ships, and settled with the screw propulsion. Comparison of power for the early engine was a question of guess work. So there was a tendency of accepting any value.

James Watt and Boulton patented their methods of calculating power as follows:

$$NHP = \frac{7 \times 128 \times \sqrt[3]{stroke \times Area}}{33{,}000} \quad (2.1)$$

or where the boiler pressure does not exceed 7 lb. f/in^2

$$NHP = \frac{\sqrt[3]{stroke \times diameter^2}}{60} \quad (2.2)$$

where

stroke is measured in feet and piston area in square inches

The Admiralty formula was more realistic as it accounted for the piston speed.;

$$NHP = \frac{speed \times area \times 7}{33{,}000} \quad (2.3)$$

speed means piston speed in feet per minute

and area means piston head area per square inches.

or simplified as

$$NHP = \frac{speed/\text{min.} \times dia^2}{600} \quad (2.4)$$

NHP is now seldom used but in the following years the following conversion factors were applied as shown in:

• 1820	NHP	=	IHP
• 1840	NHP	=	1/2 * IHP
• 1860	NHP * 3.5004	=	IHP
	1 IHP	=	750 Kilowatt

NHP stands for *Nominal Horse power* and IHP stands for *Indicated Horse Power.*

Some problems related to the above calculations were the fuel consumption. These massive engines were burning coal which was cumbersome and presented space problems in the ship. Fuel consumption was about 10 lb / IHP/hour of coal developing boiler pressure of 2 to 3 lb. f/in^2 This figure was very high for the ship owner hence efforts were undertaken to reduce the figure. It was not economical to carry so much coal on the ship. So to develop say 450 NHP the amount required fro consumption was about 4, 500 lb. of coal per hour or 108 tons (50 tonne approximately) coal per day. This was not definitely economical for the type of the ships. The situation improved as time went on well into the 20th century.

Another problem was the boiler itself. Not much was known then about safety. Therefore, there were several accidents happening due to boiler malfunctions caused by corrosion of tubes, too much thermal heat etc. the figure 2-8 shows relationship between boiler pressure and reduction of fuel consumption. That is to say, less fuel is consumed if the boiler is run at higher pressure. This prompted studies in boiler materials and thermal heat properties.

The graph shows a significant period in time when there was definite change in the development of the boiler pressure and consumption. These details were used in comparison with the diesel engine data which proved superior due to many factors.

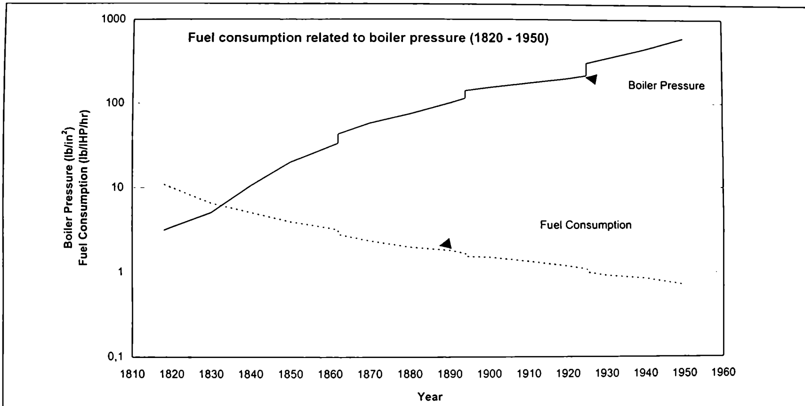


Figure 2 - 8: Fuel Consumption Related to Boiler Pressure (1820-1950)

Source: Guthrie, (1971)

2.4 Other Historical Facts about Marine Engines

The following table 2-2 gives some of the early marine steam engines and a little bit of their history.

Table 2- 2: The First Ships Fitted with Marine Steam Engines (1700 - 1820)

Year of Service	Name of Ship	Comments
1707	Papin	First steam engine on experiments on canal
1787	Unknown	John Fitch pioneered by sailing a 'Skift' up Delaware river with a engine of 12 in bore cylinder and 3 ft stroke.
1788	Unknown	'30 passenger boat travelling about 5 knots sailing between Philadelphia and Burlington.
1790	trawler	Fitted with a beam engine and was used as a passenger freight ferry.
1801	Charlotte Dundas	Experimental tug fitted with a horizontal direct drive condensing engine. Cylinder bore was 22 inches with a stroke of 4 feet.
1803	Robert Fulton	The fire engine speed of 3 miles an hour , it was steeple drive, vertical cylinder with a over crosshead cylinder 10 in bore and 2 feet stroke. Boiler pressure was 5 lb/in^2. ships speed 4 knots.
1807	The Clermont	commercial vessel 133 ft length. The engine was a 22 in bore x 4 ft stroke delivering 19 horse power. Speed 5 knots. by R. Foulton
1809	John Stevens	The first deep sea navigation undertaken from new York to Philadelphia
1818	Savannah	The first ship to use steam to cross the Atlantic took 25 days from port of Savannah (US) to Liverpool in 1819 under full sail, occasional using the engine delivering 90 hp. The cylinder bore was 40 in diameter and 5 feet stroke. The boiler pressure was atmospheric engine rotation was 18 rpm with ship speed 4 knots.
1820	Aaron Manby	The first iron ship recorded. Had an oscillating engine sailed from London to Paris.

2.4.1 Reasons for Development.

Obviously as more and more vessels appeared on the scene, competition for the upmarket design of engines and their improvement continued. Most of the reasons sighted were as follows:

1. power development to fit the ships sizes which were rapidly increasing as the trade increased and
2. faster and better means of propulsion were required, especially to compete with the Americans who were already experts at the Atlantic crossing with the sailing ships.

It had taken 100 years to develop *propulsion technology* from 1707 to 1807.

2.5 Comparison of first successful Passenger Steamers

By the start of the nineteenth century passenger steamers started to appear in the west and Europe crossing the Atlantic. A lot of people took interest in the discovered land and started to travel all over the world. Some of the earliest passenger vessels to use steam engines are discussed .

2.5.1 The Great Western 1837

The first on the market was the Great Western ship operated by the Curnard Western Shipping Lines. She was a wooden paddle steamer with a 1340 tons dead-weight. Being the first passenger vessel to cross the Atlantic, she became very famous and reliable.

Her engine details were as follows:

Description		Paddle wheels
• Engine power	750 NHP	28 ft diameter
• Cylinder	73 in bore	10 ft wide
	28 feet stroke	
• Boiler	6 lb. Pressure	

2.5.2 The Sirius 1837

The Sirius was the first ship to cross the Atlantic on steam alone. This ship demonstrated the superiority of having an engine fitted for propulsion and it proved that it could be reliable. This was very important as the ship owners of the time were not prepared to invest in the ships with engines at that time.

The ships details were as follows.

Ships displacement	**412 tons**
• Engine cylinders	2
• Bore diameter	60 inches
• Stroke	6 feet
• Boiler pressure	5 lb/in^2
• Ships speed	8.5 knots
• Engine Horse power	320 NHP
• coal consumed	about 1 ton/hour

2.5.3 The SS Great Britain

This laid the foundation of the most successful marine engine type which was later developed and employed in most of the vessels. The design basis was developed from the original idea of Newcomen which was successful in the coal mines else where in the United Kingdom. When the designer and boat builder 'Brunei saw the success of the trials being carried out on Thames, he adopted the idea and the first screw propelled engine was built. Unfortunately, its life ended abruptly after operation for four years because the ship ran aground and the engine was never revived.

Problems associated with propulsion were:

- the design of the stern tube to be waterproof (packing)
- inefficient thrust bearing
- screw design
- engine speed and gear arrangement

2.5.3.1 Constraints and Success

The following areas are the most areas which were most successful for the SS Great Britain engine:

1) Cylinder Liner:

   The cylinder liner was of the vertical altitude type as opposed to the horizontal with the whole frames arranged in a eve- type as shown in the figure 2-8. This consisted of a pair of cylinders working on an overhung crankpin at each end of the shaft with the main driving wheel between them. The shaft and screw were chain driven from the crankshaft.

2) The propeller:

Made of wrought iron with six blades (initially modified to four) and a diameter of 15 feet at 25 feet 6 inch and an achievable top speed of 18 rpm. After an unsuccessful voyage across the Atlantic, the propeller was replaced by a four bladed cast iron propeller as the other had its other three already broken during the second crossing of the Atlantic.

3) Other details

• Length overall	322 ft (98.45 m)
• Extreme breadth	50 ft 6 in (15.39 m)
• Load displacement	3620 tons (3680 t)
• Boiler casing	34' x 31' x 21' (1.4X 9.5 X 6.4) m
• Boiler working pressure	5 lb. f/in^2 (34 * 10^3 Pa)

2.5.3.2 Design Features

Some of the design features have been selected to illustrate different constraints and areas which gave opportunities for change.

1) Cylinder arrangement

   Cylinders were made cylindrical with the piston rod emerging from the top. This was adopted by the earlier engines which had proved to be successful on land i.e. for the locomotive engines. These were inclined with a eve- type arrangement resulting in one sided wear which was later adopted for marine use, eventually ending up with the horizontally arranged cylinders for the direct drive of screw propellers.

2) Number of cylinders and reversibility

   A marine engine needed to be reversed for astern propulsion when being operated. Due to this problem, requirement for more than one cylinder was instituted. If the engine had more than one cylinder then it could be started at any position and reversed easily. So four cylinders were chosen in this case to provide more power and present a symmetrical and compact arrangement engine.

3) Connection between piston and crank

   The connecting rods were long and heavy and they greatly influenced the form of the shape of cylinder and engine. The introduction of the other parts of the engine were there to accommodate the connecting rod by either shortening it and making it compact.

The engine also largely depended on the air pumps, and condensers. All these contributed to the large space required and occupied by the machinery. Another draw back was the low speed of the engine.

An arrangement to increase the speed necessitated an step up gear arrangement. The figure 2-9 shows the SS Great Britain gear arrangement and shows the associated problems.

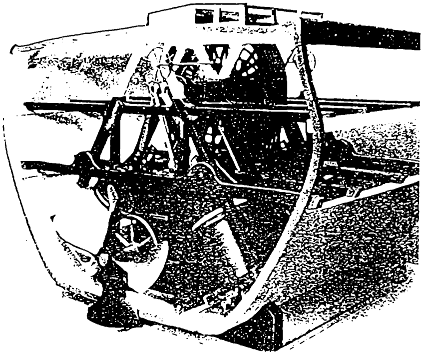


Figure 2 - 9: SS Great Britain Wheel Arrangement.

Source: Buchanaan, (1996), page 29

2.5.4 The Great Eastern.

Having seen the success of the previous ships the Great Western and the Great Britain, Brunei built another ship which was to replace the said ships. This was the Great Eastern, a paddle and screw propulsion ship, (a form of redundancy arrangement). The engine had a horizontal crosshead, connecting rods from this crosshead driving a single crank for each pair of the cylinders. Thus there were two cranks at right angles to each other.

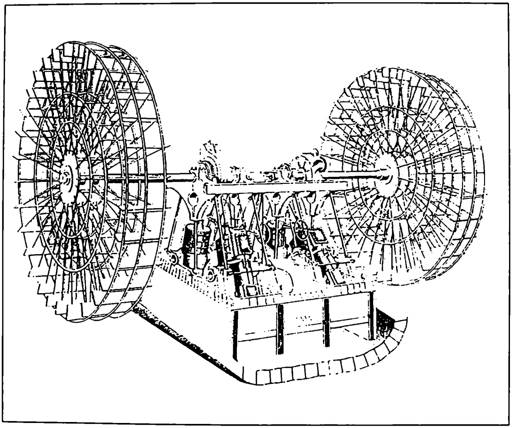


Figure 2 - 10: Paddle Engines Showing the Wheel Structure of the Great Eastern

Source: Taggart, (1969), page 80

The details of the engine were as specified . The engine speed was about 10 revs per minute and due to the structure it was difficult to develop the required propeller speed.

Table 2- 3: Particulars of the Great Eastern

Engine-room dimensions were:	52 feet high (15.84 m)
Engine power screw driving	1600 hp
Engine power paddle driving	1000 hp
total propulsive power	3600 hp
Engine speed	10.75 rpm
Ships speed	8 knots
Engine cylinders bore	84 in (2.134 m)
stroke	48 in (1.219 m)
Expected output	5000 IHP 38 rpm
Ship speed	9 knots
Propeller .- Cast iron boss	8 feet (2.44 m) diameter
Number of blades	4
screw propeller diameter	24 feet (7.315 m)
paddle wheel diameter	56 feet (17.06 m)

source: Taggart, (1969) page 79

With the above information it can be seen that the Great Eastern had more features and it incorporated all the technology of its time. The ship became successful until further developments in the screw propulsion and steam were achieved.

2.5.5 SS Turbinia

The first successful experimenter on the use of steam turbines was Sir. Charles Parsons, who developed a turbo-generator in 1884. This was a 8½ kW machine running at 18,000 rpm and by 1888 he had upgraded the power to machines of 75 kW electrical sets. The first ship to be run by turbine installation was named "Turbinia" and she ran on a single casing 2,000 SHP radial flow turbine running at 2,000 rpm on a single screw. After several trials and improvements, she claimed to have reached 34.5 knots, using steam, having been installed with a water-tube boiler working at 170 kg under-forced draught condition. The development of turbine propulsion changed the arrangement of propulsion. Instead of a low turning screw propeller, the speed available was high, therefore the reduction gear arrangement had to be arranged.

are the two systems of arrangement the first showing the earlier arrangement and the other showing the later.

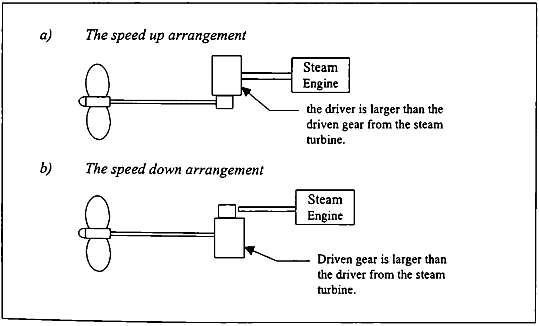


Figure 2 - 11: Drive Arrangement for Low Speed & High Speed Turbine

2.5.6 More Steamers of the World.

table 2-3 gives some of the giants of that time and the details are tabulated -.

Table 2- 4: Other Giants on the Scene (1850 - 1920)

Year of service	Ships name	NHP	Other details of the vessel and the marine steam engine
1856	Persia & Arabia	3600	150 tons pre day
1862	Scotia	4800	Last of the paddle steamers with 100 in bore diameter and 10 feet stroke.
1896	Dutch channel ferries	9000	Achieving ships speed of 21 knots.
1878	City of new York	2600	Re - engined
	Majestic Teutonic	8500	Ships speed 19 knots.
1893	Campania and Lucania	31000	Propeller speed 84 rpm
1894	Caledonia	11,000	
1890	'Kaiser' Wilhelm der Groose	27000	
1910	The Olympic		
1911	The titanic	50,000	Sank in 1912 and brought so many question concerning of safety at sea.

The above table lists some of the ships which came onto the scene within the last half of the 19th Century and the first 10 years in the 20th Century just prior to the most dramatic change of the century. Thus the up and coming success story of the diesel engine which was first on the scene by the turn of the century.

The increase of steam power for can be seen from the mid of 19th century when the powering ships were fitted with engines of about 3, 00 hp to 1920 when the power had increased over 1,000 %.

This is illustrated in the figure 2-12 data from table 2-3.

The following chart gives the increase of power of ships from 1850 to 1920.

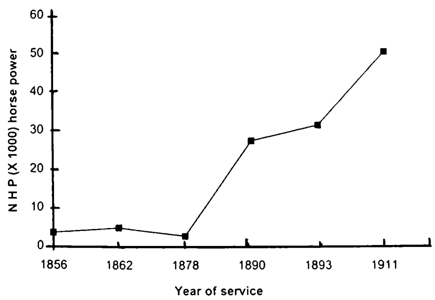


Figure 2 - 12: Increase of Propulsion Power (1850 - 1920)

CHAPTER THREE

3 MARINE DIESEL ENGINES

3.1 The First Marine Diesel Engine

It is not the intention of this chapter to engage in the historical debate of who invented the diesel engine, therefore the discussion will mainly be based on the operating principals and design criteria that were employed in the initial designs of the compression engines. The birth of a compression engine could be attributed to the Lenoir cycle where it first used a mixture of air - vapour and oil - (rock oil products) in a gas engine.

3.2 Lenoir Cycle 1860 (The Gas Engine)

Air gas mixture was drawn into the cylinder on suction stroke for about one third of the travel. When the inlet valve closed, the mixture was then exploded by making contact with an open flame. The burning mixture would expand and force down the piston, down the remaining two thirds of the stroke, thus forming the power stroke.

Draw backs of this engine were:

1. lower engine speed (rpm) resulting in low power being produced. Therefore, it could not compete with the steam engines
2. lack of fuel sources as it required gas, coal or oil products for its fuel
3. hazardous as ignition had to be done from an open flame.

The arrival of a petroleum distillate on the market in 1873, enabled it to be used in a gas engine, suitably vaporised by drawing air over a surface of petrol, and the gas engine thus became a self contained oil - vapour engine. Daimler Benz in 1883 developed the petrol motor engine which was less hazardous and is now successful in the motor industry. The engine could turn up to 800 rpm which was an improvement from the previous 200 rpm. Other scientists, like Kjelsberg 1889, Akroyd - Stuart 1890 further worked on the idea and also improved the design to incorporate, the low-compression engines where the fuel was injected into a hot un-cooled chamber, through a needle valve by a jerk pump. From here it can be seen that most of the developments were being done through various methods to develop the compression engine.

3.2.1 Diesel Experiments 1894

The success came with Dr. Diesel's experiment in 1894 who patented his designs and the diesel engine, as it known today, was born. Dr diesel's introduced into the design safety via the following aspects :

- the atomiser, which injected fuel simultaneously vaporised by a blast of high pressurised air, through a valve nozzle. this atomiser dispersed the carburettor or vaporiser in the first oil engine
- the engine could run on high compression pressure and high inlet and exhaust temperature
- could run on fuel with a reasonably high flash point
  did not require a naked flame or electric spark to keep it running.

3.2.2 Drawbacks of the Diesel Engine

These were:

a) Robust engine with heavy A- frames
b) Large diameter crankshaft and heavy running gear to maintain momentum.
c) Fuel injection demanded high air pressure from 600 lb. to 100 lb. To be provided by a two stage to three stage compressor, driven by the engine itself. Thus forming a parasite component which robbed a certain percentage of the total output power.
d) Because of the high temperatures, other components had to be absorbed and these were:
    - water coolers
    - high pressure air receivers
e) complicated piping systems to inter- connect all these systems.

Despite having problems with the auxiliaries, i.e. the air compressor, fuel injection equipment and the other attachments, this type of engine stabilised and was found to be more effective. They continued to build such types of engine until well into the first quarter of the 20th century.

3.3 Some Early Successful Motor Ships (1880 - 1920)

The early marine diesel engine was a small two cylinder unit which was fitted on a barge producing 29 BHP. This was a record for the use of the diesel engine on a marine craft. The first commercial use, however, was on a vessel named 'Vandal', a tanker. She was built in 1904 by the Nobel brothers of St. Petersburg (now Leningrad). Her motor engine produced 400 BHP and was used in the Volga and the Caspian sea (inland waters). However, the first ocean going vessel was also a tanker built in 1910. Its engine was a six cylinder Werkspoor diesel engine developing 500 BHP working on a four stroke cycle. Its displacement was 1900 tons and running speed was 8.5 knots. The cylinders had a 400 mm bore diameter and 600 mm stroke turning at 180 rpm.

Problems associated with the early motor ships were:

- reversing the engine in order to achieve the astern movement was achieved by having two camshafts
- high temperature problems associated with cooling and lubricating the cylinders as they were built with open -ended water cooled liners. The piston was air cooled
- the fuel control mechanism had to be integrated with the blast air supply system in an automatic float tank as shown in figure 3 - 1.

The control mechanism worked by letting fuel enter the floating cylinder chamber, while being supported at the fulcrum. When the tank was half full then the suction valve would be shut. The air introduced into the cylinder at the top was used for balancing the pressure. An internal pipe with a hole at the bottom was used to introduce the fuel to flow through the governor to the individual cylinder fuel valves. Such control could also be done manually.

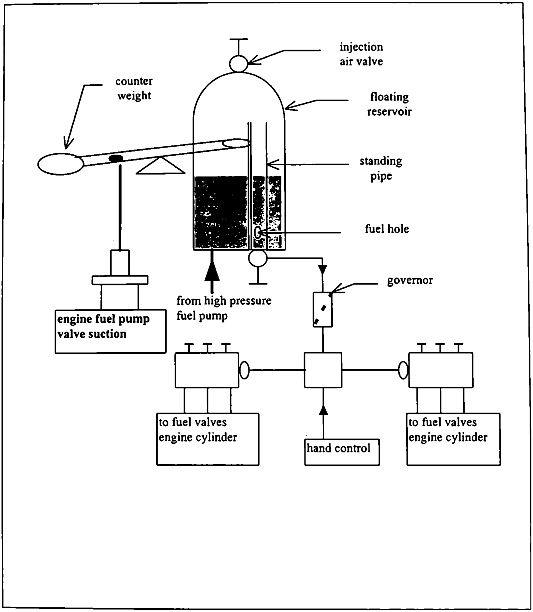


Figure 3 - 1: Integrated Fuel and Injection Air System at Cylinder Top Level

Source: Guthrie, (1971), Page 201

The success of the diesel engine in motor ships continued and below is a summary of some of the earliest ships that proved to be successful with the engines that were fitted.

Table 3-1: Early Ships fitted with Diesel Engines by 1930

Ship details			Engine details		
Name	Year built	Displacement (tons)	Speed Knots	Brake horse power (BHP)	Engine speed (rpm)
Tanker vandal	1904	1900	8,4	400	180
Tanker Vulcanus	1910		10,5	500	180
Juno	1910	4300	10,5	1460	125
Eavestone	1912			800	95
Selandia	1912		11	2500	140
Gripsholm	1925	18,815	17	13,500	125
Augustus	1926	33,650	18.5	25,000	120

3.3.1 MV Selandia

The Selandia could be claimed to be the first pioneer motor vessel as she was 370 ft (112.8 m) long, 53.2 ft (16.22 m) beam and 27 ft (8.23 m) deep which are accurate and appropriate dimensions for a ship other than the small vessels. The engine was a four stroke crosshead type enclosed, direct - reversible oil engine, while the engine of the ship was a twin screw which was all electric, the engines developing 2500 BHP (1865). It was built by Burmeister and Wain of Copenhagen in 1912 for Det Ostasiatiske Kompagni.

The main engine details are as follows;

Type: Four stroke cycle

- Number of cylinder 8
- Bore diameter 20 7/8 in (6.362 m)
- Stroke length 28 3/8 in (8.648 m)
- Three stage high pressure injection compressor
- Auxiliary diesel engine to drive all electric accessories.

The engine room for the Selandia was highly electrified, thus reducing the man working hours especially on the boiler, and other routine engineering jobs of the day. The success of this engine came with the comparison of the then present steam engine in areas of;

1. Fuel economy
2. Ships speed
3. Ships size to machinery size- earning capacity
4. Reliability and reduction of manpower.

3.3.2 MV Augustus

This vessel was a passenger vessel built in 1926. Came into the market at the time when there was great competition between diesel engines and then successful steam engine. The engine was a two stroke cycle engine and it proved superior to then, four stroke cycle which was being fitted in most of the vessels. Fuel consumption was one of its greatest success. With consumption rate of 0.305 lb./IHP/hr it was favourable compared to 0.36 of four stroke cycle engine and 1.5 lb./IHP/hr of the steam engine. Another problem cropped in This was problems associated with torsional vibration and bending stresses. Therefore another area of study had emerged to ascertain how these problems could be solved.

3.4 Cylinder Environment

The history of marine diesel engines can not be complete without scrutinising the basic principles of the diesel engine. Hence a basic definition of the engine is hereby given. The name Diesel refers to a German born inventor who was involved in the research of engines and won the patent in 1894. When the engine was fully developed the working principles were based on the following definitions.

a) The diesel engine operates on a cycle concept characterised as four stroke or two stroke cycle. This refers to the piston travel where it travels two stokes to complete a cycle in one revolution of the crank rotation and four strokes to complete another cycle taking two revolutions of the crank rotation. Two stroke cycle has an advantage over the four stroke cycle, that is it can deliver twice as much power compared to a similar four stroke cycle engine.
b) Basic differences are in the construction of the two types of engines. In the four stroke cycle engine, the air supply and exhaust are through manifolds in the cylinder head with valves being opened mechanically through push rods and rocker arms arrangement operated by a camshaft. The camshaft is gear or chain driven rotating twice as much as the crankshaft rotation.
c) The two stroke arrangement has inlet (valves) ports in the body of the cylinder, which are opened by the downward piston movement that uncovers the ports, letting the air intake (charge) into the cylinder. Consequently, the exhaust is expelled out through the port or exhaust valve which is open at this instant.

There are different arrangements of scavenging for two stroke arrangements, these are, cross flow, loop scavenge and uniflow scavenging which is very popular with present slow speed marine engines. The four stroke methods of air intake and exhaust is by valves operated either mechanically or hydraulically.

3.4.1 Thermodynamic Cycle

THE DIESEL CYCLE.

The diesel cycle is an improvement of a theoretical cycle, as was developed by Rudolf Diesel.

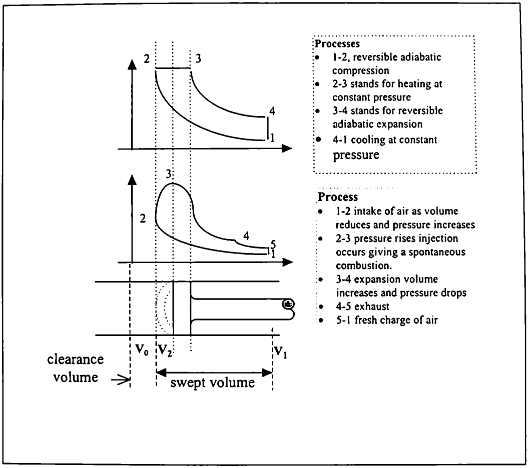


Figure 3 - 2: Thermodynamic Cycle Principles

1a) shows theoretical diesel cycle and

1b) shows the actual cycle - combined/dual (mixed or Sabbathé cycle).

3.4.2 Theories

Using the theoretical cycles formulas which are developed and are used in the diesel engine parameter calculations. Some of these formulas are as follows;

3.4.2.1 Net work (ω_{net})

It is known that the network (ω_{net}) is the area enclosed by the integral diagram shown above in the diagram thus path 1-2-3-4.

thus

$$\omega_{net} = \oint P dv \qquad (3.1)$$

and from mean values the formula is the same as;

$$\omega_{net} = P_m(v_2 - v_1) \qquad (3.2)$$

where

P_m is mean effective pressure 'MEP'

v_1 denotes piston at BDC , v_2 at TDC.

thus

$$P_m = \frac{w_{net}}{(v_2 - v_1)} \qquad (3.3)$$

The specific volume $(v_2 - v_1)$ is a constant and is a function of stroke therefore the mean effective pressure varies directly with the network produced per cylinder displacement volume

$$P_m = \frac{w_{net}}{(v_2 - v_1)} = \frac{w_{net}}{k} \qquad (3.4)$$

If the network is multiplied by the RPM then, the result is the indicated power developed by the cylinder expressed as the indicated horse power 'IHP' which has now ISO unit of kilowatt. Brake horse power is the actual power that is produced by the engine and is available as useful power.

$$IHP = N \times \omega_{net} \times RPM \qquad (3.5)$$

where N is number of cylinders.

The ratio between brake horse power and the indicated power is the mechanical efficiency.

$$\text{mechanical efficiency} = \text{BHP}/\text{IHP}$$

$$\eta_m = BHP/IHP \qquad (3.6)$$

3.4.2.2 Calculation of Engine Power:

Newton's law gives the formula force 'F' is product of pressure 'P' and area 'A'.

so force on piston equals $F = P \times A$

and work done by piston is

$$W = P \times A \times L$$

and piston work rate = work done times frequency 'N' (cycles per unit/time)

therefore

diesel work $W = PLAN$ ......(3.7)

work = PLAN/33,000 (expressed as a horse power)

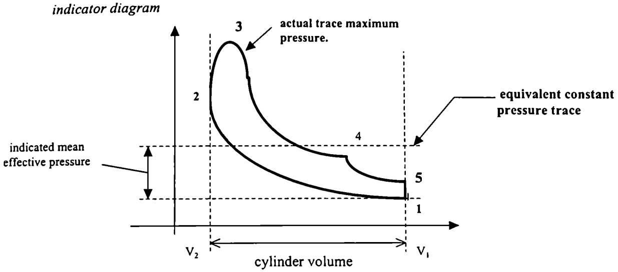


Figure 3 - 3: Relationship Pressure and Volume showing Indicated Power

thus

indicated mean effective pressure (MIP) is given by

$$P_{imep} = \text{(area of diagram) / (swept volume)}$$

$$P_{imep} = \frac{A}{V} \quad \text{...(3.8)}$$

brake mean effective pressure is found by the formula

$$W = PLAN \quad \text{..(3.9)}$$

where

P is the effective pressure (MEP), L is the length of stroke, and

A is the area of bore while N is the revolutions per minute.

The W (work done) is found by a dynamometer or a friction brake and

N is equal to rpm (for two stroke engine)

while

is equal to rpm/2 (for four stroke engine is)

therefore

$$P = W/LAN$$

note:

L and A values are obtained from the technical details of the engine - manufacturers manual or handbook.

mechanical efficiency = brake power / indicate power

= MEP/MIP

thus

$$\eta_m = \frac{T}{P_{mcp} * L * A * N} \quad (3.10)$$

also Indicated power - brake power = friction power

Torque power relationship

and also torque varies directly with the work done.

$\omega = 2\pi QN$ where Q is torque in (Nm)

thus horsepower = $2\pi QN/33,000$.

The following diagrams in figure 3 - 4 give the ideal torque and power characteristics of diesel engine.

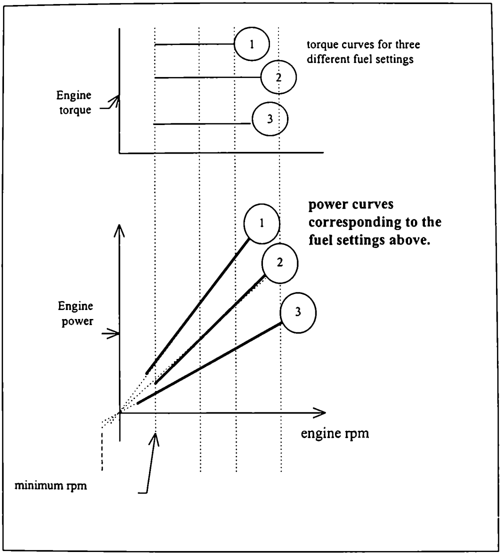


figure 3 - 4: Torque - Power Relationship

From the power curves above, it can be deduced that for higher fuel speed settings one is likely to get higher engine output as the speed increases. while with the lower setting as shown in setting 3, the power achieved is also lower. Thus the engine power output is directly proportional to fuel settings.

3.4.3 Classification of Marine Diesel Engines

There are many way of classifying diesel engines. The following basic definitions are given as they are used in classifying the engines. These are:

a) cylinder arrangement,

b) combustion process cycle

c) piston physical characteristics and

d) methods of scavenging or air intake.

In the figures to follow such arrangements have been given and illustrated.

a) Cylinder Arrangements (vee - V Type Or In Line.)

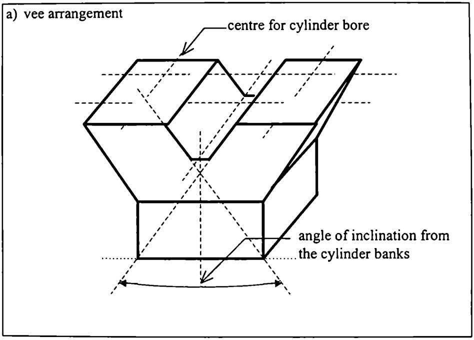


Figure 3 - 5: Showing a VEE Type Cylinder Block Casting.

Vee engine arrangements are normally applicable to high speed and medium speed engines. The size of the block depends on the number of cylinders and the physical dimensions. The number of cylinders could be anything from two to ten per row giving a high total of 20 cylinders.

a) In line engine could either be vertical in-line or horizontal

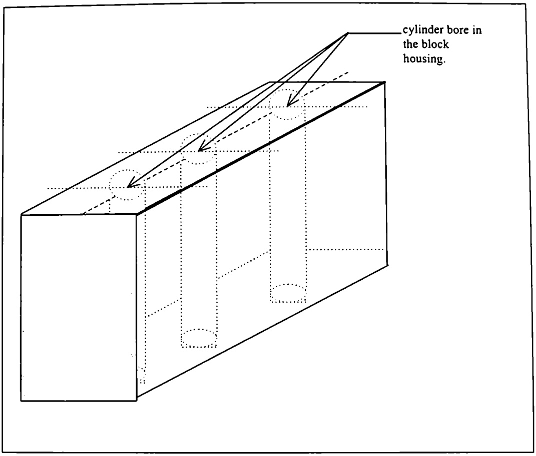


Figure 3 - 6: Vertical In-Line Engine Arrangement

The In-line engine is very popular because it is arranged in such a way that work can be done on individual units without disturbing the other parts. Also a range of power can be arrived at depending on the number of cylinders wanted. For larger engines (two-stroke cycle), individual parts are cast and machined separately. Hence, one can end up with an engine from one cylinder to 12 cylinders with power ranging from 50 hp - 40,000 hp. For medium to high speed engines, the block is compact and easier to handle.

3.4.4 Combustion Process Cycles

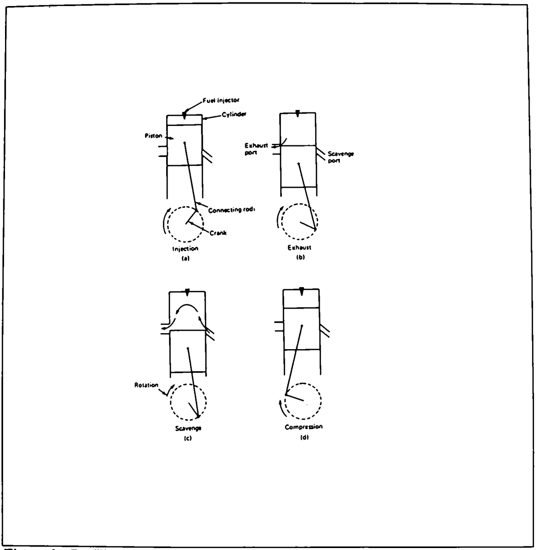


Figure 3 - 7 Illustrating the Two -Stroke Cycle

Two stroke cylinder arrangement maybe cross flow, uniflow loop arrangement with the cylinder piston arrangement as the trunk piston arrangement, It is stout and compact, crosshead crank piston any or (for long stroke double acting.).

Figure 3-8 below illustrate the four stroke cycle for a diesel engine. Notice the overlap period when both the inlet and exhaust valves are open

four stroke cycle indicator diagram

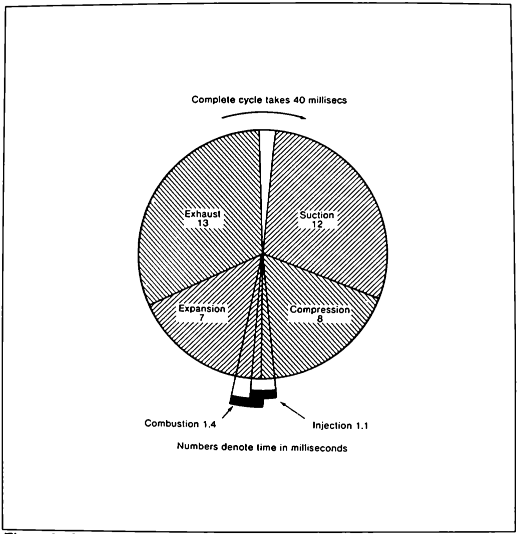


Figure 3 - 8: Illustrating the Four Stoke Cycle Principle.

The piston has to travel four strokes, the crank completing two revolution for there to be one complete cycle.

Other forms of classifying the diesel engine is by considering its physical movement. i.e. by referring to it as a reciprocating and internal combustion process.

a) **Reciprocating.**

diagram showing a cylinder and piston illustrating the two movements.

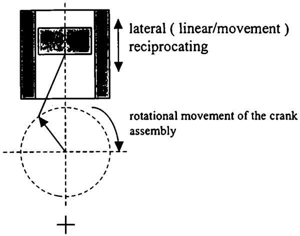


Figure 3 - 9: Piston Movements and Speed.

Reciprocating stands for the linear movements that a piston achieves from the rotary motion of the crank assembly. The speed of the piston is limited by mechanical stresses which influence reliability and durability. Speed is also related to fuel economy, hence if speed is high the consumption also goes up. Average Piston Speed is about 5 - 6 m/sec. Taylor, (1985) page 378.

b) Methods of Scavenging

There are different methods scavenging arrangements for two stroke diesel engines and the figure 3 - 10, illustrates the basic four forms.

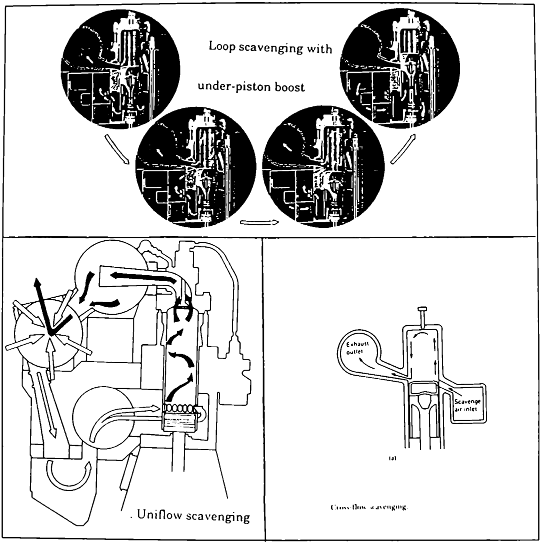


Figure 3 - 10: Different Methods of Scavenging

source: 1) Osbourne, (1994) page 16-8.

2) Taylor, (1990), page 352.

CHAPTER FOUR

4 SHIPS IN MARITIME TRADE

4.1 Pre-History of Shipping

The history of shipping starts way back before 1800 AD. In fact the Egyptians were involved in sailing as far back as 2500 BC and by 600 BC the Phoenicians had already established colonies on the coast of Africa . The Romans had already dominated the seas and the estimated imports at this time amounted to 150,000 tons of grain. Also during this period the Spanish and the Portuguese were a force to reckon with in the sea trade.

Around the year 1000 AD a lot of changes started to occur on the continent. Islam spread towards North Africa and Christianity into the whole of the European continent. Cities started to grow and trade flourished as the population increased. Because of these changes, shipping became more recognised as a means of supplying goods into the cities and towns that were emerging and growing. Treaties and control of shipping started to emerge with merchant ship owners playing a big role. Included in the change was Maritime Trading patterns. It started to emerge and also forms of control and inspection appeared. The shipowners instituted the presence of inspectors on board the vessels who exercised the functions of a supercargo and thus represented the cargo owner. The inspection system started for securing seaworthy vessels for cargo owners. Before a vessel set sail, an inspection of the vessel for its fitness and freeboard was carried out. A mark on the ship planking (an origin of the Plimsoll line of today), was made to signify that she had been inspected. Trading patterns as practised by the Italians involved sending vessels on long voyages, while those practised by the Hanseatic league involved short distances thus mainly to the European continent and the Scandinavian countries. The Hanseatic cargoes were divided into small cargoes and distributed among several ships where the ownership was also divided into share in so doing spreading the risk. Hence a form of present Insurance was born. This form of risk spreading reflected a different form of business approach. Maritime Law that is represented by legislation and practice was also started at the same time and was greatly practised by the Romans and the Greeks. This was a form of a loan or credit by the shipowner from a banker on the security of the vessel or cargo. This loan was repayable on completion of the voyage and had a premium of 6 percent sometimes going as high as 12 per cent.

During the fifteenth and sixteenth century, the Maritime trade underwent a change of character. The sea routes to the Far East were opened, discovered by the Portuguese (Vasco Da Gama) and St Columbus who sailed across the Atlantic to discover the Americas. Magellan circumnavigated the globe in 1520 making it more attractive to sailors and merchant seamen. The Portuguese established trading stations in East Africa, Malaca, the East Indies and China. Commodities brought from the Far East (especially spices) started to flood the market and the selling price started to drop thus bringing down the control exercised by the Italian cities over the seaborne trade.

The Spaniards navigated to and from the Americas in great convoy of silver carrying ships which sailed from West Indies and Central America. The English came through pirating by attacking the Spanish convoys until it led to the Spanish Armada in which unfortunately the Spanish lost and this defeat ended the Spanish era of dominance in the maritime trade greatness and England started to rise as a Maritime nation. During the nineteenth century the English colonisation began and they also started to practice protectionism, where cargoes from their colonies were only reserved for English vessels. These vessels were to be manned owned by the English, and the master and 75 % of the crew were also to be English This was then expanded to a Navigation Act by Cromwell in 1651 (ref. "Rinman et al.).

The second half of the seventeenth century saw the down fall of great trading blocs of Venice and the Hanseatic league which had controlled maritime trade. The great monopoly companies came onto the scene and these were the West India Company, East India Company etc. London became a major centre in Maritime Trade and Commerce and Edward Lloyds built his empire in what is now known as the 'Lloyds Group' father of the Lloyds List and Lloyds Register which are some of his contributions.

4.2 Ships and Shipbuilding (1700 - 1800)

'Slave Trade Era'

In the Eighteenth century Europe grew increasingly prosperous, handicrafts commerce technology and domestic industries were developed, Amsterdam, being a financial centre. London grew increasingly wealthy through commerce and shipping despite the protectionism. i.e. cotton textiles for example were subjected to high custom duty in order to protect the European trade. Slave trade and sugar industries in the West Indies also grew prompting the over increasing trade between these continents. Britain and France struggled for world supremacy and by the end of the eighteenth century, Britain survived as there was revolution in France. United Kingdom acquired the Gilbratar Straits through the 1713 treaty of 'UTRECHT'. This allowed the British to have a stake in the Slave Trade to Spanish America. The tables turned when the Slave Trade was banned by the British thus prompted the Slave Trade business to become more dangerous and lucrative. Because of this, those required to trade wanted ships which were faster and could outrun the British Naval ships. Born were the finest Clipper ships of the century. The Americans gave stiff competition on trade with the British. With the declaration of independence in 1776 and having adopted a new constitution, in the same year, they passed a resolution to favour their own shipping and shipbuilding for the maritime commerce. Successful expeditions were sent to the Far East, China and the rest of the world, and the Americans became outstanding traders. It was towards the end of the eighteenth century that the modern shipping which we have today took shape. A new pattern of shipping strategy began to take shape. A new pattern of events coupled by wars, industrialism and free trade emerged. These created psychological effects which determined the future of world shipping. This was accepted by the traders and shipowners accordingly and those that did not comply or understand, were just left behind and they fell victim and their businesses were ruined.

4.3 Factors Influencing Change (1800 - 1900)

The nineteenth century saw the beginning of a series of processes which gradually led to a phase of developments in which the present World sees itself now. A major setback was the Napoleonic wars which had prompted the British Navy to employ 2.5 million tons of merchant ships to transport supplies. With the end of the wars 1814 -1815 these ships were re-deployed in the Maritime trade. Europe was also affected by a depression which lasted until 1820. The world trade contracted and the merchant shipping suffered an economic decline. Industrialisation accelerated development in the more powerful nations and the pressure on the world markets created the basis for a rapid advance in maritime technology. New entrants in the competition were the North Americans, Swedish and the Norwegians. Because of this the British were forced to relax their projectionist legislation. The major commodities being carried then were; timber, cotton, coal and grain. A new trade emerged, and this was the emigrant trade. Major discoveries of gold were made in California and Australia.

The highly protectionism laws of Great Britain were gradually being relaxed through a series of bilateral treaties with the USA in 1815, with the Spanish and the Portuguese in 1822, with Russia and Turkey in 1822, and in 1826, the Norwegians and Sweden. A need arose for regular traffic across the Atlantic and thus the birth of liner trading. This was pioneered by an American company known as the Black - Ball Line. Its ships carried mail, gold and passengers as well as general cargo. The crossing generally took three weeks or more east bound, and about six weeks west bound due to westerly winds in the North Atlantic.

The Americas after the civil war in 1815 started development in very fast sailing ships called schooners. These entered the competition in fruit market, and also joined the opium trade to the far east and china. These competition started to force the British traditional sailors out of the market and most went ashore where they became very successful shipowner. The trend of ships being built then were swifter, sleeker and less expensive. The shipowner needed fast sailing vessels intended for illegal or semi-legal business. The shipbuilders were not able to use oak, the traditional shipbuilding material, but only soft woods which were not conducive to a quality aimed at giving the vessel a long life. The first real famous Clipper to be built for the Chinese opium trade was the 500 tons ANN McKim which was built in Baltimore. These clippers evolved and by 1840 other famous clippers like, the Rainbow, Stag Hound, Flying Cloud, Witch of the wave, Sovereign of the Sea, etc. were built. These were known to reach and maintain daily average speeds of 17 to 20 knots.

During the same period experiments on the use of steam engines at sea were underway. Iron ships came to replace the wooden ships. As this was an expensive adventure they were mostly done under experiments until Brunel picked up the idea and built the successful all iron, screw propelled The Great Britain' steam engine ship in 1840. This made an attempt to compete with the fast sailing clipper ships of United States.

4.3.1 The Golden Age of Shipping (1850 - 1900)

The year 1850 is the time that evolution in shipping accelerated in many aspects. A number of commercial, technical and political factors contributed to that acceleration. Steam and Iron ships were being built and driven by the screw propeller. Rapid expansion of the past sailing American Clippers and repeal of the projectionist laws in Great Britain 'the Navigation Act' repealed in 1849. All these played their significant part in the evolution. Gold was discovered in California and Australia, and the Great monopolies in trading to Canada, Far East, South East Asia and Africa had been abolished. The North America was also boasting of streams of emigrants. Liner shipping developed between Britain and the continent to the USA, China and Australia, with the whole world merchant fleet at its highest boom. In 1869 the Suez Canal was opened and this also facilitated the few British Steamers to compete for the Far East trade as coaling stations were established along the route. This also had a big impact on the clipper shipping. The American civil war broke in 1861 and all the clipper ships were withdrawn from the trade and subsequently sold on the second market ending the dominance of clipper shipping. The steam and Iron ships took over up to the end of the nineteenth century and start of the twentieth century.

4.3.2 Growth of World Shipping Fleet by 1900

a) World shipping statistics of existing and those on order in 1900 shows a tremondous growth in both motor ships and steam ships. The highest growth of is shown in motor ships where more than 3,000, 000 gross tonnage over steam ships were on order . Data given in Table 4 - 1, shows the data for such growth giving totl demand in terms of gross tonnage that was existing an on order by the year 1900.

Table 4 - 1: Existing and Ships on Order

Type Of Ships	Existing (Gross Tons)	On Order (Gross Tons)
Steamships	18, 600, 000	3,963,000
Sailing Ships	7, 301, 000	67,000
Total	25, 907, 000	4,030,000

a graphical representation of the above data in form of a chart figure 4-1

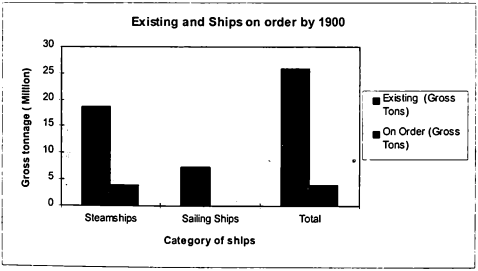


Figure 4 - 1 Existing and Ships on Order 1900

source: "Rinman et al., (1983)

b) Trend of growth of the World Maritime Trade By 1850: The following Table 4 -2 represents the main players in Maritime Trade way back in the early 1800's.

Table 4 - 2: Growth by 1850

country	British	USA	Greece	rest of world	total
net tonnage	4,23	3,6	0,3	0,9	9
percent (%)	47	40	3	10	100

source: Rinman et al., (1983)

c) Growth of the World Maritime Trade by 1900 had totalled 26 million tons. The Table 4-7 below gives the figures and distribution of the tonnage by each country. Note at this time new traders had come and these were Norway and France. Since their share of the trade was very small they were not taken as a threat initially.

Table 4 - 3: Growth by 1900

country	British	USA	Germany	Norway	France	Others	total
net tonnage	13,5	2,3	2,0	1,6	1,2	5,4	26
percent (%)	52	9	8	6	5	20	100

Source: " Rinman et al."

In 1914, just before the start of the first World War, the world fleet stood as follows:

- steamers a total tonnage of 45,403,877 tons
- and the sailing ships 3,685, 675 giving
- a total of 49,089,552 tons.

This growth in the start of this 20th Century shows a burst of trade covering the most of Europe, Scandinavia and also Japan and America. The top particpators are tabulated in table 4-8 showing the total number of vessels in terms of registered tonnage.

Table 4 - 4: Growth by 1914 and New Comers in the Trade.

country	British	USA	Germany	Norway	France	Japan	rest of world	total
steamers	10120	1757	2090	1656	1025	1103	638794	656545
sailing	1205	1417	298	535	551	0		
tonnage gross	20524 000	4330 078	5134720	195735 3	192228 6	1708 386	986205 4	454038 77
percent (%)	45,2	9,5	11,3	4,3	4,2	3,8	21,7	100

New comers in the market were;

Table 4 - 5: New Countries in the Trade by 1914

Countries	number of steamships	gross tonnage
Japan	1,103	1 708 386
Netherlands	709	1 430 475
Austria Hungary	433	1 052 364
Sweden	1 088	1 015 364
Rest of the world		6 565 545

4.4 Evolution of Ships Sizes versus Maritime Trade.

Ship size increased dramatically as the propulsion systems changed from sail to that of steam and diesel. The greatest change was seen in the passenger trade between the American continent and Europe in the 1847 (the time of the Great Western to the time of the Passenger ferry Rotterdam in 1959). Thus, a period of almost a century of supremacy in the passenger ferry trade was experienced. The decline came due to another mode of transport which was introduced soon after the Second World War, this being the jet aircraft 'Boeing 707'. The Boeing 707 introduced comfort and a more prestigious way to travel and it was much faster than the liners. Hence the supremacy of ships in the trade started to decline.

A look at the great passenger liners of the world at the time is given below with the sizes and year of first service.

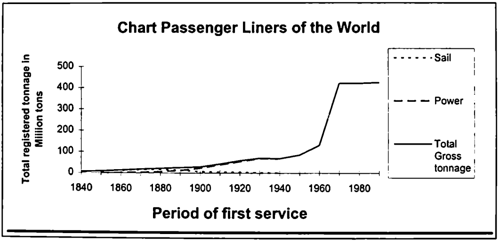


Figure 4 - 2: Chart Passenger Liners of the World

source: Data from table 4 - 6

Table showing a list of the great liners 1800-1950.

Table 4 - 6: Table Showing the Great Liners of the World (1838 - 1900)

Name	year of service	Capacity gross ton	Engine NHP	length Lpp	speed knots
The Great Western	1838	1,350	750		
The Great Britain	1847				12
City of Glasgow	1850	1,600			
Persia	1856	3,300			13
Vandabilt line	1857	3,350			12
The Great Eastern	1858	3,350	3,400	692 (feet)	13
Scotia	1862	4,800			13
The Oceanic	1871	3,700	4,500	420	13
Persia	1872	3,850			14.5
City of Berlin	1874	5,500		488	15
Servia	1881	7,400	10,300		16

Note Scotia consumed 350 tons of coal per day, and it was the last and fastest paddle vessel.

From the table it is seen that the greatest improvement were on power and gross tonnage. That is to say as the ships become larger due to trade demand then the power requirement was also increased. The technology in the engineroom went in parallel with the demand for more space. During this period early 1820 - 1900's, most of the trade was for both passengers and cargo combined. It should be noted that the American Shipping company started the mail ship which was a regular crossing between Europe and America. By 1900 the ship sizes grew even further.

4.4.1 Great Ships of the 1900's

The fastest ships of the time included in 1888 the Teutonic and Majestic which were built for speed. Hence, twin propulsion was installed with the propeller in a staggered position and the propeller blades overlapping each other with about 5ft 6 in. This was to improve propulsive efficiency. It was noted that the one of the ships had a lot of vibration and this was attributed to heavy low pressure pistons of the engines when they were synchronised. It was almost impossible to run both engines at the same speed.

Further developments resulted in the production of a four crank engine being to replace the three crank triple - expansion engines which had shown problems in balancing dynamically. It is sometimes to difficult to envisage the trend of growth for the size of the ships. Therefore an attempt to draw up the growth pattern has been presented below in table 4 - 6. This is further illustrated in chart form below figure 4-3. In 1849 the steam ships were almost insignificant that the number given is almost all for sailing ships. The power number includes also the steam engine therefore the illustration is to look at the growth of the sea trade in terms of market potential measured in gross tonnage for the ships registered each year.

The table below gives some of the vessels as they are up to date.

Table 4 - 7 Total Ship sizes up to 1990.

Year	Sail	Power	Total Gross tonnage * Million
1840			6
1850	7,88	0,7	8,58
1860	11,3	1,3	12,6
1870	14,8	2,8	17,6
1880	15,8	5,9	21,7
1890	13,7	11,6	25,3
1900	6,5	22,4	28,9
1910	4,3	38,8	41,9
1920	3,3	53,9	57,9
1930	1,5	68,1	69,6
1940	0,9	66,9	67,8
1950			84,6
1960			129,8
1970			419,9
1980			419,9
1990			423,6

4.5 The Role and Tasks of Marine Engineering

To discuss the role of marine engineering one is immediately made to consider the aspects related to operation of marine machinery, the marine engineer at work, and the tasks that are performed by the supporting groups. these supporting groups are the naval architects, the ship builder and the operator. All these above make the combination that compose the engineering profession.

4.5.1 Maritime Trade versus Ships Sizes

Demand in trade required ships of larger sizes to be built so that more cargo could be transported to satisfy the demand. The increase in quantity of cargo prompted specialisation in the handling of such cargo. Because of this specialisation entered the market. Container vessels, specialised carriers, bulk carriers and Ro-Ro type of vessels wee seen on the market. This was mainly to address the turn round time and at the same time utilise the space and carry more cargo. This was economical on part of the ship owner.

4.5.2 Ships Types and Sizes Versus Power

Propulsion power requirements centres on total economy consideration. This means less weight of machinery, propulsion parts and accessories resulting in more cargo to be carried, endurance of the prime mover and propeller with varying loads, which may occur in varying weather conditions and cargo loading conditions. Another important factor is the efficiency of the propulsion system which could be stated as heat transfer economy. Thus the power available to move the vessels' hull as provided by the prime mover.

The diagram below shows the energy, transfer and fuel economy.

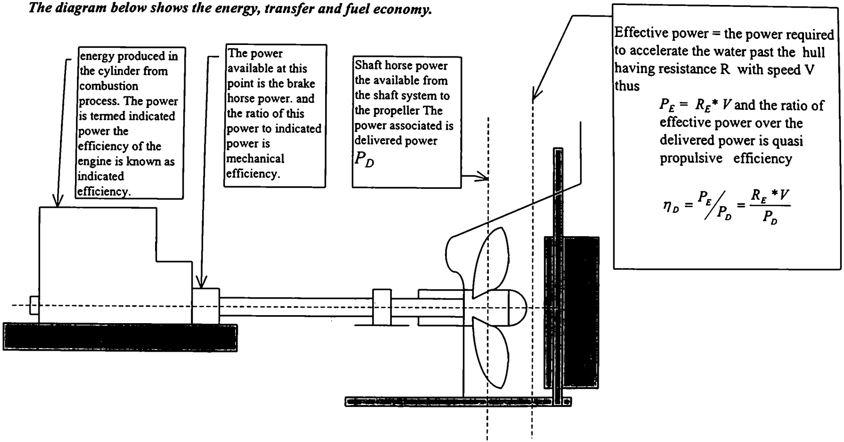


Figure 4 - 3 Power Distribution for Powering Ships

CHAPTER FIVE

5 DESIGN OF PROPULSION MACHINERY SYSTEMS

5.1 Design Concepts of the Diesel Engine

The Diesel Engine can be described as an invention of machinery which is a reciprocating, compression ignition engine. Here the key words reciprocating, (as the piston mechanism moves up and down), compression, as the charge is compressed to high temperatures and pressure where an ignition point is reached, are considered. Suffice to say, it is both a mechanical device but also involves hydraulic and chemical processes. All of these are present in the definition of a diesel engine. From the designers point of view, such items as laid out in figure 5 - 2 are of utmost importance.

5.1.1 Types of Engines

Depending on the crankshaft rotation or piston mean speed, the engine can be classified within the following speed ranges:

a) *Slow Speed Engines,*

These have a speed ranging from 50 to 200/250 revs per minute. Mostly marine engines fall in this category. Top three manufactures of these type of engines are: MAN and BMW, Sultzer and Mitsubishi.

b) *Medium Speed Engines,*

Engines having speeds of 400 to 1000/1200 revs per minute. Top manufactures of these types of engines are, Sultzer, Waltsila, Mitsubishi and Pielstick. The Power output of these engines is less per cylinder in comparison to the slow speed engines but can match the total power output by the cylinder configuration, which ranges from 12 cylinders for in-line engine and 20 cylinders for the vee-engine arrangement.

c) *High Speed Engine;*

These are the engines with a speed of over 1,200 revs. Normally the use of such engines is as auxiliary engines although they are highly utilised in the speed boats and leisure crafts. Well reputed manufactures include: Waltsila, caterpillar, Cummins and GMT.

Another definition that is often used is the ***Low Speed Engine***. This is used to denote the slow speed or medium speed engines which are directly coupled to the propeller shaft without the use of reduction gear. Their revolution matches that of the required propeller <50 - 350> range. It is known that the lower the speed of the propeller, the more the effective power transfer hence improved performance.

5.1.2 Combustion Process

The cycle that applies to the diesel engine is the dual combustion cycle. In this cycle ignition occurs when fuel is injected into the chamber where the charge has been compressed to high temperatures. This ignition causes the combustion of the charge which then expands exerting a force on the piston crown then this force is transferred down to the piston/crank mechanisms. The designers try to match the process of combustion as near as possible to the theoretical. The initial combustion is explosive then it is followed by burning that is almost at constant pressure. Most of the changes and design improvements have centred around this phenomena, to improve the combustion cycle. The cycle is normally a two stroke cycle for almost all of the slow speed diesels and four stroke for the high speed diesels, the medium speed being either.

5.1.2.1 The Combustion Chamber Design

The design of the combustion chamber is also considered, a *Direct Open Chamber* common for the slow speed and the Pre-Chamber as illustrated in the figure 5 - 1;

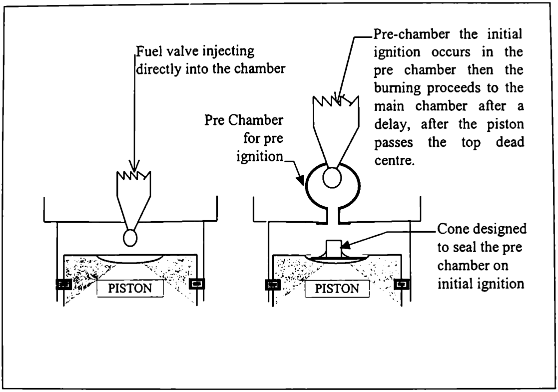


Figure 5 - 1: Open Combustion Chamber and Pre-Chamber

5.1.2.2 Cylinder Configuration

The basic layout of the cylinders could be either be an In-line configuration or a vee - type configuration depending on the grouping of the cylinders. An In-line diesel could be one cylinder to 12 cylinders and for a vee-type could be four to 20 cylinders.

5.1.3 Accessories

5.1.3.1 Running Gear

Running gear is mainly meant the arrangement of the Piston crank connection, which is in the form of *Trunk Piston or Crosshead Arrangement.* The trunk type is applicable in the medium speed and high speed engines while the crosshead is mostly used in slow speed diesels. The crosshead arrangement has its advantages over the trunk type through added lubrication. There is a separate lubrication system making it easy for maintenance and monitoring. Also the lubricating oil used for the lower part of the engines is clean, being separated from the combustion side, and can be reused for use over a long period of time.

5.1.3.2 The Power Pulses

Defines the engine thus, single acting or double acting for opposed piston engines. Method of fuel injection, *Solid Injection* which is the method of directly injecting the fuel at very high pressure into the combustion chamber. The other is the (now obsolete) air injection.

5.1.3.3 Air Supply

The air supply is mostly by a turbocharger. Most new designs are turbo-charged and supercooled. Below is a sketch of a turbocharger showing few variations in its design.

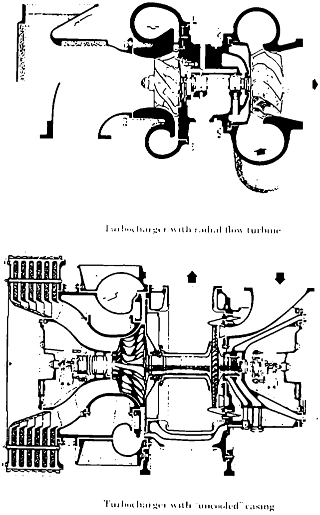
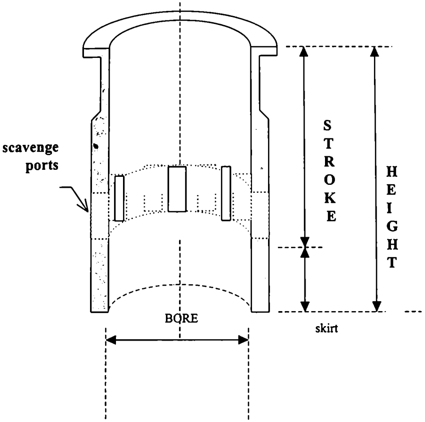


Figure 5 - 2 Modern Turbocharger Sketch : Design Details

source: Osbourne, (1994), page 16-24

5.1.4 Stroke to Bore Ratio

Cylinder proportion expressed as stroke to bore ratio



***Bore* - inside diameter of the cylinder liner**

***Stroke* - the length of piston travel inside the cylinder from top dead centre to bottom dead centre or vice-versa.**

Figure 5 - 3: Stroke to Bore Ratio

As shown above the *Stroke To Bore* ratio is normally set at 1.15 for high speed engines and 3 to 1 or more for low speed engines. The higher the stroke-to-bore ratio the higher the maximum pressure can be achieved. The air flow consideration into the cylinder restricts the ratio for medium and high speed engines.

5.1.5 Cooling Systems Arrangements

Cooling arrangements are also a design consideration for diesel engines. Most diesels are cooled by water although a few high speed engines can be air cooled. Cooling water flows through passages which surround the combustion chamber. The Piston may be water cooled or may have an arrangement for oil cooling, especially on the new designs. Figure 5 - 4 shows sketches of the design on New Sultzer engine.

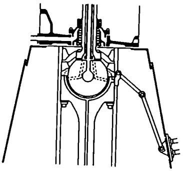
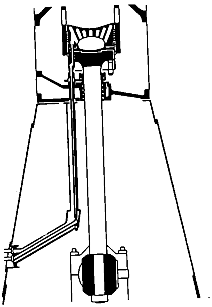
Sketch of *oil cooled piston*	Sketch of *water cooled piston*
	

Figure 5 - 4: Types of Piston Cooling ***(Oil and Water Type)***

Source: Osbourne, (1996) page 17 - 12/13)

Note that the oil cooled piston the enters at the crosshead bearing in so doing also providing for lubrication as well as cooling. The water cooled piston has the coolant directly introduced straight to the piston housing via a pipe and then to the piston pipe inserts.

5.2 Design Requirements of a Propulsion System

The design of a propulsion system mainly centres around the operational economics and environmental aspects. These are the primary influencing factors in the development of propulsion systems. The most difficult task in the early stages of the design in such a system, is the determination of the layout of the main propulsion system. In the following paragraphs a process in which a task of identifying the characteristics of a propulsion system will be discussed.

When approaching the design question for the first time, the task is made difficult, since not enough data is known, data being; the future trade patterns of the ship, and information regarding the behaviour of the propeller and the ship in heavy seas. It is important that the main engine is matched to the propeller and the ship in order to:

- give the lowest fuel cost per nautical mile at design speed and draught.
- to drive the ship at full load
- deliver enough power within safety margin ships speed
- have a lower rate of wear
- decrease maintenance work or increase mean time between overhauls (MTBO)

By using the data available and modelling techniques, a suitable propeller can be chosen together with a suitable engine as a prime mover for the system. This will allow the stated performance criteria to be achieved. The information required about the vessel is as follows;

design displacement	Δ_o
maximum displacement	Δ_{om}
design draught	D
breadth of waterline	B
length between perpendiculars	L_{pp}
design speed	V_{so}

5.2.1 Propeller Power Calculations

Using the above data and formulas, the power required to be delivered to the propeller is calculated by using a series of equations.

The propeller characteristics obtained are: the P/d ratio, A_E/A_O and K_T/J^2 curves. Knowing K_T and K_Q the power required at the propeller, then can be determined. The formula used is:

$$P_B = \frac{0.5144 R_T . V_S}{\eta_S . \eta_H \cdot \eta_R \cdot \eta_O} \quad \text{......} \quad (5.1)$$

where R_T and V_S are calculated by estimation methods.

P_B = Brake horse power (available power from Machinery)

η_S = 0.8 is shaft efficiency

η_H = (1-t)/(1-w) is aft efficiency

't' is thrust deduction factor and

'w' is wake fraction coefficient 0.231

η_R = 1.035 which is rotative efficiency

and η_O = propeller free flow efficiency found from the $(K_T J)/(K_Q . 2\pi)$

The 'P_B' can be refined through the model tests' results carried out in open water. The brake horse power needed is then calculated, after a series of calculations. Normally it will be slightly above the initial power.

5.2.2 Choice of the Prime Mover,

In choosing the main engine for propulsion the following parameters are considered

- power per revs per minute being delivered.
- physical size of the engine, length, width and height,
- maintenance cost and initial capital cost.

Using the technical information available from the manufacturers, a proper engine suitable for the calculated requirements is chosen. Comparison between different types of engines available is done critically and the correct suitable design is chosen. The propeller is normally customised later to match the engine. Designers have made it possible to match the main engine to the propeller and then ship in accordance to the customers requirements and the given specifications at an early stage of the design process. The engine room can be designed after the propulsion plant has been chosen. The main engine has its dimensions drawn with enough, revs/min reserves and power margins. The speed reserves are important for smaller ships hence when building such ships, more speed reserve should be built for calm seas. (Grossman, 1993).

5.3 Efficiency and Reliability of Propulsion Machinery

Definitions and Application:

Propulsion machinery can be split into three main components. These are:

a) The Prime Mover
b) The Transmission Arrangement
c) The Propulsor

In the previous discussion, the prime mover is the steam engine, Diesel engine, Gas engine or the Turbine. The transmission arrangement relies on gear arrangement units (if required), the thrust block, shafting systems and the propulsor (which refers to the paddle wheel, propeller and the steering arrangement incorporated). Thus the discussion following will look at the se three distinct areas of propulsion systems.

5.3.1 Efficiency of the Prime Mover

A definition of efficiency of a Prime Mover could be shortened to mean, improvement of performance, while reliability could be defined as low maintenance at optimal operation cost. Efficiency in such a case could be given in terms of thermodynamic principles.

thus $\eta_e = \eta_t \cdot \eta_i \cdot \eta_m$

where η_t = theoretical efficiency

η_i = indicative efficiency

η_m = mechanical efficiency

Theoretical efficiency depends upon the thermodynamic principles in the combustion chamber, hence by improving or increasing the P_{max} or other factors, the theoretical efficiency is greatly increased. One such example is the improvement attributed to the Sultzer and B&W research programs, where they have managed to increase Pmax in the cylinder to 180 bars in medium speed and 142 bars in slow speed engines.
This high increase of pressure requires a more efficient and better way of controlling the thermal temperature effects.

Given:

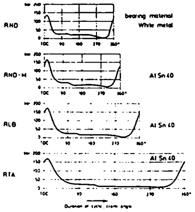
$$\eta_{t(carnot)} = 1 - \frac{T_2}{T_1} \quad \text{(5.2)}$$

where T_1 - lower heat source and T_2 - higher heat source

these resulted in other improvements e.g. the bore cooling improvements on the liner.

5.3.2 Bore Cooling Concept

This concept was introduced to take out the thermal stresses in the combustion area, while maintaining maximum compression pressures.



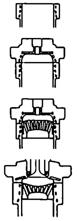
Maximum bearing loads for R-type engine crossheads

RN
1968

RN-M
1975

RL
1977

RTA
1982



Evolution of the use of bore cooling in Sulzer low speed engines

Figure 5 - 5: Bore Cooling Concept

Source: Osbourne, (1994), page 17-15

5.4 Reliability of Prime mover

Reliability mainly refers to low maintenance while achieving optimum performance. The basic reliability approach is by duplication of machinery hence, the shipowner will choose to have two Prime Movers for the propulsion machinery. This was initiated by Brunel in 1856 " *Installation of the Great Eastern*" after his disappointment with the Great Britain. The same was done on the liner "*The Titanic*", where four massive cylinder triple expansion steam engines were directly coupled to wing propeller shafts and these both expelled steam in one low pressure steam turbine directly coupled to the centre propeller.

Modern plants usually comprise combinations of diesel engines, steam turbines, gas turbines or electric motors.

Examples are given as follows:

1) COSAG: Combined Steam and Gas plant

   Mostly used for military, the gas plant is used first while the steam plant is being prepared. "Ready for sea quickly"

2) CODAG: Combined Diesel or Gas plant

   Uses Diesel for cruise speed with only the steam plant engaged for higher speeds. Only the gas turbine or Diesel engines can be used at one time.

3) CODAG: Combined diesel and Gas Turbine.

   All can be operated together with shared loads

4) CODLAG: Combined Gas turbine and Electric motor driven.

   Uses Gas turbine for maximum speed and electric motor for slow speed.

5) CODOG : Combined Diesel or Gas plant.

   Uses Diesel for cruise and modern Diesel is the most economical and light weight and gas is used for boost speeds. It uses either one or the other.

5.4.1 Redundancy arrangement

The most common form of redundancy is seen on the twin screw arrangement on most ferries and container ships. A twin screw quadruple engine is shown in figure 5 - 6.

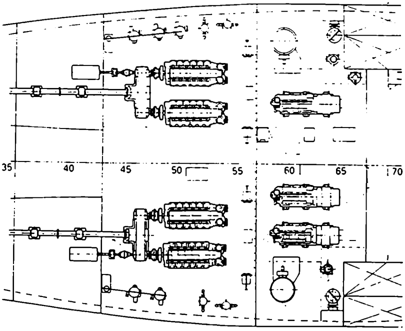


Figure 5 - 6: Twin Screw Installation of a Passenger Vessel.

source: Morgan, (1990), page 6/6.

5.4.2 Maintainability

The second form of reliability is one that looks at low maintenance, in terms of reduced time and low cost. It should be remembered that the maintenance cost are of great concern to the ship operator and the vessel only makes money when she is sailing.
From the discussion in chapter two, it was seen that the development of the Prime Mover was slow as the concept of proper maintenance was not yet adopted. One had to wait until failure occurred before any maintenance work would follow.

From this experience, it is seen that tremendous improvement in all areas is to be undertaken to improve the reliability of the Prime Mover. This is one of the advantages of the Diesel engine over the steam engine as it was difficult to improve the steam engine (despite what the turbine achieved).

Areas affected on the Diesel engine, which were improved are:

- improved fuel treatment and injection technics
- improved piston design
- improved cylinder liner lubrication
- improved cylinder and piston cooling techniques
- thick-pad bearing technology
- combustion anti-fouling ring
- improved air flow and turbocharger efficiency

These and many more are stages and areas of improvement that are still being employed to increase the reliability of the Diesel engine as a Prime Mover.

5.5 Environmental Concept

The dilemma today for the Diesel engine manufacture, is to meet the IMO low NO_X emissions limitations. The IMO NO_X limits the emission of exhaust from ships to 12g/kW. h NO_X at speeds of 720/750 rev/min. The biggest problem is to achieve this limitation without affecting specific fuel oil consumption and the overall efficiency of the diesel engine. Several manufacturers are researching into this matter in order to find out how they can meet the required standards. It was discovered that there was a trade off between NO_X emissions and fuel consumption. Therefore, all efforts to optimise the two are currently being sorted out.

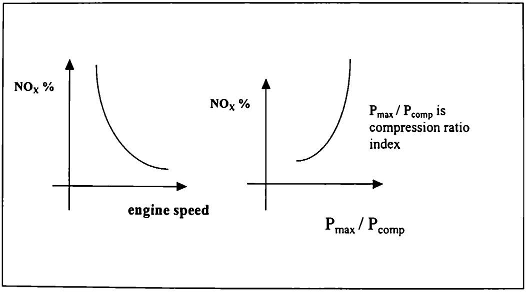


Figure 5 - 7: Relationship of NO_X and Engine Speed and P_{max}/P_{comp}

source: Masayoshi, (1992), Motor Ship.

5.6 Engine Performance and Condition Monitoring

As seen, engine reliability cannot be talked about without mentioning performance. For better performance, the first and foremost is the condition monitoring, which was principally done by personnel on watch but has recently been taken over by computer systems. The functions of such systems are:

a) Look after the condition of the raw data from the instrument and processing such data.
b) Thermal load monitoring in the cylinder environment
c) Monitoring the piston and liner temperatures
d) Direct monitoring and analysing of the combustion processes:
    - compression pressure
    - fuel pump delivery pressure
    - injection timing
    - fail safe system
    - exhaust emissions

The system principally comprises sensors (transducers) and processors which process the collected data and compare it with a set of values where a diagnosis can be made. The system may also give a recommendation as to the action to be taken or carry out corrective measures where needed i.e. reduction of speed or give an alarm indication.

5.7 Efficiency and Reliability of Propulsor

Most merchant vessels are fitted with a fixed or controllable pitch propeller. A new but old technology emerging is the use of the water jet propulsion. Efficiency of a propulsor mainly depends on the hull structure and the speed the vessel is moving. This is a direct relationship shown as a function of resistance and speed.

When the screw propeller was introduced in the 19th century, in the subsequent years to come, the use of the propeller was hit and miss. It was not until later on that other forms of propeller propulsion were introduced and the fixed pitch propeller made its mark. Now the CPP propeller has taken precedence over the others because of the various advantages which range from:

1) Engine plant operation at optimum speed avoiding overloading and variable loads
2) Spare blades are cheaper to replace one by one other than a complete solid fixed pitch propeller.
3) Ability to use the main engines for other auxiliary drives.

   Greater and more flexible manoeuvrability is achieved by thrusters, saving costs on employing tugs in a harbour.

The efficiency of the propeller is mainly affected by its physical dimensions which may include:

- propeller diameter which should be optimised.
- number of blades chosen (normally between 2 and 7) with 4 being the optimum.
- blade surface area, skewed surface reducing cavitation.
- blade thickness affecting the strength of the propeller for reliability to resist bending and fracture.

Other factors are:

- the boss diameter which should be minimal,
- rake- affecting tip-hull interaction,
- skew,
- blade clearance and
- propeller roughness.

To achieve reliability, the same concept of duplication is employed on certain ships and proper design of the propeller greatly increases the reliability. Propellers do not require any maintenance during operation before inspection and repairs are only carried out during a survey or when necessary.

CHAPTER SIX

6 SUMMARY AND CONCLUSION

6.1 Triggers of Evolution and Development

Combining the Technological changes and economic changes of the last two centuries constitute the development of ships and propulsion systems as they are seen today. If a visit is done on board a ship now, one finds a technological maze coupled with structures and systems that can not be compared to any land structure. This has come about due to hard work and untiring imaginations of several engineers, researchers and enthusiasts. In pursuing a quest for innovations and improvement the present ships of today exists as we see it. Technology is relied upon as to control and monitor operations in all areas of shipping.

6.1.1 Findings

The following factors and elements are those that triggered the change in maritime technology. These are:

1) Human activities

Exploration and discovery of New found land, the Americas, Southern Africa, and the Far East pioneered by the Spanish and the Portuguese. These were called the voyages of discovery and became very popular in Europe.

2) Quest for Commodities

The quest for commodities in the new found lands became intense. Trade had started in terms of certain commodities that were highly sought by traders in Europe. These commodities were tea, opium and precious metals (Gold), all these prompted people to travel and engage themselves in maritime trade.

- Due to the need for trade in foreign lands, larger and faster vessels were required. Therefore the ship owners were forced to design and built ships to meet this requirement. This resulted in large vessels with also large sail area to provide the required power. Skilled navigators were sought, to ascertain the return journey, as the sea routes were not yet charted.

3) War and Piracy

War and Piracy brought broke out on the high seas which brought about the importance of speed and swift craft in order to out manoeuvre the enemy.

- Therefore, the introduction of the *Naval Architecture* as a science to study the materials and structure of the vessel was started. The most successful in this area were the Clipper ships of the Americans. Also, this saw the coming of the *iron ship* and the improvement of materials used in building the ship's engine. A question of *reliability* started to creep in. Technology and improvements shifted back and forth the Atlantic.

4) Monopolistic & Capitalistic Ideas

Due to greed for special cargoes and more wealth, this brought about legislation and control over the maritime trade.

- Thus, the first Maritime Legislation and form of control was introduced.
- Dominance of the sea trade was broken as counties joined in the race for the maritime trade. This put pressure on those countries that had monopolistic ideas and were forced to change their legislation and this was the basis of *Conferences* and *Treaties*.

The points cited above could be said as the *human elements factors* that initiated the change in behaviours, and prompted those in the trade to advance and improve the marine vehicle.

6.2 The Technical Factors and Elements of Change

6.2.1 Steam Engine and Ships

The elements cited instituted an invention of technological ideas. The first was to fulfil the desired speed requirements. A reliable and efficient mode of powering the ships was required as the sail, and the handling gear became cumbersome. Hence the steam engine was adopted. Having been successful a shore in the mines, all that was required was to adapt it specifically for marine use. This technological advancement was first, successfully achieved by the Brunel with the first engine installed on the Great Western. Once it was successful a lot of enthusiasts, talented engineers and scientists embarked on the journey and several inventions. The paddle wheel and the screw propeller being one of their achievements. This invention met the goal of increasing the ships speed but also allowed for reduction in crew size that were required to handle the sail and sail handling gear, and just a few hands were required to attend the boiler and machinery. From this another skill emerged, and this was the *MARINE ENGINEER*.

Despite having all these inventions several problems were prevalent with the new designs and these were:

- the crude and non precision parts, as the science of material technology was still very low,
- heavy and bulky materials calling for more space for materials and parts of such items as boiler, engine, manoeuvring gear, the paddle wheel structure drive arrangement, resulting in reduced cargo space. Obviously this prompted for bigger ships that required more engine power to maintain the same crossing time. Because of this then the engine efficiency and

reliability had to be improved. This was then achieved with the Great Eastern, but still other factors crept in.

- travel to far away lands: more places were being discovered. requiring more cargo and people travelling. This put a demand for larger and high speed vessels.

Other problems were related to steam production and the steam boiler would not satisfy the requirement for more power. Large space, that could be used for cargo, was economically wasted, as the steam to be generated required even a greater amount of coal to be carried on board. To get more steam power higher boiler pressures were required, and to achieve this high fuel consumption was required. The steam engine had also problems related to mechanical linkages and rotating parts. Lubrication technology was undiscovered. Most of the parts rotating were so large that most of the energy was spent in rotating.these massive structures than the actually being used on the propulsion of the vessel itself. Lastly but not least problems associated with the steam installation was the power loss on transfer to the hull.

6.2.2 Diesel Engine and Ships

The Diesel engine came to fulfil the quest on powering of ships. After being convinced that the shipping business depended on a good propulsion system several trials and experiments were conducted on use of diesel propulsion.

The advantages came with the compactness of the ignition compression engine and also the power that would be produced to match a steam installation. There was a savings in terms of space. Some other advantages were:

- The great score for the engine was the fuel consumption which had proved to be better than the marine boiler. There was a direct relationship in engine room machinery and cargo space. Then, a discovery of using bunkers for marine diesel oil came to be an advantage than the steam engine installation which required coal that demanded larger space. The ship owner will always take advantage of savings, where ever, in terms of cargo space is concerned.

- Another advantage with the diesel engine is that it came at the time technology was improving also at land and was very flexible to adapt the changes, i.e. in Motor and Rail industry.

6.2.3 The Propulsion Systems

Propulsion for the vessels evolved through manual power, wind, and to mechanically driven tools. The paddle wheel proved to be superior before the invention of the screw propeller but it had its setbacks. Some of the deficiencies of the systems were as follows.

- The paddle wheel arrangement was so huge that, effective power was greatly reduced in order to keep the momentum of this structure.
- The number of cylinders to be used for an installation was limited due to the span of the vessel. The wheels were arranged sideways and because of this, the coming of the screw proper became more advantages than the paddle wheel arrangement. It was compact and could be arranged in-line with engine allowing for increase of cylinder numbers. This arrangement allowed for increase of propulsion power.

An illustration of the findings and the relationship of the events as they happened are given in the figure 6-1 in a form of a spiral. The events initiated are almost inter-linked and the causes and effects trigger each other that one ends up in a loop which never ends.

The figure shows the spiral of events and effects of change.

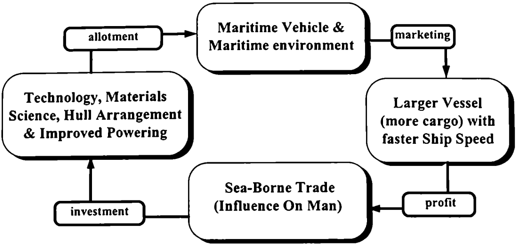


Figure 6-1: The Effects on Evolution and Development of Marine Vehicle

Demand for more cargo resulted in individuals having desires to improve the maritime vehicle and maritime environment. Therefore, the inputs to the system are : technology, material science, environmental science, hull science and powering calculations and designs, to the maritime vehicle and environment to achieve the desired needs. Each of the inventor had different inputs and sometimes unpredictable outputs. Therefore the cycle continued until somebody proved successful and the invention became success, i.e. Rudolf Diesel's *internal compression engine.*

6.3 Modern and Future Marine Propulsion Systems Technology

Looking at modern technology, one sees a tremendous improvement that has come about as a result of the inventions of the last century. In search for better technology and more power for speed, discoveries of the ignition compression engine, jet engine and turbine propulsion were achieved. The advantages of the ignition engine were so prevalent as it was a self contained and compact structure. It proved to be much safer than the steam engine itself, which was coupled with the boiler problems and its fuel inefficiencies.

6.3.1 Future of Steam and Marine Steam Engine

The principal use of steam today on a modern ship is in the Auxiliary Systems. Its application is seen in the over 50,000 kilowatt category where the gas turbine is dominant, and the boiler specially adopted for the marine environment. As for the steam engine, it could be concluded that it's use in marine industry is over (note that on land it is still being used especially on electric power installation). Some vessels still use the steam turbine for other purposes i.e. cargo pumps and, steam for other auxiliaries and heating functions .

Present boilers are more efficient than the 19^{th} century boilers, and the safety aspect of present boilers has greatly improved. Steam pressure has increased, as well as the quantity and quality has improved. Installation for heat recovery and emissions control are incorporated in order to conform with environmental protection laws.

In future a prediction could be made that the marine boiler as a source of steam could come back and provide energy for the main propulsion plant. This will burn coal which is cheaper fuel than diesel. An implication of this will be that a more efficient combustion system for the coal or mixture is to be designed. This system will need to have a more advanced heat recovery system and steam re-circulation circuits to produce, say, superheat steam, in order to upset the deficiency in achieving total efficiency. Such a system would be more applicable to larger vessels and heavy fuel consumers (like VLCC's and Bulk Carriers as currently being used), in order to reduce their operating costs.

6.3.2 Propulsion Systems

The screw propeller is taken as the high flyer of the last and this century. Looking at the present market of screw propellers, one can easily envisage that the design of propeller, has been widely exhausted. The scope and technology of the propeller ranges from the most popular fixed propeller to that of Controllable Pitch Propeller (CPP). The brand name 'KAMEWA', contra-rotating propeller, Voith Schneider propeller, self pitching propeller and the Grim wheel propeller are all popular house names. All claim improved efficiency and easier handling capabilities. Although the earlier invention of screw propeller was a great disappointment, (as witnessed on the Great Britain with loss of blades) the present screw propeller is protected from such misfortune. In conclusion it is felt that although the designs seem to be expended, the research and development in this area will still continue, especially where areas targeting matching of the propeller to the ship and prime mover are concerned. There is currently a greater demand for vessels in the range 1,000 SHP to 30,000 SHP, which can be fitted with any type of propeller mentioned. The ship owners concern is on reduction of operating costs, and fuel costs saving, which affects the choice of the propeller greatly. Therefore, increase in the propeller efficiency and matching technical skills are positive contribution and will always be welcome to the ship owner. The ships-owners' concern is to have a reliable and most efficient propulsion machinery installation.

Water Jet - Future Propulsion?

Another area of development for the future is the *Water-Jet Propulsion system*. Although depicted as the future technology its invention is old. Currently it is widely used and applied in fast ferry boats and leisure craft. The driving factor here is the speed. Therefore, where it is seen that the speed surpasses all the other factors then the choice of the water jet propulsion is inevitable. This trend will continue. Fast ferry boats, catamarans and leisure craft will be seen with water jet propulsion, especially when comfort and safety beats that of the present aircraft industry. The fast ferry boats may bring back the competition between water craft and aircraft especially having seen the sort of disasters that the air craft brings with zero survival rate. Therefore the water jet is here to stay, coupled with a more efficient prime mover.

6.3.3 Diesel Engine Installation

Future of the Diesel Engine.

The Diesel engine installation on marine vessels is the dominant type from now on, especially on merchant vessels of over 1,000 gross tonnage. The power ranges from 200 kW to 50,000 kW. The reason for this dominance has been;

- in its compactness,
- weight/power ratio,
- the ease for modification,
- the improvements in the individual parts i.e. the cylinder liner and combustion process and
- the safety aspects which surpasses all the other installations.

Diesel technology is the present dominant technology. Its future for the next half a century is guaranteed especially that now the quest for change is in operation and maintenance costs, are easily being achieved with the use of diesel engine. The market today demands speedy time and guaranteed delivery of goods. Vessels both passenger ferries and container ships with quick turn round time are more on high demand. The cost of manufacturing propulsion system is still a hinder as it still kept to a minimum. Hence, for the future, the designer of the marine diesel engine, needs to concentrate on how to make the engine more environmental friendly, while at the same time, trying to keep the production cost low and increase reliability of the product.

The technologies to be followed will be

- improved combustion processes,
- low NO_X emissions,
- improved and very adverse heat recovery processes,
- reduction of thermal losses,
- sludge treatment
- achievement of overall efficiency and
- improved reliability.

Previously the role of the diesel engine designer was associated with crude and heavy materials. The future engineer will be seen as one who is more technically oriented, environmentally concerned and a precision expert.

The Gas engine is coming stronger in the market especially as it fulfils the IMO environmental rules and recommendations on NO_X and Sulphur emissions IMO-MEPC 39/6/1 *Chapter 3 - Nitrogen allowable NO_X Emission Limits for Marine Diesel Engines* (Appendix - one). This puts pressure on the Diesel engine manufacturers to find ways and means of meeting this target. The regulations lay out an advantage to the high speed and medium speed engine manufacturers, as NO_X production decreases with increase of speed.

EPILOGUE : World trade which constitutes largely of seaborne trade, demands faster time, and lower voyage costs. Safety and Comfort of passengers and crew regulates the designs of present ships. Hence propulsion system installations which meet such criteria are in high demand for the ship owner. Depending on the type of vessels, the cargo being carried and ports of call, the propulsion machinery is almost picked from the shelf.

END

BIBLIOGRAPHY

GARDINER, R (1992). *The Shipping Revolution,* The Modern Merchant Shipping Conway Maritime Press, London, United Kingdom.

GRIFFITHS, D (1990). *Power Of The Great Liners: A History Of Marine Engineering*, Bath Press, Avon, UK.

Grossman, G, et al. (1993). *Matching Ship Propeller and Main Engine for world-wide Use...*, Marine Systems Design ICMES 93, IMER, 1993.

GUTHRIE, J (1971). *A History Of Marine Engineering*, Anchor Press, Essex UK.

HARTMANN, T (1983) *'The Guinness Book Of Ships And Shipping, Facts And Feats'*, JUPERLATIVES Limited,

MORGAN, N (1990). *Marine Technology Reference Book*, Butterworths & Co. Publishers Ltd, Essex Great Britain.

OSBOURNE A (1994). *Modern Marine Engineers' Manual*, Volume II, Second Edition, Cornell Maritime Press, Maryland USA.

RICHARD, J D (1996). *The Original Engine 1844 - 1846, of SS Great Britain.* In R.A Buchanaan (ed) Engineers and Engineering Papers of The Rolt Fellows, Bath University Press, UK.

SAIR, K.F (1981). *Development Of Marine Diesels,* MER, December 1981.

SPEARS, H.C.K (1981). *Steam Propulsion For Modern Ships*, Trans I Mare, 1978 Paper SP6, The Institute Of Marine Engineers, London, UK.

TAGGART, R (1969*) Marine Propulsion Principles & Evolution*, Gulf Publishing Company, Houston Texas, USA.

THE MOTOR SHIP, (1996). *"Redundancy Vs Reliability"* 18th Annual International Marine Propulsion Conference, 21 - 22 March 1996, The Radisson SAS Hotel, Hamburg.

THORSTEN, R et al. (1983*). The Commercial History Of Shipping*, Rinman & Lindén AB, Gotéborg, Sweden.

TORNBLAD, J (1987). *Marine Propellers And Propulsion Of Ships*, KAMEWA Vickers PLC Company, Kristenhamn, Sweden.

APPENDIX ONE

IMO document of NO_X emissions for environmental protection.

Contains Chapter 3 Nitrogen Oxides emission standards. (pages 103 -105) by the Administration in accordance with this Code, except when the owner's representative does not want the check through the ready means of verification. If some deficiencies are found, inspections may be extended to NO_x measurement in accordance with 6.3. The ready means of verification should be simpler and easier to use than other surveys, such as NO_x measurement.

2.4.3 As a general principle, a ready means of verification shall enable a surveyor to easily determine if an engine has remained in compliance with regulation 13 of Annex VI. At the same time, it shall not be so burdensome as to unduly delay the ship or to require in-depth knowledge of the characteristics of a particular engine or specialist measuring devices not available on board.

2.4.4 When a NO_x monitoring and recording device is specified as a ready means of verification, such device shall be approved by the Administration based on the guidelines developed by the Organization. These guidelines shall include, but are not limited to, the following items:

.1 a definition of continuous NO_x monitoring, taking into account both steady state and transitional operations of the engine;

.2 data recording, processing and retention;

.3 a specification for the equipment to ensure that its reliability is maintained during service;

.4 a specification for environmental testing of the device;

.5 a specification for the testing of the equipment to demonstrate that it has a suitable accuracy, repeatability and cross sensitivity compared with the applicable sections of this Code; and

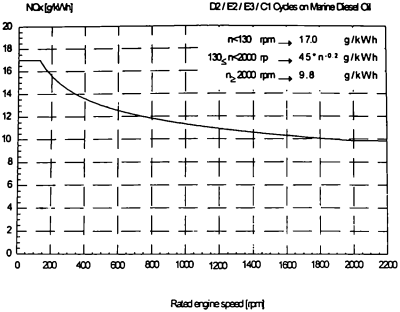
.6 the form of the approval certificate to be issued by the Administration.

2.4.5 When considering what ready means of verification should be included in an engine's Technical File to verify whether an engine complies with the NO_x emission limits during any of the required on-board verification surveys, an engine manufacturer or the ship owner may choose any of the three available ready means of verification specified in 6.1.

Chapter 3 - NITROGEN OXIDES EMISSION STANDARDS

3.1 MAXIMUM ALLOWABLE NO_x EMISSION LIMITS FOR MARINE DIESEL ENGINES

3.1.1 The graph in figure 1 represents the maximum allowable NO_x emission limit values based on the formulae included in paragraph 3(a) of regulation 13 of Annex VI. The total weighted NO_x emissions, as measured and calculated in accordance with the procedures in this Code, shall be equal to or less than the applicable value from the graph corresponding to the speed of the engine.



where n = rated engine speed (crankshaft revolutions per minute)

Figure 1. Maximum Allowable NO_x Emissions for Marine Diesel Engines

3.1.2 When the engine operates on marine diesel oil in accordance with 5.3, the total emission of nitrogen oxides (calculated as the total weighted emission of NO_2) shall be determined using the relevant test cycles and measurement methods as specified in this Code.

3.1.3 An engine's applicable exhaust emissions limit value from figure 1 and the actual calculated exhaust emissions value for the engine shall be stated on the engine's EIAPP Certificate.

3.2 TEST CYCLES AND WEIGHTING FACTORS TO BE APPLIED

3.2.1 For every individual engine or parent engine of an engine group or family, one of the test cycles specified in 3.2.2 to 3.2.6 shall be applied for verification of compliance with the NO_x emission limits in accordance with regulation 13 of Annex VI.

3.2.2 For constant speed marine engines for ship main propulsion, including diesel electric drive, test cycle **E2** shall be applied in accordance with table 1.

3.2.3 For variable pitch propeller sets, test cycle **E2** shall be applied in accordance with table 1.

Table 1. Test cycle for "Constant Speed Main Propulsion" Application (including Diesel Electric Drive and Variable Pitch Propeller Installations)

Test cycle type E2	Speed	100 %	100 %	100 %	100 %
	Power	100 %	75 %	50 %	25 %
	Weighting Factor	0.2	0.5	0.15	0.15

3.2.4 For propeller law operated main and propeller law operated auxiliary engines, test cycle **E3** shall be applied in accordance with table 2.

Table 2. Test cycle for "Propeller Law operated Main and Propeller Law operated Auxiliary Engine" Application

Test cycle type E3	Speed	100 %	91 %	80 %	63 %
	Power	100 %	75 %	50 %	25 %
	Weighting Factor	0.2	0.5	0.15	0.15

3.2.5 For constant speed auxiliary engines, test cycle **D2** shall be applied in accordance with table 3.

Table 3. Test cycle for "Constant Speed Auxiliary Engine" Application

Test cycle type D2	Speed	100 %	100 %	100 %	100 %	100 %
	Power	100 %	75 %	50 %	25 %	10 %
	Weighting Factor	0.05	0.25	0.3	0.3	0.1

3.2.6 For variable speed, variable load auxiliary engines, not included above, test cycle **C1** shall be applied in accordance with table 4.

Table 4. Test cycle for "Variable Speed, Variable Load Auxiliary Engine" Application

Test cycle type C1	Speed	Rated				Intermediate			Idle
	Torque %	100 %	75 %	50 %	10 %	100 %	75 %	50 %	0 %
	Weighting Factor	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

3.2.7 The torque figures given in test cycle C1 are percentage values which represent for a given test mode the ratio of the required torque to the maximum possible torque at this given speed.

3.2.8 The intermediate speed for test cycle C1 shall be declared by the manufacturer, taking into account the following requirements:

.1 For engines which are designed to operate over a speed range on a full load torque curve, the intermediate speed shall be the declared maximum torque speed if it occurs between 60% and 75% of rated speed.

.2 If the declared maximum torque speed is less than 60% of rated speed, then the intermediate speed shall be 60% of the rated speed.

.3 If the declared maximum torque speed is greater than 75% of the rated speed, then the intermediate speed shall be 75% of rated speed.

.4 For engines which are not designed to operate over a speed range on the full load torque curve at steady state conditions, the intermediate speed will typically be between 60% and 70% of the maximum rated speed.

3.2.9 If an engine manufacturer applies for a new test cycle application on an engine already certified under a different test cycle specified in 3.2.2 to 3.2.6, then it may not be necessary for that engine to undergo the full certification process for the new application. In this case, the engine manufacturer may apply the measurement results from the first certification test to the calculation of the total weighted emissions for the new test cycle application, but the corresponding weighting factors from the new test cycle must be applied.

Chapter 4 - APPROVAL FOR SERIALLY MANUFACTURED ENGINES: ENGINE FAMILY AND ENGINE GROUP CONCEPTS

4.1 GENERAL

4.1.1 To avoid certification testing of every engine for compliance with the NO_x emission limits, one of two approval concepts may be adopted, namely the engine family or the engine group concept.

4.1.2 The engine family concept may be applied to any series produced engines which, through their design: are proven to have similar exhaust emission characteristics, are used as produced, and, during installation on board, require no adjustments or modifications which could adversely affect the NO_x emissions.

4.1.3 The engine group concept may be applied to a smaller series of engines produced for similar engine application and which require minor adjustments and modifications during installation or in service on board. These engines are normally large power engines for main propulsion.

4.1.4 Initially the engine manufacturer may, at its discretion, determine whether engines should be covered by the engine family or engine group concept. In general, the type of application shall be based on whether the engines will be modified, and to what extent, after testing on a test bed.

4.2 DOCUMENTATION

4.2.1 All documentation for certification must be completed and suitably stamped by a certifying authority that is recognised by the Administration. This documentation shall also include all terms and conditions, including replacement of spare parts, to ensure that the engines maintain compliance with the required emission standards.