CCDoTT

Center for the Commercial Deployment of Transportation Technologies

ALTERNATIVE POWERING FOR MERCHANT SHIPS

Task 1 – Current and Forecast Powering Needs

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FINAL

for:

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CONTENTS

TABLES

FIGURES

1 INTRODUCTION

1.1 Administrative Background

This report was produced by Chris B. McKesson for the Center for the Commercial Deployment of Transportation Technologies (CCDoTT). The report documents a project to study the economic impact of alternative powering systems for container ships. The concept of the project is to assess whether there is economic incentive to develop alternative powering systems for container ships: Would such systems result in improved shipping economies?

This investigation is referred to as the CCDoTT Alternative Powering for Existing Ships project.

There is a similar CCDoTT project conducted simultaneously which considers the application of alternative powering schemes to proposed very-fast ships, specifically using the Fast Ship Atlantic project as a technology baseline. This larger project looks further over the horizon than does the present project, but there is nevertheless a significant similarity between the two projects. The larger project is a contracted effort being performed by John J. McMullen Associates, Inc.

1.2 Purpose and Organization of this report

This report is the first of three deliverables of this project. This report established the naval architectural baseline for the project by reviewing and summarizing the trends in container ship design, and particularly in powering and propulsion: What are the powering characteristics of current container ships, and what is the expected trend in their growth over the next 10 to 15 years?

Subsequent reports from this project will address the characteristics of the alternative powerplants that are suitable for container ships, and the application of the most promising alternative powerplant to a baseline or notional container ship, to determine what economic performance results.

2 STATE OF THE ART CONTAINER SHIPS AND THEIR PROPULSION

The modern container ship is a miracle of transport efficiency. It is a mature system that has evolved rapidly in the half century since it was invented. The selection of powerplants for container ships has been the result of a natural selection process, which also in part has guided the determination of ship characteristics.

The paragraphs in this section present the current state of development of such ships, and the expected trends in their continuing evolution.

The viability of a candidate powerplant will of course depend upon the characteristics of the ship it is used in. This section focuses on cataloging the trend in container ship size, power, speed, and route.

This chapter is organized in order of decreasing immediacy (i.e. present to future): It first treats the current state of the art container ship. Following the discussion of the existing ship is a discussion of the near-term developmental ship. (A near term developmental ship is one of which the first unit may actually exist today, and it is expected that additional similar vessels will be built in the coming years.) The third section is an attempt to look over the horizon at far-term ship characteristics.

2.1 State of the art container ship

2.1.1 The Demand for Ship Size

The "State of the Art" as used herein is the container ship that is at the leading end of ship trends. This ship is not the single most extreme or advanced ship – those ships will tend to be prototypes or (almost) experiments.

The first salient feature of container ship evolution has been ship size. Container ships have continued to grow in size. A few years ago (1994) the 6000 TEU REGINA MAERSK was a "Supership." Today Maersk continues to blaze trails into unbroken ground, with the 1999 delivery of 8,000 TEU SORØ MAERSK.

Figure 1 shows the size versus year-of-build for the current fleet of Maersk Sealand container ships. As is evident there has been a steady evolution toward larger ships.

For the purposes of this report we will treat the 6000 TEU ship as the "state of the art." The 8000 TEU ship represents the ships that are currently on the horizon, and larger and presumably faster ships are "over the horizon."

Clearly the development of ships like these is the result of economies of scale. But their development also imposes and is constrained by demands upon propulsion machinery. (Certainly there are other constraints such as port facilities, canals, etc. This project considers only propulsion-related matters.)

2.1.2 The Demand for Power

Figure 2 depicts a trend for container ship propulsion. As may be seen the 6000 TEU state of the art implies a propulsion power demand of 60-80,000 shaft kilowatts. This need is met with the latest generation of large low speed diesels, such as the MAN/B&W K98MC-C, which is available up to 93,000 hp (68,000 kW). The K98 series engines have a fuel consumption of approximately 171g/kWh. A 12 cylinder version (93,000 hp) will weigh approximately 2,157 tonnes (dry). As of January 2000, five of these engines had been delivered, all of them for 6400 TEU container ships.

The availability of large direct drive diesels may be the current determining factor for the speed of state of the art ships. Figure 3 below depicts the speed versus size (TEU) for the current Maersk Sealand fleet. As may be seen, after a trend toward increasing size with increasing ship speed, the speed seems to have stabilized at around 25 knots. For the largest ships this speed, per figure 2, would correspond to the largest MAN/B&W diesels available.

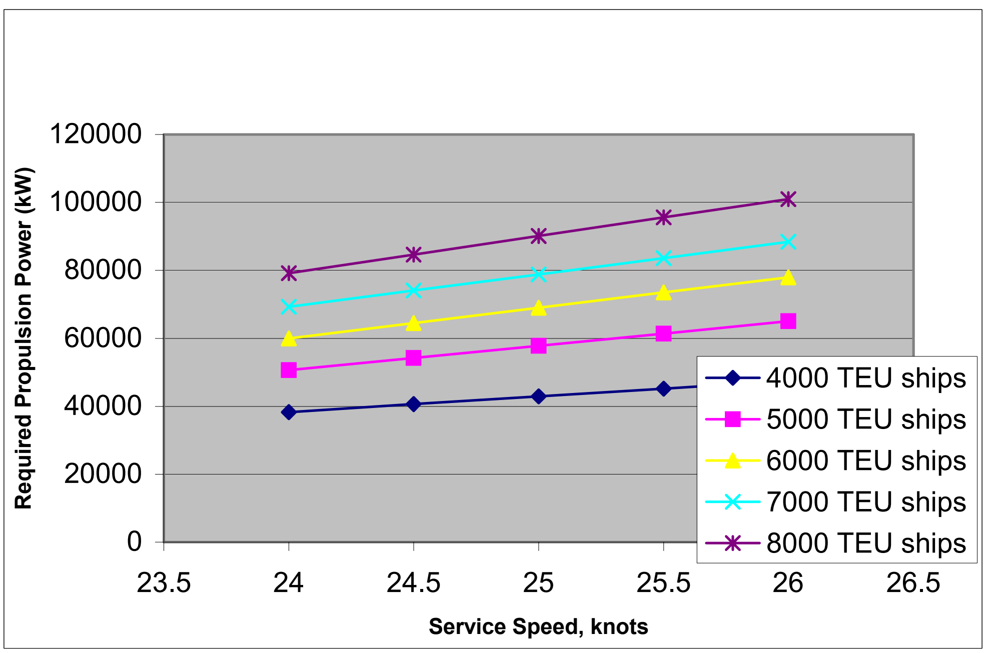
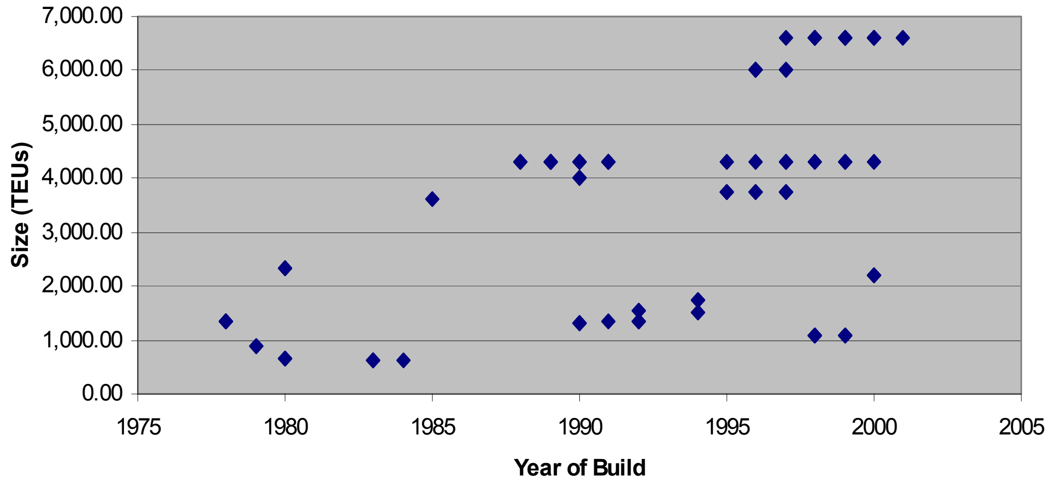


Figure 1 - Container ship Size vs Speed & Power

Figure 2 - Size vs Year-of-Build for Maersk-SeaLand fleet



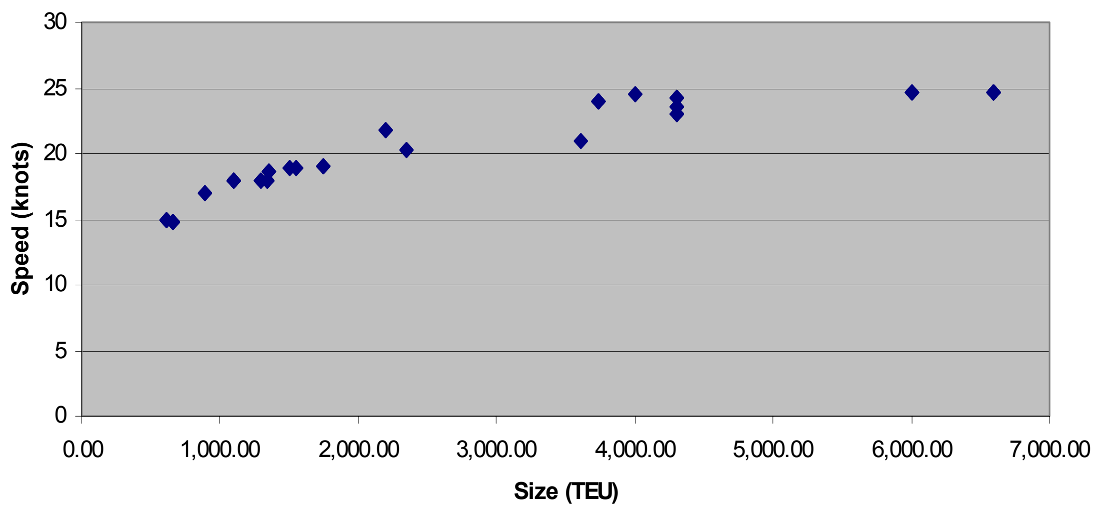


Figure 3 - Size vs Speed for current Maersk-SeaLand fleet

2.1.3 The Demand for Range

A container ships' design will optimize fuel capacity in consideration of route length and the desire for maximum cargo capacity. The ship need only carry a minimum of fuel, sufficient to guarantee that she completes her journey and is able to refuel. There is little or no incentive for the ship to carry excess fuel as it adds weight and takes away from its primary mission of carrying cargo.

Unsurprisingly the large container ships ply transoceanic liner routes. A sampling of such routes is presented in Table 1 below.

Table 1 - Major shipping routes over 4000 nm

Port A	Port B	Distance (naut. miles)
Southampton	Kuwait	11107
Panama	Yokohama	7680
Kuwait	Yokohama	7500
Yokohama	Kuwait	7500
Wellington	Cape Town	7081
Cape Town	New York	6785
Auckland	Panama	6550
Panama	Wellington	6490
Sydney	Vancouver	6390
San Francisco	Straits of Magellan	5990
Lobito	Panama	5815
Cape Town	Singapore	5650
Cape Town	London	5150
San Francisco	Valparaiso	5140
London	Lobito	5050
Vancouver	Guam	4965
Fremantle	Aden	4925
Fremantle	Cape Town	4808
Panama	London	4725
Cape Town	Bombay	4600
Gibraltar	New Orleans	4550
Cape Town	Colombo	4440
Sydney	Yokohama	4380
Gibraltar	Panama	4330

In 1997, ports on the west coast of the United States accounted for 42 percent of the value of U.S. waterborne trade with other countries compared with only 24 percent in 1980. East coast ports' share by value, however, declined from 41 percent to 38 percent over this same period and the share of value for Gulf ports also dropped from 33 percent to 18 percent (USDOC Census 1997, table 1069; USDOT MARAD 1998). Certainly this is due to changes in trading partnerships, sources of trade, and other economic factors. It also results, nevertheless, in an increasing emphasis on the longer Pacific routes.

The sailing distance from the US West Coast to Japan is approximately 4800 miles. From the US West Coast to Singapore is about 7800 miles, and from Singapore to Panama is 11000 miles.

The picture that emerges is that the greatest demand for large ships (in terms of the greatest route volume) is found on Pacific routes, and that these ships must have a service range of at least 5000 miles, and perhaps as much as 12000 miles or more.

The range requirement is a major driving element in a powerplant tradeoff. Powerplant tradeoffs can be made – to at least a first level of approximation – on the basis of weight and fuel economy.

Fuel consumption of course represents a recurring operating cost. Thus the pressure to operate efficiently exists throughout the ship life. In addition, both the fixed weight of the machinery and the consumable weight of the fuel must be carried by the ship, and thus represent lift capacity that is not available for cargo.

2.1.4 The Implications for the Propulsion Plant

From these considerations alone comparative parameters for a machinery plant can be developed, as given in Table 2 below. This table presents the machinery+fuel weight budget for a 6000 TEU ship, and a calculation of tonnes (metric) of fuel per TEU-mile.

Considering the weight parameter, it may be seen that for a nominal slot weight of 6t to 10t per TEU, the weight of the propulsion machinery and fuel equals 8% to 12% of the ship's cargo capacity. At a nominal US$1/US Gallon the fuel consumption cost is about 2.5¢ per TEU mile. Fuel weight, for a 6000 mile range at 25 knots, accounts for about ½ ton per TEU.[1]

This type of notional weight and cost data will be used later in this project for comparison with alternative power plants. Note that the table uses the engine dry weight. This means that the weights estimated are too low by at least the weight of the engine fluids. Note, however, that the table also ignores engine infrastructure, foundations, exhaust stacks, etc. It is not intended to be a complete estimate of machinery plant weight but is instead merely a simple comparative for investigation of alternative powerplants.

[1] It is worth noting at this point that these numbers are very small and highlight the very high efficiency of modern marine cargo shipping. By this analysis, to move a ton of cargo one mile at 25 knots requires 1/3 fl. Oz. (about a tablespoon) of fuel.

Table 2 - Comparison of Powerplant Weight Parameters for varying ship range

Engine	Name	12-K98MC		
Engine Weight	Tonnes	2157	2157	2157
SFC	g/kW-h	171	171	171
Power	KW	68640	68640	68640
Speed	Knots	25	25	25
Range	n miles	4000	6000	8000
Fuel Weight	Tonnes	1878	2817	3756
Engine+Fuel	Tonnes	4035	4974	5913
Fuel per TEU-mile	tonnes/TEU-mile	7.825E-05	7.825E-05	7.825E-05
Capacity	TEUs	6000	6000	6000
Fuel cost	$/TEU-mile	$ 0.025	$ 0.025	$ 0.025

2.2 *"On the Horizon" container ships*

Container carriers are continuing to order bigger ships. P&O Nedlloyd has reportedly considered contracting for the construction of 10,000 TEU vessels. Late in 1999 Hong Kong's Orient Overseas Container Line placed an order for two 7,200 TEU vessels with South Korea's Samsung Heavy Industries. Samsung has been marketing a 9,000 TEU design, and states it also has a 10,000 TEU design available, the size P&O Nedlloyd is reportedly studying for Asia Europe service.

For this report, the model of an "On the Horizon" container ship will be the 8000TEU ship. According to the powering data presented in Figure 2, this ship would require 80,000 kW of propulsive power to attain a service speed of 24 knots, and 100,000 kW for a speed of 26 knots. Other authors have suggested that the On-The-Horizon next generation ship will be as much as 10,000TEU, if a suitable powerplant were available.

Other authors have suggested that the next generation of ship will be twin-engined / twin-screw ships. In such case they might be fitted with as much as 160,000 kW using engines available today, and thus could be up to, say, 18,000 TEU in capacity.

The economics of manning and maintenance motivate the builder to avoid making the step to twin screw. Thus of immediate interest is the expressed intent of engine manufacturers to continue to develop ever-larger diesels. Hyundai (HHI) have announced their intent to develop a 140,000 hp "super diesel" for a predicted generation of 12,500 TEU container ships. While no details on the engine are available, the announcement itself indicates at least one firm's estimate of future demands.

Other approaches include developing more efficient propulsors. IHI revealed (The Naval Architect, April 2001) their research and development of a contrarotating propulsor for a 10,260TEU ship. This propeller attained an efficiency which allowed the ship to reach 25 knots with 20% sea margin on 59,290 kW.

However they are driven, these super ships are expected to continue to sail on today's routes. The length of these routes – some being well in excess of 20 days – continues to motivate shipbuilders to keep speeds high. As discussed, however, maintaining today's 25+ knots speeds for these larger ships will only be possible with a new generation of propulsion plant.

As shipbuilders develop ever-larger ships, a significant development need is thrust upon the ports themselves. The larger ships, some as much as 21-lanes wide, require container cranes with larger outreach. They require channels of greater depth, larger container staging yards, more rail service, more trailer drivers, etc.

Modest increases in ship size could be accommodated in existing ports. At some point, however, the port is forced to undertake an infrastructure expansion, and the costs for this are necessarily passed to the shipper. The time it takes to pass the cost through (initially they may be borne by tax payers in order to attract shippers), however, is such that the ship acquisition decision does not always take into consideration the cost of port redevelopment.

Of course, some types of port redevelopment are virtually impossible. Buying new cranes is easy, but adding a few hundred acres of staging area may be impossible. Many of today's ports are in mature urban areas and acquisition of additional land is economically infeasible.

This, the pressure of maintaining an interface with existing ports, is another disincentive in the drive to build ever-larger container ships.

2.3 "Over the Horizon" (Speculative) container ships

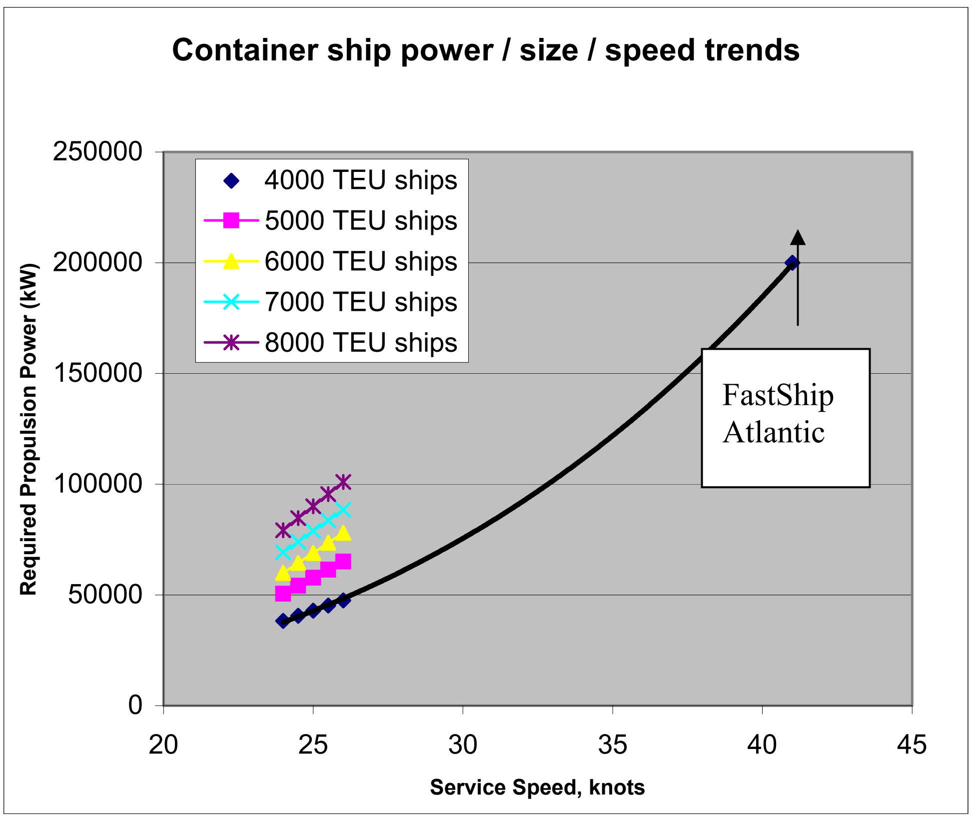
As one peers further over the horizon the view necessarily becomes "fuzzier." There are a few landmarks, however, that are visible from afar. In the realm of container shipping one of these is the FastShip Atlantic project. This is a concept for a very fast 4000-5000 TEU ship. This ship has been extensively described in the professional journals and will not be dealt with at length here, but it does provide a benchmark for the "Over the Horizon" container ship.

The FastShip Atlantic has the dimensions given in Table 3 below. Her powerplant consists of five Rolls Royce marine Trent gas turbines connected via gear drive to the waterjet propulsors, delivering a total of 300,000 horsepower (225,000 kW). The FastShip has been added in Figure 4 to see how she fits into the trend established by more conventional ships. As may be expected, the FSA power demand is almost exactly a cubic extrapolation from the existing ships' data.

Table 3 - Characteristics of FastShip Atlantic

	FastShip Atlantic	Air Cargo	Sea Standard	SL-7
Crossing time	3.5 days, 85 h	0.5 days, 12 h	10 days, 240 h	3.7days, 89 h
Speed	36-40 knots	450 knots	25 knots	36 knots
Power	250 MW (5*50MW)		70 MW	90MW
Capacity (TEU)	1,432	15	6,000	
Fuel per hour	54 t/h		12 t/h	16 t/h

Figure 4 – Container ship power trends with FastShip Atlantic added



FastShip Atlantic is envisioned for a USA – Northern Europe liner route. The envisaged ports are the Port of Philadelphia PA and the Port of Cherbourg, France. The distance between these ports is about 3200 nautical miles. The planned sailing time is about 85 hours.

The resulting fuel+engine powerplant weight for the FastShip Atlantic is given in Table 5. While the results therein are most certainly crude approximations, they nevertheless show the FastShip to have four times higher fuel costs per TEU-mile, as compared with 25-knot ships. Further, due to the lack of economies of scale, her weight propulsion+Fuel, per TEU, is as much as 17-28% of her payload capacity.

Table 4 - Powerplant parametric data for FastShip Atlantic

Engine		RR Marine Trent
Propulsion System Weight	tonnes	1992
SFC	g/kW-h	229
Power	kW	250000
Speed	knots	38
Range	n miles	3200
Fuel Weight	tonnes	4821
Engine+Fuel	tonnes	6813
Fuel per TEU-mile	tonnes/TEU-mile	0.0003766
Capacity	TEUs	4000
Fuel cost	$/TEU-mile	$ 0.119

FastShip Atlantic also requires a custom-adapted port, due to her use of a unit-train container loading concept. Apart from this consideration, however, the FastShip also indicates a different type of response to shipper's demands. In an era of JIT delivery the container ship is, for many merchants, their warehouse. The cargo in transit is the only reserve of product that they carry. In such a case, doesn't it make more sense to have a frequent delivery of smaller lots, as opposed to a monthly delivery of 10,000 boxes? Indeed, from a strictly mercantile point of view the most desirable system would be a dripping pipe: One item at a time steadily flowing at exactly the rate needed to replace sold inventory. Clearly the mega-ship is a step away from the pipeline concept, and the more-frequent smaller ship is a step towards. The difference of course is the loss of the economy of scale between these two options.

2.4 Current Propulsion Baseline - Diesel Engines

Container ship powering demands two characteristics: Reliability and Economy. Due to excellent economy the diesel engine remains predominant. The diesel driveline chosen for most line-haul container ships consists of a low-speed two-stroke diesel turning a direct-connected single propeller. Such a propulsion plant consists of a single large engine turning the propeller at shaft RPM with no intervening reduction gear. A leading manufacturer of such engines is MAN B+W, who in fact trace their corporate origins directly to Rudolf Diesel himself.

MAN/B+W have provided an excellent summary of the development of container ship diesel propulsion:

“A substantial number of recent large container ship contracts have called for main engine outputs up to a the highest ratings available, and for a period, most large container ships were thus specified with main engine MCR outputs of some 65,000 bhp

However the launching of ratings up to about 75,000 bhp per unit changed the picture. Now units with such outputs exist and in anticipation of a market for above 8000 TEU container ships, engines with even higher outputs have been introduced.

The change in ship size does not in itself explain the substantial increase in the average engine power seen in recent years. Hence it can be assumed that the design speed has increased. Increase in the average engine size is an indication of a changed demand pattern toward higher powered ship types.

The propulsion power requirement is considerably higher for a container ship sailing with high-value commodities than for bulk carriers and large tankers transporting raw materials, for which the sailing time is of less economical consequence. Hence, the propulsion power requirement for a Post Panamax container ship is 2-3 times the power requirement for a VLCC.

The increasing containerization and competition in this market, together with demands for the lowest possible freight cost per TEU, will imply a continued race for transporting as many TEUs as possible on the long-haul routes. This means that an increase in the average power requirement for container ships is to be expected.”

The “flagship” of the MAN B+W product line, and an engine often chosen for container ship propulsion, is the K98-MC engine. This engine is 980mm bore, and produces up to 90,000 horsepower (12-cylinder version.) The first of these monster engines was tested in 1999 at Hyundai, Korea – see Figure 5.

Other manufacturers have reported their intent to introduce engines larger than the K98. Examples include IHI’s representation of their intent to introduce a 140,000 hp engine.

RINA reported in June, 2001 that “the two leading designers of low-speed diesel machinery, Wartsila (Sulzer) and MAN B+W have both launched extended-cylinder inline versions of their most powerful models. This is being done to provide suitable plants for future generations of container liners without branching into twin-engine/twin-screw variants.”

Specifically, “Sulzer can now offer a 14-cylinder RTA96C engine capable of developing 80,080kW, while MAN B+W has just announced 13- and 14-cylinder versions of its K98MC and K98MC-C models. These will provide 74,360kW and

80,080kW (K98MC) and 74,230kW and 79,940kW (K98MC-C). (The MC-C designation indicates a shorter stroke and slightly faster running speed.) Even more remarkable, this latter designer says both types could be built with up to 18 cylinders and outputs of nearly 103,000kW, if necessary!"

These future engines are not yet in existence, and it appears that when they do emerge, they will be very similar to the existing K98. Thus for the purposes of this study we may use the particulars of the K98 series to derive engine parameters representative of all low-speed container ship diesels. The principal characteristics of the K98 are given in the MAN B+W catalog, reproduced as Figure 6.

We should note that, of course, much more detailed information is available on this engine. In the later sections of this report, however, comparisons will be made against much less mature powerplants. For these less-mature powerplants the only available information will be top-level data similar to that in Figure 6. Therefore, in order to provide a level field of comparison for all engine options this report will consider the diesel only at the same high level.

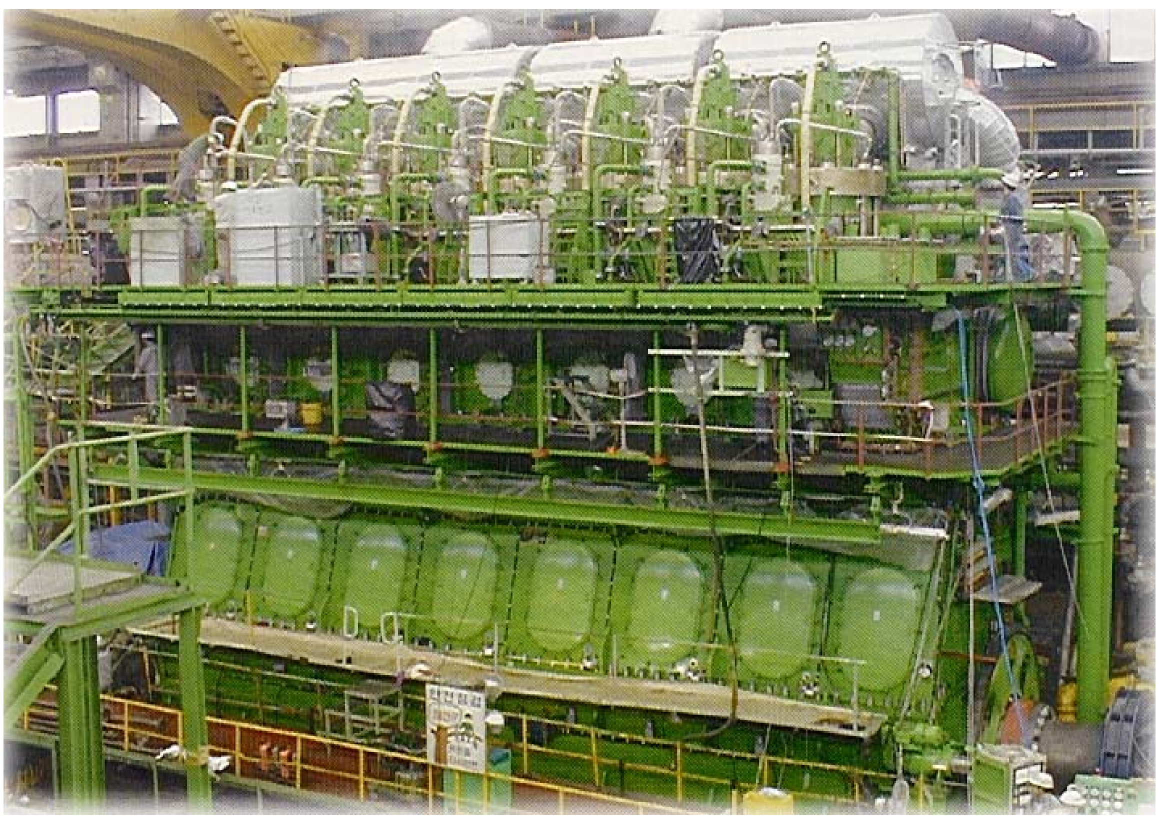


Figure 5 - The first MAN B+W 8-cylinder K98 engine, on test at Hyundai

Bore: 980 mm, Stroke: 2 660 mm **K98MC**

Layout points		L1		L2	L3	L4
Speed r/min		94		94	84	84
mep bar		18.2		14.6	18.2	14.6
		kW	*BHP*	kW	kW	kW
6 K98MC		**34 320**	*46 680*	27 480	30 660	24 540
7 K98MC		**40 040**	*54 460*	32 060	35 770	28 630
8 K98MC		**45 760**	*62 240*	36 640	40 880	32 720
9 K98MC		**51 480**	*70 020*	41 220	45 990	36 810
10 K98MC		**57 200**	*77 800*	45 800	51 100	40 900
11 K98MC		**62 920**	*85 580*	50 380	56 210	44 990
12 K98MC		**68 640**	*93 360*	54 960	61 320	49 080

Specific Fuel Oil Consumption (SFOC)

	L1	L2	L3	L4
g/kWh	171	162	171	162
g/BHPh	126	119	126	119

Lubricating oil consumption: approximately 7.5-11 kg/cyl. 24 h
Cylinder oil consumption: 0.8-1.2 g/kWh ~ 0.6 - 0.9 g/BHPh

Cyl. No.	**6**	**7**	**8**	**9**	**10**	**11**	**12**
L_{min} mm	12 865	14 615	17 605	19 355	21 105	22 855	24 605
Dry mass ton*	1 152	1 318	1 528	1 678	1 856	2 006	2 157

* The mass can vary up to 10% depending on the design and options chosen.

H_1: Vertical lift
H_2: Tilted lift
H_3: With electrical double jib crane

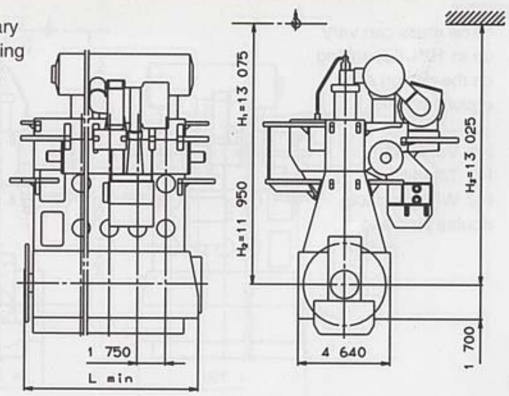


Figure 6 - Page from MAN B+W sales catalog describing the K98 series

3 CONCLUSIONS

The trends in container shipping:

- Container ships are continuing to grow in size as owners search for further economies of scale
- Smaller, more frequent ships would be desirable to cargo shippers if their economies matched the larger ships
- Ship size growth is currently constrained by available engine powers, with 60-90 MW being the current power level: Larger engines would permit construction of larger ships.
- Current powerplant weights are very high, but this is compensated for by very impressive fuel efficiencies.
- Route lengths are growing, trade is increasing on longer routes.
- Longer routes require higher fuel weights which detracts from the cargo capacity of the ship. This underscores the importance of maintaining very high fuel efficiencies, i.e. low-as-possible fuel deadweight.
- Ship propulsive efficiency – in terms of amount of fuel consumed to move one container one mile – is extremely high. Improvements in propulsive efficiency will be difficult to come by, given the high state of refinement of the current system.