The proposed cold box (plate fin heat exchanger) is widely used in onshore cryogenic installations. An availability analysis concludes 99.98 % availability, which is at the same level or better than ship machinery in general.

8.5 LIQUIFICATION PLANT:-

Hamworthy KSE was awarded the contract by the Norwegian gas distribution company Gasnor in October 2001. The LNG production capacity is 60 ton/ day (2500kg/hr), which corresponds to the boil-off rate on traditional size LNG carriers. This plant uses the same type of cooling cycle (Brayton) and control prin-ciples as the reliquefaction system for LNG carriers. The same 3-stage N_2 compressor with expander and the same type of cold box that will be used on LNG Carriers are also installed.

However, as the plant is onshore and the feed gas comes from the gas pipelines from the offshore fields in the North Sea, this plant needs additional equipment and systems.

The plant shown in Fig thus consists of the following basic parts:

- Natural gas dehydration unit
- Natural gas CO_2 removal unit
- Nitrogen cooling circuit (same as proposed for LNG carriers)
- Main liquefier (cold box) with LNG receiver (similar type as proposed for LNG carriers)
- LNG storage tank and truck loading station.

Natural gas from the high-pressure feed line is reduced in pressure down to 120 barg and dehydrated down to a H_2O content of 1 ppm. The dry feed gas is further reduced in pressure down to 52 barg prior to removal of CO_2 down to a level of 50 ppm.

Liquefaction is accomplished at about 50 bar abs against cold nitrogen gas, which is cooled in a single-expansion cycle with three compressor stages and one expander stage. The heaviest gas fractions are separated out and the gas liquefies in the lower-mid section of the cold box.

The liquid is sub-cooled in the bottom section and led to the LNG flash drum via a valve, where the pressure is reduced to 0.5 barg, and the LNG is sent to a storage tank. The system is equipped to give a variable production rate by adjusting the mass flow of nitrogen. The first LNG was produced on this plant on March 15, 2003.

LNG carriers, like oil tankers, are not permitted to immobilize their propulsion machinery while in port and port areas. Hence, redundancy is required. For the steam ship, redundancy is considered fulfilled by having two boilers, whereas no redundancy is required for the single steam turbine, propeller shaft and propeller.

For diesel engines, which require more maintenance on a routine basis than steam turbines, either a multi-engine configuration or an alternative propulsion power supply possibility for a single engine configuration is required. Shuttle tankers in the North Sea are equipped with twin low speed engines and twin propellers. This ensured that approximately half of the propulsion power

Assumptions:	Heavy fuel burning diesel engines as propulsion engines Reliquefaction plant fitted as the primary system for cargo pressure and temperature control
IACS Rules for Redundancy for Reliquefaction Plant	
Alt. 1:	A spare capacity at least equal to the largest single reliquefaction unit should be fitted.
Alt . 2:	Auxiliary boiler(s) capable of burning the boil-off vapours and disposing of the generated steam via a steam dumping system
Alt. 3:	Gas Oxidiser, i.e. burning the boil-off gas in a separate burner unit positioned in the vessel's stack
Alt. 4:	Controlled venting to the atmosphere of cargo vapours, if permitted by the authorities in question

Redundancy Considerations for Reliquefaction Plant for LNG Carriers

The International Association of (marine) Classification Societies' (IACS) redundancy considerations for a reliquefaction plant for LNG carriers are as stipulated in Fig. 24. ***With the ME- I engine, the configuration shown in Fig. 5, comprising one reliquefaction unit, one high pressure compressor and one oxidizer, will comply with redundancy requirements and offer full fuel flexibility.*** Redundant low speed engine propulsion concepts, as outlined above, ensure that sufficient power is available for safe navigation and, for the twin engine concept with completely separated engine rooms, even an additional margin towards any damage is obtained. For LNG carriers, a twin engine configuration is proposed to alleviate any possible doubt on reliability and redundancy. The twin-engine configuration is shown in Fig. 25.

CHAPTER 9

VOYAGE- ANALYSIS & PERFORMANCE

9.1 SELECTION OF ALTERNATIVES

The feasibility of gas-diesel engines for propulsion and electric power generation onboard LNG carriers was studied by engine builders some ten years ago. The need for gas compression turned out to be a too high burden for the operating economy of the ship. The quantifiable characteristics of the other alternatives were compared using a specially developed comparison tool, whereas their non-quantifiable characteristics were
discussed and compared together with major LNG carrier owners, operators, managers and shipyards over the past few years. When comparing the operational economy of the various alternatives, it is important to take the whole machinery installation into account. Two-stroke diesel engines have high efficiency, but the need to reliquefy the boil-off gas gives installations featuring this type of engines a higher total energy consumption. The most attractive alternative to the traditional steam turbine installation turned out to be dual-fuel-electric machinery. As a runner up but at clear distance to dual fuel- electric machinery, an installation featuring twin two-stroke engines, each in direct-drive to a fixed-pitch propeller, a reliquefaction plant, and a group of fourstroke diesel generating sets emerged.

9.2 ONE-TIME INVESTMENT COSTS

To determine the difference in one-time investment costs, cost of relevant machinery components are added up. The calculation includes components like prime mover, boiler plant, reduction gear, shaftline, propeller, and so forth. Calculation reveals, that the three alternative machineries all cost less initially, than the steam-mechanical machinery. Figure 5 presents these onetime machinery investment costs.

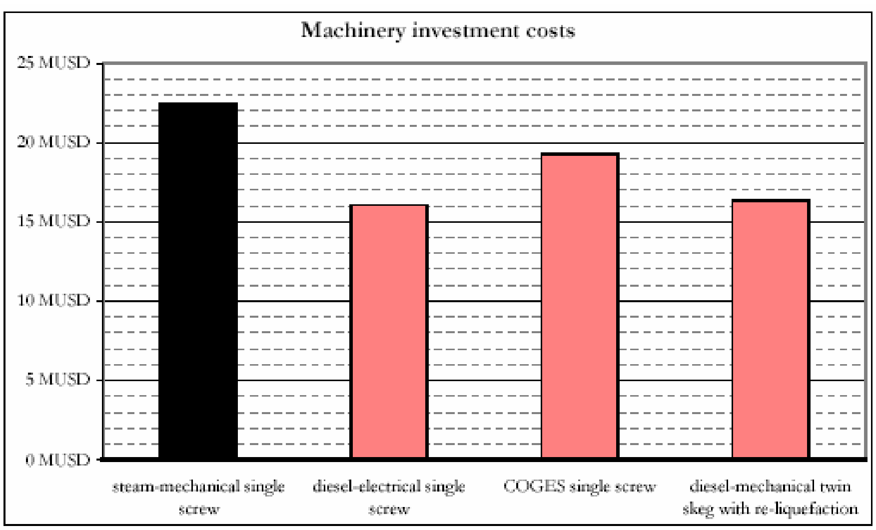

Figure 5 One-time machinery investment costs

As the graph indicates, the novel machineries' investment cost is around 3.7 MUSD less, than the steam-mechanical machinery's investment cost. This represents an about 15..30% reduction in machinery investment cost. This cost difference can be amortized to an economic lifetime of 20 years, with an 8% opportunity cost for money. Resulting is an annual capital cost difference between 320 000 and 650 000 USD, in favour of the novel machineries. To put this investment cost difference into perspective in the ship scale, large LNG carriers have recently been contracted at prices of 160..170 MUSD. In ship scale the investment cost difference is thus about 2..4%.

9.3 RECURRING VARIABLE COSTS

Variable costs are usually divided into two different sub-categories, operating costs and voyage costs. Operating costs are semi-variable, being incurred by the vessel being kept operational. These costs can only be avoided by laying up the vessel. Operating costs consist, mainly, of manning costs, insurance premiums, annual small repairs and maintenance, various stores and lubricating oils. Operating costs vary from ship to ship, and operator to operator, but on an average, annual operating costs can be assumed to be around 3.2 MUSD for a large, contemporary LNG carrier. Voyage costs, on the other hand, are truly variable costs. They are voyagedependant, and incurred by the actual voyage. Voyage costs include fuel oil costs, pilotage, fairway and canal dues and port changes. Voyage costs are very much dependant on bunker prices, cruising speed, boil-off rate and operating route, just to mention few, but can here be assumed to be about 4.8 MUSD per annum. Thus for reference all recurring annual variable costs can be calculated to sum up to about 8.0 MUSD.

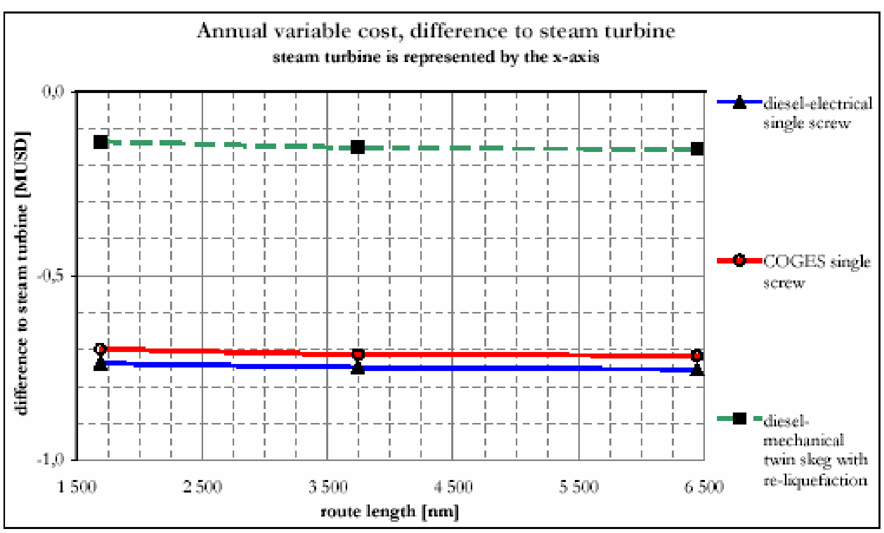

Figure 6 Recurring annual variable cost, versus route length, presented as difference to the steam-mechanical machinery

However, the only relevant differences between the four options are in their respective machineries. It would thus be fair to assume, that the majority of operational costs, as well as some voyage costs, like pilotage, port dues etc, are equal for all machineries. The only differing variable costs thus are, in fact, incurred by the choice of machinery. Figure 6 presents the three novel machineries' annual variable costs. The comparison is presented as a difference to steam turbine's costs, so it does not indicate an absolute cost level, but relevant.
The main difference comes from fuel oil costs. Lubricating and cylinder oil costs are practically nil for both steam and gas turbines, but are becoming relevant for medium speed, and especially for slow speed diesels. There are also small differences in maintenance costs, but these differences are rather insignificant. When compared to the estimated annual operating and voyage cost sum up of 8.0 MUSD, both diesel-electrical and gas turbine machineries seem to be able to yield around 9% savings.

9.4 WHAT AFFECTS THE VARIABLE COSTS?

Variable costs are, naturally, very much dependant on boundary conditions, which are applied in calculations. But what happens, if some of the boundary conditions change? This is a question, which is important from the operator's point of view, as the operator can only affect some of the boundary conditions. Some prevailing boundary conditions, like price of bunker and value of LNG are, from the operator's point of view, given.

9.4.1 Operating route

LNG is transported over very varying distances. It's way below 1000 nautical miles from Algeria to the other side of the Mediterranean, while from Persian Gulf into the Far East it is well over 6000 nautical miles. Length of the LNG trading routes thus varies quite widely today, and maybe even more in the future. Short routes of course have relatively more port time, as well as time spent maneuvering and cruising at slow speeds. In long hauls the full speed, open sea leg is emphasized. One could thus expect, that length of the operating route might play a role in machinery selection. But, as Figure 6 shows us, length of the operating route does not really have relevance. The calculation was done for three routes, representing lengths of about 1700, 3800, and 6500 nautical miles. Even though at slow speeds the steam and gas turbines go down in efficiency, while diesels do not, there are no noticeable differences in the end results. This might necessarily not be the case in very short routes, from 300 to 1000 nm, where the full speed leg is really small. But, at least from 1700 nm upwards, the length of the route does not play a role in machinery selection.

9.4.2 Fuel flexibility

Fuel flexibility means the ability for the machinery to utilise varying proportions of bunker and LNG. Depending on the tank insulation and ambient conditions, among other things, boil-off equals 40..60% of the ship's total fuel input. The remaining 40..60% of fuel input is usually provided with bunker. But if bunker price is very high, or if LNG is valued very low, it might prove more economical to force additional boil-off to feed the machinery. Under such market conditions, the most economical operating mode would thus be to have LNG input representing 100% of total fuel input. Fuel flexibility is therefore quite important from the operator's point of view. When an LNG ship is operated for 30 years, or even longer, it is vital, that fuel costs can be minimised, by switching to the most economical fuel, following changes in market conditions. Steam-mechanical machinery has the ultimate fuel flexibility. Steam turbine can be equipped to LNG fuel inputs from 0% to 100%, and the rest of the fuel input can be the cheapest bunker available. This is a clear advantage of the steam turbine machinery, as, in fact, the actual boil-off rate varies following the ambient conditions. Steam turbine has no problem in consuming all the boil-off there may be.

Gas turbines can here roughly be divided into two categories. First there are the aero-derivative gas turbines, which use clean distillate fuels like MGO as their liquid fuel. Then there are industrial gas turbines, which are able to burn heavier and cheaper intermediate fuels, such as IF30 or even IF180. Due to the differences in liquid fuel, these two types of gas turbines have differing operating economies. HFO-burning gas turbine has the second best fuel flexibility, being able to utilise LNG for 0% to 80% of total fuel input. This applies to gas turbines, which have their COGES cycle output around 22 MW. This LNG input range is wide enough for the gas turbine to be able to take all the boil-off which may be coming. At least 20% of fuel input must nevertheless be HFO, since this machinery is equipped with a booster diesel engine.

MGO-burning gas turbines have the disadvantage of having to use rather expensive liquid fuel. For this reason it is usually not liquid fuel, which is used for additional fuel input, but forced boil-off. In such a case the amount of LNG input is fixed at gas turbine's total fuel input, representing about 80% of total fuel input. This machinery has, from the economical point of view, no fuel flexibility at all. Total lack of fuel flexibility also applies to the re-liquefying diesel-mechanical machinery. This machinery uses 0% LNG as fuel input, and since the primemovers can not utilise LNG, the amount can not be changed. As long as the re-liquefaction plant is dimensioned correctly, it has the capacity to re-liquefy all the boil-off coming from the tanks. This machinery burns 100% bunker, no matter what its price in relation to LNG is. Diesel-electrical machinery's LNG input is also fixed. It is fixed at the amount of gas-burning diesel engines, while HFO input is fixed at the amount of single fuel diesel engines. This machinery must thus burn the pre-determined amounts of LNG and bunker, no matter what their prices are. Actually, since the amount of boil-off can vary, gas-diesel capacity must either be overdimensioned for normal use, or the occasional excess boil-off gas must be disposed of by burning it.

9.4.3 Value of LNG

Of course, fuel flexibility has no meaning, unless the value of LNG, or price of HFO, changes. Actually, value of LNG is quite a complex issue. This is also, one could claim, the essential issue with respect to voyage costs, and subsequently to machinery selection. This is thus a question, which deserves some attention. As mentioned, boil-off gas is natural in each LNG carrier. Quantity of boil-off is not, however, dependant on the choice of machinery. First thing to note here is thus, that since the amount of natural boil-off is equal with all four machineries, it can be considered as 'free' source of power in comparison. But, the fourth optional machinery, based on two stroke diesel engines, can not burn boil-off. Instead, the boil-off gas is re-liquefied, and put back into the cargo tanks. Because no boil-off is burnt, this machinery naturally burns much more liquid fuel than all the others. But, on the other hand, it is also able to deliver more cargo inside the same cargo tanks, than the alternativemachinery- including ships. To be able to compare this option justly, reliquefied boil-off gas must be assigned with some value. To highlight the importance of boil-off valuation, Figure 7 presents compositions of relevant variable costs for each four machineries.

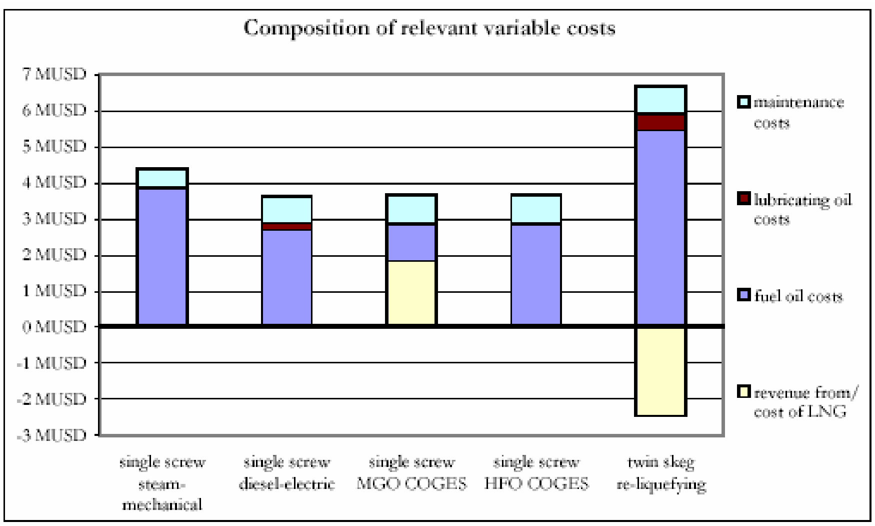

Figure 7 Composition of relevant variable costs

The figure also includes two COGES machineries. These refer to gas turbine based machineries, which can utilise different kinds of liquid fuels. As the amount of natural boil-off is not enough to give most gas turbines a 100% fuel input, back-up fuel must be added. If the gas turbine can utilise HFO, it is used. But if the gas turbine can only utilise MGO, it is, from economical point of view, too expensive to be burnt. In such a case the 100% fuel input for gas turbine is provided with additional LNG, which is forcefully vaporised. Such a ship will end up delivering less cargo than its counterparts, and the value of forced boil-off is thus added to its variable costs. In the figure above, LNG is assigned an energy-equivalent value to HFO. This means, that the energy contained within LNG is valued at the same price, as the energy contained in HFO. Looking at the figure it is also evident, that value of LNG is the key issue for profitability of re-liquefying technology, as well as for the MGO-burning gas turbine. If energy contained in LNG is more valuable than energy contained in HFO, it is good business not to burn it, but to re-liquefy, and to sell it at a higher price. But what is the right price of LNG? Unlike for example oil, natural gas or LNG does not really have a world market price, as such. Different buyers get their gas at different prices, representing varying production costs and differing competitive environments. Usually in long term contracts the gas price is pegged to a basket of alternative fuels, such as oil and coal. One way of determining the value of LNG is by estimating it through the concept of opportunity costs. If LNG would not be forced, it could be used in the buyer's power plant for power production. This would mean, that the power producer needs to use less alternative fuels, such as crude oil, in his power production. In opportunity costing LNG's price could thus be set to the crude oil's energy-equivalent price. With the crude price of 28 USD/barrel, this would translate into an LNG price of approximately 201 USD/tonne. Because natural gas is, at least in part, used due to its environmental merits, an environmental premium could be added to this value. But, it is often the producer of gas, who arranges the transportation. For the producer, LNG is not that expensive, as he could calculate it only to be worth the gas production and liquefying costs. At its very lowest, production and liquefying costs of LNG equal about 91 USD/tonne. In a medium sized offshore production plant, on the other hand, the production and liquefying costs sum up to around 147 USD/tonne. Table 1 summarises some of the alternative aspects into the value of LNG.

LNG price	price description
91 USD/tonne	on-shore producer's average cost price
125 USD/tonne	energy-equivalent price to HFO
147 USD/tonne	off-shore producer's average cost price
201 USD/tonne	energy-equivalent price to crude oil
229 USD/tonne	Japan's current average LNG price

Table: Some different aspects into the value of LNG

It would thus appear, that the value of re-liquefied, or forced boil-off, can be argued to be anything between 90..250 USD/tonne. LNG producer could use values of 90..150 USD/tonne, depending on market conditions, availability of LNG supply, and accounting policies. If all produced LNG could be sold at a good price, true opportunity costing values up to 230 USD/tonne should be used. On the other hand, LNG consumer would most likely be more correct in using values between 200..230 USD/tonne. Value of LNG is thus quite of an ambiguous concept.

But has this any relevance with respect to annual variable costs? Figure 8 answers this question by showing the relationship between annual variable costs, and the value of LNG. The graph shows differences to the steam mechanical machinery, which is represented by the x-axis, and calculation is based on HFO price of 114 USD/tonne.

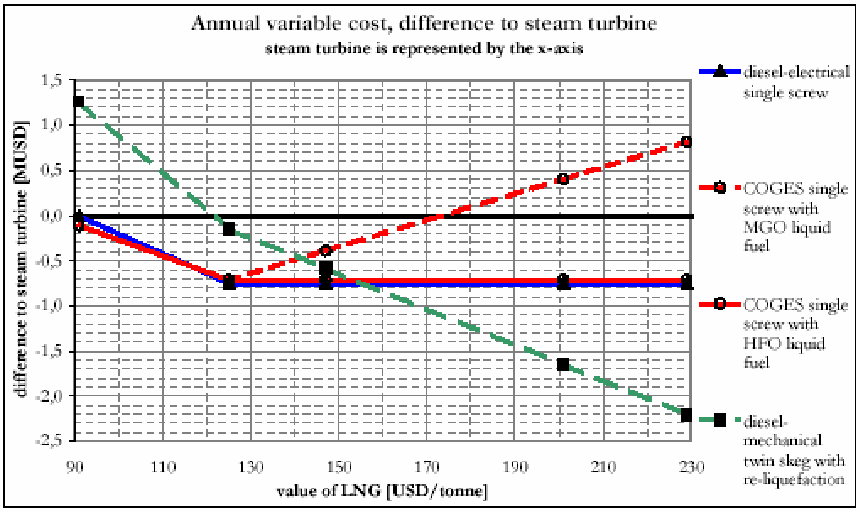

Figure 8 Recurring annual variable cost, versus the value of LNG, presented as difference to the steam-mechanical machinery

The diesel-electrical machinery maintains its advantage over steam turbine at all LNG values. When LNG is valued below 125 USD/tonne, or 110% of HFO per tonne price, diesel-electrical machinery becomes less economical. Below this price it is more economical to burn LNG, rather than HFO. Unfortunately diesel-electrical machinery's LNG input can not be increased beyond the installed capacity of its gas burning engines. Steam turbine can be operated entirely on LNG, if need be, and will thus be more competitive in low LNG values. Gas turbine machinery, which can utilise HFO as its liquid fuel, behaves much the same way as the diesel-electrical machinery. Below LNG value of 125 USD/tonne, or 110% of HFO price, the back-up HFO is no longer fed into the gas turbine, but replaced with additional forced boil-off. This improves its economics a little bit in lower LNG values, but there will still be a HFOburning booster diesel engine, which can not use LNG. The MGO-burning gas turbine has to force additional boil-off constantly. This machinery's optimum operating point is thus at 125 USD/tonne, or 110% of HFO price, since higher LNG prices do not favour boil-off forcing. This machinery finally loses its advantage over steam turbine at break-even LNG value of 175 USD/tonne, or 155% of HFO price. As one could expect, re-liquefying is good business, if LNG is valued high. Break-even LNG value with respect to steam turbine is at 120 USD/tonne, or 105% of HFO price. Re-liquefying becomes the most economical option beyond LNG value of 155 USD/tonne, or 135% of HFO price.

9.4.4 Price of HFO

And what happens, if bunker price changes? Actually, it is only relevant, what is the value of LNG in relation to the price of HFO. This is what determines, if it is more economical to burn HFO or LNG. Figure 8 has been calculated with a HFO price of 114 USD/tonne, but the results could as well be presented in a more universal scale of LNG/HFO price ratio. Additionally, when the one-time investment costs are amortized to the ship's expected economic lifetime, recurring annual variable costs can be added to it. Figure 9 presents these results, applying 20 years and an 8% cost of capital to amortize.

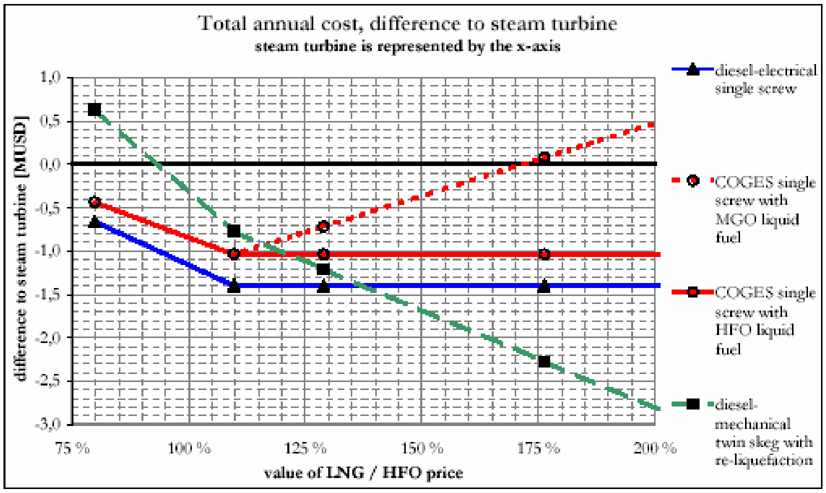

Figure 9 Total annual cost, versus the ratio of LNG value and HFO price, presented as difference to the steam-mechanical machinery

These results, presented in Figure 8 and in Figure 9, have been arrived to by assuming, that all the fuel flexibility, which is available in a machinery, is utilised to its maximum extent.

9.4.5 Membrane or Moss?

LNG ships are usually divided into two subtypes, according to their cargo containment system. Ships having their cargo contained in Technigaz or Gaz Transport systems, are commonly referred to as membrane-type tankers, whereas ships with their cargo carried in large, spherical tanks, are referred to as Moss-type tankers. Ships of the two subtypes are distinctly different from one another. Moss-type ships enclose a larger volume due to their main-deck-penetrating spherical tanks. Moss-type ships have also wider beam, than their membrane-type counterparts. Despite these differences, all results presented in this paper are equally applicable to ships of both subtypes. Having said this, there are still some differences between the subtypes. Moss-type ships have wide beams, their cargo contained in spherical tanks, and typically quite spacious engine rooms. In these Moss-type ships a more compact machinery does not enable any reductions in main dimensions, nor any increase in cargo volume. In an membrane-type ship, on the other hand, a more compact engine room would enable an increase in cargo space, or, alternatively, a reduction in main dimensions. Quite compact all-aft engine room can be achieved with electrical podded propulsors. These propulsors of course require the ship to have an electricity producing main machinery.

9.4.6 Single or twin propulsor?

One of the acknowledged benefits of a twin screw design is its improved redundancy. Diesel-electric and COGES machineries, as well as the dieselmechanical re-liquefying machinery, can all be easily built as either single or twin propulsor ships. If the steam-mechanical ship would be built twin screw, it would be much more costly. In practice twin screw steam-mechanical ship is really not feasible.

9.5 Shipyard Premium

So far all LNG carriers have been delivered with a single screw steammechanical propulsion. All the novel alternatives, discussed in this paper, are thus prototypes from the yard’s point of view. As steam turbine is the default design, it is likely, that shipyards will add premium to any novel LNG tanker’s price. The calculated investment cost difference, presented earlier in this paper, is thus different, than the actual ship’s price difference, which can only be indicated by yards. Part of the premium should be viewed as an uncertainty guarantee. This part indicates, how much the yard thinks its risks increase, should it be contracted to build a prototype with a new power plant concept. One could expect, that re-liquefaction plants, and gas turbines, will probably carry the highest risk premiums. Medium speed diesel technology, even if fuelled by low pressure gas, is perhaps the least unknown technology for most LNG carrier building shipyards. Another part of premium is due to the loss of serial ship effect. When ships are built in series, benefits of learning, repeatability, and, one could say, kind of mass production, are beginning to emerge. Established LNG ship building yards in the Far East have built, and are in the process of building LNG ships in series. For such yards the serial ship effect premium, and the threshold to choose a novel machinery, might be higher, than for the yards, which are yet less established in the LNG market. Shipyard premium might, all in all, become big enough an obstacle for novel machineries to enter the market. What could a supplier of such a novel technology do, so that the shipyard would reduce its premium? There might not be much, a supplier can do about the serial ship effect, but risk premium is something, a supplier could reduce. One answer would be for the technology supplier to carry a part of the risk. This could be arranged through the delivery of a complete power and/or propulsion package. The more tasks and responsibilities the supplier is willing to take care of in the building phase, the less risk there is associated for the yard to carry. Such a package could help persuade the yard to select a novel machinery. In the same context, the supplier could also offer something extra for the owner. If the supplier is contracted to deliver a machinery package, and if it is also willing to take responsibility over it, supplier could as well offer up-time guarantees, for example. Such a package, offering benefits for both the owner and the yard, could significantly help penetration of new machineries into the LNG market.

9.6 Conclusion

So far nothing has been able to beat steam turbines in LNG carriers. Lately, as technology has advanced, alternative and promising methods of handling boil-off gas have emerged. More specifically, there are three alternative technologies to power the tomorrow's LNG carriers. These are gas burning low pressure diesels, gas turbines in combined cycle, and re-liquefaction of boil-off. All of these novel technologies appear to offer economical benefits for the owner. Initial investment costs of these three machineries are lower, and all of their annual costs are smaller, given the right boundary conditions. All the novel machineries can be built to have higher redundancy, than what is feasible with steam turbine. These novel machineries can also be equally well applied onboard both the membrane- and Moss-type LNG carriers. Also the length of the operating route does not appear to be an issue in machinery selection.

However, attention must be paid to correct identification of the prevailing boundary conditions. Re-liquefaction technology is sensitive to rise in bunker price, and especially to reduction in value of LNG. Re-liquefaction technology probably has the highest economical risks associated with it, but it is also capable to offer the highest returns. If it is the LNG consumer, who owns the cargo during transit, re-liquefaction emerges as a very prominent solution. Quite contrary to re-liquefaction, the MGO-burning gas turbines are sensitive to a high LNG price. This machinery is, over a wide range of LNG and HFO prices, more economical than the steam turbine machinery. However, it appears to lose constantly to the HFO-burning gas turbine, as well as to the diesel-electrical machinery. For LNG projects, where it is the gas producer, who is responsible for transportation, MGO-burning gas turbines however do provide a good solution. HFO-burning gas turbines and diesel-electrical machineries have rather similar operating economics. They both beat steam turbine over the entire range of varying boundary conditions, and are able to offer quite constant and secure economical benefit for the operator. These machineries both thus pose the smallest economical risks with quite certain returns. Both of these novel machineries can be considered as rather safe options for the operator. Shipyard premiums are an issue, which might impede penetration of these novel technologies. Here a supplier could ease the selection by offering the shipyard a complete packaged delivery.

CHAPTER 10

TECHNICAL COMPARISON OF THE DIFFERENT PROPULSION TYPES

Comparision between steam & diesel propulsion:-

Size of LNG Carrier and Boil-Off Gas rates

Ship particulars	
Cargo capacity	150.000 m3
Boil off rate in loaded conditions *	0,12% per day
Volume of methane	180,0 m3/day
Mass of methane (Density = 470 kg/m3)	84.600 kg/day
Energy in methane (LCV: 50,000 kJ/kg)	4.230 GJ/day
Boil off rate in ballast conditions *	0,06% per day
Volume of methane	90,0 m3/day
Mass of methane (Density = 470 kg/m3)	42.300 kg/day
Energy in methane (LCV: 50,000 kJ/kg)	2.115 GJ/day

Size of LNG Carrier and Boil-Off Gas rates

Voyage profile	
Distance (Pilot-Pilot)	6500 nm
Nominal Service Speed	20 knots
Loaded voyage	325 hours
Ballast voyage	325 hours
Reserve	24 hours
Time for unloading	24 hours
Time for loading	24 hours
Time per round-trip	722 hours
Round-trips per year	12,1
Propulsion power in loaded conditions	28920 kW
Propulsion power in ballast conditions	28920 kW

Voyage profile

Basic Data for Economical Comparison		
Oil prices		
Heavy Fuel Oil	150	US$/tons
Lubrication oil for four-stroke engines	700	US$/tons
Cylinder L. O. for two-stroke engine	800	US$/tons
System oil for two-stroke engine	700	US$/tons
LNG prices		
LNG sales prices	188	US$/ton
LNG sales prices (LCV of methane = 50,000 KJ/kg)	4,0	US$/Mbtu

Basic Data for Economical Comparison

Power Consumption			
Options	Steam turbine TurboGenerator	Two-Stroke Diesel Engines with Reliquefaction	Dual-Fuel Two-Stroke Diesel Engines
Engine power for propulsion			
Loaded conditions	29808 kW	29212 kW	29212 kW
Ballast conditions	29808 kW	29212 kW	29212 kW
Electrical power consumption			
Loaded conditions			
Electrical power consumption	1500 kWe	4743 kWe	3615 kWe
Engine power	1563 kW	4941 kW	3766 kW
Ballast conditions			
Electrical power consumption	1500 kWe	3122 kWe	2558 kWe
Engine power	1563 kW	3252 kW	2664 kW

Power Consumption

Operation Costs at Loaded Conditions			
Options	Steam turbine	Two-Stroke Reliquefaction	Two-stroke (LNG + HFO)
Propulsion Power			
Delivered Power	29808 kW	29212 kW	29212 kW
Energy Needed	369,1 GJ/h	210,8 GJ/h	210,8 GJ/h
Available Energy in BOG	176,3 GJ/h	0,0 GJ/h	176,3 GJ/h
Extra Energy Needed	192,9 GJ/h	210,8 GJ/h	34,6 GJ/h
Equivalent HFO Cons.	4,8 t/h	5,3 t/h	0,9 t/h
Fuel oil costs	723,2 $/h	790,5 $/h	129,6 $/h
Cylinder oil costs	0,0 $/h	35,1 $/h	35,1 $/h
System oil costs	0,0 $/h	4,7 $/h	4,7 $/h
Maintenance costs	0,0 $/h	29,2 $/h	29,2 $/h
Auxiliary Power			
Delivered power	1563 kW	4941 kW	3766 kW
HFO Consumption	0,5 t/h	1,0 t/h	0,8 t/h
Fuel oil costs	72,6 $/h	150,3 $/h	114,6 $/h
System oil costs	0,0 $/h	3,5 $/h	2,6 $/h
Maintenance costs	0,0 $/h	12,4 $/h	9,4 $/h
Operation cost per hour	795,8 $/h	1025,6 $/h	325,1 $/h

Operation Costs at Loaded Conditions

Operation Costs at Ballast Conditions			
Options	Steam turbine	Two-Stroke Reliquefaction	Dual - Fuel Two-stroke
Main Engine(s)			
Delivered power	29808 kW	29212 kW	29212 kW
Energy Needed	369,1 GJ/h	210,8 GJ/h	210,8 GJ/h
Available Energy in BOG	88,1 GJ/h	0,0 GJ/h	88,1 GJ/h
Extra Energy Needed	281,0 GJ/h	210,8 GJ/h	122,7 GJ/h
Equivalent HFO cons.	7,0 t/h	5,3 t/h	3,1 t/h
Fuel oil costs	1053,7 $/h	790,5 $/h	460,0 $/h
Cylinder oil costs	0,0 $/h	35,1 $/h	35,1 $/h
System oil costs	0,0 $/h	4,7 $/h	4,7 $/h
Maintenance costs	0,0 $/h	29,2 $/h	29,2 $/h
Auxiliary Power			
Delivered power	1563 kW	3252 kW	2664 kW
HFO Consumption	0,5 t/h	0,7 t/h	0,5 t/h
Fuel oil costs	72,6 $/h	98,9 $/h	81,1 $/h
System oil costs	0,0 $/h	2,3 $/h	1,9 $/h
Maintenance costs	0,0 $/h	8,1 $/h	6,7 $/h
Operation cost per hour	1126,3 $/h	968,8 $/h	618,6 $/h

Operation Costs at Ballast Conditions

Annual operation costs and value of lost LNG (Fuel oil as add-up energy)			
Options	Steam turbine	Two-Stroke Reliquefaction	Dual - Fuel Two-stroke
Operations costs during			
Loaded conditions	3.140.000 $/yr	4.040.000 $/yr	1.280.000 $/yr
Ballast conditions	4.440.000 $/yr	3.820.000 $/yr	2.440.000 $/yr
Total operation costs per year	7.580.000 $/yr	7.860.000 $/yr	3.720.000 $/yr
LNG account (per trip)			
Lost during loaded voyage	2.438 m^3	- m^3	2.438 m^3
Lost during ballast voyage	1.219 m^3	- m^3	1.219 m^3
Total Economy			
Operation costs	7.580.000 $/yr	7.860.000 $/yr	3.720.000 $/yr
Value of lost LNG	3.910.000 $/yr	- $/yr	3.910.000 $/yr
Total expentures per year	**11.490.000 $/yr**	**7.860.000 $/yr**	**7.630.000 $/yr**
Saving per year	**- $/yr**	**3.630.000 $/yr**	**3.860.000 $/yr**

Annual operation costs and value of lost LNG (Fuel oil as add-up energy)

The benefit of diesel engine propulsion of LNG carriers is calculated to be above. US$ 3.5 million per vessel per year. Especially the LNG selling price has a positive impact on the advantage of diesel engine propulsion. The benefit gained in operating costs and the additional income from the sale of LNG by diesel engine propulsion and reliquefaction will, in all cases, be sufficient to justify even large differences in investment costs, if such are called for at all. Basically, diesel propulsion offers a CO2 emission reduction of about 30% compared to the steam plant.

10.1 Comparision between steam, diesel & diesel-electric-

A state-of-the-art 145,000 m3 LNG carrier, with main particulars as shown in figure 4. was used as the basis for the technical and economical evaluation. Figure 3 and tables 1 and 2 show the predicted power requirements, efficiency figures and initial costs of the different propulsion options.

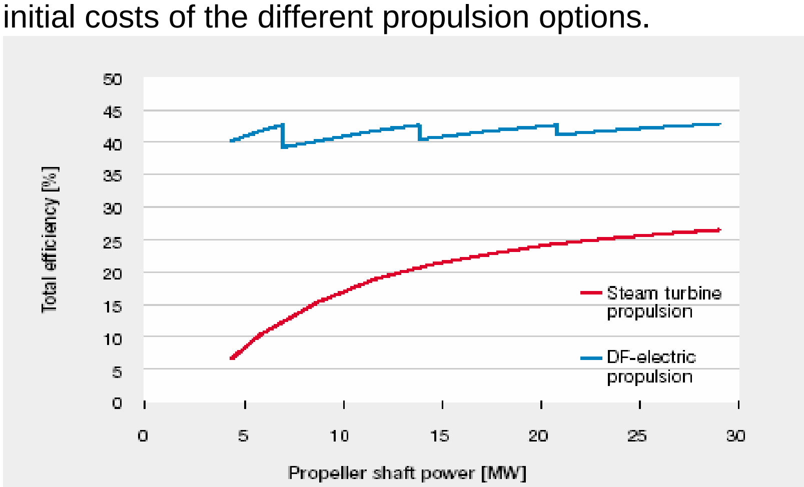

Fig. 2 Efficiency comparison between DF-electric and steam turbine propulsion for the case quoted in this article.

The difference in needed power is merely due to different efficiency losses between the propeller and the engine or turbine. Since the diesel-electric version is producing electrical power, the loss of efficiency is greater than for the mechanically driven propeller.

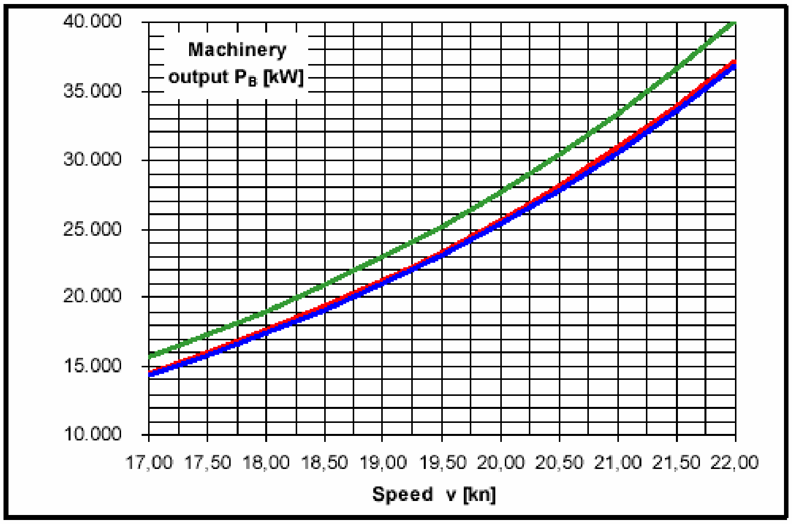

Figure 3: Predicted Brake Power Requirements

Comparison of Propulsion Efficiency Figures

Steam Turbine (Single Screw)		DF Diesel Electric (Single Screw)		2-Stroke Diesel Engine (Single Screw)	
Fuel / Boil-off Gas	: 1.00	Fuel / Boil-off Gas	: 1.00	Fuel	: 1.00
Boiler	: 0.88	DF-Diesel Engines	: 0.46*	2 Stroke Engine	: 0.49
Steam Turbine	: 0.35	Alternators	: 0.97	Shafting	: 0.99
Gearbox	: 0.98	Converters.	: 0.98		
Shafting	: 0.99	E-Motors	: 0.96		
		Gearbox	: 0.98		
		Shafting	: 0.99		
Total Efficiency	: 0.30	Total Efficiency	: 0.41**	Total Efficiency	: 0.48

*) in gas mode 0.48

**) in gas mode 0.43

Table 1: Comparison of Propulsion Efficiency

Prelim. Comparison of Initial Costs (excl. Installation)

Steam Turbine (Single Screw)		DF Diesel Electric (Single Screw)		2-Stroke Diesel Engine (Single Screw)	
Boilers incl. main propulsion turbine	: 13.50	4 df-diesel engines incl. Alternators	: 11.50	Main engine	: 7.20
Gear Case	: 3.00	2 E-motors, transformers converters	: 5.50	Reliquefaction plant	: 6.00
2 turbine gensets	: 1.60	Gear case	: 2.20	3 diesel gensets	: 2.70
1 diesel genset	: 0.90	Propeller & shafting	: 0.65	Propeller & shafting	: 0.65
Propeller & shafting	: 0.65	Ruder/steering gear	: 0.25	Ruder/steering gear	: 0.25
Ruder/steering gear	: 0.25	Exhaust gas Boiler	: 0.30	Exhaust gas Boiler	: 0.30
		Thermal Oxidiser	: 0.50		
Total Initial Cost	: 19.90	Total Initial Costs	: 20.90	Total Initial Costs	: 17.10

*) all figures in million USD

Table 2: Preliminary comparison of initial costs

Figure shows the different cargo capacities which can be achieved with the various propulsion alternatives, while maintaining the same main ship particulars.

Principal Particulars:

- Length over all: abt. 280,00 m
- Length between perpendiculars: 268,00 m
- Breath moulded: 43,20 m
- Depth to maindeck: 26,10 m
- Cargo* (100% - Steam): abt. 145.500 m³
- Cargo* (100% - Diesel mechanical): abt. 149.000 m³
- Cargo* (100% - Diesel Electric): abt. 150.500 m³
- Gross Tonnage: abt. 95.500
- Draught (steam / diesel electric): 11,95 m
- Corresp. Deadweight all told: abt. 72.700 t
- Draught (Diesel mechanical): 12.1 m
- Corresp. Deadweight all told: abt. 74.300 t
- Speed at design draught: abt. 19.50 kn *) cargo capacity based on CS1 system for 0.15% BOR

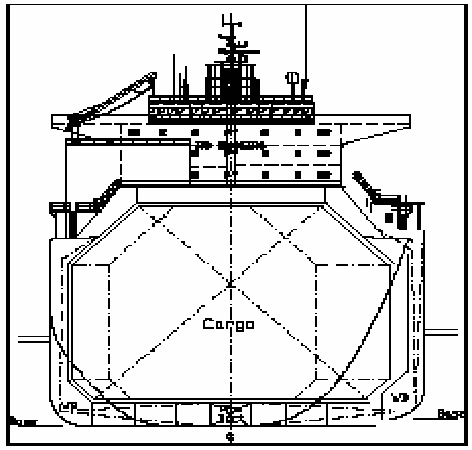

Figure 4: Principle particulars for a 145,000 cbm LNG carrier

10.2 ECONOMICAL COMPARISON OF THE DIFFERENT PROPULSION SYSTEMS

Five propulsion alternatives were evaluated. Although the alternatives allow different cargo capacities due to variations in the engine room space demand, all options were calculated with a cargo capacity of 145,000 m³. Including the different cargo capacities would lead to an unrealistic comparison of the options to increased payload. In reality, a ship with a lesser capacity could be lengthened for a marginal price increase in order to achieve a cargo capacity equal to those designs with smaller engine room space demands.

The following options were compared:

"Benchmark" ship: steam propulsion using natural BOG and HFO for propulsion

- Slow speed diesel with BOG reliquefaction
- Diesel-electric completely fired by LNG (natural BOG and forced BOG)
- Diesel-electric fired by natural BOG and additional MDO
- Diesel-electric HFO fired with BOG reliquefaction

The options were calculated for 3 different trades:

- **Arabian Gulf to Boston**
  345 sea days, 20 port days, 36 sailing days
- **Trans-Atlantic**
  328 sea days, 37 port days, 18 sailing days
- **Trans-Caribbean**
  279 sea days, 86 port days, 6,5 sailing days

The economic assumptions are as follows:
"Benchmark" ship contract price: 165 M US $

The costs for different propulsion systems as shown earlier were taken into account

Financing over 20 years at 7,5% interest rate
BOG-reliquefaction system (redundant) – 6 M US $ extra investment and 3,500 kW extra power
Additional maintenance / lubrication cost for DE and slow speed diesel considered
The costs' difference of the various propulsions systems as shown in table 2 were accounted for.

Further economic basis were:

Efficiencies:
Steam: 0.30
Diesel-electric: 0.41 (0.43*)
2-stroke-Diesel: 0.48

Fuel Price:
HFO: 135 USD/t
MDO: 210 USD/t
LNG (FOB) 104 USD/t (2USD/mmbtu)
LNG (CIF) 156 USD/t (3USD/mmbtu)

Lower heating values:
HFO: 40,4 MJ/kg
MDO: 41,8 MJ/kg
LNG: 49,2 MJ/kg *) in gas mode

The fuel prices used are initial values. In order to consider increasing future fuel prices we assumed that the HFO and MDO prices increase in linear fashion to the LNG CIF price. The LNG FOB price was assumed to increase by only 50% of the CIF price increase.

10.3 RESULTS

Figure shows fuel costs as a percentage compared to the "benchmark" ship, which represents 100%. The fuel costs are shown for current fuel prices for the Gulf to Boston trade. Although the slow speed diesel with BOG reliquefaction has the best efficiency, it is evident from the graph that the propulsion options burning LNG have greater cost savings. The higher heat values and lower fuel prices of the LNG overcompensate the slightly lower efficiency.