

The evolution of lubrication for marine propulsion systems

R. F. Thomas, C.Eng., F.I.Mar.E.
BP Marine International

SYNOPSIS

The paper traces the evolution of lubrication and lubricants for marine propulsion plants over a period of 200 years. An account is given of the birth of the modern petroleum industry and the effect this had on the lubricants used at sea. The development of lubricants for steam reciprocating, steam turbine and diesel machinery is discussed taking account of the change in the operating parameters for these various systems.

HISTORICAL BACKGROUND

By the beginning of the 18th century all the principles required for the steam engine were known and had been separately investigated. The integration of these principles was achieved by Thomas Newcomen, who, in about 1712, made the first use of steam power on land. In 1736, Jonathan Hulls, of England, patented a steam-propelled tug-boat, in which a paddle wheel at the stern was to have been driven by a Newcomen engine. The proposals do not appear to have attracted much attention when they were published and the scheme never had a practical trial.

The first boat to be actually driven by steam power was that used by J. C. Périer in 1775 for an experiment on the river Seine, near Paris. Further experiments were carried out by Marquis Claude de Jouffroy d'Abbans, resulting in the *Pyroscaphe* working for 15 minutes against the current on the river Saone near Lyon in 1783. Unfortunately, Jouffroy failed to obtain the necessary support from the French Government and the Revolution later interrupted his experiments.

Pioneer work on marine steam propulsion was not confined to Europe. In 1786 the American inventor John Fitch of Windsor, Connecticut, demonstrated his first steam-driven boat on the river Delaware. He completed another boat 2 years later, some 18 m in length, with one steam cylinder 300 mm in diameter. On 12th October 1788 this steamed from Philadelphia to Burlington, a distance of 20 miles at a mean speed of 5.5 knots. In 1790, Fitch started a public service on the river Delaware with a steamboat propelled by paddles at the stern. These were driven by a beam engine with one cylinder 450 mm in diameter, and a speed of approximately 7 knots was achieved. Although the service was advertised in the local paper it was not commercially successful. Another pioneer in America was James Rumsey who, in 1787, demonstrated a steamboat with water jet propulsion on the river Potomac. Later he came to England and a steamboat of approximately 100 tonnes built to his principle attained 4 knots during trials on the river Thames in 1793.

Meanwhile, important developments had taken place in Great Britain as a result of experiments in mechanical propulsion made by Patrick Miller (as shown in Fig. 1). Newspaper reports of the day gave an account of the experiment which took place on 14th October 1788¹. Among those on board was Robert Burns, the poet, who was a tenant of Patrick Miller and William Symington whose new patent engine propelled the craft. Later in 1801 Symington was commissioned by Lord

Mr. R. F. Thomas is Group Head Technical Service in BP Marine International and joined BP Tanker company Limited in 1958 as Engineer Cadet under the alternative training scheme. On completion of his cadetship he served as an engineer in the fleet before taking up a shore appointment in 1971. Since then he has held various positions in the BP Group before taking up his present appointment in 1984. In 1981 he was awarded the Denny Gold Medal for his paper Development of Marine Fuel Standards.

Dundas to engine a steam tug-boat, the *Charlotte Dundas*, for experiments on the Forth and Clyde canal. This vessel has been described as the first practical steamboat.

The American pioneer, Robert Fulton, attended the trials and in the course of the next year built his first experimental steamboat in Paris and carried out trials on the river Seine. He later achieved commercial success in 1807 on the river Hudson, between New York and Albany, with the P.S. *Clermont*. In Europe the first steamer to operate commercially was the P.S. *Comet* in 1812 which initially ran between Glasgow and Helensburgh on the river Clyde in Scotland. The P.S. *Savannah* was the first steam vessel to cross the Atlantic, or indeed any ocean, in 1819. In fact, she was a sailing ship adapted for auxiliary steam propulsion. She had one steam cylinder 1000 mm in diameter with a 1.5 m stroke, operated from a boiler at 0.07 bar (1 p.s.i.g.).

It was, however, some years before steam navigation had any real impact on ocean transportation. In 1838 the P.S. *Sirius* was the first vessel to cross the Atlantic under continuous steam power. This was possible because she was one of the first Atlantic steamers to be fitted with condensers, thus eliminating stops to de-salt the boilers. The boiler pressure had also started to rise as shown in Fig. 2¹.

INTRODUCTION

Before the birth of the modern petroleum industry and the availability of mineral oil, effectively the only lubricants available were fixed oils. Fixed oils are not volatile without decomposition and are obtained from certain tissues of animals or plants. Their fundamental difference when compared with

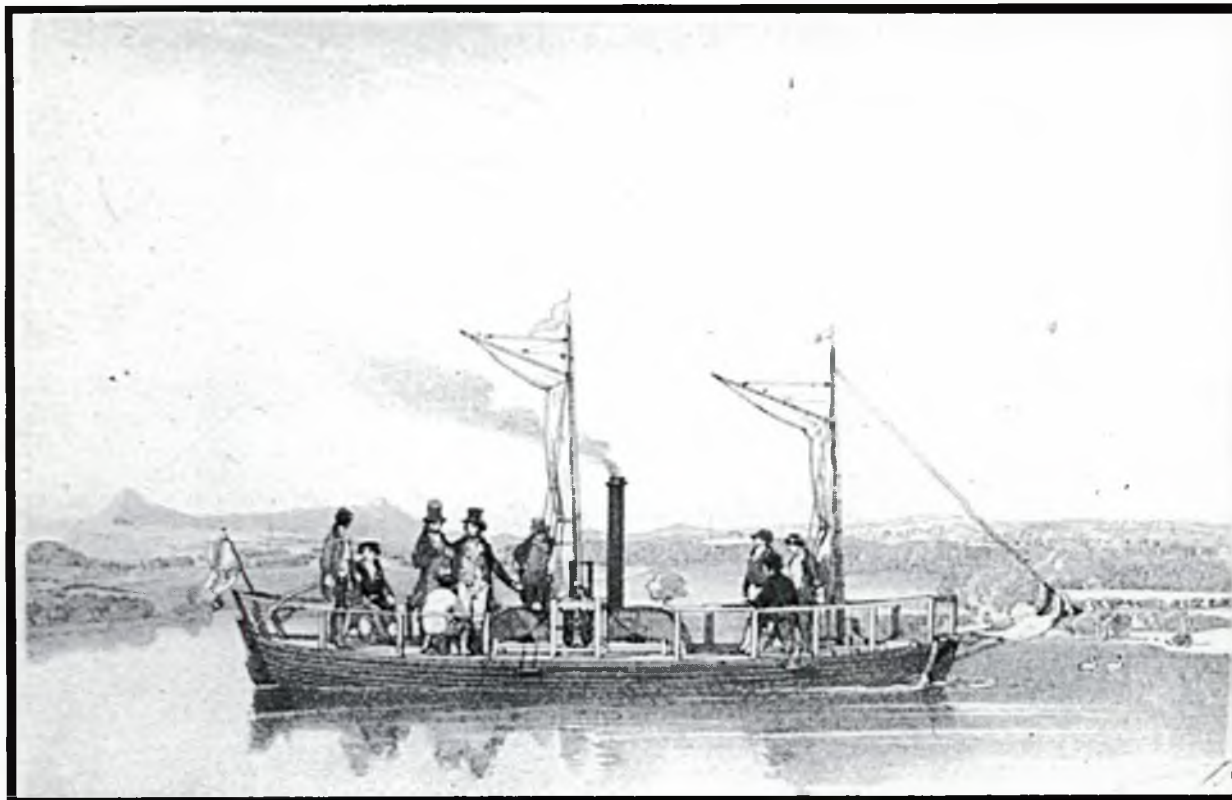


Fig. 1. Patrick Miller's Steamboat (1788)

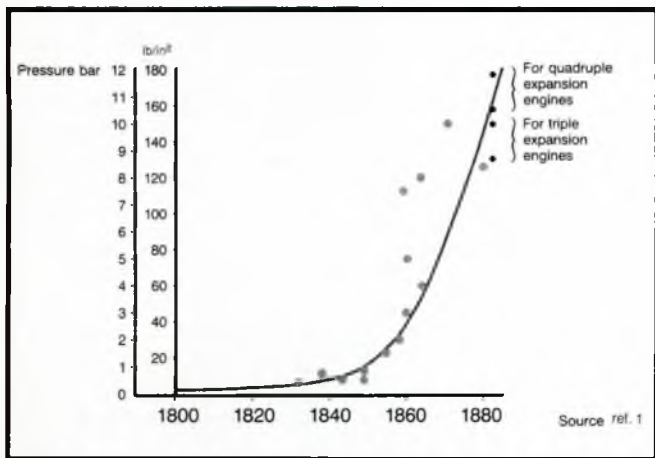


Fig. 2. Operating pressure of marine boilers, 1800–1880s

Table 1. Main fixed oils applicable to marine lubrication

Animal oils/fats	Vegetable oils
Tallow	Castor
Tallow oil	Rape (Colza)
Lard oil	Olive
Neatsfoot oil	

mineral oil is that oxygen is an essential constituent. The distinction between fixed oils and fats is one of temperature, in that all fixed oils become fats at low temperatures and all fats become oils above 60°C.

Animal oils are obtained by heating the fatty tissues of animals or by boiling out the fatty oil with water. Vegetable oils occur mostly in the seeds or fruits of plants or trees and are obtained by pressing or by chemical extraction with solvents. Animal oils are usually either colourless or yellow, whilst vegetable oils can be colourless, yellow or slightly green due to the presence of chlorophyll.

Table 1 shows the main fixed oils applicable to marine lubrication.

SOURCES OF FIXED OILS

Tallow is the fat from certain animals, beef tallow is obtained from oxen and mutton tallow from sheep and goats. On a small scale the rendering of the fat is carried out by heating which can be with direct heat or by boiling in water. In rendering tallow for lubrication, it is important to use only fresh fat and to remove by setting and straining all water and extraneous matter which by subsequent decomposition might cause the tallow to become acidic. Tallow at 15–25°C is a mixture of solid and fluid fats. When used for lubrication it should preferably not contain more than 4% of free fatty acid. Overall, beef tallow is less inclined to become rancid than mutton tallow. If tallow is subjected to pressure the liquid portion can be separated out and this is known as tallow oil. Acidless tallow oil is carefully made tallow oil.

Table 2. Typical characteristics of fixed oils

Product	Density at 15°C (kg/litre)	Viscosity (cSt)		Viscosity index (VI)	Open flash point (°C)	Free fatty acid (%)	Pour point (°C)	Drying characteristics
		at 40°C	at 100°C					
Tallow (beef or mutton)	0.935-0.950	44.5	9.12	193	285-310	2-10	38 to 51	Non
Tallow oil	0.913-0.918	-	-	-	280-315	1-5	0 to 3	Non
Lard oil	0.914-0.917	} 47	5.76	38	260-315	3-25	0 to 15	Non
Neatsfoot oil	0.914-0.917							
Castor oil	0.960-0.966	250	18.7	81	275-295	1-6	-13 to -9	Non
Rape or colza oil	0.913-0.916	44.7	9.31	198	275-295	3-3	-9 to -2	Semi
Olive oil	0.915-0.938	39.5	8.14	186	245-320	3-20	-2 to 7	Non

Source: refs. 2 and 3.

Table 3. Summary of typical characteristics of fixed oils

Density (at 15°C)	0.91-0.95 kg/litre
Viscosity	Low-medium
Viscosity index	Medium-high
Oxidation stability	Very low
Load carrying	High
Water resistance	Low
Corrosion resistance	Low
High temperature performance	Low

Lard oil is pressed from pig fat and is made in a similar manner to tallow oil. The temperature at which it is pressed determines the setting temperature which may range from 0 to 15°C. Prime lard oil is nearly colourless with a pale yellow or greenish tinge.

Neatsfoot oil is obtained by boiling the feet and hocks of oxen in water and skimming off the fat which rises to the surface. Commercial neatsfoot oil often included the feet of sheep and horses. The result is nearly odourless oil which in the early days was esteemed as a lubricant for engines and heavy machinery.

Castor oil is obtained from the seeds of the castor tree or shrub which grows in all tropical and sub-tropical countries. The kernel forms 80% of the seed and yields approximately 50% of its weight in oil. The oil is extracted by pressing and is refined by steam and filtration. When properly refined it keeps well and does not easily turn rancid. Castor oil is an excellent lubricant which possesses great 'oiliness'.

Rape oil, otherwise known as colza oil, is obtained from the seeds of wild turnips which can be grown in temperate or sub-tropical climates. The process is that of pressing or extraction with solvents. Crude rape oil is dark in colour and sometimes contains impurities which are removed by treatment with sulphuric acid followed by agitation with steam and hot water. This treatment has to be carefully controlled, because slimy deposits can remain if it is insufficient, whilst excessive treatment can result in the development of extra free fatty acid.

Olive oil is obtained from the fruit of the cultivated olive tree which grows mainly in countries bordering the Mediterranean or where there is a suitable climate. The finest olive oil is obtained by hand picking the olives before they become too

ripe, gently pressing them by hand and collecting the oil. This oil, which is used for salads as well as lubrication, is known as 'virgin oil'. Olive oil from the second pressing which is carried out with heat is also suitable for lubrication but as it contains a rather high percentage of free fatty acid it easily becomes rancid.

The main typical physical characteristics of fixed oils are shown in Tables 2 and 3.

EARLY LUBRICATION OF STEAM RECIPROCATING MACHINERY

The principles of lubrication of steam reciprocating machinery have remained unaltered since the days of the first experimenter. What has evolved is the lubricant and the environment in which it has to operate.

Irrespective of the type of steam reciprocating engine, cylinder lubrication is required to perform two functions at an elevated temperature. It has to form the seal between the piston ring and liner and also prevent frictional wear. As the mean piston speeds were very low with the early engines it is unlikely that fluid film conditions existed even at mid-stroke. With the later engines, although fluid film conditions may have existed for part of the stroke, boundary lubrication would have occurred at the extremities.

Prior to the introduction of mineral oil, the fixed oil used for cylinder lubrication was tallow. This would have been heated, probably in a kettle on the top of the cylinder and applied intermittently through a grease cup on the cylinder head. By today's standards this seems a primitive method, but by all accounts was satisfactory. Engine designers, however, increased boiler pressures and hence the steam temperature, as shown in Fig. 2. The importance of this, from the lubrication aspect, is the effect of temperature and steam on tallow. Fats, when exposed to the action of heat and steam, decompose to give fatty acids and glycerine, which over a period of time may give rise to very serious corrosion. In many instances the result was porosity of the cylinder and general wastage of associated parts. In severe cases the steam passages also became choked with metallic soaps, oxides of iron and free carbon. Apparently it was some time before the chemists were able to show the marine engineer that the mechanism was the same in principle as that used for making candles.

The fundamental difference was that in the manufacture of candles extreme care was taken to avoid any contamination. Alternative cylinder lubricants became available as a result of the birth of the modern mineral oil industry (discussed later).

Lubrication was also required for the bearings which for the earlier engines were situated in open crankcases known as open-fronted engines. The oil originally used for this purpose was probably determined by the trading pattern of the vessel which dictated the availability and cost of the various lubricants. For example rape oil, because of its fairly widespread availability, was a popular choice, as was olive oil. Castor oil was used in the East Indies, where it was plentiful and cheap.

In addition to these lubricants the engineer frequently used flowers of sulphur (pure, ground, crystalline sulphur) in the event of a bearing running hot. The practice was to pour some down the oil holes and the result depended on the heat of the bearing. It appears that the function of the flowers of sulphur was to combine with the brass dust and brass ridges to form sulphides of the metals which were softer than the bearing metals. Being in a plastic state, this lined the bearings and provided a new surface for the journal to run in. If this theory is correct flowers of sulphur cannot be considered as a true lubricant but rather one means of controlling a hot bearing until remedial action can be carried out.

BIRTH OF THE MODERN MINERAL OIL INDUSTRY

From the literature it appears that James Young from Glasgow, Scotland, can be considered responsible for the birth of the modern petroleum industry and the availability of lubricating oils based on mineral oil. In 1847, James Young leased a small petroleum spring in Northern England and refined the products. The spring was however exhausted over a period of 2–3 years, but it directed his attention to the discovery of methods by which liquid hydrocarbons could be artificially produced. This led to the start of the shale oil industry and his patent, no. 13992, on 17th October 1850, which may be regarded as the inauguration of the modern petroleum industry. Being in possession of the master patent, Young granted licences to various companies in America and elsewhere for the production of finished oils from coal, shale and crude oil.

Among the first countries in which petroleum was worked on a commercial scale was Burma, the source of Rangoon petroleum. The value of the oil had long been appreciated and various attempts had been made to refine it. In 1853 a process was invented by Warren De La Rue and the patent was acquired by Prices Patent Candle Company. The company sent agents to Burma to arrange regular supplies of crude for shipping to England where it was refined to give wax for candle making, oil for lubrication and oil for illumination.

Prior to the discovery of oil by Colonel Drake in Pennsylvania on 28th August 1859, there had been a thriving export trade of refined products to America. Following this initial discovery numerous other wells were sunk in the neighbourhood and the petroleum industry of the United States was launched.

With the availability of mineral oil for lubricating oil one might have expected an early and widespread adoption of mineral oil for the lubrication of marine propulsion systems. This, however, was not the case as the early mineral oils, which were produced by simple distillation, had properties which were inferior to those of fixed oils. Instead, 'compound oils' were introduced which have better properties than fixed oils.

DEVELOPMENT OF STEAM CYLINDER OILS

Reference to Fig. 2 shows the increase in operating pressure and hence temperature to which the cylinder lubricant was subjected. Although experiments were carried out as early as 1856 on the concept of superheating steam, it was not until 1872 that a design was patented and a boiler was built with a working pressure of 6.8 bar. Initially the installed superheater arrangements were little more than a steam drier and it was not until the latter part of the 19th century that true superheating was adopted for marine propulsion systems.

With the advent of higher steam pressures there was a general requirement for more viscous cylinder oils. The early mineral oil-based lubricants, although having a greater viscosity range than fixed oils, were not highly refined and did not have the 'oiliness' characteristic of fixed oils. In order to overcome this deficiency 'compounded oils' were introduced containing mineral oil and fixed oil. The proportion of fixed oil varied according to the steam conditions and was in the order of 5–10%. Usually, the fixed oil was acidless tallow derived from tallow. One might have expected decomposition of the fixed oil component in those compounded oils to be in the form of fatty acid. However, being in such a small proportion there was no adverse effect, rather the fixed oil component tended to prevent carbonized matter from the mineral oil component being baked and forming crusts.

The action of wet steam in the cylinder has the effect of washing away the oil film on the internal surfaces. Although the steam enters the high-pressure cylinder of a compound or triple expansion engine in a dry state, the fall in steam pressure on expansion produces condensation, to the extent that generally the steam arriving at the low-pressure cylinder is very wet.

To lubricate the cylinder under wet conditions the cylinder oil must readily combine with the moisture and cling to the cylinder wall. It was therefore essential that such oil was compounded. Whilst it was not necessary to have such a high viscosity as that for the high-pressure cylinder, low-pressure wet cylinders required a more compounded oil, in the order of 10% fixed oil.

Impurities in the steam could have an effect by combining with the cylinder oil and forming deposits. The greater the viscosity of the oil, the more difficult it was to avoid such deposits because of the tenacious nature of the high-viscosity oils and their ability to retain the impurities. Lower-viscosity oils were preferable when there was a high probability of impurities entering with the steam. This was particularly the case under conditions of superheat.

The presence of impurities usually meant that the boiler had 'primed' and, as under such conditions the steam was initially wet, heavily compounded oils were the general rule. Priming can occur for various reasons; namely water reaching the steam outlet because of too high a water level, and excessive steaming or a sudden excess demand for steam when the boiler is operating at low load. There was an exception to the rule in that under conditions of high superheat when in a 'priming' situation, only dry boiler salts would have reached the cylinder. These dry salts contained alkali from the boiler treatment and would have formed a soap with the tallow present in the cylinder oil. This would have aggravated the deposit problems, whereas if a straight mineral oil had been used, soap could not have been formed.

For saturated low-pressure steam conditions there is no great difference between dark and filtered cylinder oil with respect to deposit formation by impurities. It should be noted

that filtered cylinder oils are derived from dark cylinder oils by repeated filtration to give a degree of transparency and such oils are sometimes described as amber oils. For superheat steam conditions filtered oils were superior because in dry, high-temperature conditions the bituminous matter in dark oils combined with the impurities decomposed by oxidation to form brittle carbon.

In general, the presence of impurities under saturated steam conditions requires compounded oil, whilst impurities under superheat conditions demand mineral oils which have been filtered.

On a ship, consideration has to be given to the extraction of the oil from the exhaust steam to eliminate the danger of the oil returning to the boiler. All compounded oils were difficult to extract in comparison with mineral oils. Dark oils, however, combine with the water to form semi-emulsified clots and a trace goes into a fine emulsion.

Overall it was found that more straight mineral oil was required when compared with a compounded oil to give the required cylinder lubrication. Hence the best practical results were given by using a slightly compounded cylinder oil to give efficient and economical lubrication.

The cylinder oil consumption depended on the size of the engine with larger engines requiring less on a g/bhp h basis than smaller engines. Wet steam conditions required more oil than dry or superheat conditions. In these conditions, especially where there was a possibility of steam impurity, the oil had to be applied as economically as possible. In general the consumption was in the range 0.05–0.6 g/bhp h.

Earlier reference has been made to the long-term effect of the fatty acids of fixed oils under conditions of heat and steam. Changeover to a compounded oil had to be carried out over a period of at least 3 months. During this time the proportion of compounded oil was gradually increased so as to give the acid products from decomposition time to loosen and get cleared through the exhaust. If the compounded oil was introduced too quickly, the deposits were rapidly dissolved resulting in excessive scoring and wear of the cylinder. To prevent even more damage it would have been necessary to revert to the fixed oil and repeat the changeover in a controlled manner.

Before the effective final demise of steam reciprocating machinery for main propulsion purposes, quadruple engines were built incorporating high superheat temperatures in the order of 350°C. Indeed some systems were built with reheaters, so extending the dry steam conditions to the intermediate cylinders. For these exacting conditions a high-quality unfil-

tered, dark cylinder oil was used. For medium superheat a filtered oil with low carbon-forming properties was recommended. If only one steam cylinder oil was carried on board for the purpose of grade rationalization its properties had to be a compromise between those required for high-temperature dry steam conditions and those for low-temperature wet conditions. The advent of an adhesive additive to give 'oiliness', which was the key feature of fixed oils, resulted in less compounding and enabled feed rates to be reduced.

In concluding this review of steam cylinder oils it should be noted that these oils were more viscous than diesel cylinder lubricants. This superficially appears to be wrong when comparing the maximum steam temperature (350°C) with the peak temperature of a diesel engine cylinder (1800°C). As the diesel liner is effectively water-cooled the maximum surface temperature is only in the order of 220°C, whilst in the steam engine positive steps are taken to maintain the liner temperature as high as possible to prevent condensation. Hence the average temperature of the cylinder liner in a high-pressure steam engine is considerably higher than that for a diesel engine. A selection of mineral-based steam cylinder oils is shown in Table 4.

DEVELOPMENT OF BEARING OILS

The bearings and other external parts of steam reciprocating engines, whilst not subjected to the temperatures seen in the cylinders, experience low rubbing speeds and high bearing loads. For engines operating below 150 rev./min the usual arrangement was for the engine to be open-fronted and to have a 'once through' system of lubrication. The oil having passed once through the bearings drained to waste. In all early engines the oil supply was intermittent and as the engine evolved, wick-feed or siphon oilers were generally used. Clearly, under such conditions fluid film lubrication could not exist and hence it was important to have an oil which possessed good boundary characteristics.

In multi-cylinder engines the top end bearing of the high-pressure cylinder was subjected to fairly high temperatures because of conduction by way of the piston rod, whilst the low-pressure cylinder top end bearing may have had to contend with a considerable amount of water leaking from the glands.

It was important that besides being a good boundary lubricant, the oil used should either resist the washing effect of water or emulsify with it. The basic requirements were met by fixed

Table 4. Mineral steam cylinder oils

Application	Density at 15°C (kg/litre)	Flashpoint COC (°C)	Pour point (°C)	Kinematic viscosity (cSt)		Viscosity index (VI)	Remarks
				40°C	100°C		
High superheat	0.913	333	6	980	49	95	High quality, paraffinic dark cylinder oil
Medium superheat	0.900	294	-9	500	32	95	
Low superheat and dry saturated	0.914	288	6	1000	53	100	Compounded oil
Wet saturated	0.932	288	-6	740	36	79	Compounded oil

oils and the use of mineral oil initially met with resistance by some shipowners. This resistance came from the shipowners' wish to carry the minimum number of grades of oil, as at that time rape or colza oil was used for bearing lubrication as well as for lighting.

At around 1870 a process was developed for artificially thickening vegetable oils to give 'blown' fixed oils. These oils were manufactured by blowing the fixed oils with hot air (70–120°C) under controlled conditions. The result, due to oxidation, was an increase in density and viscosity. Eventually rape oil or blown rape oil was compounded into mineral oil for the manufacture of marine bearing oils. The proportion of fixed oil was in the range 10–25%.

For those steam reciprocating engines for main propulsion systems, which in later years had enclosed crankcases, a different system of lubrication was used. For these enclosed crankcases a full oil circulation system could be used with oil being supplied at 2–3 bar. It was essential that the oil used had a high resistance to emulsification, so that any water entering the crankcase could be drained off at suitable intervals. On many vessels centrifuges were fitted for purification of the system oil. These requirements which were effectively diametrically opposite to that for open-fronted engines were met by the use of carefully selected straight mineral oils.

DEVELOPMENT OF STEAM TURBINE OILS

The first practical steam turbine was patented and built by Charles Parsons in 1884. This was one of the most significant events in the evolution of heat engines and brought to fruition the dreams of scientists and engineers who, over the centuries, had been fascinated by the problem of rotary power. In 1894, the first turbine-driven vessel called *Turbinia* was built on the River Tyne under the direction of Parsons. Various modifications were made to overcome propeller cavitation problems and in 1897 the vessel made a dramatic appearance at the Spithead naval review, when spectators were amazed at its speed of 34.5 knots. By this time the turbine had already been used commercially for land power generation. However, the first commercial turbine-driven vessel in the world was the Clyde steamer *King Edward* in 1901. Development was rapid and in 1906 the *Mauretania* entered service with turbines of some 52 MW. Fig. 3 shows the *Turbinia* alongside the *Mauretania*. Both the *Turbinia* and the *Mauretania* had direct drive, but to adapt the steam turbine for propelling low-speed vessels it was necessary to introduce reduction gearing. Initially this was single reduction, in later years double reduction and in some instances epicyclic. The bearings of a marine steam turbine represent one of the best examples of fluid film lubrication, as the speeds are high and the bearing loads low. A low-viscosity oil to reduce fluid friction to a minimum would be ideal under these conditions. As there is considerable heat, by conduction through the rotor, the lower the viscosity of the oil, the more efficient the cooling. On the other hand for lubricating the gears, which have a high tooth loading, a low-viscosity oil would not be sufficient and a higher-viscosity oil was essential to prevent excessive wear.

Historically, the concept of two separate oils has been considered by engine builders but has always been discarded at an embryonic stage because of the additional complications and higher capital cost, hence marine turbine oils must be a compromise in viscosity.

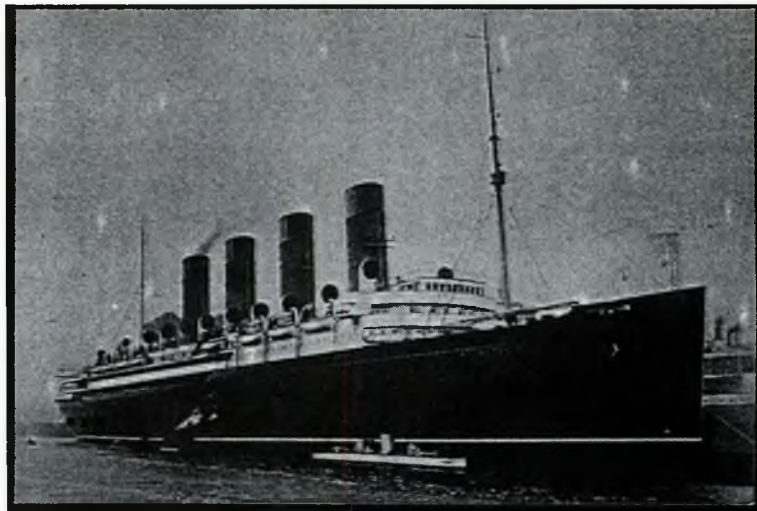


Fig. 3. Illustration of *Turbinia* alongside *Mauretania* (1906)

The first marine steam turbine oils were equivalent in their viscosity to an SAE 30 grade plain mineral oil, but these were found to be too viscous and a low-viscosity grade of the same type was adopted. Even though the oil has to lubricate the gears, in general, marine turbine oils are at the upper end of the SAE 20 range and lower end of SAE 30.

It is essential that a marine turbine has good demulsibility characteristics, namely the ability to separate readily from water which is mainly condensed steam, thus the oil must be free from any emulsifying substances such as soaps or fatty acids. Plain mineral oils chemically change as a result of oxidation, which is caused by their reaction with oxygen under high temperature and the catalytic effect of certain metals, namely copper and iron oxides. If left in service for a long period of time, in practical terms the oil would darken (become acidic), develop an odour, develop emulsifiers and form a sludge.

In the late 1920s the industry adopted solvent-refined oils, resulting in the significant reduction of emulsion problems. The oils, at the time, were referred to as 'non-sludging'. Even these oils, however, after long periods of use, still produced high acidities and caused rusting of the ferrous surfaces above the oil level. These rust particles dropped back into the oil, catalysed further oxidation, scored bearings and caused malfunctions of associated servo systems.

By the early 1940s oxidation-inhibited versions of these solvent-refined oils were introduced which had a significantly lower tendency to oxidize. Acidic products were therefore not produced at the same rate and the problem of vapour space rusting was effectively reduced. A new problem appeared, namely rusting below the oil level in new turbines which was seen as black magnetic oxide.

The next evolutionary stage was to find suitable materials to add to the oxidation-inhibited oil to provide the required protection against rusting without affecting the oxidation stability, good demulsibility or other necessary properties. This led to the development of a suitable rust inhibitor and oils containing both oxidation, and rust inhibitors are often referred to as 'double inhibited' or 'R and O' (rust and oxidation-inhibited) oils.

Modern turbine oils besides being 'double inhibited' also contain a special anti-foam agent. Foaming is basically similar to emulsification, as both foam and emulsion consist of one phase dispersed in another, namely the oil. Good anti-foam characteristics are required as excessive foam can lead to oxi-

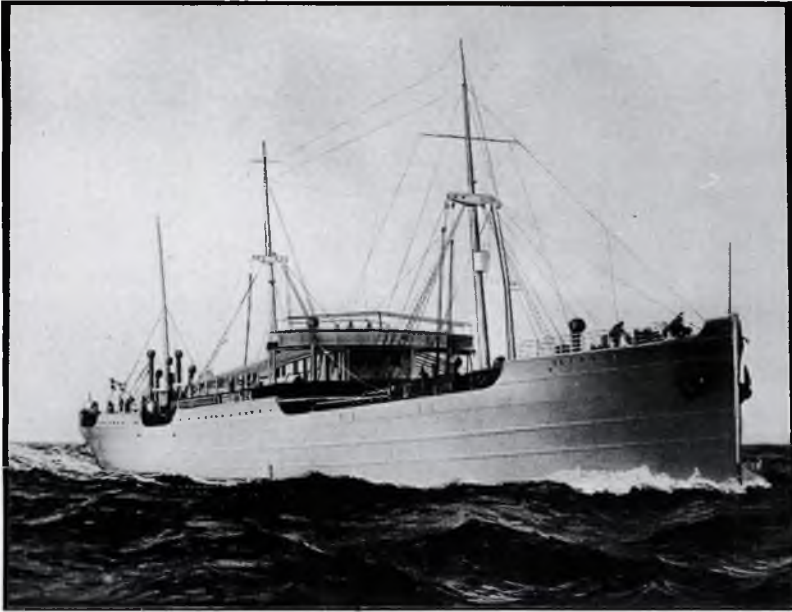


Fig. 4. M.V. *Selandia*

dition. Where the oil is used as a hydraulic medium, entrained air, being compressible, could lead to erratic operation of the governing system. By suitable viscosity selection a good turbine oil has an adequate load-carrying characteristic. If this needs to be enhanced for an advanced steam turbine system a suitable extreme pressure additive is included.

DEVELOPMENT OF MARINE INTERNAL COMBUSTION ENGINES

In 1888 the internal combustion principle was first applied for marine use in an 8.5 m launch built at Hull and fitted with a Priestman 2-cylinder engine which burnt either petrol or paraffin oil. Another important development was the 'hot bulb' engine which was introduced by Akroyd Stuart in 1890. For this engine the fuel was injected at the end of each compression stroke to be vaporized and ignited by the 'hot bulb' extension of the cylinder head. The bulb was heated externally by a blow lamp to red heat before starting the engine and once started there was sufficient residual heat to maintain the cycle.

Dr. Rudolf Diesel formulated his original engine cycle concept in his 1892 paper "The theory and construction of a rational heat motor to replace the steam engine and the present day heat motors". His calculations indicated a theoretical thermal efficiency of 55% and he forecast that 47% was practical.

The earliest motorship on record was an oil tanker, the *Vandel*, built in St. Petersburg (now Leningrad) in 1904, for use on the Caspian Sea and she was fitted with non-reversing engines of 270 kW with electrical transmission. She was followed by two similar vessels, the *Delo* and *Emanuel Nobel*. In 1910 the first diesel engine for ocean service was built, a Dutch oil tanker *Vulcanus*, whilst the first motor cargo vessel was the *Selandia* (shown in Fig. 4), built in 1911. These vessels were fitted with what were called 'heavy oil engines'. In fact they operated on diesel fuel and it was many years later that the use of residual fuel was adopted.

The heavy oil engines had both their supporters and detractors. In 1912, Sir Marcus Samuel said that the *Vulcanus* had

"demonstrated beyond any possible doubt that anyone who goes on building steam engines with the knowledge which is now afforded is only courting disaster"⁴. This view was not shared by everybody and in 1914 Mr. J. Hamilton Gibson remarked, "Frankly, I do not like the idea of propelling large vessels by means of a series of explosions in a battery of oil or gas engines... In fact, it has been well said that the problems are more suited to the gunner than to the engineer"⁵.

DIESEL ENGINE CYLINDER LUBRICANTS

Irrespective of the type of diesel engine or the fuel which is burnt, the function of the cylinder lubricant is to prevent gas leakage by forming a seal between the ring pack and the liner and to minimize wear. Fundamentally these are the same functions as those required for cylinder lubrication of a steam reciprocating engine, except that the causes of wear are more complex. Indeed this subject is probably the most controversial topic surrounding diesel engines and the causes of wear

can be broadly classified as follows:

- Frictional
- Abrasive
- Corrosive

Frictional wear is caused by metal-to-metal contact. Abrasive wear is caused by ash from incomplete combustion of the fuel and by entrained debris in the combustion gases. Corrosive wear is caused by moisture and acidic products formed during combustion. An efficient cylinder lubricant should minimize the effects of these causes of wear. There are, however, additional factors which influence wear in a particular engine that are beyond the control of the lubricant:

- Features of engine design
- Materials selection
- Quality of workmanship
- Operating conditions
- Fuel quality

As direct-drive diesel engines evolved up to the early 1950s some designs did not have a physical division completely isolating the combustion space from the crankcase. This division is known as the diaphragm and has a piston rod gland, often referred to as the stuffing box, through which the piston rod passes. Clearly the oil applied for cylinder lubrication to the non-diaphragm engines had to be compatible with the system oil being used for lubrication of the bearings.

In the early days the oil used was a straight mineral oil of an SAE 30-40 grade. Liner wear on some designs was higher than expected and some oil technologists advocated the use of lightly compounded oils. It was argued that the 'fixed' oil component, in the order of 5-10%, would assist in the removal of asphaltic deposits formed as a result of combustion by their solvent effect at elevated temperatures, and that the 'oiliness' effect of fixed oils would be of benefit. Unfortunately an oil of such a formulation would have carried the risk of emulsification in the presence of water.

The first advance came in the late 1920s with the introduction of solvent-refined lubricating oils. These oils formed less 'tar-like' deposits, hence the rings were able to move freely, the gas seal was improved and the tendency for the ring to break was reduced.

In the late 1940s there was an increase in the number of applications for diesel fuel which tended to create a world shortage, resulting in an increase in the price differential between diesel and the lower grades of fuel such as boiler oil. Once the feasibility had been demonstrated technically of burning boiler oil^{6,7}, owners were anxious to take advantage of the lower fuel costs and the builders developed engines for this purpose. The opportunity from the lubrication point of view was to provide a specific cylinder lubricant, as it was at this time that the diaphragm was introduced for crosshead engines designed to burn residual fuel oil.

The effect of residual fuel on existing engines depended on the engine type. In the case of 4-stroke engines some owners reported no change in liner wear rate after conversion to residual fuel, whereas for 2-stroke designs the liner wear rate increased from 2- to 4-fold. Also the quantity of cylinder oil had to be increased by up to 30%. Much of this increase was in an endeavour to prevent the sticking and eventual breaking of piston rings.

As a result of the evolution in oils for medium- and high-speed engines, caused by the emergence of the chemical additive industry, experiments were made with detergent oils. These oils were known as heavy duty (H.D.) oils and although effective for medium- and high-speed engines, were not effective in direct-drive marine diesel engines with separate cylinder lubrication.

Another method used to overcome the problem of sticking rings was to add a fluid to the cylinder oil. Experiments⁷ were made with various fluids, including cresylic acid. Some fluids did not blend with all cylinder oils but good results were obtained with cresylic acid blended with light oil in a proportion of 1 to 4. The disadvantage of the acid was that it could also be harmful to the skin unless washed off immediately.

It was apparent that a lubricant having a much higher alkalinity value was necessary to combat the severe operating conditions imposed by burning high-sulphur fuel. At the time when this need was realized there were no suitable oil-soluble additives that could impart sufficient alkalinity. An early improvisation to meet this demand was the development of a 'two-phase' lubricant in which a water-soluble additive was employed and a solution of this additive was emulsified with lubricating oil. This was followed by a 'dispersant' type of lubricant in which a solid alkaline additive was held in suspen-

sion in the lubricating oil by 'compounding' the latter with a small percentage of grease. In service these cylinder lubricants proved to be effective in improving engine cleanliness and reducing wear, but both had rather poor long-term storage qualities because of separation of the individual phases.

Research and development took place for an oil-soluble additive which would provide the necessary engine protection without the disadvantages inherent in the 'two-phase' lubricants. In the late 1950s the breakthrough came – one oil-soluble additive was developed and was quickly followed by others. The single-phase lubricants that resulted from these additives were the starting point for the development and evolution of the cylinder oils in the marketplace today.

The environment in which the cylinder oil now has to operate is more severe than that of a decade ago because of the directional change in design parameters to improve the specific fuel consumption of the present generation of marine crosshead engines. Also there has been a change in fuel quality as a result of more severe refining processes to yield lighter end components from the barrel. These trends and their effects on cylinder oil performance are summarized in Table 5.

Adequate oil film strength is necessary to take account of the high specific power outputs and piston ring gas loadings. Directionally this means an increase in the viscosity of the oil, particularly at the liner/ring operating temperature. The optimization of the oil film strength, however, may detract from the spreading property of the oil. This spreading property becomes more important as the oil viscosity increases and is essential to the achievement of satisfactory oil availability on the swept surface of the liner.

Throughout the industry it is generally accepted that an alkaline oil of 70 TBN (total base number; mg of KOH/g) provides cost-effective corrosive wear control when burning residual fuels having a sulphur content up to 4% by weight. Alkalinity is only one of the parameters for control of corrosive wear; what is of great significance is the efficiency of the neutralization process, sometimes referred to as the acid neutralization rate⁸.

The balanced characteristics of detergency, dispersancy, thermal and oxidative stability of the cylinder oil all contribute to the control of the deposits on the piston crown and ring lands, grooves, skirt and scavenge spaces. These deposits have a relationship to abrasive wear. Extensive laboratory tests de-

Table 5. Changing design trends and their effects on lubricant performance

Design parameter	Trend	Effect on oil film	Lubricant performance characteristics affected
1. Cylinder power output	Increasing	Higher thermal loading	Thermal/oxidative stability, detergency/dispersancy
2. Cylinder maximum pressure	Increasing	Higher film loading, greater tendency to blow-by, more acid generated	Film strength, load carrying (anti-scuff), detergency/dispersancy, alkalinity
3. Surface temperatures (liner/piston ring)	Increasing	Reduced viscosity, higher film temperature	Film strength and load carrying, detergency/dispersancy
4. Piston stroke	Increasing	Reduced oil availability, increased film residence time	Spreadability, thermal/oxidative stability, detergency/dispersancy
5. Fuel quality	Deteriorating	Possibly more acid generated, possibly more combustion debris	Alkalinity, detergency/dispersancy

signed to evaluate the deposit-forming tendency have indicated that those cylinder oils with good deposit control show good wear control in service.

DEVELOPMENT OF DIESEL ENGINE SYSTEM OILS

Irrespective of the type of diesel engine, 2-stroke or 4-stroke, one of the functions of the system oil is to lubricate the bearings. Since the beginning of the installation of diesel engines in ships, apart from a very few exceptions, it has been the general practice to enclose the crankcase. By this design some form of pressure circulation of the oil is possible, whether by gravity, pump, or use of crankcase compression. In those instances where crankcase compression was used, it was usual to have mechanical lubricators for the majority of the moving parts and in some cases ring oilers for the main bearings. Whatever system was employed in the early period, a high-grade straight mineral oil of suitable viscosity SAE 30 was used. In addition it had to be able to separate readily from water and other impurities and have good oxidative resistance.

Many early marine diesel engines used salt water as the piston cooling medium and in order to minimize the build-up of scale the outlet temperature was restricted to 50°C. Engine builders soon adopted alternative cooling media, namely, fresh water or oil. To take full advantage of oil as a coolant, ideally a separate system should have been installed, as the optimum oil to be used should have a comparatively low viscosity for ready absorption of the heat in the pistons. Such an oil should be sufficiently refined so as to prevent the formation of 'tar-like' deposits on the under-piston crown, to remain stable and to quickly separate from impurities. The price of such an oil would be cheap compared with the price of the system oil. As far as is known a separate piston oil cooling system was not adopted for a marine diesel engine, therefore in those engines where piston oil cooling is used the system oil has to perform a dual function.

For those engines which are of the trunk piston type, which today are medium-speed main propulsion units, the evolution of this oil follows on from the use of H.D. oil to which previous reference has been made. Although some medium-speed auxiliary engines had operated on residual fuel in the 1930s, it was the *Princess of Vancouver* which in 1955 first used residual fuel in a medium-speed main propulsion unit. Development of oils for this application came from the medium-speed engines in the industrial market. For marine applications particular attention had to be given to the demulsibility characteristics of the oil. In the evolution of trunk piston engine oils there has been an increase in viscosity from the SAE 30 grade to the SAE 40 grade. For operation on residual fuel, additives are required to give an initial alkalinity of 30-40 TBN, adequate detergency/dispersancy and thermal/oxidative stability.

System oils for modern crosshead engines, namely those fitted with diaphragms, can be classified under two headings.

Oils for engines with water-cooled pistons

Oils for engines with oil-cooled pistons

With the advent of suitable chemical additives an 'R and O' oil was developed. This oil is superior to straight mineral oil and historically was used as a system oil for both water- and oil-cooled piston crosshead engines. In the early 1970s some engine builders with designs incorporating oil-cooled pistons expressed a preference for an alkaline oil. This was because it was considered that the detergency effect of such oils would maintain the cleanliness of the piston undercrown cooling

space. The industry response to this preference was the development of an alkaline oil of 5-9 TBN. Oils at the upper end of the range have a dual application in that they can be used in distillate fuel auxiliary engines.

For the present generation of crosshead engines with water-cooled pistons an 'R and O'-type oil is still proving to be satisfactory in service.

With the introduction of the power take off to increase the thermal efficiency of the propulsion unit, the system oil is required to carry out a third function, namely the lubrication of highly rated gears. Whilst, of course, for many years gear trains have been found within engines, these gears have been conservative in design. However, this factor would not appear to be the case in some installations at present under construction.

CARE AND MAINTENANCE OF LUBRICANTS

It is axiomatic that all lubricant systems should be thoroughly cleaned before filling. In addition to the removal of all physical debris, attention should be given to the removal or passivation of any previously applied surface protective. If this aspect is not addressed there is the possibility that the characteristics of the new oil charge will be altered because of surface reaction.

Maintenance of circulatory oils by on board treatment is essential to ensure satisfactory service performance. This treatment normally consists of strainers and a centrifuge, with the exact arrangement varying between propulsion arrangements. The volumetric rate of circulation of the oil is normally such that a centrifuge is operated as a by-pass arrangement from sump to sump.

For the steamship, the primary function of the centrifuge was to remove water, usually as condensed steam. Historically it was the practice to water-wash the oil by the introduction of a small quantity of steam condensate to the centrifuge oil inlet. The effect of this was to remove water-soluble oxidation products, so preventing their accumulation in the oil-soluble state and to assist in the removal of sludge-forming compounds. It was usual for the water rate to be 5-10% that of the oil throughput, with the water approximately 10°C above that of the oil. With the present generation of steam turbine oils this practice is no longer normally required, although it may be recommended as a remedial action to wash out contamination in the system.

Historically for motorships, water-washing of the straight mineral oil was carried out in a similar manner to that described above. In this instance the water-washing assisted in the removal of water-soluble oxidation products and acidic compounds originating from the sulphur content of the fuel. It also assisted in coagulating some of the finely divided, suspended carbonaceous solids which are products of combustion. With the present generation of diesel engine system oils water-washing is not normally required.

In 2-stroke engines, the practice of returning inadequately treated piston rod drain oil to the sump is a short-sighted cost-saving measure which can lead to the need for early partial or total renewal of the main engine charge. Re-use of treated piston-rod drain oil, without detriment to the system oil, is possible for certain designs of engines, and for technical prudence has to be carried out under carefully controlled conditions. Experience has shown that for some designs it is not possible to adequately treat the piston rod drain oil on board and in such circumstances the only technically responsible recommendation is that of disposal.

CONCLUSIONS

At present (1988) some 97%, in terms of numbers of ships⁹, are motorships and there is every indication that this dominance will continue as long as a suitable fuel is available in the requisite quantity so that there is no extreme price escalation resulting from a gross short-fall in supply.

There is no doubt that the diesel engine will develop further and in the process increase the demands made upon the lubricant. Whilst it is technically possible to formulate an oil to function under the most extreme conditions, if large proportions of expensive components are used, there will be a significant increase in price. The cost of the lubrication element of engine operation can be simply converted into a fuel equivalent rate. Obviously this element will have to be less than the incremental fuel gains made in future diesel engine designs.

Since the beginning of commercial steam navigation the lubricant has been the life-blood of the engine and this will always be the case, whatever type of propulsion system is selected by the shipowner.

ACKNOWLEDGEMENT

The author wishes to thank the British Petroleum Company p.l.c. for permission to publish this paper. Figs. 1 and 3 are by courtesy of the Trustees of the Science Museum (London) and Fig. 4 by courtesy of MAN B&W Copenhagen.

GLOSSARY

Viscosity

Viscosity is the most important physical property of a lubricating oil and is a measure of its internal friction or resistance to flow. The fundamental unit of dynamic viscosity is the poise which is named after Jean Louis Poiseuille (1799–1869) who investigated the flow of liquids in capillaries in the 1840s. The poise is the ratio between the applied shear stress and the rate of shear of a fluid. Because of the size of a poise a smaller unit, one-hundredth of a poise [a centipoise (cP)] is customarily used. In the petroleum industry, however, kinematic viscosity is normally used which is the characteristic of the flow of the oil under the influence of its own weight. The unit is the stoke, named after Sir George Gabriel Stokes (1819–1903). For convenience the centistoke (cSt) is the more usual unit. Kinematic viscosity is the ratio of the dynamic viscosity of a fluid to its density at the temperature at which its dynamic viscosity was measured.

Viscosity index

The viscosity of a mineral oil reduces as the temperature increases and the extent of this change is expressed by the viscosity index (VI), which is used extensively by the lubricant industry. When the concept of VI was developed in 1929 an oil with the smallest change in viscosity between 40° and 100°C was assigned a VI of 100, whilst that having the greatest change over the same temperature range, a VI of 0. The VI of any oil may be calculated from knowledge of its viscosity at the reference temperatures or more conveniently can be extrapolated from published Tables. The VI of an oil depends on the crude oil source and the method of refining. For some specialized lubricating oils the VI is increased by the effect of additives.

SAE classification

The Society of Automotive Engineers (SAE) in America first published a viscosity classification for automotive engine oils in June 1911, which through the years has been expanded and revised. Applicable to marine propulsion systems are the classifications, SAE 20, SAE 30, SAE 40 and SAE 50. These viscosity ranges are shown below.

SAE viscosity grade	Viscosity range (cSt) at 100°C
20	5.6–9.3
30	9.3–12.5
40	12.5–16.3
50	16.3–21.9

Oiliness

The expression 'oiliness' is frequently used as a synonym for good boundary lubrication performance. Today, boundary lubrication conveniently describes those conditions not covered by hydrodynamic or thick-film lubrication. In boundary lubrication the ability of the oil to adhere to the metal surfaces is an important characteristic. Fixed oils have good 'oiliness' as they have a long-chain molecular structure which is able to form a chemical attachment to a suitably reactive metal surface. The active end or polar head of the molecule adheres to the metal with sufficient strength to prevent it being torn off during rubbing contact. These long-chain molecules stand up very much like the pile of a carpet, with their polar heads anchored to the surfaces, allowing relatively free lateral movement (shear within the oil film), whilst preventing contact of the metal surfaces.

Straight mineral oils are composed chiefly of saturated hydrocarbons in the form of chain and ring structures which are chemically inactive and do not possess polar heads. Straight oils are therefore generally regarded as relatively poor boundary lubricants but, as many refined mineral oils contain minute traces of polar compounds, they do in fact possess limited boundary lubrication properties when operating conditions are not unduly severe. The 'oiliness' of a mineral based lubricant can be enhanced by compounding with fixed oils, or by other additives.

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Discussion

G. Victory (Fellow) I found this paper fascinating, evocative and of great value in that it follows the story of lubrication from its earliest days to the most recent developments. To encompass this task in 10 pages has meant that a great deal of information has had to be compressed into a few lines on each aspect of the subject, and this has left me with the feeling that I would like to know more about several of the problems raised. Certainly, more information on the earlier lubricants would be welcome. Similarly, there are some things, perhaps peripheral, which had to be left out. Perhaps Mr. Thomas could be persuaded to expand on the subject on which he has done so much research and provide a book for publication in the Institute's 'Marine Engineering Practice' series – it should be a best seller!

In this context I wonder whether Mr. Thomas could give any information on the use of 'soft soap'? Surely it was not only used at sea for washing hands! Similarly where do colloidal graphite, molybdenum disulphate, and synthetic oils feature in the history or the future of marine lubrication? Was there a reason why we used a saponified oil and water mixture in open eccentric troughs, or were we merely making a virtue of necessity as the water was going to get in anyhow?

I would take up cudgels on only three points. Under 'Development of diesel engine system oils' Mr. Thomas mentions 'instances where crankcase compression was used' in diesel engines. I wonder which ones? They must have been very small as it is imperative that crankcase volume is kept to a minimum, and this is only possible with small engines, which I do not think would be used in the marine field (perhaps as hot-bulb engines or small generators but not, I think, propulsion).

Earlier in the paper, Mr. Thomas says that animal oils are obtained by heating or boiling, and vegetable oils are obtained by pressing or chemical extraction. But certain waxes can be obtained by boiling. One of these, which I have seen extracted, is the wax which floats off when the 'bay-berry' – common on the New Jersey shore – is boiled in water. The wax is used, *inter alia*, to make Christmas candles which burn with a very pleasant aroma. If bay-berry wax was used on bearings it would make for a happy ship as, for consolation, a hot bearing would be indicated by a beautiful smell! I wonder whether there are any other unusual sources of oils or waxes?

Mr. Thomas also says 'straight mineral oils . . . possess limited boundary lubrication properties'. I think this might be queried by veteran car and motorcycle enthusiasts, for even with the availability of so-called 'modern oils' the straight mineral oil is still the choice of, and is recommended by, most enthusiasts and Clubs! And how does Mr. Thomas explain the adherence of veteran and vintage racing machines to Castrol 'R' – a castor based oil – when all these modern additives of the chemical industry are available?

I wonder whether we are perhaps on a tread mill! We are told that the declining fuel quality and the increased M.E.P.s, combustion pressures and temperatures have forced the introduction of more and more additives and devices to try to correct faults which we ourselves have introduced in a so-called 'drive for economy'.

Meanwhile we have paid little heed to what we may be doing to the environment. Higher pressures and temperatures mean a greater evolution of nitrous oxides (NO_x) a very poisonous mixture of gases. Sulphur dioxide evolution is increased by residual fuels as is the formation of vanadium pentoxide – both very deleterious to mankind. We have also to look at the

products of the additives themselves. I wonder what the products of combustion of cresylic acid are? Certainly it is not in itself a substance which one would want to have around one's home.

Perhaps we are chasing our tails or, like lemmings, rushing headlong to destruction! Mr. Thomas gives us a lead in that if we look at the fuel equivalent involved in the much higher application rate of lubricating oil, and the ever increasing price of the oils which are required to 'keep up with the Joneses', we may find that the law of diminishing returns has pulled the plug on the real effectiveness of engine manufacturers' claims.

Cdr. K. I. Short (Baltic Exchange) I do not believe that we have had a lubricating oil paper for several years so this one is timely. It is an excellent primer, with just enough in it to whet our appetites but not enough to cause indigestion.

It should be noted that 'Colonel' Drake did not discover oil in Pennsylvania. What he did was to drill the first oil well in an area where oil had already been located and the land had already been purchased to develop the find on the advice of Dartmouth and Yale scientists. Incidentally, he had never been in the army and the only uniform he had worn was that of a railroad conductor!

I would like to suggest possible additions on the following topics that would enhance the paper:

1. The removal of heat is one of the important functions of oil circulating through bearings – this function deserves greater emphasis.
2. Stern tube bearings, gas turbines and nuclear propulsion. The particular requirements for lubrication of these three categories of machinery and how they are being accomplished would, I feel, be of interest.
3. The current position regarding the development and supply of synthetic oils would be of interest.
4. Biodeterioration of lubricating oils. It is known that bugs feed off additives in lubricating oil. What are the methods of avoiding this hazard?

With regard to running-in of machinery, I have never been happy about the need to demonstrate machinery at full power for acceptance trial purposes before it has had time to 'bed-in'. Would the author please give the current views of the lubricating oil specialists on the running-in of machinery with modern lubricating oils?

How does one define an oil? Is it in the same category as an elephant, which in the legal world is notorious as being something which no one can describe but which everyone knows when they see it? A mineral oil has the general formula C_xH_y . Would the author please give a similar typical formula for one of the fixed oils?

As this paper is directed to mariners, may not the whales be legitimately disappointed at the lack of credit given in the paper to their sacrificial contribution to fixed oil production for lubricants and other purposes over the years?

It appears that compounding of mineral oils with fixed oils is probably not a potentially toxic or other environmental hazard. But is this true for lubricating oils with chemical additives? I understand (by courtesy principally of G. H. Clark's 'Marine Lubrication') that these additives include such chemicals as cresylic acid (known to be harmful to the skin), lead oleate, lead naphthenate, alkaline additives, sulphurized fats, alkyl disulphide, xanthogen tetrasulphide, toluene sulphochloride, chlorinated wax, thio-ether phosphate, tri-cresyl

phosphate, tri-butyl phosphate, barium, calcium, magnesium and sodium sulphonates, zinc dithiophosphate (ZDP), benzyl cresols, soluble molybdenum compounds and so on.

There are two principal routes, apart from straightforward spillage, by which such additives and their derivatives, as the former do their job in the oil, can reach the environment:

1. by being burnt directly in the engine.
2. by contamination of fuel oil, either by deliberate dumping of used lubricating oil into it (of which practice there is evidence), or by pickup by fuel oil of lubricating oil, used or unused, from insufficiently cleaned barges, etc. (Lloyd's Register F.O.B.A.S. has already reported the finding of hydrofluoric acid in a fuel oil sample but how it got there was not determined.)

The above raises various questions.

1. Is sufficient attention being given to the potential environmental hazards of additives in lubricating oils?
2. Are any restrictions or limits laid down for additives by type or quantity?
3. Are warnings of potential hazards from additives given to users?

Lubricating oil technology is a complicated science and for the layman correct lubricant selection has to be based on advice from experts. This advice must take into consideration such factors as the duty expected, wear and tear, materials involved, things that could go wrong, availability, cost, and so on.

As temperatures and pressures to be handled rise in the future will not more and more lubricating oil formulations be produced with an increasing number of additives? Can the author hazard a guess as to what can be expected in this respect in the near future?

Are the lubricating oil specialists addressing the problem of the ever increasing number of specifications which are being evolved to meet machinery development requirements? Are they thinking in terms perhaps of general purpose oils instead of a unique oil for each duty so as to cut down on the number of different lubricants needed in a particular vessel?

Is there communication between oil companies and is there adequate guidance available regarding mixing of oils containing additives obtained from different suppliers?

In his Conclusion the author says the 'lubricant has been the life blood of the engine'. Few, I think, will disagree with this, but it goes much further. Lubricants are design components of machinery. Engine development depends upon parallel development of suitable lubricants. One only has to look at the development of medium speed engines over the past 20 years to burn heavy fuel to recognize that this is a truism. Without suitable alkaline lubricating oils this development could never have taken place.

The English language also seems to recognize the importance of and be fascinated by oil and lubrication as we find a myriad of such expressions in everyday use:

- 'His palm has been greased'.
- 'It needed a lot of elbow grease'.
- 'The wheels have been oiled'.
- 'What an oily character he is'.
- 'He should be boiled in oil'.
- 'Let us pour oil on troubled waters'.
- 'He is properly oiled don't you agree'.
- 'I must not delay you much longer from lubricating your throats'.

K. Rothert (Chevron Chemicals) The author is to be complimented on the wide coverage given in his paper to marine engine lubrication.

I would like to discuss the part of the paper referring to low-

speed marine crosshead diesel engine lubricants. The development of marine lubricants is a long and deliberative process that arises from a technical or commercial need and results in a high quality product.

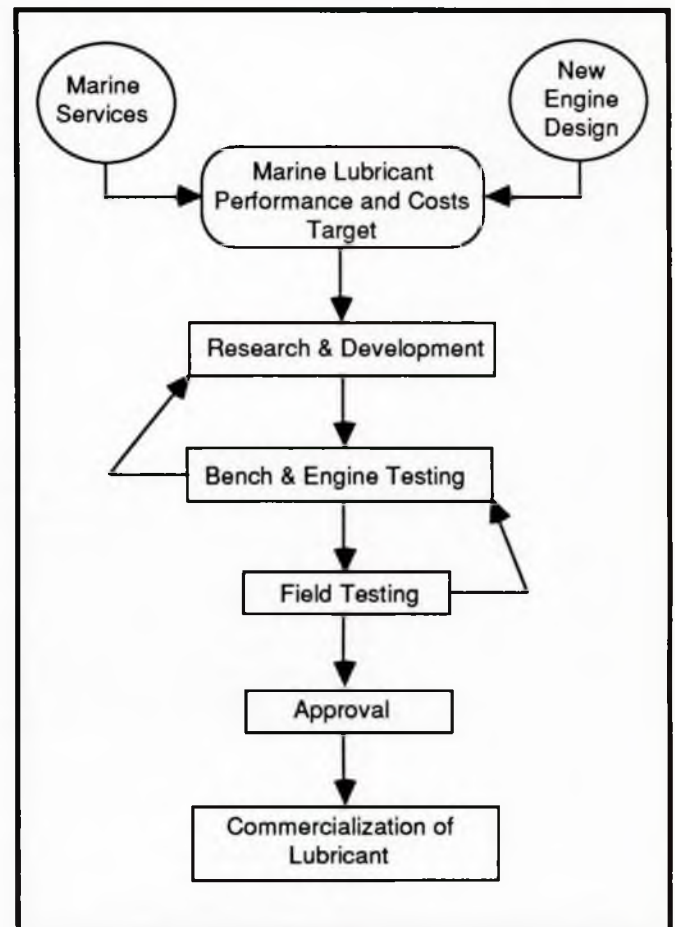


Fig. 1. Lubricating oil additive development and evaluation

Fig. 1 is a simplified diagram of how marine lubricants are developed. The engine is the final arbitrator of a lubricant's performance. This has been a continuing development since the first diesel engines, as presented by the author.

The marine engine today dominates the propulsion of ocean vessels. This is due to it possessing the highest thermal efficiency of any marine engine coupled with its ability to burn heavy residual fuels with high reliability.

Table 1 summarizes the major characteristics of fuels which influence engine performance. To control wear in the engine it must be recognized that the lubricant can only overcome a few of these fuel factors – primarily the effect of sulphur content. Good cleaning and preparation of fuels on board ship and good air filtration and oil filtration are essential.

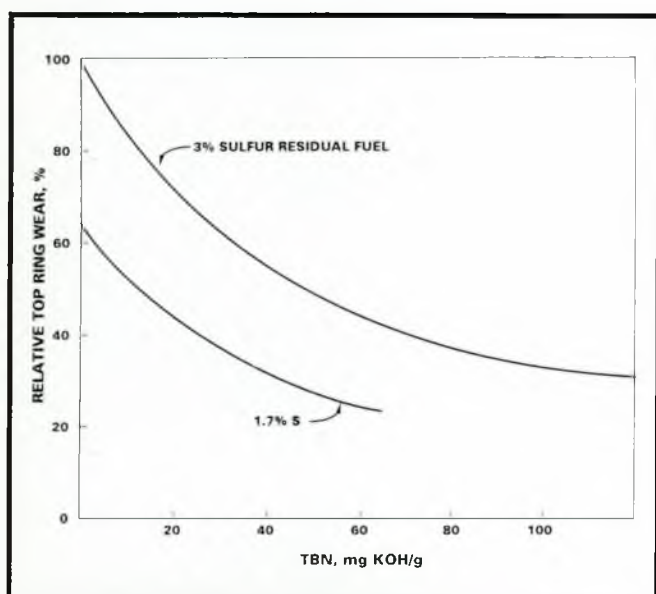
The author gives us an interesting background to the development of today's high-alkalinity 70 TBN cylinder lubricants, starting with 2-phase emulsion-type products of the early 1950s. Table 2 is a summary of some major additive developments for diesel engines starting with the first compounded diesel engine lubricant of 1935 containing calcium dinaphthenate and used to overcome piston ring sticking in high speed diesel engines. This Table shows that in 1954, 40 TBN marine cylinder lubricants of the single-phase lubricant type were introduced, as indicated by the author. With modern engine

Table 1. Fuel properties affecting engine performance

Property	Performance areas
Viscosity	Injector lubrication and fuel atomization, centrifuge performance
Cetane number	Smoke, combustion
Diesel index	Ignition
Volatility	Ignition and combustion
Flash point	Fire hazard in handling, related to volatility
Pour and cloud point	Low temperature operation, both can be limiting
Ash content	Abrasive wear and deposit formation
Sulphur content	Corrosive wear
Carbon residue	Carbon deposits in the combustion chamber
Specific gravity	Related to heat content and centrifugeability
Heating value	Power output and fuel consumption
Water and sediment	Fuel system and injector life
Trace metals (vanadium, sodium)	Valve wear and burning
Asphaltenes	Compatibility

Table 2. Diesel lubricant developments

Year	Performance areas description	Additive type
1935	First commercial detergent diesel engine oil	Dinaphthenate
1936	First high speed diesel engine oil	Dichlorostearate phenylstearate
1939	First oxidation inhibited diesel oil basis for first specification oils	Cetylphenate and phosphate
1941	U.S. army 2-104 & Navy 14.0.13 (9000 series) and first service station detergent oil	Diparaffin sulphide added
1943	First army and navy oil also used for trucks, buses and cars with hydraulic lifter valves	Cetyl dithiophosphate added
1946	First ZDTP oxidation and corrosion inhibited oils for cars and trucks	Ca sulphonates and phenates + ZDTP
1954	MCL with all metallic components	40 TBN Ca phenate
1959	MCL shipboard radioactive wear studies	Up to 120 TBN Ca sulphonate and phenate. Ashless dispersant added
1963	First high speed and railroad diesel oils with ashless dispersant	10-30 TBN balanced formulations
1970	Marine TPEO with ashless dispersant	13 TBN balanced formulations
1975	MCL with metallic and ashless components	70 TBN balanced formulations
1978	High sulphur fuel railroad diesel oils	13 TBN balanced formulations
1984	Wear inhibited TPEO	ZDTP

**Fig. 2. Effect of crosshead engine oil alkalinity and fuel sulphur levels on ring wear**

technology and more severe, higher sulphur fuels, high quality marine cylinder lubricants of 70 to 100 TBN are today available to shipowners.

During the early development of marine cylinder lubricants it was difficult to assess which lubricant properties influenced engine wear. Our company undertook radioactive piston ring wear tests in a 760 mm bore engine in a ship operating between the U.S. and Europe. Fig. 2 shows the results and the precision of the data obtained in these evaluations. Two factors were found to influence significantly the engine wear – the level of sulphur in the fuel and the level of the lubricant alkalinity (TBN). Based on this type of ship data, oil companies and additive suppliers are able to develop lubricants and handle initial lubricant evaluations in the laboratory. To do this it is important to have a proper technique which correlates as closely as possible with field performance. Fig. 3 is an example of top piston ring wear studies in a laboratory crosshead engine and the correlation with ships' field data. The curves use the parameter of the 'oil alkalinity throughput factor' which is the TBN of the oil multiplied by the oil feed rate (TBN/bhp h). These curves are of similar form to the earlier radioactive field ship test data.

Extending this development beyond alkalinity studies, the

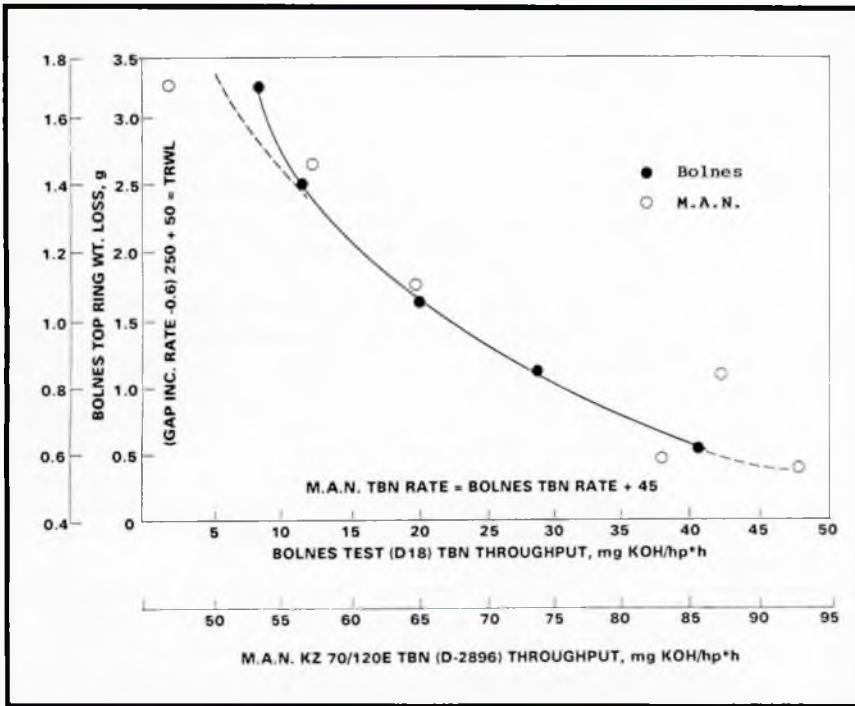


Fig. 3. Correlation of MAN and Bolnes 3 DNL top ring wear

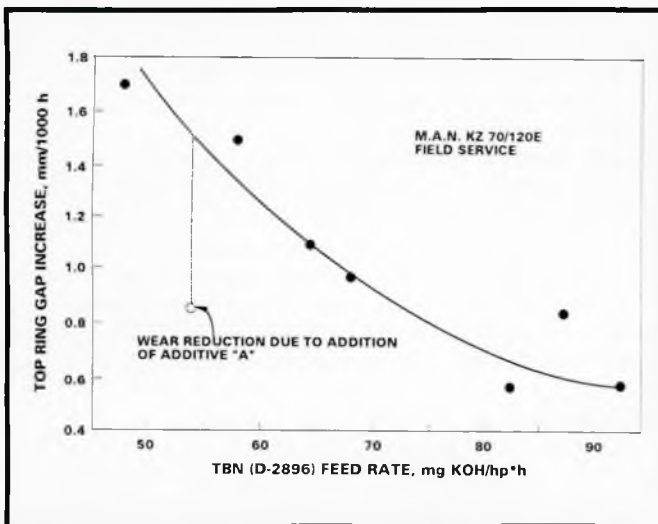


Fig. 4. Effect of cylinder oil feed rate on top ring wear

industry has shown that there are also other ways by which piston ring wear can be reduced. After thorough laboratory studies a non-metallic detergent was evaluated in a ship and the results, shown in Fig. 4, illustrate wear reduction due to something else besides alkalinity.

The author mentions the importance of piston ring sealing and indicates that this is an important function of the piston ring. For the piston ring to seal and function correctly it must not be impaired by heavy deposits from the fuel or lubricant. This leads to other performance characteristics that must also be built into a high quality lubricant. The oil industry/additive suppliers are continually trying to improve the development of marine cylinder lubricants, balancing the alkalinity, the detergency and oxidation and other properties, such as extreme pressure capability.

Our focus on new lubricant developments is to meet the

challenge of the future designs expected for the 1990s. We must thank the author for summarizing how lubricants met the challenges of the past – his comments lend thought to approaches for the future.

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J. Cowley [Britship (I.O.M.) Ltd.] I would like to thank Mr. Thomas for his interesting account of how lubricating oils have been developed to meet the problems of increasing engine ratings and deteriorating quality of fuel. Much has been written on these problems in the Institute's Transactions in particular but

much less has been said on the role of lubricating oil and, until recently, virtually nothing on the environmental aspects.

However, at the last meeting of the IMO Marine Environment Protection Committee, it was decided to put air pollution on the work programme and consider what steps might be taken with respect to the provision of environmentally appropriate fuels. With respect to the latter, I would assume that the oil industry could comply with any specification, at a price, and I personally find it hard to see any straightforward solution to reducing the environmental effects of ships. But if IMO were to require better quality fuels, what effect would it have on the lubricating oil industry and lubricants? To me, the cost of such bunkers would most certainly be unacceptably high and hence my first question to Mr. Thomas is would it make economic sense through possible improvements in lubricants? What additional contributions to reduction in environmental pollution can come from, for example, additives to cylinder lubricants? Could the environmental effects of the noxious gases be reduced?

Without effective cylinder lubrication, worn liners and piston ring problems would severely worsen the environmental effects due to poor combustion. In this respect, the paper refers to increases of 30% in the quantity of cylinder lubricating oil mainly necessary to prevent the sticking and breaking of piston rings in 2-stroke engines when changed to burn residual fuel oil. But this additional oil must itself have a negative environmental effect due to the noxious gases released into the atmosphere. The paper also refers to the emergence of the chemical additive industry and, when commenting on the effectiveness of cresylic acid in preventing the sticking of piston rings, mentions its potential harmful effects on the skin.

These solutions prompt my next question relating to pollution from lubricating oil and the additives. Cresylic acid, for example, is a severe pollutant and is included in the highest category (A) of marine pollutants in Annex II of MARPOL 73/78 dealing with noxious liquid substances. Other additives are not mentioned by name in the paper but may also have harmful effects on the marine environment as noxious gases or residues.

Perhaps Mr. Thomas could comment on the positive and negative effects of lubricating oils on the environment? It would also be useful if he could indicate the fate of the lubricating oil 'used' in marine propulsion systems. Could he, for example, give an estimate of the proportion of cylinder oil which is burned, state the expected products of combustion from the oil and its additives, and estimate the proportion which ends up as sludge?

With respect to crankcase oil, the improvements to increase the stability and reduce oxidation will be environmentally advantageous because they will reduce the amount which needs to be disposed of, provided full advantage is taken of the longer life. This is not only necessary from economic aspects but from environmental considerations also, since these same improvements will increase its pollution potential because of its lower tendency to biodegrade in the environment. Would Mr. Thomas outline any recent or possible developments that enable maximum advantage to be taken of the improved performance of crankcase lubricating oils, both from the longer life aspects and as a guide to engine performance and conditions? In addition, could he say whether there is any generally accepted economical and environmentally appropriate method for disposing of used crankcase system oil, and mention the methods which are available in practice?

R. E. H. Orr (Yard) It was fascinating to discover from Mr. Thomas's paper what lubricants were in use in the earliest days of marine propulsion systems and how lubricants have evolved over the last two centuries. I note, however, that the paper makes no reference to synthetic oils. While such oils were not evolved for marine propulsion systems they have come aboard with the gas turbine used for propulsion purposes. Synthetic lubricating oils were certainly there when aero-derivative gas turbines arrived but maybe they were there with some of the earlier versions.

It is not just a matter of this synthetic oil being in the gas turbine's sump because when one U.S. manufacturer provides his gas turbine module along with it comes a lubricating oil storage and conditioning assembly. This assembly has to be located within a specific configuration relative to the gas turbine module.

Synthetic oils are required because of the high temperature environment in which certain gas turbine bearings are situated and scavenge temperatures are sufficiently high that the main gearbox lubricating oil system can be used as heat sink via an oil/oil heat exchanger. While the experience of using synthetic oils at sea will mainly be in surface warships, since they are the main users of gas turbines afloat, brief descriptions of synthetic lubricating oil systems appear in the literature describing cases where the gas turbine has been applied to the propulsion of merchant ships. In addition aero gas turbines, with the synthetic oil that they use, are to be found on hovercraft.

J. C. Beland (Exxon) I would like to congratulate the author on what is obviously an extensively researched paper. This research has allowed him to provide us with a concise history of the development of marine lubricants from the 1700s up to the present day.

There have been occasions when I have had to delve back in time to answer lubrication queries for old machinery and I know only too well how difficult it can be to find some of the information given in the paper. The paper gives a better feel of the history of marine lubricants and what has been achieved in their development and I would recommend it to all new entrants into the field of marine lubrication.

It is interesting to look back and see how marine propulsion

machinery, specifically the marine diesel engine, has advanced and the reasons why. In particular, in recent years, we have seen increases in fuel prices putting pressure on marine propulsion machinery designers to develop engines with improved fuel economy. As the author points out these improvements in fuel economy have been made by increasing cylinder power output, pressure, temperature and piston stroke/bore ratio. In reply to these developments oil companies, including my own, have introduced new products to lubricate engines under these more severe régimes.

At the present time and in the foreseeable future today's marine lubricants can match the requirements of the marine diesel engine. However, our work in marine lubrication research makes us realise that this situation will not remain static forever and that there will be further advances in engine design. Because of this I would like to ask the author to change from historian to fortune teller, expand on his conclusions, and give us more information as to where he thinks the lubrication of marine diesel engines is going from here.

F. J. Thomas (Chevron Chemicals) The author is to be congratulated on a very interesting paper on a subject which covers ship propulsion from the end of the era of sail to the current highly efficient motorships of today. I would like to add a contribution to the thorough research by Mr. Thomas. My comments will cover the earlier period of engine development with particular respect to lubrication of piston rings and cylinder liners.

The initial concepts of the mechanical propulsion of a ship owes a lot to the engineers of the 18th and 19th Century. The early power plants can be traced to land-based engines, starting from Thomas Newcomen who made the first practical beam engine, an atmospheric steam engine, in 1712. It is of interest to know that this was an engine with no cylinder head, and the piston had a leather piston ring with a layer of water on the top to support sealing. These engines often operated for more than 50 years, at between 8 and 16 strokes per minute.

These early steam engines operated before the introduction of mineral oils. As the author states, the lubricants used before mineral oils were known as 'fixed oils' and are of two categories – those derived from animal fats and those derived from vegetable or plant seeds. The use of these types of lubricants has a long history, probably back to 3500 B.C.

Szeri (ref. 1) suggests that lubricants, probably animal fats, were used in the bearings of chariots in Mesopotamia and Egypt from about 3500 B.C. Bitumen may have been used as a lubricant possibly on door hinges, and traces of bitumen were found on the bearing of a potters wheel unearthed in Jerico, dated at 2000 B.C.

The early steam engines used animal fats like tallow for cylinder lubrication before mineral oils were available. The first reported mineral oil used in steam cylinders was in 1865 (ref. 2). However, these tallows formed free fatty acids when in contact with moisture. When changing to mineral oils to overcome this problem, it was found that mineral oils were not as effective as tallow products because the water from the steam washed the mineral oil from the rubbing surfaces. This led to compounded oils, as discussed by the author, mixtures of mineral oils and tallow or other fats. As reciprocating steam engines moved to dry steam and superheated steam, with the absence of moisture, lubricants could again be based on blended mineral oils, eliminating fixed oils as the fats decompose at high temperatures.

The early internal combustion engines used mineral oils, as vegetable and animal oils decomposed into either stearic acid and glycerine or oleic acid and glycerine (ref. 3). In 1849, the

first chemical compound, which we would now call a lubricant additive, was used in greases (ref. 4). The diesel low-speed crosshead engines, prior to 1940, used lubricants based on well refined mineral oils. The same oil was used for cylinder lubrication and for lubricating the bearings and running gear. The viscosity of the oils was usually SAE 40 or SAE 50 grade. These products used either paraffinic HVI base stocks, or naphthenic MVI base stocks, or mixtures, sometimes incorporating cylinder stocks/bright stocks. Under high temperatures, paraffinic oils tended to form extremely hard carbon deposits which could lead also to piston ring sticking, ring breakage, port deposits and piston undercrown deposits. The naphthenic MVI oils formed soft carbon deposits and were less prone to piston ring sticking or port deposits. These naphthenic MVI oils were not as thermally stable as the paraffinic HVI oil and had a greater change in viscosity as the temperature increased.

In engines burning heavy residual, high sulphur fuels, the engine wear was noted to be 2- to 4-times higher than that with distillate fuels, as pointed out by the author. By 1948, John Lamb had demonstrated how to handle fuels for satisfactory operation, including heating and centrifuging of fuels. It is of interest to note that the *Selandia* in 1912, had to heat the Borneo fuels using steam coils, as these fuels could become semi-solid (ref. 5).

From the time of the first Newcomen engine, engineers have striven for reliability and increasing power together with improvements in the cost of operation. The original 1712 Newcomen engine was estimated to have a thermal efficiency of about 0.5%. This was later improved to about 1% by John Smeaton by 1772, and then James Watt, in 1776, made a significant breakthrough, doubling the efficiency to 2% by adding the condenser to the steam engine and, by 1800, improved the engine to about 4% efficiency.

The steam reciprocating engine lasted approximately 100 years and gave very reliable service, using lubricant technology cited by the author. The highest efficiency, recorded in 1947, for the reciprocating steam engine which was fitted with an exhaust turbine, was 19.7%, (414 g/kW h specific oil consumption). This engine was installed in the *Baron Ardrossan* (ref. 6). The diesel engine at this time gave double this efficiency, which led to the displacement of the steam reciprocating engine by the diesel engine.

Dr. Diesel experienced lubrication problems with the early prototype diesel engines. The following is taken from Cummins (ref. 7) who described Dr. Diesel's early experiences. The first diesel engine, 150 mm bore x 400 mm stroke, which ran in July 1893, had a long plunger-type piston with no piston rings. It was sealed at the lower end of the cylinder by a U-shaped bronze band forced against the cylinder by oil pressure. This seal was a failure.

In January 1894, the engine was modified. The new piston was lubricated from an oil-filled groove attached to the bottom of the skirt. On February 17 1894, the engine ran for 1 min at 88 rev./min under its own power, and by April, the maximum power achieved was 13.2 ihp (9.7 kW).

Early in 1895, the engine was modified; the cylinder bore was increased to 220 mm, keeping the same piston stroke of 400 mm and was fitted with an iron cylinder and a cast-in water jacket. On June 26 1895, this engine obtained a brake thermal efficiency of 16.6%, and a brake specific fuel consumption of 519 g/kWh.

In January 1896, design of a new engine was started and completed in October 1896. The piston was water cooled and operated through a crosshead attached to one half of the A-frame. The cylinder bore was increased to 250 mm, and the

stroke of 400 mm was retained. This was a flat crowned piston. For lubrication, grooved extensions beneath the piston skirt dipped into an annulus-shaped sump at the bottom of the stroke to pick up oil for the cylinder wall and piston lubrication. This was the first successful lubricant system for a diesel engine. By February 1897, this diesel engine was running satisfactorily and on 17th February 1897, Professor Schroter came to Augsburg and supervised the official engine test, which gave a brake thermal efficiency of 26.2% (brake specific fuel consumption 324 g/kW h). On October 10 that same year, the brake thermal efficiency reached 30.2%. Dr. Diesel had produced the world's most efficient heat engine.

The author indicates the earliest motorship was the Russian oil tanker *Vandal* (1904). It is of interest to note that Nobel Bros. (Sweden) owned a number of oil wells in the Baku Area of South Russia, and introduced diesel-powered vessels to operate on the River Volga and the Caspian Sea. The *Vandal* was their first diesel-powered tanker of 650 dwt. The first ocean-going vessels were the Sulzer-powered 2-stroke engine vessel *Romagna* (June 1909) and the Werkspoor 4-stroke engine-powered vessel *Vulcanus* (1910). It should be noted that in 1911, the vessel *Toiler*, powered by an AB Diesel Motorer engine, crossed the Atlantic to enter service on the Great Lakes. As mentioned by the author, the pioneer diesel-powered, large ocean-going vessel, *Selandia*, 7400 dwt, was launched in 1911 and made marine history when her maiden voyage was reported by Mr. Ivar Knudsen of Burmeister & Wain in March 1912 (ref. 5).

Table 1 below shows some examples of the wide range of 4-stroke and 2-stroke diesel engines in the early years, the first decade of diesel marine propulsion.

In the early days of diesel engines, there was often no compunction about modifying piston strokes to suit a client, or even about designing new engine sizes. One engine builder (ref. 8) stated 'never was an order allowed to pass by default'. This builder stated 'between 1914 and 1930, that there were no fewer than 25 combinations of bore and stroke'. In some instances only two engines were made from a design.

By 1920, a typical cylinder liner's life was from 6 to 8 years and the basic engine lubricant system was established, which is similar to that now in use today. From 4 to 8 quills were used for the lubrication of the cylinder and piston rings. The point of entrance for the cylinder lubricating oil was usually in line with the second piston ring when the piston was at bottom centre.

In the early days, three different types of cooling medium were used; air, oil and water, depending on the piston design. For example, the cooling of the pistons in the engine of the *Vulcanus* was carried out with a combination of air and oil cooling. Cooling by oil was by diverting from the crosshead to the piston. This arrangement gave very good service until trouble was experienced with a formation of carbonized oil on the underside of the piston crowns, resulting in severely cracked pistons. The *Vulcanus* had an open crankcase, similar to the earlier steam engines.

Fresh water cooling was tried next and many ingenious designs of link or telescopic pipes were put into service. With these water-cooled pistons, leakage of water entering the crankcase and mixing with the lube oil was a problem. To eliminate this risk, the oil-cooled piston was favoured.

Marine engineers were concerned about the problem of heavy wear on the upper parts of the cylinder liner and even questioned if any lubricating oil reached this part of the crosshead engine. With respect to the oil-cooled pistons in the 1920s, carbonization of oil deposits on the piston undercrown was a problem. Also bearing troubles often occurred as the same oil was used both for the cylinder liner and the bearings.

Table 1. Example of early marine diesel-powered ships (1903–1915)

Year	Vessel	Engine design	Engine cycle (SCSA)	Number of engines	Number of cylinders	Indicated power/engine (kW)	Bore (mm)	Stroke (mm)	Engine speed (rev./min)	Service
1903	<i>Petit Pierre</i>	Dyckhoff	4	1	1	18.4	210	300		R. Seine
1903	<i>Vandal</i>	AB Diesel Motorer	4	3	3	88.3	290	430	240	R. Volga
1904	<i>Sarmat</i>	AB Diesel Motorer	4	2	4	132.4				R. Volga
1904	<i>Venoge</i>	Sulzer	4	1	2	29.4	260	450	260	L. Geneva
1904	<i>Aigette</i>	M.A.N.	4			147.1				
1907	<i>Minoga</i>	AB Diesel Motorer	4	2	4	88.3	275	300	300	Submarine
1907	<i>Circe and Calypso</i>	M.A.N.	4	4	4	220.7	330	360		Submarine
Jun 1909	<i>Romagna</i>	Sulzer	2	2	4	279.5	310	460	250	Ocean
Jun 1910	<i>Fram</i>	AB Diesel Motorer	4	1	4	132.0				Auxiliary
Dec 1910	<i>Vulcanus</i>	Werkspoor	4	1	6	441.3	400	600	180	Ocean
1910	<i>Kars and Ardagan</i>	AB Diesel Motorer	4	2	6	367.8				Submarine
1911	<i>Toiler</i>	AB Diesel Motorer	4							Great Lakes
1911	<i>Hagen and Loki</i>	Krupp	4	2	6	919.4	450	800	140	Submarine
Feb 1912	<i>Selandia</i>	B&W	4	2	8	919.4 (742.9) Effective	530	730	140	Ocean
May 1912	<i>Jutlandia</i>	B&W	4	2	8	919.4	530	730	140	Ocean
Jun 1912	<i>Fionia (No. 1)</i>	B&W	4	2	8	919.4	530	730	140	Ocean
1912	<i>Monte Penedo</i>	Sulzer	2	2	4	625.2	470	680	160	Ocean
1912	<i>Eavestone</i>	Carels (Westgarth)	2	1	4	588.4	508	914	95	Ocean
1912	<i>Juno</i>	Werkspoor	4	1	6	1073.8	560	1000		Ocean
Apr 1913	<i>Siam</i>	B&W	4	2	8	1140.0	590	800	125	Ocean
Jun 1913	<i>Annam</i>	B&W	4	2	8	1132.7	590	800	125	Ocean
Mar 1914	<i>Fionia (No. 2)</i>	B&W	4	2	6	1461.8	740	1100	100	Ocean
Aug 1914	<i>Malakka</i>	B&W	4	2	6	1140.0	630	960	125	Ocea
Aug 1914	<i>Bandan</i>	B&W (H&W)	4	1	6	956.2	670	1000	110	Ocean
Oct 1914	<i>Tong King</i>	B&W	4	2	6	1140.0	630	960	125	Ocean
Dec 1914	<i>Pan Gan</i>	B&W (H&W)	4	1	6	956.2	670	1000	110	Ocean
Jan 1915	<i>Chumpan</i>	B&W (H&W)	4	1	6	956.2	670	1000	110	Ocean

The piston rings tended to become carbonized and blow-by gases passed by the rings. The opinion in those days was that there was an over-abundance of lubricating oil which led to carbonization. These lubricants did not have additives and their performance was a reflection of the base stocks used, engine performance, service conditions, maintenance practices, and the fuels used.

The early diesel engines worked because of the perseverance of the ship's marine engineers. John Lamb recalls, quoting from Mallet (ref. 9), his experience as second engineer on an early twin-screw tanker; he noted frequently one engine at least was out of action and, during a 3 month voyage, only five out of 64 crankshaft crankpin and crosshead bearings had not been remetalled. Every piston had been removed several times to free piston rings and seven had been renewed because heads had fractured, while five cylinder covers had cracked and needed replacing. Overheating proved to be a major headache. About 100 gallons of lubricating oil was used daily, laboriously emptied from barrels on deck and carried below by bucket. The engineers did their rounds clad in oilskins and sou'westers to shield them from the pleasures of an oil bath. It is fair to add that this ship was an unfortunate example and was later re-engined.

Scavenge fires were not unknown in the early marine diesel engines; Richards (ref. 10) quotes the experiences on the *Aorangi*, a quadruple-screw 1925 diesel vessel. This ship was used as a troopship in the second world war; she had a habit of having scavenge fires in the main engines and the resulting fireworks display from the aft funnel at night would light up the convoy! Stories about this ship were legendary among engineers. The engine room was known as the 'chamber of horrors'; Richards (ref. 10) quotes a young engineer arriving aboard in 1952 and asking the chief engineer what uniform he

might require, to be told 'two boiler suits – one on and one off!' This ship had 26 men in the engine room on sailing day!

Even at the time of the maiden voyage of the pioneer ocean-going vessel *Selandia*, concern was raised at the risk of crankcase explosions from the vaporized lubricating oil. The *Selandia* was one of the first diesels to have forced lubrication and an enclosed crankcase, which held 15 tons of oil. In the discussion by J. T. Milton, Vice President of I.Mar.E., in ref. 5 (p. 82) he reassured the marine audience of the safety of enclosed crankcases. Unfortunately, crankcase explosions did occur. One of the worst cases was on the 1931 ship, the *Rieno Del Pacifico*; the accident occurred in September 1947, on sea trials after a major overhaul with the loss of many lives.

We have seen great developments in the diesel engine, from the 745 kW effective power of the *Selandia*, to the latest designs (ref. 11) of a 12-cylinder engine with a rating of 49,320 kW (67,060 bhp). The effective thermal efficiency had increased from 30% in 1912 to greater than 53% in the modern engine of today.

The author reviews the background of marine cylinder lubricants. It was in 1953 when the major breakthrough occurred – a 2-phase emulsion-type high alkalinity (TBN) lubricant was developed. This oil reduced significantly cylinder liner and piston ring wear resulting from high sulphur residual fuels. Unfortunately, storage stability at temperatures above 32°C was not always satisfactory.

The oil industry then quickly developed single phase cylinder lubricants either by dispersing in the oil the high alkalinity additives or by solubilizing these additives in the oils. Today, the single phase cylinder lubricant is widely used. These lubricants are available from 40 to 100 TBN, with 70 TBN used most widely.

I would again like to thank the author for his efforts in documenting this historical record of marine lubrication.

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T. McGeary (Bycoflam) I would like to congratulate Mr. Thomas on a very good paper condensing the essential facts of a complex subject into a few pages easily understood by the

marine engineering community.

In the section headed 'Diesel engine cylinder lubricants' you state that 'Extensive laboratory tests . . . have indicated that those cylinder oils with good deposit control show good wear control in service'. I wish to add the following comment. I believe this is related to the efficiency of the neutralization, as mentioned in the previous paragraph of the paper.

Optimum neutralization of the acid products of combustion is achieved when each acid molecule is neutralized by an alkaline molecule. In practice the acid molecules attack the lubricant as a whole, which is a blend of lubricant base stock/detergent–dispersant additive/alkaline material. The attack reduces its ability to lubricate and produces sludges of the three components which must be scavenged by an impaired detergent. Fuel debris must also be scavenged.

Hence the author's point is confirmed that high efficiency of neutralization results in good deposit control and good wear control – but I suggest that the wear is as much attributable to corrosive as to the abrasive wear caused by fuel debris.

I began my lubrication career in 1964 and can recall the time, I believe 1967/68, when B&W expressed concern about the leakage of acid sludge past the piston rod diaphragm into the system oil of 2-stroke crosshead engines. The result was that several companies introduced system lubricants with an alkaline additive package giving about 3 TBN. By the early 1970s this problem became a virtue because the alkalinity was increased from 7 to 10 TBN allowing one lubricant to be used for system oil and diesel auxiliaries.

Author's reply

In response to **Mr. Victory** on some of the early historical aspects, no reference has been found to additional uses of soft soap besides washing hands. Soft soap however was a lubricant used in hydraulic machinery when the fluid was water. In such cases soft soap appears to be the best lubricant because soaps found in or added to the water concentrate upon all the surfaces with which the fluid comes into contact, and form very tenacious films which prevent the cutting and grinding of the valve faces (see ref. 2 of the paper).

Applied to fixed oils and fats, saponification occurs which leads to a breakdown into alcohols and fatty acids. If this reaction is carried out with an alkali, such as potash, a soap is formed. For the open eccentric trough situation it is considered that fixed oils were used in this application because of their oiliness.

With reference to colloidal graphite, this compound does feature in the history of marine lubrication. The use of ordinary graphite (black lead) was used in conjunction with tallow as a steam cylinder lubricant when steam pressures were low. As the graphite was always of the natural type it was merely ground and not colloidal, hence it could not be used in suspension with oil or water, but only in conjunction with lubricants such as tallow, which, being solid or semi-solid at ambient temperatures, prevented the graphite from separating out. As discussed in the paper a steam cylinder lubricant with a high content of tallow decomposes at elevated temperatures, which over a period of time may give rise to serious corrosion.

Colloidal graphite may be defined as a graphite so finely divided that it does not sink in the liquid in which it is suspended. When suspended in water an interesting lubricant is produced which was extensively used in land installations for saturated steam conditions. Unfortunately no reference has been found to its application at sea. By all accounts (ref. 1) there is no reason why it should not have worked in the marine environment as the condensate was oil free.

For marine diesel engines colloidal graphite was incorporated in marine cylinder oil (see ref. 4 of the Bibliography of paper). The amount added was as low as 0.1–0.2 %wt and it was important that this material was of the highest purity (over 99.5%) and free of silica. Scientific tests have shown that the continued rubbing of the graphited oil between the piston rings and the liners caused a portion of the colloidal graphite to migrate from the oil and become firmly attached to the metal. Here it formed a strong thin film which penetrated the metal surface. It would appear that as long as this 'graphoid' surface was continually lubricated with oil containing colloidal graphite, any graphite cum metal removed by abrasion was replaced at an equal rate by fresh graphite up to a certain film thickness.

Molybdenum disulphide, like graphite, is a layer-lattice material, but molybdenum disulphide would not seem to feature in the history of lubricants for marine propulsion systems, with respect to the various oils described in the paper. Both these materials are solid lubricants which modify the frictional characteristics of the rubbing surfaces.

The author agrees with **Cdr. Short** that historically sperm oil was one of the fixed oils used by industry but would beg to differ that it was used in marine propulsion systems because of its low viscosity. Sperm oil derivatives were however widely used as friction modifiers up until the early 1970s when the sperm whale was declared an endangered species.

Straight mineral oils were the original recommendations for most vintage and veteran vehicles because these were the only

lubricants generally available, apart from the castor-based racing oils, and the engines were designed to run within their limitations. Although such engines may now benefit from the advances in deposit control and wear resistance of modern multi-grade engine oils, the fact that these oils do not thicken so much at low temperatures can mean that some of this old machinery will generate its full level of mechanical noise (clatter), and possibly leakage, well before full operating temperature is reached. This is not encouraged, but the choice of the heavier multi-grades such as 20W-50 provides an acceptable route.

It is true that the original introduction of detergent motor oil did cause some loosening of accumulated crankcase deposits with unfortunate results, and the stories of these disasters continue to be told. But in the following 50 or so years it has been shown that the overall benefits of mild detergency apply to all types of engine regardless of age.

The castor-based racing oils certainly provided a level of scuff resistance well beyond anything possible with straight mineral oils, and equivalent to an additive-treated mineral oil with very respectable performance. However this was at the expense of severe oxidation, as evidenced by heavy piston lacquering requiring very frequent dismantling for physical cleaning. Many enthusiasts are happy to continue to do this – their own labour comes free – and the aroma from the exhaust pipe is a bonus, as suggested by **Mr. Victory**.

While certain mineral oils can be defined in the manner indicated by **Cdr. Short**, this is not the case for the base oils used for the production of marine lubricants. Mineral-based oils are formed from essentially three categories of chemical compounds, which are paraffins (normal and iso), naphthenics and aromatics, comprising only carbon and hydrogen. The precise chemical composition of the finished base oil depends on the crude oil source and the refining process employed. All fixed oils are chemical combinations of alcohol radicals and fatty acid radicals. In vegetable oil and most of the animal oils the alcohol radical is glyceryl (C_3H_5 , which is trivalent and therefore combines with three fatty acid radicals). For example olein $C_3H_5(C_{18}H_{33}O_2)_3$ is the main constituent of many fixed oils such as tallow, neatsfoot and olive oil.

For over 50 years the industry has had oil-filled stern tube bearings, which for decades have been filled with main engine propulsion lubricants. It should however be appreciated that this route, which has been found to be acceptable by ship-owners, uses a lubricant for a purpose for which it is not specifically formulated.

The lubricant requirements for some gas turbines can be met by the use of mineral oils similar to that for steam turbines, but for some designs a synthetic lubricant is required which is referred to later. With regard to those vessels with nuclear propulsion, where the lubricant is in close proximity to the nuclear plant, special oils and procedures have to be adopted as radiation has an adverse effect on mineral oils. The use of nuclear propulsion is predominantly military, with the exception of some USSR ice breakers and a Japanese research vessel.

Additives

The lubricants available in the marketplace are a combination of base oils and additives, where the additives enhance the chemical and physical characteristics of the base oils. These additive components are chemical compounds which are often quite complex in their structure. Without these additives

marine propulsion systems would not be able to operate at their present temperatures and pressures, which have given a significant reduction in the specific fuel rate over the past decade. All additives are evaluated with respect to health and safety and the manufacturer provides extensive health and safety data. In turn the supplier produces similar data for a particular lubricant. As can be seen from the overview given below, the development of the combination of the additives used in a lubricant is an iterative process. In the future there is no doubt that the evolution will continue and the number of additives available to the formulator will possibly increase.

In the paper reference is made to the birth of the chemical additive industry for lubricants, when experiments were made with detergent oils. A date for this, namely 1935, is given in Table 2 by Mr Rothert. The function of the detergent additives is to control deposits which are formed at high temperatures. These are formed by a complex mechanism and arise partly from the products of incomplete combustion in the blow-by past the piston rings and partly by oil oxidation. Oxides of nitrogen and acidic sulphur oxides also contribute to the mechanism of deposit formation. If left unchecked deposition of carbon will take place, together with formation of lacquer or varnish deposits on the pistons, and ultimately sticking of the piston rings. The primary detergents found in marine diesel engine lubricants are metallic salts which include acetates, naphthenates, phenates, salicylates and sulphonates, with a metal ion which is usually barium, calcium, or magnesium.

Compared with the early detergents the most important evolution was the introduction of 'overbasing' which allowed the development of the single phase cylinder lubricant referred to in the paper. Early detergents could only neutralize a limited amount of acid, but the introduction of 'overbasing' meant that the additive had the potential to neutralize considerably more acid. One indication of a detergent's performance as an acid neutralizer is the total base number (TBN). Thus it follows that the higher the TBN value, the greater is the amount of acid that a given detergent can theoretically neutralize. Depending on the application, the TBN value for a detergent can range from effectively zero to over 400.

In the case of marine cylinder lubricants (MCL), where for the crosshead engine 70 TBN is the present accepted level, obviously detergents which exhibit a high TBN are used in the formulation. The actual chemical selection however depends on many factors which include acid neutralization rate, cleanliness, performance and compatibility with other additives in the lubricant. For crankcase lubricants, whether they be for crosshead or trunk piston engines, account has to be taken of the effect of water when selecting the detergent additive to prevent emulsification.

Also often found in MCL and crankcase lubricants are dispersants which keep in suspension the deposit-forming materials in the oil. They may often be required because the detergent additive in general is not able to disperse these materials which, if not controlled, will agglomerate into larger particles capable of blocking oil filters and hindering the action of oil scraper rings. The action of the dispersant is to keep the contaminants suspended in the oil with a relatively low particle size. Dispersants are usually 'ashless' (non-metallic) compounds such as polyisobutenyl succinimides or polyisobutenyl succinic esters.

As previously defined in the paper, wear in a diesel engine cylinder can be broadly classified as frictional, abrasive and corrosive. Another group of additives are anti-wear agents which are usually associated with the reduction of frictional wear. One of these is zinc dialkyl dithiophosphate (ZDTP), which is a generic term for a complex compound. ZDTP does

not define a single compound because there can be variations in the dithiophosphate molecule which can significantly alter the performance characteristics, such as hydrolytic and thermal stability. The effect of ZDTP is to lay down a thin film of phosphide and sulphide which results in a lower coefficient of friction between the rubbing surfaces.

Without the inclusion of a suitable anti-oxidant a lubricant operating at elevated temperatures would experience rapid oxidation, which would result in an increase in viscosity. Anti-oxidants alleviate this problem and the chemicals used for this performance aspect include aromatic amines, hindered phenols and ZDTP.

A rust inhibitor is essential where the lubricant is likely to come into contact with a humid atmosphere or water, which can be either fresh or salt, as may occur with a crankcase oil. In order to give the required protection, various chemicals are available which include some alkaline detergents and alkenyl succinic acids.

Foam inhibitors often referred to as an 'anti-foam additives' are included in most marine lubricants. Their purpose is to prevent or at least minimize the problem of a lubricant foaming. The commonly used anti-foam additives include silicones and polyacrylates and they function by modifying the surface tension of the lubricant.

Pour point depressants are added to some marine crankcase oils to modify the wax crystal structure of the lubricant at low temperatures. One of the chemicals commonly used for this purpose is polymethacrylate.

With reference to bio-deterioration of lubricating oils, this is a process which is caused by a number of parameters which include water, temperature and additive composition. The additives are of course controlled by the formulator and, as research has shown, some are more prone to microbial attack. These types are not included in state of the art lubricant formulations.

For completeness it should be noted that steam turbine oils contain a very small amount of additives (~1 %wt) and the additive characteristics are referred to in the paper.

Environment

Marine propulsion systems, whether they are powered by a continuous or intermittent combustion process, have an effect on the environment. As consumers of fossil fuels they emit carbon dioxide (CO₂), nitrous oxides (NO_x) and sulphur dioxide (SO₂) and the extent of these emissions depends on the fuel used and the process employed. As the great majority are powered by an intermittent combustion process, namely the diesel cycle, the environmental effect of this requires amplification.

While CO₂ is not toxic, its effect on the environment has been highlighted as one of the contributing factors of the 'greenhouse effect'. For the present generation of marine diesel engines operating under optimum conditions the formation of carbon monoxide, a toxic gas, is only minor and is academic if correct attention has been given to the excess air ratio and combustion temperature.

To obtain the present high thermal efficiency in diesel engines the combustion temperature is in the order of 2200–2400°C, at which temperature oxygen and nitrogen react to form oxides of nitrogen (NO_x). Initially NO is formed but in the expansion process a small proportion is converted to NO₂ and N₂O. Because engines are optimized for high efficiency the overall NO_x emission can be as high as 1800 p.p.m.

The amount of sulphur in fuel used for marine propulsion systems depends upon the grade used. For distillate fuels this is in the range 0.2–1.5 %wt, whereas for residual fuels the

average value is about 3.0 %wt. The exact level depends on the origin of the crude oil from which the fuel is derived. On combustion, oxides of sulphur (SO_x) are produced, which are mainly in the form of SO_2 . Some of these oxides, including SO_3 , are neutralized by the alkaline effect of the lubricant in the cylinder, but as only a small amount is converted, cylinder lubrication cannot be considered as an eliminator of SO_x . The ultimate environmental effect of SO_x and NO_x is well known in that both are contributors to acid rain.

If IMO were to implement better quality fuels, one would expect a highly defined specification, which would include low limits on sulphur. Such an international implementation would have a significant effect on marine cylinder lubricants. With a low sulphur fuel of say 0.3–0.5 %wt, a level which already exists in some inland markets, the alkalinity reserve, as expressed in TBN, could be reduced from the generally accepted value of 70 TBN for crosshead engines to 10–15 TBN. Under the same conditions a similar figure would apply for trunk designs. In order to obtain a level of NO_x emission of 100 ppm, as already required in some parts of the world, the present indications are that this can only be achieved by chemical treatment of the exhaust gas external to the engine.

In response to **Dr. Cowley** on the fate of lubricating oil 'used' in marine propulsion systems, this is not as straightforward as it would seem. The proportion of cylinder lubricant burnt depends on numerous factors which include the composition of the lubricant, method of lubrication and condition of the ring pack. In the case of crosshead engines, that which is not emitted with the exhaust gas flows to the scavenge drains and also forms a component of the piston rod gland drain oil. It should be appreciated that the flow to the scavenge drains is essential for efficient cylinder lubrication as one of the functions of the lubricant is to provide a transport medium for the combustion debris. In trunk designs this debris is carried down into the circulating oil.

Disposal of scavenge drains and used oil can either be carried out by onboard incineration or by landing ashore at a suitable port. It cannot be ignored that there is a cost in disposal of used lubricants in order to comply with the various environmental regulations and it is well known that in some countries one method of used lubricant disposal is to add it to the residual fuel oil pool. Under these conditions one has to hope that suitable dilution is applied, otherwise there is a potential danger of burning a fuel with high ash levels.

For crosshead engine system oils the life can be extended by the avoidance of deliberately adding piston rod drain oil which must contain some highly oxidized material and will include a level of carbonaceous deposits from combustion debris.

The example of cresylic acid mentioned in the paper, which it is agreed is a pollutant and a noxious substance, was included as an illustration of one of the means employed in an endeavour to burn residual fuels before the availability of single phase cylinder lubricants. Whilst being what might be termed a 'non-green' compound it did at least provide some beneficial effect by reducing wear and hence controlling particulate emissions which are also detrimental to the environment.

Overall the present day marine lubricants have a positive effect on the environment. If it were not for these oils, shipowners would not be able to operate their vessels with highly efficient diesel engines burning residual fuel. Without these lubricants evolutionary technical progress would have ceased, and one can envisage a situation where the propulsion system would be less thermally efficient, and hence for transportation of the same number of tonne-miles to meet the demands of world trade, the emissions in the form of CO_2 , NO_x and SO_x would be considerably greater.

Running-in

There is no doubt that if a cylinder liner is not properly run-in, it is unlikely that an efficient gas seal will be formed with the piston rings. Also until the surfaces are properly bedded-in there is a danger of scuffing occurring at high loads. Running-in can be sub-divided into two stages; firstly, that which takes place once the engine is first assembled, and secondly, that which occurs after the engine and ship have been delivered. Of course between these two stages the vessel will have been demonstrated on sea trials which includes some time at full power. It now seems the accepted practice to shorten the shop trial, which may possibly be a matter of shipyard economics. During this period the engine is invariably operated on distillate fuel. Sometimes a straight mineral oil is used, but there is a potential danger of deposit formation and even ring sticking because such an oil does not contain any additives. Other yards prefer a low TBN cylinder oil with a viscosity of at least that of normal cylinder oil (SAE 50). Another alternative is to use a running-in compound which gives good results under controlled conditions.

Once in service it is considered essential that the running-in procedure is continued, but unfortunately restricted service power is not always possible because of the trading pattern of the vessel. Whilst the power may not be ideal, the cylinder feed rate should be set in accordance with the engine manufacturer's guidance notes. Initially this figure is greater than the normal service cylinder oil consumption. Periodic inspections should be made of the ring pack through the scavenge ports and the initial bedding-in process observed. Depending on the results the feed rate can be incrementally reduced until the optimum service feed rate is achieved. It is considered that there is an advantage in breaking-in new liners by accelerating the corrosive wear on residual fuel using a low TBN cylinder oil.

After a liner has been renewed in service running-in can be accelerated by the use of a low TBN oil. As most vessel cylinders do not have individual lubricator boxes it would mean that for a limited period an in-service old liner would experience some corrosive wear, but the effect of this, although negative, would be far outweighed by the rapidity of the running-in of the new cylinder.

For trunk piston engines in the test shop, running-in oils exist which have a high concentration of anti-scuff additive which protects the cylinders. Running-in with oil is not an easy operation and in all cases the oil has to be changed at the end of the operation. An alternative approach is to use a running-in compound which is added to the fuel, irrespective of whether this is a distillate or residual grade. The compound is a complex salt in solution with a fluid mineral base. During combustion an abrasive aluminium oxide ash is formed from the fuel mixture and this helps to promote an increased rate of localized bedding-in of the rubbing surfaces.

Synthetics

Both **Cdr. Short** and **Mr. Orr** make direct reference to synthetic oils. Such oils have been available for nearly 50 years but their application to marine propulsion system lubricants has been minimal except for specialist applications. As a generalized statement a synthetic lubricant is synthesized from other materials to meet specific requirements which generally cannot be derived from naturally occurring products. Extreme temperature conditions in service is an application for synthetic lubricants. As far as marine propulsion systems are concerned, the main application is for aero-derivative gas turbines.

There are however some specialist auxiliary machinery applications where, despite the considerable cost of such

products in relation to mineral oil based lubricants, there is a perceived cost benefit. Because of the considerable cost of synthetic lubricants it is not expected that they will find application in diesel or steam-powered marine propulsion systems in the foreseeable future.

The future

In response to Mr. Beland, Cdr. Short and others, one of the conclusions in the paper requires expansion with reference to the future development of the diesel engine. What has taken place over the past 25 years, with respect to crosshead engines, is a reduction in the specific fuel consumption which has been in the order of 20-25%. During the same period there has been an increase of 40-60% of cylinder oil consumption when expressed in g/bhp h. Now the cost of the cylinder oil used can be simply converted into a cylinder oil fuel equivalent penalty (COFEP) and clearly for economic advantage this penalty must be less than the incremental fuels gains made.

The penalty for conventional cylinder oils can be plotted on the nomogram shown in Fig. 1 below, in which account is taken of the standard cylinder oil price, fuel price and any variation of the standard cylinder oil price which may exist because of the particular fuel being burnt or because of other technical requirements. (Note the standard cylinder oil price is defined as that for the 70 TBN/SAE 50 products.) The price of cylinder oil is determined by its component cost and market forces, but as it is purchased under a term contract it is not subject to severe price fluctuations. This is not the case for fuel oil which is purchased on the spot market and is subject to wide price

variations. In this decade the price has fluctuated in the range US \$ 35-220/tonne. Such a wide variation has a significant effect on the COFEP. The ratio of the actual cylinder oil price being used compared with standard oil can be made by dividing the actual price by the standard price.

Determination of the penalty is illustrated in Fig. 1, where the following values have been used:

- Cylinder oil feed rate 0.9 g/bhp h (1.2 g/kW h)
- Standard cylinder oil price US \$ 1600/tonne
- Actual cylinder oil price US \$ 1920/tonne
- Fuel oil price US \$ 60/tonne

From the cylinder oil prices given, a factor of 1.2 (1920/1600) is calculated. Using these values, the procedure for determining the COFEP from Fig. 1 is as follows.

1. Construct a vertical line representing 0.9 g/bhp h to intersect the standard cylinder oil price (US \$ 1600/tonne).
2. From this intersection construct a horizontal line to intersect the fuel price line (US \$ 60/tonne).
3. Drop a vertical line from this intersection to the factor line (1.2 as previously calculated).
4. From this intersection construct a horizontal line to cross the vertical axis where the COFEP in g/bhp h can be determined.

Fig. 2, which is a development of Fig. 1, allows determination of the COFEP value if the formulation gives a price factor of greater than 1.3, as they can be accommodated in Fig. 1. The plotting on Fig. 2 follows the same principle as that previously described, except that in the third quadrant (bottom left) the

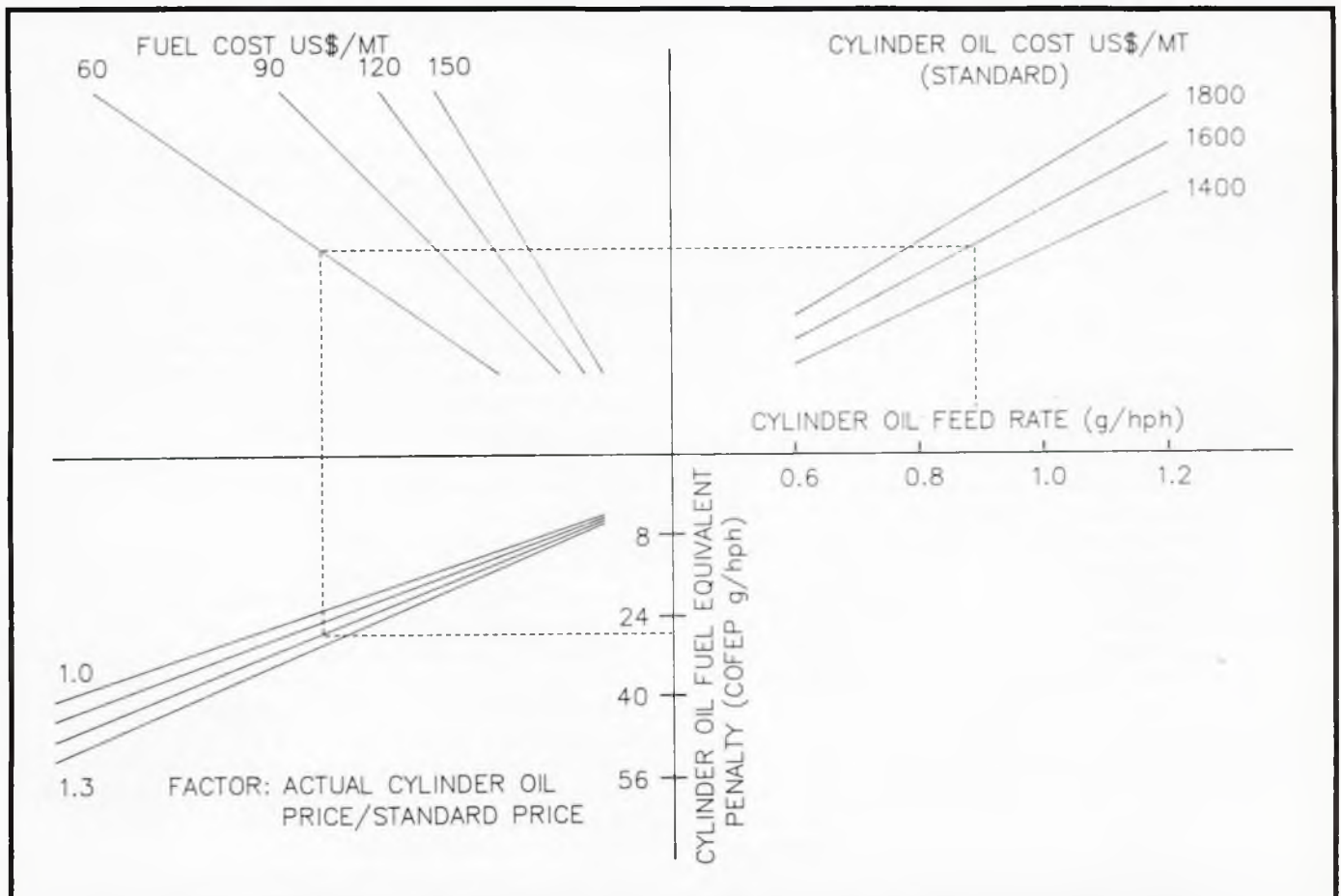


Fig. 1. Nomogram for determination of the cylinder oil fuel equivalent penalty (COFEP)

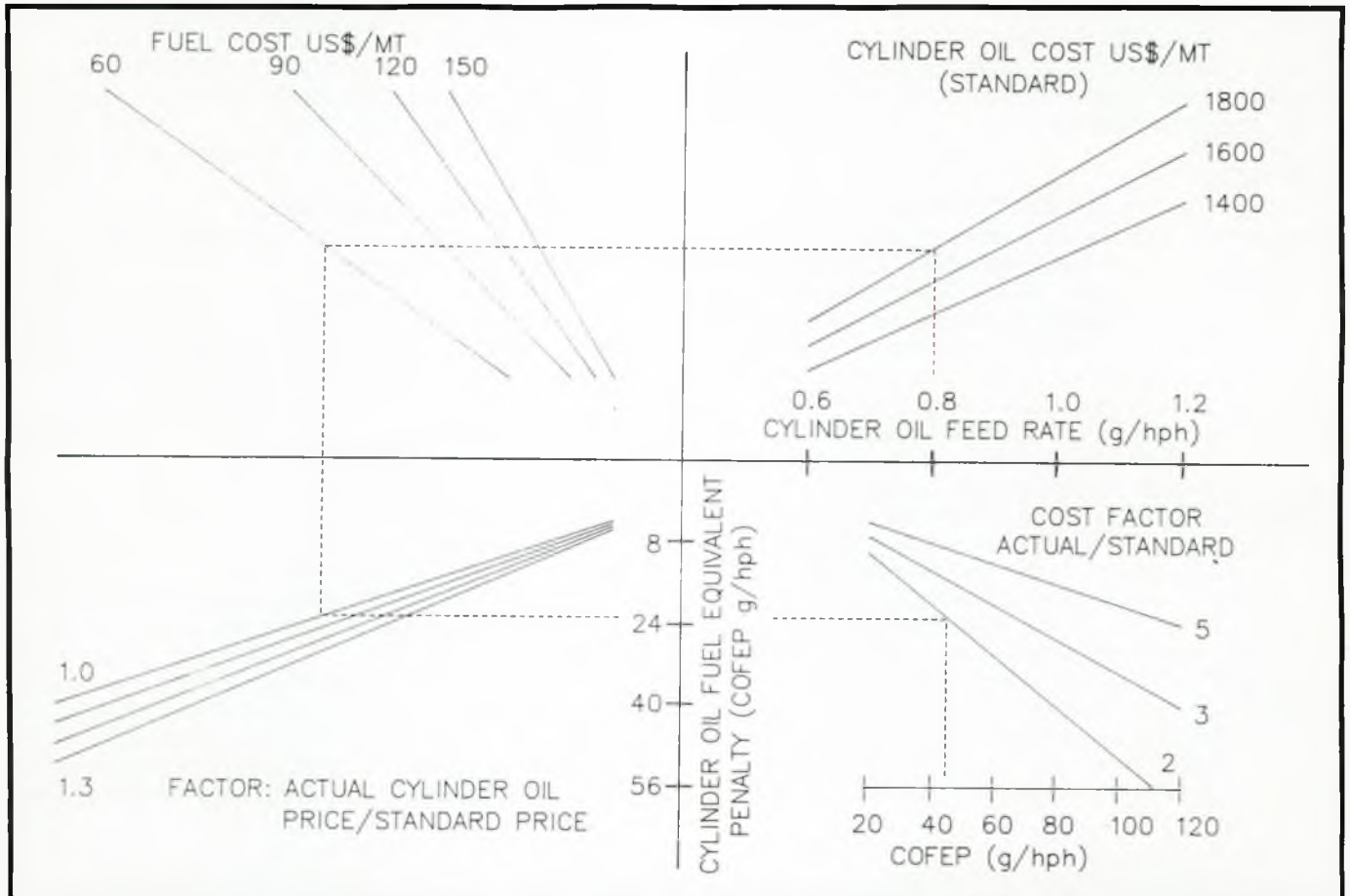


Fig. 2. Nomogram for determination of the cylinder oil fuel equivalent penalty (COFEP) with alternative higher priced lubricant

factor 1.0 is used. From this intersection with the vertical from step 3, construct a horizontal line to intersect the cost factor lines in the fourth quadrant (bottom right). As before the cost factor is the actual price divided by the standard price. Finally drop vertical lines to determine the new COFEP value. This is illustrated in Fig. 2 with the values 0.8 g/bhp h (1.07 g/kW h).

- Standard cylinder oil price US \$ 1800/tonne
- Actual cylinder oil price US \$ 3600/tonne (cost factor 2.0)
- Fuel oil price US \$ 60/tonne

Whatever cylinder lubricant is used there has to be sufficient available at the piston ring/liner interface to form a gas seal and minimize wear. In the process of minimizing wear it is essential that sufficient lubricant is available to act as a transport medium to remove debris from the ring pack to prevent a build-up of carbonaceous matter.

Whilst the development of cylinder lubricants will continue, engine designers need to take account of the COFEP, which must be added to the specific consumption before translating theoretical concepts into actual designs with their associated economic assumptions.

Trunk piston engines, like the crosshead engines already referred to, have also gone through evolutionary design stages to give a reduction in the specific fuel consumption. This has been achieved by a general increase in pressure and temperature in the operating cycle, so making greater demands upon the ring pack. In addition, other trends have taken place which also have an effect on the lubricant. These are a reduction of the oil charge in some designs, when expressed on a kg/kW basis

and also a reduction of the lubricating oil consumption by attention to the ring pack design. These trends have a significant effect on the oil in circulation with respect to the alkalinity reserve and insolubles management.

One of the functions of the trunk piston engine lubricant is to provide a level of alkalinity reserve which, as previously discussed, is derived from the detergent-type additives incorporated. When in service the lubricant experiences alkalinity depletion and this has been shown (ref. 2) theoretically to follow the formula: $TBN_t = TBN_0 - A(1 - e^{-r})$ where TBN_t = TBN of oil after t hours
 TBN_0 = TBN of new oil
 A = neutralization effect, $A = 0.3 y f s$
 t = running hours
 r = ratio of oil consumption/oil charge
 y = 'sulphur conversion factor', 0.07 for 4-stroke engines
 f = ratio of fuel consumption/oil consumption
 s = %wt sulphur in the fuel

The above formula assumes a continuous make-up procedure, which is not normally carried out in practice, but the indicated trends have been found to be valid and some interesting conclusions can be drawn.

Firstly the effect of a change in initial TBN has a purely linear effect on the depletion curve. Secondly as the running hours increase, the term in the brackets tends to approach unity and hence the stabilized TBN is given by $TBN_0 - A$. Hence the only lubricating oil parameter which affects the stabilized TBN is the oil consumption rate.

For many years the traditional level of reserve has been 50%

of the initial TBN value, but recently there have been recommendations for some designs to maintain a minimum TBN in excess of the traditional value. Clearly if such a recommendation applies to an installation with a low oil consumption, one solution would be to use an oil with a higher TBN which would have a higher cost.

The combined effect of increased b.m.e.p., low oil consumption and reduced sump size places greater stress on the lubricant, which has multi-purpose functions. These functions are lubrication of the cylinder to minimize wear, lubrication of the bearings and running gear, and cooling of the under-piston crown. As a result of the first function debris from the ring pack is transported to the circulating oil and this carbonaceous

matter is seen as insolubles. Treatment of the oil is carried out by periodic make-up, filtration and also often by suitable centrifuging of the charge. Even after all this, there is sometimes a definite trend for the insolubles burden to continue to increase to a point where partial or total renewal of the charge is necessary so that the lubricant can satisfactorily perform the functions defined above. It is therefore concluded that insolubles management is one of the key issues that faces the industry.

Fig. 3 shows the effect of total oil used in a trunk piston engine under two conditions. In the case of curves A and B, a charge of 1.2 kg/kW has been assumed, whilst curves C and D relate to a charge of 0.5 kg/kW.

For a particular installation, having established the total oil used on a g/kW h basis (consumption + oil charge requirement), the lubricating oil fuel equivalent penalty (LOFEP) can be determined from Fig. 4 or Fig. 5, depending on the total oil used. In both Figs. 4 and 5 it is suggested that the cost of the standard lubricating oil be taken as that of a 30 TBN of the viscosity grade for the particular engine (SAE 30 or SAE 40). By way of illustration in Fig. 4, the following values have been used:

- Total oil consumption 1.5 g/kW h
- Standard trunk piston engine oil price US \$ 1500/tonne
- Fuel oil price US \$ 90/tonne

In Fig. 5, by way of illustration, the following values have been used:

- Total oil consumption 0.625 g/kW h
- Standard trunk piston engine oil price US \$ 1600/tonne
- Actual trunk piston oil price US \$ 1760
- Fuel oil price US \$ 90/tonne
- Factor 1.1 (1760/1600, applied in third quadrant, bottom left)

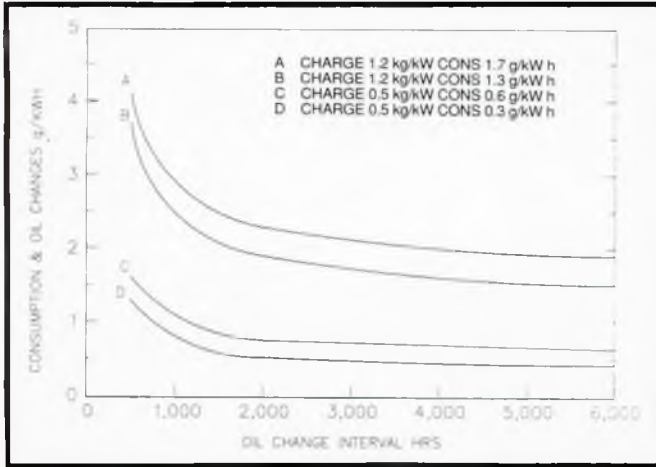


Fig. 3. Total oil used in a trunk piston engine related to oil change period

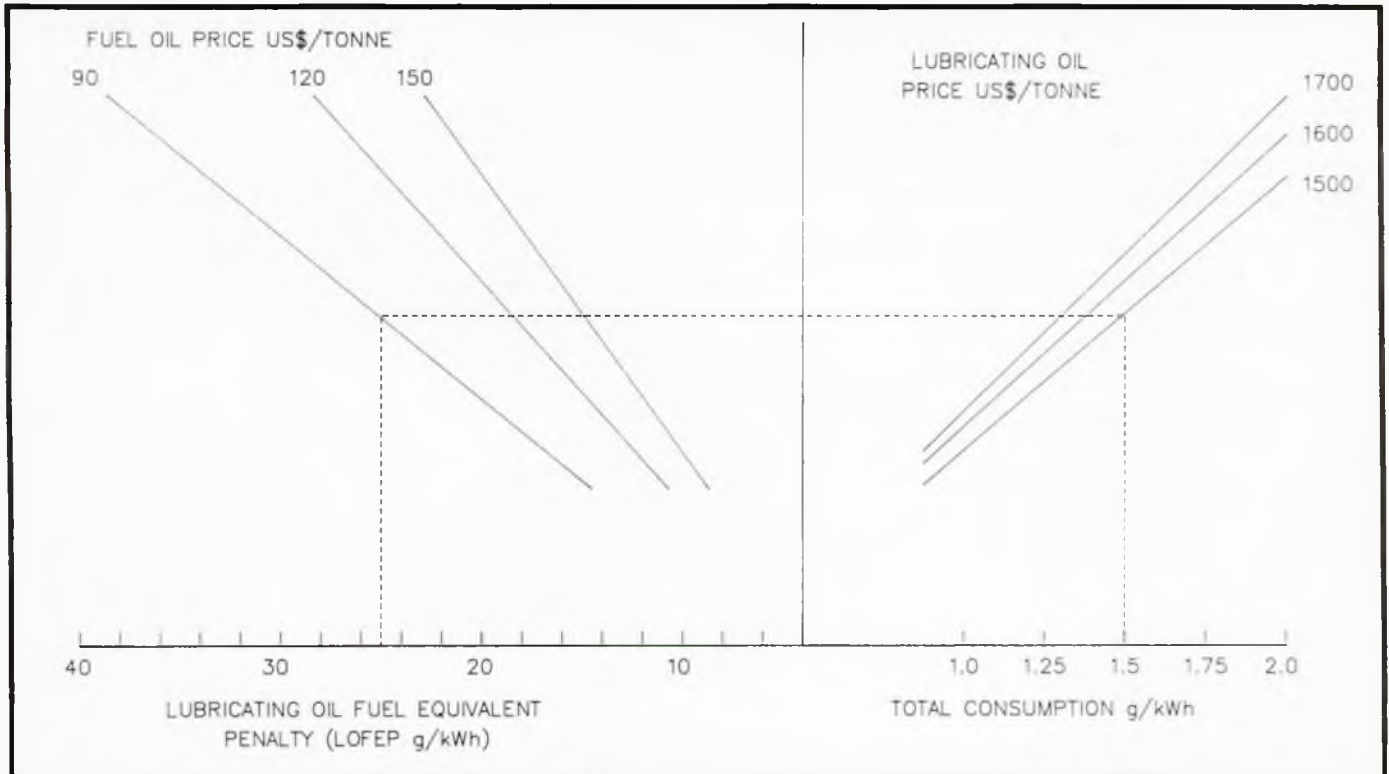


Fig. 4. Nomogram for determination of the lubricating oil fuel equivalent penalty (LOFEP) for trunk piston engines with a usage of 1.0-2.0 g/kW h

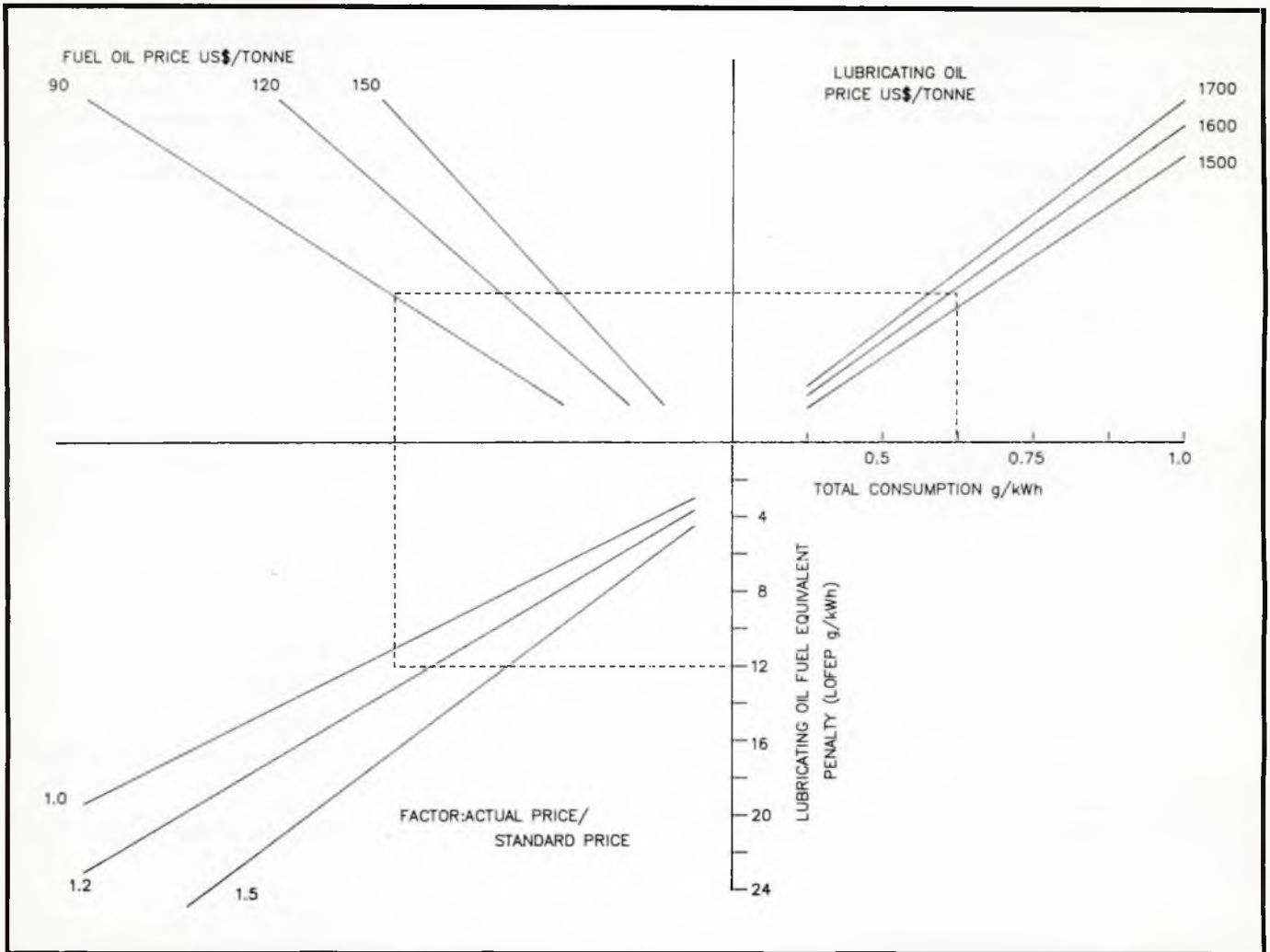


Fig. 5. Nomogram for determination of the lubricating oil fuel equivalent penalty (LOFEP) for trunk piston engines with a usage of less than 1.0 g/kW h

The third quadrant allows for the cost effect of alternative lubricants to be examined. This may be due to a change in cost because of a variation in TBN or consideration of an alternative lubricant.

In conclusion, the author would like to thank all the contributors for their interesting comments.

... and oil to make his face to shine ...
(Psalm 104, verse 15)

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