

Review of shipboard energy technology *

Thoughts and facts behind the scene

In this paper some of the important technological challenges in the past are reviewed together with thoughts and facts behind them, as well as their success and failure from the techno-economical and business points of view, and, finally, what we have learnt from them. Topics taken up are nuclear powered merchant ships, marine rehear plants, gas turbine propulsion, steam bottoming plants in some depth, coal-fired ships and contra-rotating propellers. In addition to ingenuity, endeavours, established research and development procedures, the importance of enthusiasm of engineers, fact finding visits, a quality assurance approach and demonstration steps are also pointed out.

Atsuo Fukugaki has been a professor in the Faculty of Engineering, Tokai University since 1990. He obtained his BSc. in Mechanical Engineering at the University of Tokyo in 1954 and immediately joined Mitsubishi Heavy Industries Ltd at the Kobe Shipyard and engine Works and moved to the Tokyo Head Office in 1964. He obtained his MSc. in Nuclear Engineering at the University of Michigan in 1961 under the IAEA Fellowship Programme. His major activities in MHI until 1990 were engineering of marine propulsion plants for naval vessels and merchant ships, including steam, diesel, gas turbine, coal-fired steam and nuclear plants. In 1989 he obtained his Doctors Degree in Engineering from the University of Tokyo. He was appointed President of the Marine Engineering Society in Japan in May 1993 for a two year term.

It is certainly a great privilege to be asked to present a paper in this esteemed Institute having a brilliant history. The Institute of Marine Engineers chooses a timely subject every other week and an expert is invited to present a paper on this topic. The development of main propulsion machinery over the past 25 years was very well documented by the late Mr A.F. Harrold, ex-president of this Institute [1]. Technological progress in marine engineering in Japan is well covered in the annual review of the autumn issue of the Bulletin of The Marine Engineering Society in Japan every year. In addition, a variety of international conferences, journals and other publications serve as the source of information on the latest activities in the world. Because of this, there is little for me to add in general terms. So I decided to speak about some restricted subjects. Although the title of my paper is "Review of shipboard energy technology thoughts and facts behind the scene", it does not cover a wide area. I have selected some specific subjects in which I have had great interest, and that I have been involved in directly or indirectly, and that I have been keeping track of, or have kept myself informed about any progress, mishaps and settlements. These topics are nuclear powered ships, marine rehear plants, gas turbine propulsion, steam bottoming plants, coal-fired ships and contra-rotating propellers. As the President of The Marine Engineering Society in Japan, I thought that this kind of address, a history of technology not based on literature but based on experience, would be worthwhile to the members of our society and it so happened that this occasion here has come earlier.

Nuclear powered ships

The commissioning of NSS Nautilus in April 1954 and a subsequent place-

ment order for NS Savannah aroused worldwide interest in nuclear ship propulsion.

The International Atomic Energy Agency (IAEA) had already initiated the promotion of peaceful uses of atomic energy, and the first Geneva Conference was held in 1954. In Japan many governmental and private organisations were busy in the short period of 1955-58 preparing for the coming nuclear era. I joined a study group with Osaka Shosen KK (OSK) presently the MOL Line which was active enough to present two papers to the second Geneva Conference in 1958, namely, 'Nuclear Powered Emigrant Ship' and 'Nuclear Powered Submarine Tanker'. Optimistic views about the economics of nuclear powered ships abounded. I was awarded a fellowship from the IAEA to study nuclear power technology in the United States in 1960. Upon my return two years later, however, nuclear fever was over, supposedly due to the Suez boom in shipping and shipbuilding industries.

Mutsu, the first Japanese nuclear powered merchant ship

The launch of Mutsu was applauded by all Japanese as opening the door to a new era. She was completed in July 1970 except for her nuclear plant. Her departure from the IHI pier was seen off by 4500 waving attendants and she received a warm welcome by 23 000 people on entry to the port of Ohminato, with a brassband playing. It was really a pity that scallop aquaculture developed in the Bay of Mutsu shortly after her arrival and soon became a major product of this thinly populated area. It was natural that fishermen became nervous about radioactive contamination, since even a rumour could easily have caused their growing market to collapse totally. The reactor of Mutsu was successfully restarted after an unusual 16 year com-

plete shutdown. Tests and trials were conducted four times in 1990 and she completed four legs of an experimental voyage in 1991, aggregating 3816 hours and 47 592 sea miles, thus accumulating precious operational data desired for a long time. I should like to compliment all of those concerned for their long sustained and painstaking efforts to achieve this remarkable success. Now the fishermen should be happy, with the threat of contamination having been removed.

Nuclear propulsion and nuclear power stations

Non-naval nuclear powered ships are listed in Table I. Although they fulfilled their mission, economics and port entry problems hindered further application, except for Soviet/Russian icebreakers. On the contrary, however, nuclear propulsion is ideal for submarines and secured a firm position, as is apparent from Table II.

Nuclear power stations, initiated by Calder Hall No 1, now supply 17% of total electricity in the world and will play a key role in controlling the global warming effect. Is it not apparent which is easier for human beings to manage: some 20 000t of spent nuclear fuel or 20 billion tonnes of carbon dioxide gas per year?

Marine rehear plant

Steam versus diesel competition continued through the 1960s. Cylinder output of diesel engines increased from 1000-1500 bhp in the late 1950s to 2000-2500 bhp in the early 1960s. Advanced steam plants triggered by MST-13 of General Electric were developed and put onto the market to compete with diesels, with a drastic improvement in steam condition and fuel rate, namely, from 600 psig x 850F, two stage feed water heating cycle of 240g/

* The editor wishes to express his gratitude to the Institute of Marine Engineers for granting this publication.

shph to 850 psig x 950F, four stage feed water heating cycle of 210g/shph. This was successful and steam plant restored the market.

In the mid 1960s, super large bore diesel engines, having 1050 mm bore and

a cylinder output of 4000 bhp, were developed to produce a higher horsepower range for VLCCs and high-speed container ships monopolised by steam plants. In order to retain economic competitiveness, all the steam turbine manufacturers rushed to develop reheat plants. Successful applications are listed in Table III. Reheat plants were certainly the goal in those days and I should like to extend my sincere thanks to the engineers of GE, IHI and KHI for their enthusiasm and efforts. As is well known, however, marine reheat plants failed to gain wide acceptance. Reliability and maintenance burdens were uncertain and in many cases justification of extra cost was difficult under the circumstance of cheap bunker oil price before the oil crisis.

On the other hand, super large bore diesel engines were adopted on a number of containerships at the beginning but their application on VLCCs was exceptional. They were too big to be viable and failed to attain a reliability equivalent to 900 mm bore engines and faded away.

Under the rapidly growing market in the 1970s, market segmentation formed naturally. Both diesels and steam plants enjoyed the growing market and a happy co-existence continued until the first oil crisis.

A sharp fall in the oil trade after the oil

crisis caused many VLCCs to operate on slow steam and to be laid up, followed by a diesel retrofit boom, including high-speed containerships. Steam turbine manufacturers tried hard to survive with a strong campaign for highly advanced reheat plants, as shown in Table IV.

However, their desperate efforts were in vain. Nobody could change the market trend towards their introduction of diesels. The gap in fuel rate was too great for reheat plants to catch up.

I shall now take a look at land-based reheat installations in Japan. In central power stations, of course, the majority of reheat plants are up to 75 MW per unit. Non-reheat plants are exceptional and are up to 66 MW per unit, built 30 years ago. In the field of industrial power plants, there are 12 units, aggregated to 1365 MW and occupying 10% of total capacity. Here the average capacity is 114 MW. The economics of steam plants are highly dependent on the capacity; if the capacity is small, they are less efficient and unit costs increase. In addition, marine reheat plants are handicapped by additional provisions for astern operation, both in cost terms and as regards reliability. In the light of the above observation, marine reheat plants of about 30 000 shp (22 MW) might have been far too small to enjoy the real benefit of reheat.

Table I. Nuclear powered merchant ships

Del/Ret	Name	Type	Reactor	shp	Record
1962/71	<i>Savannah</i>	Cargo ship	1-80 MW	22 000	8 years
1968/79	<i>Otto Hahn</i>	Ore carrier	1-38 MW	11 000	10 years
1972/93	<i>Mutsu</i>	Experiment	1-36 MW	10 000	3816h
1959/66	<i>Lenin</i>	Ice breaker	3-90 MW	44 000	
1970/88	<i>Lenin</i>	(Re-engined)	2- MW	32 400	30 years
1974	<i>Arktika</i>	Ice breaker	2-150 MW	75 000	
1977	<i>Sibiri</i>	Ice breaker	2-150 MW	75 000	
1985	<i>Rossiya</i>	Ice breaker	2-150 MW	75 000	
1988	<i>Sevmorput</i>	Lash	1-135 MW	40 000	
1989	<i>Taymyr</i>	Ice breaker	1-171 MW	48 000	
1989	<i>Sovietski Soyuz</i>	Ice breaker	2-150 MW	75 000	
1990	<i>Baygach</i>	Ice breaker	1-171 MW	48 000	
1991	<i>Oktyabrskaya Revolutsiya</i>	Ice breaker	2-150 MW	75 000	
1994	<i>Ural</i>	Ice breaker	2-150 MW	75 000	

Type	Engine	USA	UK	France	CIS	Total
Submarine	Nuclear Diesel					
Aircraft carrier	Nuclear Steam		-	-	-	
			3	2	5	
Cruiser	Nuclear Steam			-	3	
				1	22	
Destroyer	Gas turbine Steam		18	7	50	
			-	-	12	
Total	Nuclear Others		18	6	208	
			32	19	184	

Table II. Type of engines on naval vessels

Del	Owner	Name	Type	Yard	Plant	shp	Steam cond
							kg/cm ² /°C/°C
1942		<i>Examiner</i>	Cargo	Bethlehem		8000	86.8/400/400
1943	CPS	<i>Beaver Glen</i>	Cargo	Fairfield		9000	59.8/454/454
1945		<i>Venore</i>	O/C	Bethlehem		11 000	102/400/300/300
1956	CPS	<i>Empress of Britain</i>	Pass	Fairfield		60 000	42.2/454/454
1966	Idemitsu	<i>Idemitsu Maru</i>	VLCC	IHI	R-801	33 000	84.4/510/420
1969	Idemitsu	<i>Shouju Maru</i>	VLCC	IHI	R-805	33 000	84.4/510/500
1968	Sun lease	<i>Ponce De Leon</i>	Car	Sun SB&DD		32 000	102/
1968	INC	<i>Energy Transport</i>	VLCC	SSK	MST-14	30 000	102/510/510
1969	INC	<i>Energy Evolution</i>	VLCC	SSK	MST-14	30 000	102/510/510
1970	INC	<i>Energy Generation</i>	VLCC	SSK	MST-14	30 000	102/510/510
1970	INC	<i>Energy Resource</i>	VLCC	SSK	MST-14	30 000	102/510/510
1970	INC	<i>Energy Production</i>	VLCC	SSK	MST-14	30 000	102/510/510
1969	Esso	<i>Esso Norway</i>	VLCC	Kieler HW		30 000	110/
1969	KOTC	<i>Arabiyah</i>	VLCC	SSK	R-804	30 000	84.4/510/510
1969	KOTC	<i>Al Funtas</i>	VLCC	SSK	R-804	30 000	84.4/510/510
1970	KOTC	<i>Al Badiyah</i>	VLCC	SSK	R-804	30 000	84.4/510/510
1970	OOVI	<i>Golar Patricia</i>	VLCC	KHI	UR 315	30 000	100/520/520
1970	OOVI	<i>Golar Betty</i>	VLCC	KHI	UR 315	30 000	100/520/520
1974	OOVI	<i>Golar Kanto</i>	VLCC	KHI	UR 315	30 000	100/520/520
1970	G Larsen	<i>Golar Nichu</i>	VLCC	KHI	UR 315	30 000	100/520/520
1972	G Larsen	<i>Fernmount</i>	VLCC	KHI	UR 315	30 000	100/520/520
1972	G Larsen	<i>Golar Kansai</i>	VLCC	KHI	UR 315	30 000	100/520/520
1973	G Larsen	<i>Golar Robin</i>	VLCC	KHI	UR 315	30 000	100/520/520
1976	G Larsen	<i>Golar Patricia</i>	VLCC	KHI	UR 450	45 000	100/520/520

Abbreviations:

CPS: Canadian Pacific Steamship Co
INC: Island Navigation Co
KOTC: Kuwait Oil Tanker Co
OOVI: Ocean Oil Ventures Inc

Table III. Marine reheat plant

Gas turbine powered merchant ships

Gas turbine powered merchant ships are listed in Table V. During the 1950s, pioneering efforts were made to apply industrial gas turbines for merchant ship propulsion, all burning heavy fuel. These, however, were of an experimental nature. After a pause of a decade, the success of GTS Admiral William M Callaghan in 1967, installed with aero-derivative gas turbines, and following order placement of four high-speed containerships by Sea Train, drew keen interest in gas turbine propulsion on merchant ships.

Admiral William M Callaghan

I was assigned to evaluate gas turbine propulsion in 1970. First, I visited the Rheinstahl Nordseewerke where the first Sea Train containership was under construction, then attended the ASME 15th International Gas Turbine Conference in Brussels, where, surprisingly, many of the 17 papers were presented on marine gas turbines. Subsequently, I went onboard Admiral William M Callaghan on her 43d westbound voyage from Bremerhaven to Bayonne, New Jersey, via Pentland Firth. In the United States, I visited Military Sea Transport

service speed, and use of gas turbines for main propulsion. SUNEXPORT, a joint venture of Sun Shipbuilding and American Export & Isbrandtsen Lines won the bid for a seven year charter with an option to extend up to 20 years.

In reality, Admiral William M Callaghan served as a moving testbed to facilitate evaluation of gas turbines, so as to prepare for the coming DD963 Spruance class destroyers and, actually, this was a competition between first generation and second generation gas turbines, i.e. PWA FT4 engine starboard and GE LM2500 engine port, and invaluable information was accumulated.

Through this visit and subsequent economic analyses, I was convinced that for merchant ship application, bunker C burning is essential [2].

Sea train containerships

These ships proved the high availability of gas turbine ships and a quick change-out of 5-8h, but the operation became stabilised only after four years of operational experience. During this period, 44 unscheduled change-outs were necessary for four vessels, eight engines and over four years operation. The oil crisis hardly hit the operational economy. The price differential between heavy distillate and bunker C escalated from 6 US\$/t at the design stage to 38 US\$/t in 1976, distillate at 112 US\$/t

Marinisation of aero engines stems from the 2200hp Gatric Metropolitan Vickers engine on MGB 2009 back in 1947. Again, 10 years later, success of the 18 000 hp FT4 Pratt & Whitney engines on USCG Hamilton class cutters in 1957, and the 4000 hp Proteus Bristol Siddeley engine on Brave class patrol craft, made the advantage of gas turbines on naval vessels decisive, as can be seen in Table II.

Service (MSTS), Sun Shipbuilding, Pratt & Whitney, GE Schenectady and GE Cincinnati. This was really a most fruitful fact finding trip.

Evaluation of Admiral William M Callaghan was unique. MSTS does not own the ship. Pairs of shipowners and shipbuilders were requested to quote a charter rate per vehicle deck area, based on the simplest specification stipulating limitation of hull size, minimum

Table IV. Use of advanced reheat plants by various companies

		shp	bar x°C/°C	g/shph
1974 KHI	ASPP	80 000	140x540/540	168
1976 STAL LAVAL	5CR	36 000	104x538/538	180
1977 STAL LAVAL	VAP 5CR/FBC	27 000	127.5x600/600	175
1978 GE	MST-23	50 000	169x566/566	161

Table V. Gas turbine powered merchant ships

Del	Owner	Name	Type	GT type	shp	Astern
1951	Shell UK	Auris	Oil tanker	BTH		Elec
1958	Shell UK	Auris	Oil tanker	BTH		Hydr
1954	JMOT	Hokuto Maru	Trainer	Mitsubishi		Steam
1956	USA Marad	John Sergeant	Cargo ship	MS 3002R		cpp
1967	Sunexport	Adm Callaghan	ro-ro ship	FT4/LM2500		Gear
1971	Sea train	Euro Liner	Container	FT4 x 2		cpp
1971	Sea train	Euro Freighter	Container	FT4 x 2		cpp
1972	Sea train	Asia Liner	Container	FT4 x 2		cpp
1972	Sea train	Asia Freighter	Container	FT4 x 2		cpp
1973	BHP	Iron Monarch	ro-ro ship	MS 5002R		cpp
1974	BHP	Iron Duke	ro-ro ship	MS 5002R		cpp
1974	H Reksten	Lucian	LNG carrier	MS 5002R		cpp
1975	Chevron	Chevron Oregon	Tanker	MS 3002R		cpp
1976	Chevron	Chevron Washington	Tanker	MS 3002R		cpp
1976	Chevron	Chevron Colorado	Tanker	MS 3002R		cpp
1977	Chevron	Chevron Louisiana	Tanker	MS 3002R		cpp
1977	Chevron	Chevron Arizona	Tanker	MS 3002R		cpp
1975	USS	Seaway Prince	ro-ro ship	MS 3002R		Elec
1976	USS	Seaway Princess	ro-ro ship	MS 3002R		Elec
1976	USS	Union Rotorua	ro-ro ship	MS 5002R		cpp
1977	USS	Union Rotoiti	ro-ro ship	MS 5002R		cpp
1976	BHP	Iron Carpentaria	Bulk	MS 3002RB		cpp
1977	BHP	Iron Curtis	Bulk carrier	MS 3002RB		cpp
1977	Finn Line	Finnjet	Passenger	FT4 x 2		cpp

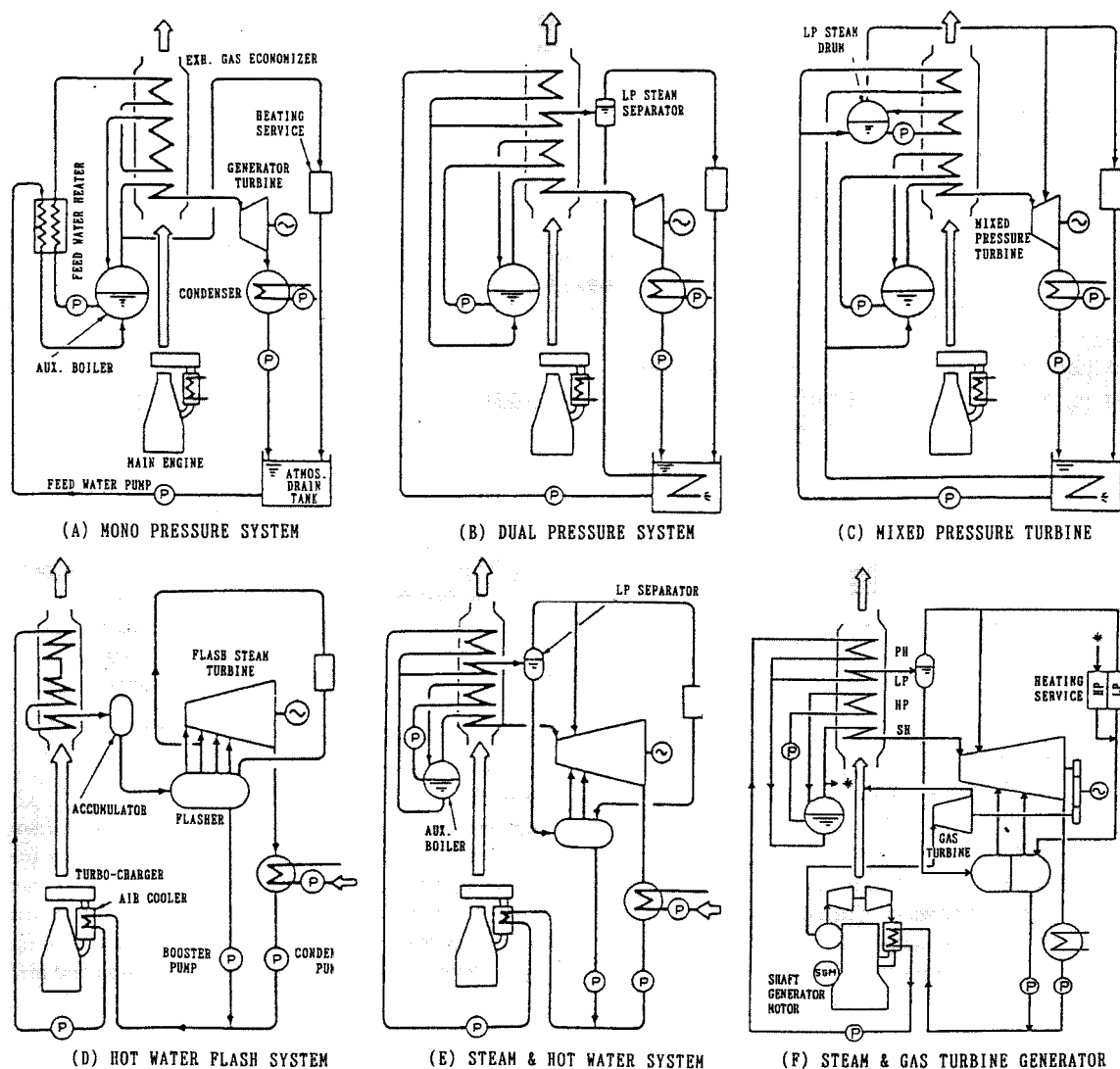
Abbreviations:

BTH: British Thomson Houston

BHP: Broken Hill Pty

USS: Union Steamship Co of New Zealand

Fig.1. Evolution of steam bottoming plants



and bunker C at 74 US\$/t. A trial was undertaken to burn blended fuel of 75% bunker C and 25% distillate at a price of 84 US\$/t. Although this is technically feasible, the SFC gap against diesel remains unchanged. Finally, they are retrofitted with Stork engines.

Australia and New Zealand case

In view of a lack in the skills and a network for maintenance support of diesel engine parts in these areas, the guidelines for the selection of main propulsion machinery were minimum maintenance and the advantage of rotating machinery was attractive. An option of industrial gas turbines was mainly due to the endeavours and sales success of GE people. Another advantageous aspect of gas turbines in this area was fuel price. Firstly, the price of Gyppsland waxy residue from the Tasmanian Strait was two thirds of bunker C due to its high pour point of 40C, but when it is heated, it is an ideal fuel for gas turbines with 0.28% sulphur and less than 1 ppm of vanadium. Secondly, the price gap between distillate and bunker C was only 10%.

Unfortunately, however, the oil crisis destroyed this endeavour. Most of them were sold, laid up, retrofitted with diesel, or otherwise scrapped.

Chevron product carrier

This was a unique case with operational success. The intention of Chevron was to replace their fleet of aged T-2 tankers, aiming at highest operational economy, by quantum leap ideas. Firstly, the ships were owned by a syndicate led by the Bank of California and chartered to Chevron on a leveraged lease scheme; thus the financial burden was eliminated.

Secondly, the vessels were fully gas turbinised and electrified with one main gas turbine of the GE industrial regenerative type and one Ruston auxiliary gas turbine. The main propulsion motor drives a directly coupled cpp and all cargo pumps are motor driven, so just pushing buttons provides all necessary control, ending in a minimum manning scale of 13. Adoption of a cpp and bow thruster is suitable for these short turn-around coastal vessels with frequent harbour in and out manoeuvres.

Thirdly, gas turbine modules are self-contained and the small cooling load is taken care of by an air cooled fin-fan unit, eliminating salt water piping. Thus, the only piping is small bore gas-oil pipes. A minimal outfitting requirement enabled ships to be built by a barge manufacturer at a far cheaper price. Although these vessels were not free from the adverse effects of the oil crisis, I should like to compliment the staff of Chevron Shipping who worked out this remarkable managerial and technological innovation.

Future prospects for gas turbines

Actually, gas turbine powered merchant ships were victims of the oil crisis as were steam plants. Steam plants lost a huge market, in excess of 4M shp. As compared with this, damage to the gas turbine business was minimal. Aero-derived gas turbines have a much broader market. In the future marine sector, they will certainly play a key role in high-speed craft and ultra high-speed cargo transportation, as typified by the Techno Super Liner (TSL) project. On the other hand, technological

progress in the development of industrial gas turbines is very intense. Higher pressure ratios and higher Turbine Inlet Temperature (TIT) now provide a unit capacity in excess of 200 MW, as compared with a maximum of 34 MW with the aeroderived counterpart. Thermal efficiency of the combined cycle in

Fig.2. Combined steam and gas turbine generator

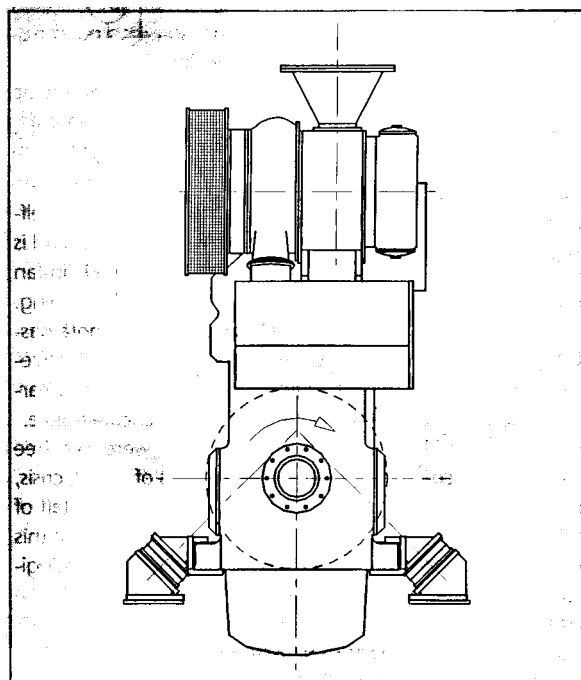
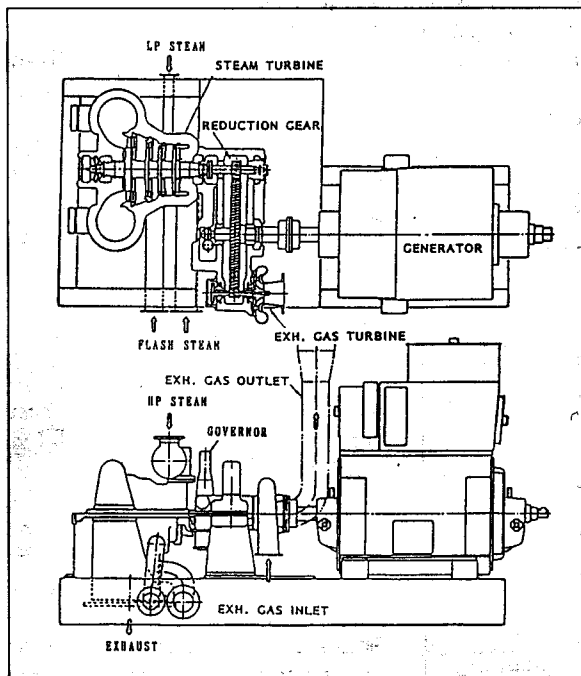


Fig.3. Energy flow analyses

terms of HHV (LHV) is 43.7% (48%) at a TIT of 1150 °C and 46.5% (51%) at 1350 °C. This is much higher than the 41% of current super critical steam plants and the 44% of the ultra super critical plant under development. Combined cycle plants of 600-1000 MW with 46 gas turbines are now being speedily installed. They secured a firm position in the market by high thermal efficiency, low emissions, operational flexibility and short delivery.

Steam bottoming plants on motor ships

This might be a memento of a group of marine engineers who struggled day and night to squeeze out precious electricity from ever decreasing exhaust gas energy from the main propulsion diesel engines.

The economic advantage of steam bottoming is known to save about 10% of fuel costs as compared with the diesel generator. In addition, maintenance costs and man-hours on generator diesels become negligible. Steam bottoming plan can supply the required electric power onboard when the output of the main engine is greater than a certain threshold power, hence exhaust gas energy is sufficient. For diesel engines in 1975, with a fuel rate of 150g/bhph and an exhaust gas temperature of 310 °C, this threshold was about 18 000 bhp.

Progress of steam bottoming technology [3]

A variety of new ideas were developed and applied by the ingenuity and endeavours of Mitsubishi Heavy Industries (MHI) engineers, firstly to recover maximum exhaust gas energy, secondly to use up recovered heat efficiently, and finally to reduce the required electric power and heating steam to a minimum. Newly developed systems were immediately adopted and operational experiences were fed back for subsequent development. Evolution of steam bottoming plants is illustrated in Fig 1 in chronological order, and the delivery years of the first unit of each respective system were as follows:

- 1978: Dual pressure system.
- 1982: Dual pressure system with mixed pressure turbine.
- 1984: Steam and hot water system with flash steam turbine.
- 1986: Combined steam and gas turbine generator.

Dual pressure system

The exhaust gas economiser consists of superheater, HP evaporator, LP evaporator and preheater. The HP evaporator is designed to generate steam required by the generator turbine and the LP evaporator is designed to generate LP heating steam from lower temperature exhaust gas which has so far been wasted. Heat recovery was greatly improved by this system and the threshold power came down to 12 000 bhp, which was low enough for handy size bulk carriers and cargo ships, ordered in great numbers at that time.

Mixed pressure system

Introduction of low fuel rate engines of 137 g/bhph in 1980 resulted in reduced

exhaust gas energy, with quantity reduced from 7.6 to 6.2 kg/bhph and temperature reduced from 310 to 275 °C. The threshold power was pushed up to 21 000 bhp against the customer's need of 14 000 bhp suitable for Panamax bulk carriers and Aframax tankers, ordered in substantial numbers in those days.

Minimisation of electric power and heating steam on the one hand and the most efficient utilisation of generated steam on the other hand became the target, since there remained little room to increase heat recovery in view of dew point corrosion. Steam jet ejectors were replaced by motor driven vacuum pumps and gland exhaust fans, then bunker tank heating was rationalised. SW cooling pump motors were changed to a two speed type, where low speed operation suffices for winter conditions, leading to substantial electric power savings. Scoop circulations were adopted in several cases.

The exhaust gas economiser was designed to maximise evaporation of both HP and LP steam, and all the steam so generated is admitted to a mixed pressure turbine, excluding that utilised for heating; thus steam dumping was eliminated. Surplus electricity can be used up for propulsion augmentation and any shortage of electric power can be supplemented by the shaft generator, ending in an ideal no dump and no waste system irrespective of ambient conditions.

Hot water flash steam system

In 1982, long stroke engines with a very wide derating zone (minimum bhp of 55% and minimum rev/min of 72%) were brought onto the market. Exhaust gas energy was reduced to 5.8 kg/bhph and temperature down to 250 °C, therefore the threshold power was again pushed up to 25 000 bhp. New ideas were looked at to reduce this to 17 000 bhp corresponding to a minimum bhp for slow speed VLCCs, being revived at that time. The only solution to this end was to recover exhaust gas heat down to 120 °C and to supplement the shortage of energy by recovering scavenge air heat. The hot water heat recovery was the only possible way to achieve this recovery, as will be elaborated on later.

The heat of exhaust gas and scavenge air are recovered as sensible heat of the pressurised hot water. Steam is generated by decompression flashing of hot water in a cascaded flasher and all steam so generated at varied pressure is admitted to the respective stage of the flash steam turbine.

This system, however, was not realised

due to the inferior Rankine cycle efficiency, as clarified below.

Steam and hot water system

The cause of the inferior Rankine cycle efficiency in the hot water flash system is apparently because all steams are saturated steams and hence the enthalpy drop in the turbine is smaller. Therefore it was finally decided to adopt a dual pressure system in the higher gas temperature zone so as to generate superheated steam, and to apply hot water heat recovery only in the low end gas

temperature zone so as to maximise heat recovery.

Combined steam and gas turbine generator

In 1984 the so-called super long stroke engines appeared on the market. By this time the efficiency of turbochargers was improved beyond the requirement of the engine, giving rise to surplus exhaust gas. A turbo compound system was proposed by licensors to reduce the fuel rate by 3-4 g/bhph.

The same level of fuel rate improve-

ment can be attained by fully exploiting the expansion work in the cylinder. It was found, however, that this caused a sharp drop in the exhaust gas temperature beyond a certain point. The conclusion reached was that optimisation should be to maximise the combined output of the propulsive power of the main engine, the mechanical power of the gasturbine and the electric power of the bottoming cycle.

The practical solution was a combined steam and gas turbine generator as shown in Fig.2. This system helps to reduce threshold power and simplifies engine room arrangement. A result of energy flow analysis on this plant is shown in Fig.3. for those who are interested in the detail.

Comparison of various systems and supplement

Fig.4 shows the quantity and temperature level of waste heat of the main engines in successive generations. The drastic reduction of waste energy in the derated engine is marked.

Table VI shows a comparison of three bottoming cycles. The difference in heat recovery capability and the Rankine cycle efficiency are obvious.

Fig.5 shows a comparison of the heat recovery characteristics of four systems. The superiority of the hot water system is apparent, having no pinch point restriction in heat transfer.

Figure 6 shows a comparison of electric power supply and demand. The difference in threshold power is pronounced at such a low inlet gas temperature as 240 °C.

Problems associated with steam bottoming plants

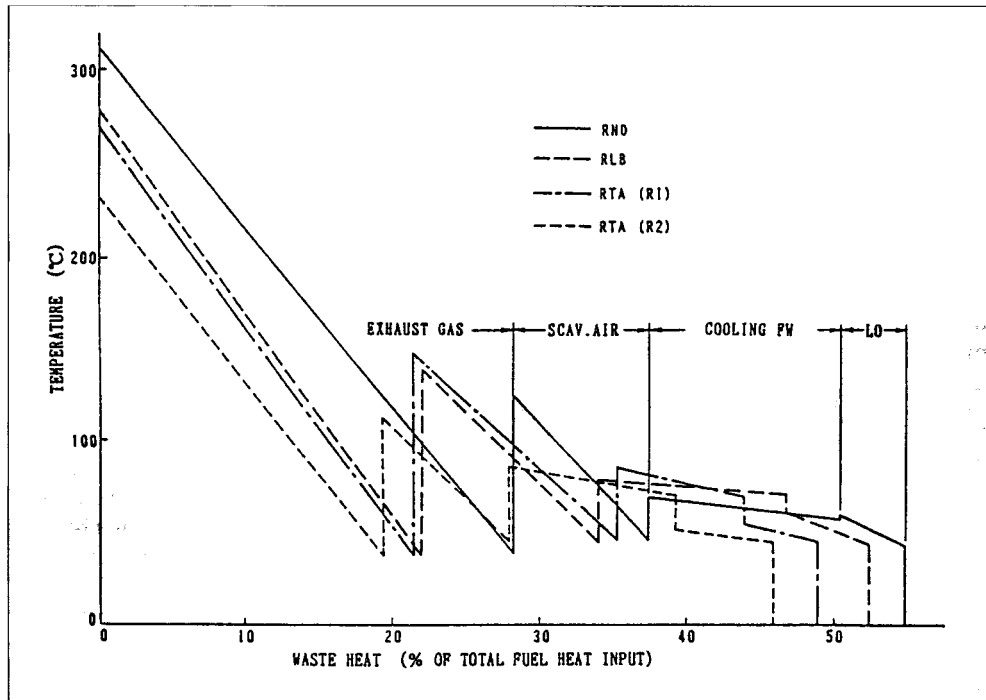
Although care had been taken to mitigate dew point corrosion and fouling of the exhaust economiser, vessels were not free from unexpected problems.

In January 1979, one of the cargo ships with a dual pressure system, using spiral fin tubes and steel ball soot removal, caught a sootfire in the Arabian Gulf. Then in April another containership, using square fin tubes and a steam jet sootblower caught a sootfire off Los Angeles. A thorough investigation was carried out to find the cause and to devise remedies. It was concluded that sootfire should be assumed in the exhaust gas economiser, but meltdown of tubes could be avoided by maintaining sufficient water flow in the tubes, based on the results of sootfire simulation experiments. Thus the control circuit was rectified to operate the boiler water circulating pump for a sufficient period after finishing with the engine.

In April 1985, excessive fouling with the steam and hot water system was repor-

Fig.4. Quantity and temperature of waste heat

Table VI. Comparison of heat recovery and electric power



SYSTEM	MIXED PRESSURE SYSTEM	HOT WATER FLASH SYSTEM(MARK-N1)	STEAM & HOT WATER SYSTEM(MARK-N2)
HEAT TRANSFER DIAGRAM			
HEAT RECOVERY	0 0	1 3 6	3 6
SCHEMATIC DIAGRAM			
ELECTRIC POWER	1 0 0	1 2 2	1 3 2
RELATIVE THERMAL EFFICIENCY	1 0 0	9 0	9 7

ted on one of the bulk carriers. Steel balls for soot removal were trapped in the thick layer of extraordinary sticky soot. In order to be free from this problem, it was immediately decided to install a feed water heater capable of heating up drains to 120°C lest the exit gas temperature should fall below 140°C, which is well above the dew point, with the drawback of reduced electric power in winter conditions. We thought our problems were over.

It is regrettable that sootfire accidents at large have still been increasing, as shown in Fig.7, including in small bare tube economisers only used for heating service. NK formed a special committee to solve this problem and issued a 'Guide to prevention of soot fire on exhaust gas economizers, in April 1992 [4]. I hope this guide will be effective in solving the problems.

Well, history repeats itself. I recall an elevation of feed water temperature in steam plants from 250°F to 280°F in the 1950s. A design feed water temperature of 250°F was common practice

for bunker fuel with 1.3% sulphur, based on Gulf crude. But dew point corrosion on economisers increased with bunker fuel with 3% sulphur, based on Middle East crude. A variety of research was undertaken and finally this problem was overcome by raising the feed water temperature to 280°F, with a small penalty, however, of a reduced boiler efficiency by a fraction of one percent. At the same time, tubular gas air heaters suffering heavy corrosion were abandoned and replaced by rotary regenerative gas air heaters.

Modern coal-fired ships

International tenders to bid for coal-fired bauxite carriers in 1979 drew worldwide attention, reflecting the 'back to coal' movement, after the IEA ban on the use of petroleum fuel for new central power stations. The outcome on the marine sector, however, was quite restricted, as listed in Table VII.

The reason why this topic has been chosen is to illustrate an actual example of procedures for quality assurance on

entirely new and unproven systems and components. In November 1980, a contract was awarded to MHI by the Australian National Line (ANL) to build two 74 700 dwt coal-fired bauxite carriers for Queensland Alumina Ltd, for use along the Australian coast.

Designing a fully automated marine coal-fired plant, equivalent to oil-fired plant in safety and reliability, was a highly challenging task. Marine coal firing technology had not been used for a long time; neither reliable design data nor records of service results for coal and ash were available. A great amount of research and engineering work had been done to finalise the design, covering combustion of coal, coal transfer, ash handling, safety against explosion etc, by

means of a literature survey, fact finding visits, analyses, laboratory tests and model tests [5].

Top priority was given to the highest reliability and safety. To this end, a close re-examination of the basic design was undertaken in the search of any subject area where operational problems might arise. Consequently, some 160 items were picked up and thoroughly analysed for clearance. Here, a coal transfer system is selected as an example of this reliability enhancement programme.

Coal transfer system

A dense phase pneumatic transfer system was employed in view of its suitability for pipe transfer to prevent dust in the engine room. Major concerns about the coal transfer system were arch formation or hang-ups in the discharge hopper and size degradation of coal during transfer which deteriorates combustion characteristics.

The latest theory of powder technology was applied to design the hopper configuration and design criteria were worked out to ensure smooth mass flow, avoiding channel flow and arch formation. This was confirmed by a model test, including consolidation effects due to vibration and ships motion.

As shown in Fig.8, each bunker has four coal inlets and four coal outlets so as to prevent formation of excessive peaks and troughs of coal inside, hence minimising segregation of coal into lumps and fines. Eight independent coal transfer pipes are carefully arranged and cross connected to two daily hoppers with a minimum of bends and horizontal runs of pipes, so as to ensure an uninterrupted flow of coal and to avoid coal blockage.

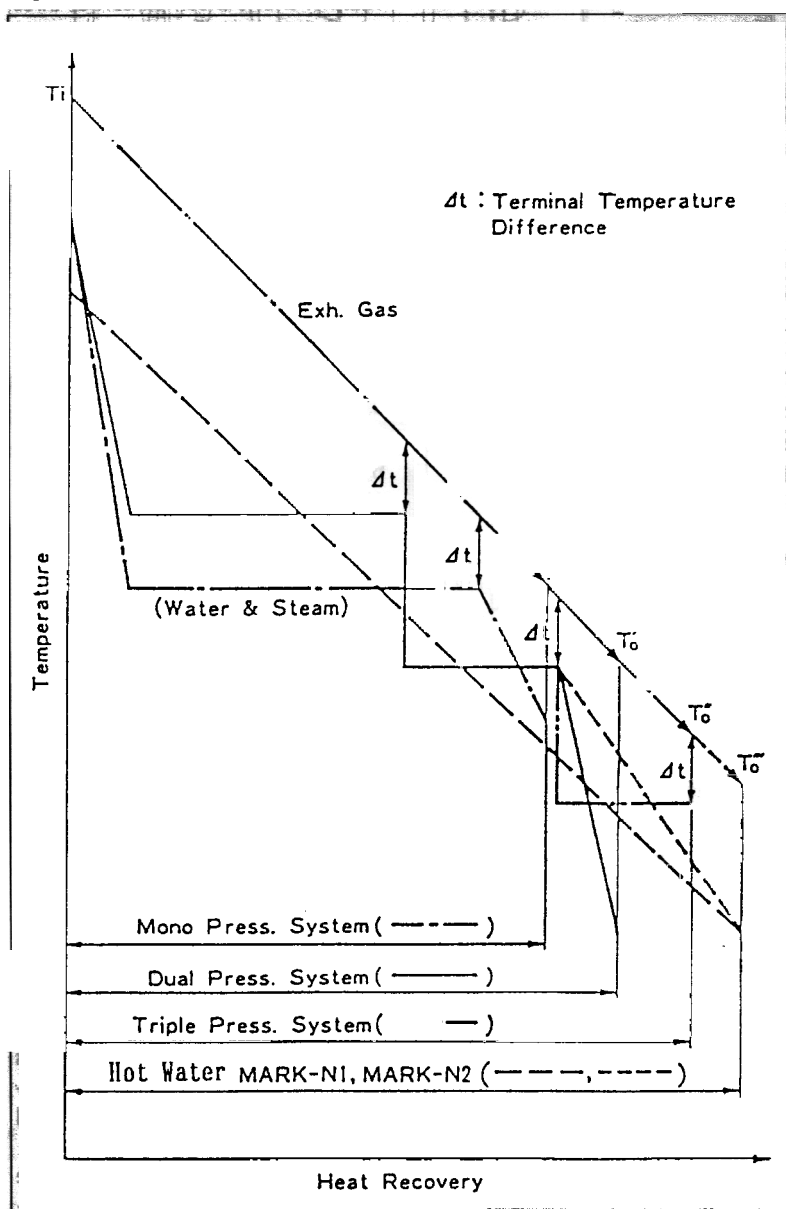
20t of Callide coal were sent to MacCawber, Yorkshire UK, to perform a full scale model test to ascertain performance, size degradation and reliability of this system.

A similar situation occurred in 1936 when MHI was preparing for the first stoker fired high pressure water tube boiler for passenger ships. At that time 40t of Chinese Fushun coal, and 40t of Japanese Sakito coal as an alternative, were sent to the UK. Combustion tests were performed at Valley Road power station near Bradford, and finally a Taylor multiple retort type underfeed stoker was selected.

Supplement

Thorough fact finding visits were made, encompassing 11 coal-fired steam plants (six in Japan, four in the USA and one in Australia), "Kinsman Independent" one of the coal-fired steamers on the Great Lakes and two coal transfer systems in operation in the UK and Aus-

Fig.5. Heat transfer diagram



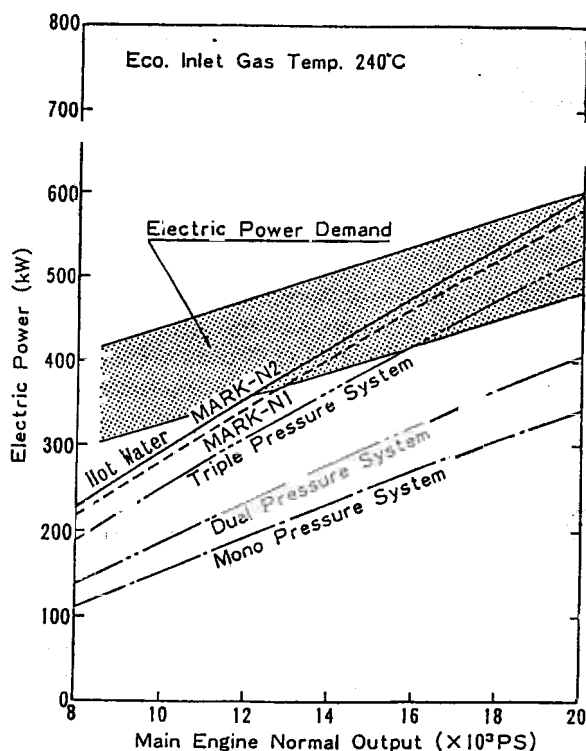


Fig. 6. Electric power supply and demand

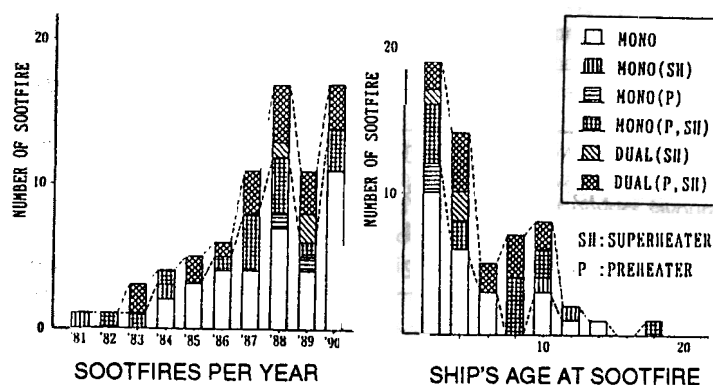


Fig. 7. Number of vessels with sootfires

Del	Name	Type	Owner	Builder
Newbuilding:				
1982	River Boyne	75 kdw BC	ANL	MHI Nagasaki
1983	River Embley	75 kdw BC	ANL	MHI Nagasaki
1983	Carpentaria	75 kdw BC	Bulkship	Italcantieri
1983	Capricorn	75 kdw BC	Bulkship	Italcantieri
1983	Energy Independence	32 kdw BC	NECCO	GD Quincy
Conversion:				
1983	Jade Phoenix	128 kdw BC	Phoenix	Hyundai Mipo
1983	Golden Phoenix	128 kdw BC	Phoenix	Hyundai Mipo
1987	-	154 kdw BC	Elcano	Bazan

Table VII. Modern coal-fired ships

tralia. Seeing is believing. The results were marvellous.

What pleased me most in this coal-fired ship project was the excitement and enthusiasm of young engineers. Since nobody knew about coal-fired ships, they were assigned more and more important jobs, as they studied harder and became more and more knowledgeable. These were the real fruits of the project.

Contra-rotating propeller

Slow revolution, large diameter propeller

In 1976, Burmeister & Wain announced an epoch-making 50 rev/min for their fuel saving Panamax bulk carrier, by providing a reduction gear for a slow speed diesel engine, which was supposed to be directly coupled. This idea was not realised until 1982, when two remarkable vessels, so-called super energy saving ships, were delivered. One is "Shinoh-maru" built by MHI for Shinwa Kaiun, where two sets of 140 rev/min diesel engines are geared down to drive a 9.3 m diameter four bladed cpp at 60 rev/min. The other is "Hoei-maru" built by KHI for Nippo Kisen, where one 126 rev/min diesel engine is geared down to drive an 11 m diameter three bladed cpp at 45 rev/min. Both vessels were engaged in carrying iron ore from Australia to Japan for the Nippon Steel Corporation.

big impact, giving rise to super long stroke engines introduced in 1984.

Contra-rotating propeller (crp)

The final area left in which to improve propulsive efficiency was in trying to reduce whirl flow energy loss by the crp [6,7]. Power saving amounts to about 15%, half of which is the crp and the rest is the effect of slower revolution, only attainable by a crp.

This idea is well known but nobody tried it for a long time, except for an experimental installation on NSS Jack in 1967, since there existed an insurmountable difficulty in proving the reliability of this complex system, as illustrated in Fig.9, for large ocean going vessels. In this area, however, MHI and IHI made a great step forward. This year, two VLCCs with crp were delivered. One is "Cosmo Delphinus" built by MHI for Shinwa Kaiun in March and the other is "Okinoshima-maru" built by IHI for the Idemitsu Tanker Company in August.

A summary of the crp system for "Cosmo Delphinus" is given in Table IX.

In both vessels, prudent procedures have been taken so that shipowners can be convinced to adopt the crp. In addition to comprehensive research, development and engineering work, the most up-to-date quality assurance procedure was strictly followed. Pinpoint analyses, backed up by confirmation tests, were undertaken in the critical area, thanks to the advanced and exquisite technologies in tribology, analysis, measurement, simulation, etc. Vulnerable points in the crp system might be bearings and seals. MHI adopted hydrostatic plain bearings and IHI adopted compound roller bearings, based on a different philosophy. In the case of MHI, the procedure was as follows:

- 1986 Laboratory test of 150 mm diameter.
- 1986-7 Full scale test ashore of 510 mm diameter.
- 1988 Retrofit and sea trial on car carrier "Toyofuji No 5."
- 1988 Continuous monitoring and open inspection of above.
- 1990-1 Full scale test ashore of 670 mm diameter for VLCC

IHI took similar steps. An endurance test of 500h was conducted prior to retrofit of the first crp on "Juno", a 37 000 dwt bulk carrier in 1989.

The case of the crp is typical of so-called R&D and D (Research & Development and Demonstration). This step will be a 'must' for a large unproven system with unknown risks. I should like to congratulate MHI and IHI for their great achievement. The next target will be high-speed containerships where the benefit

The request of Nippon Steel was to cut down fuel per tonne of ore to one half of their latest ore carriers. Their philosophy was to provide a big enough impact for shipbuilders so as to bring about a breakthrough in marine transportation. Both ships satisfied the requirement. The details for "Shinoh-maru" are given in Table VIII.

Extremely slow revolutions adopted on these two vessels certainly provided a

Fig.8. Coal transfer system

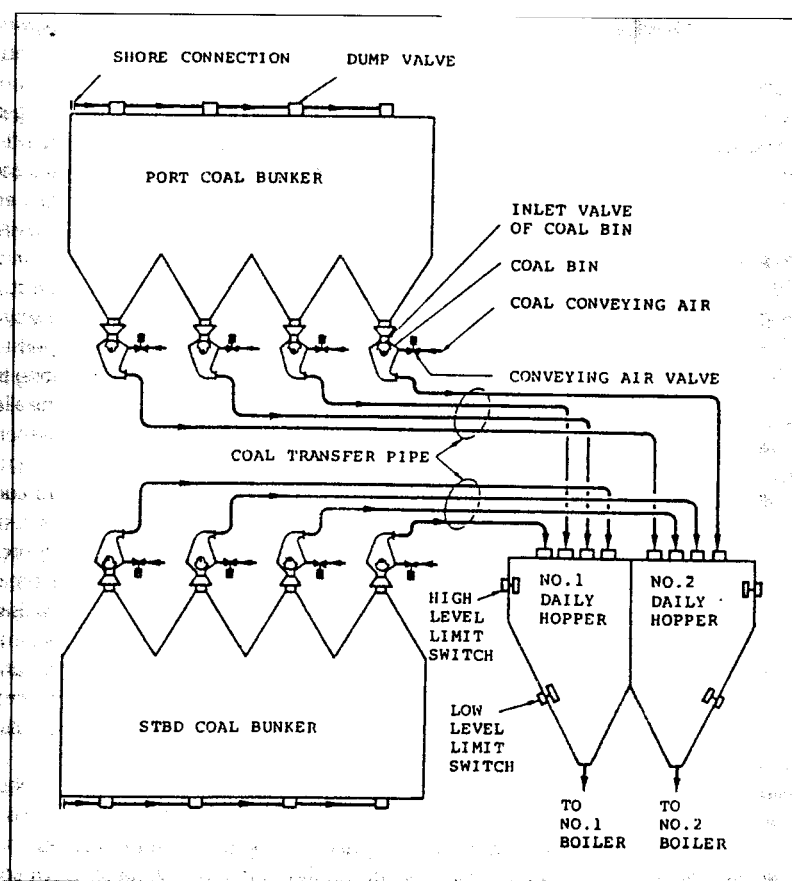


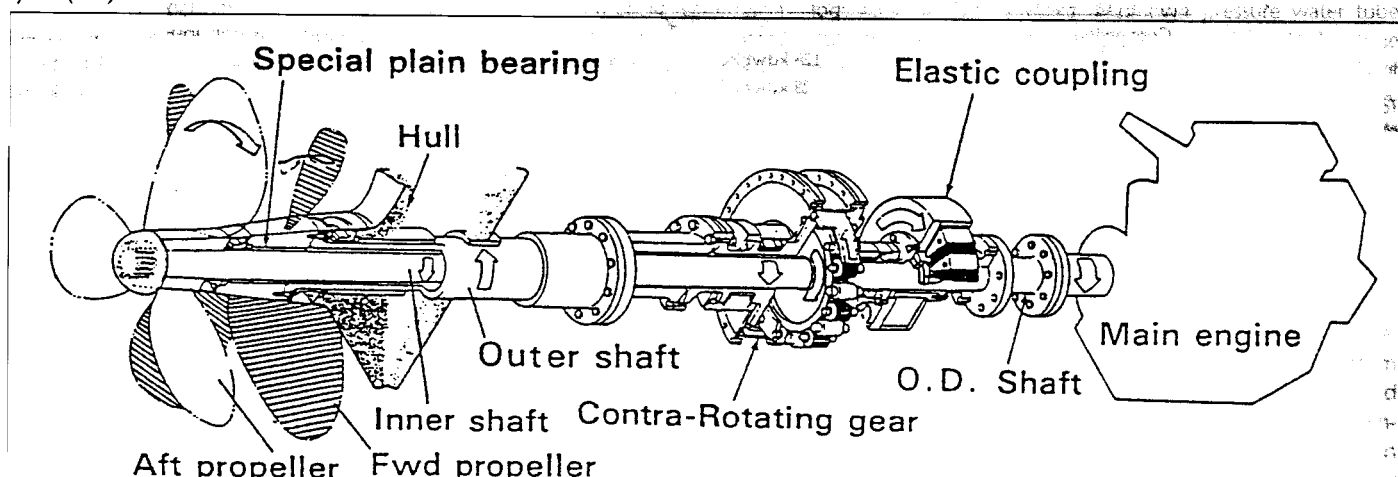
Table VIII. Details of "Shinho-maru"

Year built	1976	1980	Shinho-maru
dwt (1000t)	115	133	209
Service speed(kn)	15	14	12.6
kg of fuel/t of ore	18	12	6

Table IX. Summary of crp system for "Cosmo Delphinus"

Main engine	: Mitsubishi 7UEC75LS-II, 28 000 BHP x 84 rev/min
Forward propeller	: 9.9m diameter, 50.4 rev/min, reversed
Aft propeller	: 8.8m diameter, 84 rev/min, directly coupled
Reduction gear	: Renk Tacke GmbH, star type epicyclic gear
Elastic coupling	: Geislinger/Niigata Engineering Co Ltd
Bearing	: MHI
Seals	: MHI and Eagle Industry Ltd
Split outer shaft	: Forgemaster Engineering Ltd

Fig.9. Contra-rotating propeller system (MHI)



of the crp would be much more pronounced.

Advanced turbo prop (ATP)

In the field of aircraft propulsion, research and development on ATP are well known, aiming at an improvement of propulsive efficiency by a relative 30% (from 62% to 80%) with a bypass ratio of 40-50. Proposed models are Rolls-Royce Contrafan, PWA Propfan and GE UDF (unducted fan). They all adopt contra-rotating fans with backward curved blades of unusual shape, keeping tip speed below sound velocity. As a reversing mechanism, FWA has adopted reverse reduction gears, while RR and GE have adopted reversing turbines.

Concluding remarks

I have attempted to describe some specific technological challenges in the past, together with the thoughts and facts behind them, as well as their successes and failures from the techno-economical and business points of view, and, finally, what we have learnt from them. Although my description is very simplified, I am sure you understand my intention. It is easy to criticise things in the past with hindsight, but this is not fair. We have to bring ourselves back to the circumstances of the past and share the views and emotions of the engineers in charge; their satisfaction and joy or disappointment, agony and regret then we can learn more. In some cases I referred to the technology in other sectors to facilitate better understanding. Also, I pointed out the importance of fact finding visits. In these areas, I believe, academic societies can make contributions to their membership and co-operation of learned societies, as agreed between IMarE and MESJ, will certainly help to promote international friendship and better exchange of information. I am happy to announce that more than 40 mem-

bers of MESJ were approved as Overseas Affiliate Members of IMarE. This is the first outcome of our co-operation. I would be most happy, if this short article could add something more to the high standing of IMarE.

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Discussion

H. Woods (Shell International Marine Ltd) I first met Professor Fukugaki in 1978 when he was the leader of the builder's design team for a 30 000 dwt tanker Shell required for the Australian coastal trade. The ship has operated exceptionally well and is still the envy of other Australian oil companies. A major factor in the success of the vessel was the detailed examination of alternatives by Professor Fukugaki and his recommendations which we could not fault. Taking this experience into consideration I have no intention of questioning any item of the Professors paper.

I would like to thank Professor Fukugaki for his paper. It picks out developments throughout the recent past and gives brief snippets of their history.

Developments have been made with considerable effort, ingenuity and expense. But what does the paper tell us about why such resources have been expended? Fuel efficiency is a reason for most of the developments, along with reliability and reduction in maintenance costs. Perhaps another is the natural quest for the engineer to try to 'see if he can do it better'. Unfortunately, we are all limited by the laws of physics.

Over the years we have all been playing a game of 'catchup', driven by the cost

of fuel. Excursions into marine gas turbines were driven by the promise of ease of operation and ease of maintenance, not fuel efficiency. For most of the time this has been a promise unfulfilled. Fuel efficiency of gas turbines has improved over the years and maybe their day will come again, perhaps to drive LNG ships where clean gas fuel will relieve the turbines of the problems of burning heavier fuel. Shell's first use of gas turbines was just before I joined them. This was the Auris that Professor Fukugaki mentioned in the paper. We continue to investigate the use of gas turbines but I wonder if I will have left the company before they are re-introduced.

I said we have been playing a game of 'catch-up' and we have been trying to catch up with the fuel price all the time. Maintenance cost is also a consideration but it pales to insignificance in the light of fuel cost. Fuel cost now drives everything. After the initial fuel oil price increases in the early 1970s the battle for fuel efficiency was joined by the turbine manufacturers and they made considerable improvements: from two feed-heater designs through four feed-heaters, added reheat and, finally, to the Very Advanced Propulsion system designed by a Swedish manufacturer, but all to no avail. Unfortunately for them the laws of physics favoured the diesel engine designer who leapt ahead in the game, not without some skating on thin ice with respect to reliability perhaps, but it was enough to prevent the turbine manufacturers catching up. There was another little 'catch-up' game played on motorship plant design with steam bottoming plants. This was for the same fuel cost reasons. Professor Fukugaki describes this game well. The rapid developments in diesel engine efficiency made each design of steam bottoming plant obsolete almost before it was put into service, so it was, on to the next'.

We in Shell were investigating bottoming plant using organic fluids such as types of Freon and other mixtures of gases. Organic fluids had promise as they operated at relatively low temperatures, but the study was not developed into hardware and perhaps the design would have ultimately fallen victim of the diesel engine designer's progress. Further, with today's emphasis on not using ozone depletion gases we are perhaps fortunate that we have no plants in service. One of the problems I remember at the design stage was how to keep the fluid in the system!

We did use one of the designs of steam bottoming plant, similar to Professor Fukugaki's design shown in Fig 1(C) in the paper, for a ship which was built by

his company and, unfortunately, I can vouch for the incidence of soot fires, for we lost the economiser.

We all expect fuel prices to remain high and the 'catch-up' game will continue. Where will it lead us now? Have we almost squeezed all we can from the diesel engine and, perhaps, we are as close as we will get to the limits set by physical laws? Professor Fukugaki, at the end of his paper, writes about propeller systems and, perhaps, the real gains will be made in these areas in the future. So let me ask the Professor: Where will we be running next to try and catch up?

Prof A. Fukugaki (Professor of Tokai University, President of The Marine Engineering Society in Japan) I should like to express my hearty thanks for your encouraging contribution to open the discussion. I agree with most of your appraisal and criticism on the past technological challenges, referred to as 'catch-up'. Finally, you raised a very difficult question, but the answer may be very simple: Nobody knows for sure where we will be running next to try and catch up.

One of the governing factors in the future economy and technology will be the environmental issue, including the global warming effect due to CO₂ and air pollution due to SO₂ and NO_x. For many years, the marine sector has been outside of increasingly severer environmental regulations, except for oil pollution. If compared with total world emission, the marine sector produces only 2% of CO₂, 4% of SO₂ and 7% of NO_x. Although most of marine emissions are discharged far from the land and well outside the washdown distance, the effect of ships is much more pronounced in the harbour area. Therefore, a moderate reduction of marine emissions, as being worked out by the IMO, would be reasonable and within the reach of current technology. So I am sure that the necessary technology will be developed and verified in a short period of time.

Residual fuel will remain a primary source of marine fuel, even though low sulphur fuel may be required in harbours, along the shore and in some congested areas. The marine sector has been serving as a waste incinerator for residual fuel and will continue to play the same role, since this is the least hazardous way for mankind to make use of the residuals which otherwise would have to be abandoned.

I think it is the duty of all marine engineers to work out the right answer to the question raised by Mr Woods. I believe that often-repeated and contradictory requirements for marine propulsion systems remain unchanged, i.e. sa-

fe, reliable and fuel efficient systems, together with easy operation and small maintenance burdens, satisfactory to both shipowners and operating personnel. For the past two decades we have concentrated too much on fuel efficiency to the detriment of operation, reliability and maintenance. So I feel more effort should be paid in the coming years to easier operation, higher reliability and reduced maintenance, and, in addition, to environmentally amicable and user friendly marine systems and components.

I.E. Burrows (Harrisons (Clyde) Ltd)

As an operator of a 12 year old vessel, fitted with a dual pressure system corresponding to Fig.1(B) in the paper, I have been studying Fig.7 with concern. Perhaps we are fortunate in not yet experiencing a sootfire. Fig.7 in the paper shows that there are many more sootfires with monopressure systems than with dual pressure systems but gives no indication of the number of ships at risk in each case. Could Professor Fukugaki let us know the relative number of ships in each case?

Fig.7 also indicates that the likelihood of a sootfire decreases as a ship gets older. Most ship problems increase as a ship gets older. Is there any explanation for the decreasing incidence in this case?

Our system uses the MHI steel ball system of soot removal and is known to our crew as the PACHINKO machine. Maintenance is not a problem although we do have to buy 500 000 new balls about once a year. It has been suggested that we change over to a system which depends on a pneumatically powered vibration generator similar to a ships foghorn. Does the Professor have any experience of this system of soot removal and, even if he does not, could he perhaps give us his opinion about the possible efficiency of such a system?

Prof A. Fukugaki (Professor of Tokai University, President of The Marine Engineering Society in Japan)

I am very glad to learn that you have had success with a dual pressure economiser fitted with a PACHINKO machine. Regarding your first question, I agree with your point that the number of sootfires should be evaluated as a percentage of the ships at risk. Although exact figures are not available, the following figures should satisfy your request. Between 1981 and 1989, 57 ships experienced sootfires. Amongst them 26 ships were without a turbo-generator and the remaining 31 ships (including 16 ships with a dual pressure system) had a turbo-generator. The total number of ships at risk was close to

2000 ships without a turbo-generator and 250 ships with a turbo-generator (including 125 ships with a dual pressure system), so the probability of sootfire is about 10 times higher for ships with a turbogenerator. There is little difference between monopressure and dual pressure systems as regards the probability of sootfires for ships with a turbo-generator.

With regard to your second question, my understanding is as follows. In the light of the fact that 219 out of 250 ships with a turbo-generator are free from sootfires, there are several ways to prevent sootfires, and the operating personnel should have developed correct practices based on their experience, e.g. as to when and how to wash economisers with water. So, I believe, the learning effect was greater than the ageing effect of the system. This explains the reduction of sootfire incidence with the ships' age. However, I should also like to point out that no system could be reliable with ignorance and negligence on the part of the operating personnel.

Regarding your third question, I have no experience with a pneumatically powered vibration generator, but my opinion is as follows. We cannot escape from a situation where a large extended area of an economiser acts as a soot collector. The governing factors of soot accumulation are adhesion potential, inertia force and elasticity of soot particles. If the particle is large, it has a larger inertia force and becomes more likely to adhere to the metal surface. Low cycle vibrations transmitted to soot particles from the infra sound generator suppress the soot adhesion, act to detach soot and prevent agglomeration of soot particles. This system, however, is said to be ineffective against wet soot below the dew point.

Dr.Z. Bazari (Lloyd's Register) Comparing diesel engines and gas turbines and considering the sophisticated systems such as the steam bottoming cycles etc, used to improve the overall energy efficiency of the propulsion and auxiliary systems for merchant ships, my questions are as follows:

1. I get the impression that you see a future for gasturbines in the merchant shipping market. Is this right?
2. How do you compare the future for gas turbines with that of diesel engines in terms of overall system efficiency, in view of the fact that the steam bottoming technology may be applied to both prime movers? Is there any chance for gas turbines to approach diesels in the future, and how?

3. Am I correct in saying that the future of gas turbine application to merchant ships, in addition to energy efficiency, will depend on how reliably the turbine blades can cope with poor quality heavy fuel oil, with high levels of ash and sulphur content?

If the answer is yes, what are the developments in gas turbine technology which aim at solving this reliability issue?

4. What will be the alternative fuels in the future?

Prof A. Fukugaki (Professor of Tokai University, President of The Marine Engineering Society in Japan) I am afraid I misled you in stressing the future potential of gas turbines for marine propulsion. My view, on the contrary, is as follows:

1. I do not see a future for gas turbines in merchant ships in general. Their application will be restricted to very high-speed cargo carriers such as surface effect ships, which requires the lightest possible engines, or to LNG carriers where ideal fuel is readily available.

2. With regard to the thermal efficiency, combined cycles with gas turbine topping and steam bottoming have a higher potential than diesel engines in the near term, since the quantity and temperature level of gas turbine exhausts are much higher than those of diesel engines at present. Adiabatic turbo-compound diesel engines have a higher potential for the future, but many breakthroughs will be required, in addition to NO_x handicaps.

3. You are correct that compatibility with poor quality marine fuel is the key factor for gas turbine application to merchant ships. I am pessimistic in this regard, however nozzles and blades of gas turbines will undoubtedly suffer severe hot corrosion with poor quality marine fuel and there is no rationale to solve this problem. Wider acceptance of high temperature combined cycles in thermal power stations could only become possible by the use of LNG which would be necessary to satisfy the environmental regulations for SO₂.

4. I believe that residual fuel will remain a primary source of marine fuel for a lengthy period in the future, since high sulphur residual fuel can not be widely used ashore due to environmental regulations. Alternative fuels will continue to attract attention in the marine sector in the future, but it will take many more generations before any alternative fuels secure a firm position in the market.

Sir Robert Hill KBE (Deputy President, IMarE) Thank you for a most fascinating paper. I sense that you have some regret that nuclear power has not become more widely used for merchant ship propulsion, but I suggest that in the light of shipping accident statistics it is perhaps just as well that nuclear power is not in common use. You say that the reactor of "Mutsu" was restarted after an unusual 16 year shutdown. Could you please give some indication of the work carried out and the modifications to the reactor plant during the shutdown period?

Prof A Fukugaki (Professor of Tokai University, President of The Marine Engineering Society in Japan) I agree with your reasoning as to why nuclear power has not become more widely used for merchant ship propulsion. What I regret is the ill fate of "Mutsu", i.e. the unreasonable delay in the development schedule, as summarised below. "Mutsu" first sailed on 26 August 1974, attained first critical on 28 August, but the reactor was shut down at 1.4% of rated power on 1 September due to abnormally high radiation levels above

the reactor compartment. Since then the reactor of "Mutsu" had been shut down for 16 years due to the following reasons, most of them related to the time required to secure public acceptance of the vessel. It took four years to select the repair yard which would modify the shielding. "Mutsu" was moved to Sasebo in October 1978, but had to wait another two years to settle the risk compensation for fishermen. The modification work on the shielding commenced in August 1980 and was completed in June 1982.

The cause of the abnormal radiation level was the neutrons streaming through the narrow gap in the primary shield above the pressure vessel. An outline of the shielding modifications is as follows. The primary shield above the pressure vessel was changed from heavy concrete to a combination of serpentine concrete and hydrogenated zirconium, both effective for neutron shielding. A new primary shield, consisting of a combination of serpentine concrete and polyethylene, was added under the reactor vessel. The secondary shield above the containment vessel

was changed from a combination of lead and polyethylene to a massive heavy concrete layer having balanced absorption characteristics for both neutrons and gamma rays.

"Mutsu" returned to the port of Ohminato in August 1982 and had to wait six years prior to entry to the new port of Sekinehama, in January 1988. This was because it was an outside port facing the ocean, it took two years to finalise the site and secure a budget to construct the new port, followed by four years for the construction period. Open inspection of the reactor was undertaken from August 1988 to October 1989 and it was found that all of the pressure parts and reactor core were surprisingly sound. Minor pitting was found on the cladding of some of the control rods which were renewed. All of the fuel elements were thoroughly inspected and the few suspected of incipient corrosion were replaced. The reactor was successfully restarted in March 1990, thanks to the long sustained efforts of the marine engineers in charge who had maintained the reactor system perfectly which would not have operated forever.
