ME-GI Dual Fuel
MAN B&W Engines
A Technical, Operational and Cost-effective Solution for Ships Fuelled by Gas
ME-GI Dual Fuel MAN B&W Engines

Abstract
This paper describes the latest developments in ME-GI dual fuel MAN B&W two-stroke engines and associated fuel supply systems.

The discussion and interest in lowering CO₂, NOₓ, SOₓ and particulate emissions have increased operators’ and shipowners’ interest in investigating future fuel alternatives. The ME-GI engine and the ME-LGI variant offer the opportunity of utilising alternative fuels such as LNG, LPG and MeOH. Recently, MeOH has been given quite a lot of attention from Swedish owners as one of the potential new fuels of the future because of its low price, lack of sulphur, it is easy to store on board, and a distribution system can easily be established. Furthermore, MeOH can be produced from several sources, such as natural gas, coal and from a variety of biomass.

The recent trend indicates that gas applications will be installed not only on LNG carriers, but also on LPG carriers, RoRo, tankers and container vessels, i.e. in principle all types of vessels.

Therefore, this paper not only describes gas fuel supply containment system solutions for LNG carriers, but also for other vessel types.

The different gas supply systems and techniques available on the market will be discussed in this paper. In principle, there are three different solutions for combining the gas supply system with the MAN B&W two-stroke ME-GI engine. The three solutions are shown below in Fig. 1.

Furthermore, we will explain how ME-GI engines can be installed on new ships or retrofitted on vessels already in service, and how to install gas supply systems on new or retrofitted ME-GI engines.

Introduction
Future fuels for ships is a subject under much discussion these days. It seems that the decision to invest in dual-fuelled vessels will be based primarily on the owners’ expectations to the future development in gas and fuel oil prices in combination with the emission control regulations. LNG safety regulations covering the delivery process are being developed, and several LNG bunkering terminals, mainly in the Baltic region, are being prepared. The locations of the LNG terminals in the Mediterranean Sea, in Singapore, the USA and in the Far East are also under discussion. So it seems that LNG as a fuel soon will become a reality worldwide.

For LNG carriers, the supply of LNG is a lot easier, since the LNG supply is already on board, and there is a long tradition for handling the LNG in a safe manner. For other ship types, rules and...
procedures for handling LNG onboard are under development, where experience from LNG operation in Norway seems to set a new standard.

MAN Diesel & Turbo (MDT) has performed a full scale test on the 4T50ME-Gi research engine in Copenhagen. This was done in order to demonstrate that the engine was able to fulfil Tier II and, later on, Tier III, in combination with the MDT developed EGR system. Another important purpose was to demonstrate that the engine can operate on high-pressure gas delivered from a fuel gas supply system comprising an LNG pump and a vaporizer. In February 2010, MAN Diesel & Turbo signed a development agreement with Korea’s Daewoo Shipbuilding & Marine Engineering Co., Ltd. (DSME) to jointly develop and exploit the adaptation of DSME’s high-pressure cryogenic gas-supply system for integration with the ME-Gi test engine.

However, different applications can call for different gas supply systems, and a number of projects have shown that operators and shipowners demand alternative solutions. Therefore, MDT aims to have a number of several different gas supply systems prepared, tested and available. MDT is therefore in close cooperation with other gas supply manufacturers such as Burckhardt Compression, TGE, Cryostar, HHI and Hamworthy. MDT has already scheduled new joint tests with some of these manufactures at different locations.

MAN Diesel & Turbo, and others, have shown that dual fuel engines can be more than just an economically sound choice for LNG carriers, VLCC and container vessels. Dual fuel engines are also safe, reliable and environmentally desirable, as a result of the experience obtained over many years from two-stroke diesel engines for the marine market for single as well as twin-propeller vessels in all types of commercial application.

More specifically for LNG carriers, the type of optimum gas supply system seems to depend on the type of trade of the LNG carrier, e.g. operation as a carrier train between two destinations, or spot market trading.

In January 2011, 90 MAN B&W two-stroke S70ME-C engines were delivered for 45 LNG carriers for the Qatar gas project. Another eight engines are on order also for LNG carriers, and have been prepared for a later GI conversion. All these engines are, however, ordered for operation on liquid fuels, i.e. HFO, MDO, and MGO as are more than 17,000 MC/ME type engines worldwide for different marine market applications.

The technology for a gas driven two-stroke ME-Gi engine is available and ready to install. Many projects involving the ME-Gi are being investigated at the moment. The system for handling of the boil-off gas can be combined with the engine’s gas supply system in many different ways, thereby offering many possibilities, especially for LNG carriers. But basically two different solutions are available for LNG carriers. Figs. 2 and 3 illustrate the two different system configurations. One system where the a piston compressor feeds the ME-Gi with high pressure fuel gas, and one system where a LNG pump and vaporizer are feeding the ME-Gi with high pressure gas. The two systems are offered in many different configurations, and from different manufactures. This paper describes the different possibilities.

Since 2004, MDT has worked with Burckhardt Compression, who developed and designed the ME-Gi gas supply system in detail using the Laby

![Fig. 2: ME-Gi engine with LNG pump supply system (reliquefaction unit not shown)](image-url)
GI compressor. In 2009, Burckhardt Compression got the first order for a Laby-GI compressor, a full scale demonstration test was done and quite recently the Laby-GI was successfully installed on an FSRU and handled over to the owner. During this work we have acknowledged how important it is to enter a new market with a manufacturer who also places safety, reliability and customer satisfaction high on the agenda for design and production of their components.

Hamworthy and MDT have worked closely on a number of different projects over the years, especially on the reliquefaction side. Today, Hamworthy offer gas supply systems using either the Laby-GI compressor or a system based on the LNG pump solution. Hamworthy also offers gas supply systems to owners interested in using LPG as fuel.

MDT has also had a long cooperation with Cryostar. Cryostar has been very successful in the cryogenic business for decades, where their Cryogenic pump system has been used and installed on land-based production facilities. Already back in 2006, Cryostar and MDT invented and developed the high-pressure gas supply system comprising an LNG pump and a vaporizer. In 2009, Cryostar did a demonstration of their ME-GI gas supply system on their facilities in France.

TGE and MDT have worked together for a relative short period, but in this short time, TGE has demonstrated that they have extensive knowledge about cryogenic gasses, and that they have a detailed understanding of all safety aspects related to using cryogenic gasses. TGE offers both a reliquefaction plant combined with the Laby-GI compressor, and a gas supply system for LNG fuelled ships based on the LNG pump technology. TGE has also developed gas supply systems for owners interested in using LPG.

HHI and Mitsui is part of our licensee family, and both licensees have recently announced that they are preparing their test beds for building of ME-GI engines in the future. Gas installations are being prepared on their test bed facilities, followed by full-scale installation and testing of an ME-GI at end-2012 and beginning of 2013. In this connection, HHI have developed their own gas supply system design, which they also offer to other shipyards. Mitsui will use a gas supply system developed by MHI for their gas test facilities.

MDT has also had a long cooperation with Cryostar. Cryostar has been very successful in the cryogenic business for decades, where their Cryogenic pump system has been used and installed on land-based production facilities. Already back in 2006, Cryostar and MDT invented and developed the high-pressure gas supply system comprising an LNG pump and a vaporizer. In 2009, Cryostar did a demonstration of their ME-GI gas supply system on their facilities in France.

TGE and MDT have worked together for a relative short period, but in this short time, TGE has demonstrated that they have extensive knowledge about cryogenic gasses, and that they have a detailed understanding of all safety aspects related to using cryogenic gasses. TGE offers both a reliquefaction plant combined with the Laby-GI compressor, and a gas supply system for LNG fuelled ships based on the LNG pump technology. TGE has also developed gas supply systems for owners interested in using LPG.

HHI and Mitsui is part of our licensee family, and both licensees have recently announced that they are preparing their test beds for building of ME-GI engines in the future. Gas installations are being prepared on their test bed facilities, followed by full-scale installation and testing of an ME-GI at end-2012 and beginning of 2013. In this connection, HHI have developed their own gas supply system design, which they also offer to other shipyards. Mitsui will use a gas supply system developed by MHI for their gas test facilities.
**ME-GI Concept**

The MC/ME engine family has been on the market since 1982. The engines have been in service on almost any type of marine application on container vessels, tankers of all sizes, bulk carriers, car carriers, RoRo and general cargo vessels.

There are many good reasons for choosing the two-stroke direct-coupled MC/ME engine types, e.g., high thermal efficiency, reliability, availability and safety, and the fact that it is a simple and robust solution that offers no load response reduction and no methane slip when operating on fuel gas.

The MC/ME engine is a well-proven product in the industry. The GI (Gas Injection) solution was developed in parallel and was finished for testing in the early 1990s. In 1994, the first GI engine, a 12K80MC-GI-S, was put into service on a power plant at Chiba, Tokyo, Japan. The Chiba engine has operated as a peak load plant for almost 20,000 hours on high-pressure gas. In 2003 the engine was converted to kerosene operation due to the prices on the gas fuel.

At the same time, in 1994, all major classification societies approved the GI concept for stationary and marine applications.

Technically, there is only little difference between fuel and gas burning engines, but the GI engine provides an optimal fuel flexibility. Fig. 4 shows the components which need to be modified and added on the engine to allow it to operate on gas.

The gas supply line is designed with ventilated double-wall piping including HC sensors for safety shutdown. For control of the gas engine, the GI control and safety system is an add-on system to the well-proven ME control system.

Apart from these systems on the engine, the engine and auxiliaries will comprise some new units. The most important ones, apart from the gas supply system, are listed below.

The new units are:

- Ventilation system for venting the space between the inner and outer pipe wall of the double-wall piping
- Sealing oil system, delivering sealing oil to the gas valves separating control oil and gas. This system is fully integrated on the engine, and the shipyard no longer needs to consider this installation.
- Inert gas system that enables purging of the gas system on the engine with inert gas.
- The GI system also includes:
  - Control and safety system, comprising a hydrocarbon analyser for checking the hydrocarbon content of the air in the double-wall gas pipes.

The GI control and safety system is designed to fail to safe condition. All failures detected during gas fuel running, including failures of the control system itself, will result in a gas fuel stop and a change-over to HFO fuel operation. Blow-out and gas-freeing purging of the high-pressure gas pipes and of the...
complete gas supply system follows. The change-over to fuel oil mode is always done without any power loss on the engine. Recent tests have shown that a normal gas stop takes place completely bumpless, i.e. it is simply not possible to hear which type of fuel is being burned.

The high-pressure gas supply flows through the main “chain” pipe which connects each cylinder’s gas valve block and accumulator. This “chain” pipe design performs two important tasks:

- They separate each cylinder unit from the rest in terms of gas dynamics, utilising the well-proven design philosophy of the ME engine’s fuel oil system.

- They act as flexible connections between the stiff main pipe system and the engine structure, safeguarding against extra stresses in the main and branch pipes caused by the inevitable differences in thermal expansion of the gas pipe system and the engine structure.

The buffer tank, containing about 20 times the injection amount per stroke at MCR, also performs two important tasks:

- It supplies the gas amount for injection at a slight, but predetermined, pressure drop.

- It forms an important part of the safety system.

Because the gas supply piping is of the common rail design, the gas injection valve must be controlled by an auxiliary control oil system. This, in principle, consists of the ME hydraulic control oil system and an ELGI & ELWI (electronic gas injection) valve system, supplying high-pressure control oil to the gas injection valve, thereby controlling the timing and opening of the gas valve.

**ME-GI injection system**

Dual fuel operation requires the injection of both pilot fuel and gas fuel into the combustion chamber.

Different types of valves are used for this purpose. Two are fitted for gas injection and two for pilot fuel. The auxiliary medium required for both fuel and gas operation is as follows:

- High-pressure gas supply
- Fuel oil supply (pilot oil)
- Control oil supply for actuation of gas injection valves
- Sealing oil supply.

The gas injection valve design is shown in Fig. 5. This valve complies with traditional design principles of the compact design. Gas is admitted to the gas injection valve through bores in the cylinder cover. To prevent a gas leakage between the cylinder cover/gas injection valve and the valve housing/spindle guide, sealing rings made of temperature and gas resistant material have been installed. Any gas leakage through the gas sealing rings will be led through bores in the gas injection valve.

![Fig. 5: Gas injection valve – ME-GI engine](image-url)
to the space between the inner and the outer shield pipe of the double-wall gas piping system, where the leakage will be detected by HC sensors.

The gas acts continuously on the valve spindle at a max. pressure of about 300 bar. To prevent gas from entering the control oil actuation system via the clearance around the spindle, the spindle is sealed by sealing oil at a pressure higher than the gas pressure (25-50 bar higher).

The pilot oil valve is a standard ME fuel oil valve without any changes, except for the nozzle. The fuel oil pressure is constantly monitored by the GI safety system which will detect any malfunction of the valve. Both HFO, MGO and MDO can be used as pilot oil.

The oil valve design allows operation solely on fuel oil up to MCR. The gas engine can be run on fuel oil at 100% load at any time, without stopping the engine. For prolonged operation on fuel oil, it is recommended to change the nozzles and gain an increase in efficiency of around 1% when running at full engine load.

As can be seen in Fig. 6 (GI injection system), the ME-GI injection system consists of two fuel oil valves, two fuel gas valves, ELGI for opening and closing of the fuel gas valves and a FIVA (fuel injection valve actuator) valve to control the injected fuel oil profile via the fuel oil valve, and an ELWI valve to control the position of the window valve as an extra safety feature to prevent gas leakages and, thereby, ensuring a double-valve block towards the combustions chamber. Furthermore, it consists of the conventional fuel oil pressure booster, which supplies pilot oil in the dual fuel operation mode.

Safety features
Under normal operation, where no malfunctioning of the fuel oil valve is found, the fuel gas valve is opened at the correct crank angle position, and gas is injected. The gas is supplied directly into an ongoing combustion. Consequently, the risk of having unburnt gas that might slip past the piston rings and into the scavenge air receiver is considered to be unlikely. Monitoring the scavenge air receiver pressure, and combustion condition safeguards against such a situation.

The purpose is to monitor at an early stage if any gas leaks occur across the gas injection valves. The window valve has a double safety function, securing that gas injection in the combustion chamber, is only possible at the correct injection timing. In the event of a gas failure, it can also block the gas from entering the combustion chamber, thereby ensuring that only a very small amount of gas will enter.

The pressure sensor is located between the window valve and the gas injection valve. The small gas volume in the cylinder cover on each cylinder will reveal the gas pressure during one cycle. By this system, any abnormal gas flow will be detected immediately, whether due to seized gas injection valves, a leaking gas valve or a blocked gas valves. The gas supply will be discontinued and the gas lines purged with inert gas. Also in this event, the engine will continue running on fuel oil only without any power loss.

Furthermore, the combustions pressures are constantly being monitored.

![Fig. 6: ME-GI injection system](image-url)
In the event of too high a combustion pressure, the gas mode is stopped, and the engine returns to burning fuel oil only.

**High-pressure double-wall piping**

A common rail (constant pressure) gas supply system is to be fitted for high-pressure gas distribution to each valve block. Gas pipes are designed with double walls, with the outer shielding pipe designed so as to prevent gas outflow to the machinery spaces in the event of rupture or a leak in the inner gas pipe. The intervening space, including also the space around valves, flanges, etc., is equipped with separate mechanical ventilation with a capacity of approx. 30 air changes per hour. The pressure in the intervening space is below that of the engine room with the (extractor) fan motors placed outside the ventilation ducts. The ventilation inlet air is taken from a non-hazardous area.

Gas pipes are arranged in such a way that air is sucked into the double-wall piping system from around the pipe inlet, and further on to the individual gas valve control blocks, back to the chain supply pipe and via the suction blower into the atmosphere, see Figs. 7 and 8, and Appendix I.

Ventilation air is exhausted to a fire-safe place. The double-wall piping system is designed so that every part is ventilated. All joints connected with sealings to a high-pressure gas volume are ventilated. Any gas leakage will therefore be led to the ventilated part of the double-wall piping system and detected by the HC sensors.

The gas pipes on the engine are designed for 50% higher pressure than the normal working pressure, and are supported so as to avoid mechanical vibrations. Furthermore, the gas pipes are shielded against heavy items falling down, and on the engine side they are placed below the gas valve block in a chain pipe design. The pipes have been pressure tested at 1.5 times the working pressure. The design is to be all-welded, as far as practicable possible, using a conical metal-to-metal sealing. Flange connections are only used to the extent necessary for servicing purposes.

The “chain” pipe design to the individual cylinders is designed with adequate flexibility to cope with the thermal expansion of the engine from cold to hot condition. The gas pipe system is also designed so as to avoid excessive gas pressure fluctuations during operation.
For the purpose of purging the system after gas use, the gas pipes are connected to an inert gas system with an inert gas pressure of 4-8 bar. In the event of a gas failure, the high-pressure pipe system is depressurised and, subsequently, purged automatically. During a normal gas stop, the automatic purging will be started after a period of up to 30 min. Time is therefore available for a quick restart in gas mode.

**Maintenance of LNG carriers equipped with ME-GI system**

Gas transportation contracts are typically long term and sailing schedules are tight. Missing a schedule can have far-reaching consequences. Our usual emphasis on maintenance will guarantee a high availability and smooth operation, and every effort is made to avoid any performance risk with an ME-GI engine as the prime mover.

The proper maintenance planning is essential to satisfy the vessel’s operating needs.

Quite a significant number of contracts have been signed for LNG carriers. These new carriers feature efficient HFO burning MAN B&W low speed two-stroke diesel engines, in combination with reliquefaction and MAN GenSets.

Not only has MAN Diesel & Turbo played a very active role in the development, design and configuration of the propulsion arrangement for the new generation of LNG vessels, but is also considering maintenance.

Accordingly, MAN Diesel & Turbo is currently building a service centre in Ras Laffan where experienced service engineers will be available on a 24-hour basis. Key spare part components will be on stock to ensure a high reliability and availability at all times for these LNG carriers. The service centre will be located in the region close to the loading terminals for these LNG carriers, in support of the operation and maintenance of the engine arrangements for vessels.

This service model can also be offered to new LNG carrier trains and other gas-fuelled ships that intend to use the ME-GI as propulsion for their ship.

Also with the new ME-GI engine components, operation and maintenance is a straightforward process for the skilled and experienced engine crew, at least if the maintenance jobs are planned, prepared and controlled. In general, superintendents and engine crews are well educated, skilled, and dedicated professionals. MAN Diesel & Turbo is constantly offering new education programmes to marine engineers to keep them updated with the newest information about maintenance and technology.

**Engine operating modes**

One of the advantages of the ME-GI engine is its fuel flexibility, which is a major benefit for especially for operators of LNG carriers. Burning the boil-off gas with a variation in the heat value is perfect for the diesel working principle. At the start of a laden voyage, the natural boil-off gas holds a large amount of nitrogen, and the heat value is low. If boil-off gas is forced, it can consist of both ethane and propane, and the heat value could be high. A two-stroke, high-pressure gas injection engine can burn those different fuels without seeing a drop in the thermal efficiency of the engine. The control concept comprises three different fuel modes (see Fig. 9):

- fuel-oil-only mode
- minimum-fuel mode
- mixed gas mode

The fuel-oil-only mode is well known from the ME engine. Operating the engine in this mode can only be done on fuel oil. In this mode, the engine is considered “gas safe”. If a failure in the gas system occurs it will result in a gas shutdown and a return to the fuel-oil-only mode.

The minimum-fuel mode is developed for gas operation, and it can only be started manually by an operator on the Gas Main Operating Panel in the control room. In this mode, the control system will allow any ratio between fuel oil and gas fuel, with a minimum preset amount of fuel oil to be used.
The preset minimum amount of fuel oil (pilot oil) to be used is max. 5% at 100% engine load. At lower engine loads, the pilot fuel amount is reduced to approx. 2% at 10% engine load. Both heavy fuel oil, marine diesel oil and marine gas oil can be used as pilot oil. When the operator has started gas mode operation, the engine will stay in gas mode until the operator decides to stop gas operation. Tests have shown that a pilot oil amount down to 1.5% is possible, however, the engine will then have some load limitation in the fuel oil mode.

The mixed gas mode is offered to give the operator full fuel flexibility and the option to inject a fixed amount of gas fuel. The ME control system will add up with fuel oil until the required load for operation is reached.

Gas fuels correspond to low-sulphur fuels, and for this type of fuel we recommend the cylinder lube oil TBN40 to be used. Excellent cylinder condition with this lube oil was achieved from the gas engine on the Chiba power plant. A heavy fuel oil with a high sulphur content requires the cylinder lube oil TBN 70. Shipowners intending to run their engine on high-sulphur fuels for longer periods of time are recommended to install two lube oil tanks. When changing to minimum-fuel mode, the lube oil should be changed as well.
Emission control – ME-GI engines

Compared with HFO operation, gas gives a cleaner exhaust. Having very low or no sulphur, SO\textsubscript{x} sulphur oxides are negligible in the exhaust gas. Particulates will be reduced considerably as well as the emission of NO\textsubscript{x} and CO\textsubscript{2}.

Table I lists an arbitrary comparison of emissions from an HFO burning and a gas burning 50-bore ME-GI engine.

All typical NO\textsubscript{x} reduction techniques can be used on an ME-GI engine, except water emulsification. In the ultimate event, an SCR catalyst can cut NO\textsubscript{x} emissions by up to 98%, as was experienced on the stationary 12K80MC-GI in Chiba, Japan. But the EGR system is also an option. With the EGR system in combination with gas operation, the engine can easily fulfil Tier III. The NO\textsubscript{x} level when operating on gas is 15-20% lower compared with HFO operation, and only around 30% of the exhaust gas needs to be bypassed across the EGR, this will lead to a higher efficiency on gas compared with HFO operation in Tier III zones. Cleaning of the EGR scrubber water is another issue that becomes a lot easier when operating the engine on gas, because exhaust from gas contains limited particulate matter and no SO\textsubscript{x}.

On the marine market, five vessels with MAN B&W two-stroke engines are in operation with SCR, and this is also the case on 15 power stations. All in the range of reducing NO\textsubscript{x} by 94-98%.

---

**Comparison of emissions from an HFO burning and a gas burning 70ME type engine**

<table>
<thead>
<tr>
<th></th>
<th>Estimated emissions 6S70ME-C</th>
<th>Estimated emissions 6S70ME-GI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load 100% g/kWh</td>
<td>Load 100% g/kWh</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>577</td>
<td>CO\textsubscript{2}</td>
</tr>
<tr>
<td>O2 (%)</td>
<td>1359</td>
<td>O2 (%)</td>
</tr>
<tr>
<td>CO</td>
<td>0.64</td>
<td>CO</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>11.58</td>
<td>NO\textsubscript{x}</td>
</tr>
<tr>
<td>HC</td>
<td>0.19</td>
<td>HC</td>
</tr>
<tr>
<td>SO\textsubscript{x}</td>
<td>10.96</td>
<td>SO\textsubscript{x}</td>
</tr>
<tr>
<td>PM (mg/m3)</td>
<td>0.54</td>
<td>PM (mg/m3)</td>
</tr>
</tbody>
</table>

*Table 1*
Gas Supply Systems from Cryostar

Recent developments in LNG carrier propulsion and cargo handling include dual fuel diesel-electric systems (capable of burning BOG, MDO and HFO), low speed diesel engines (burning HFO) linked to reliquefaction plants and, more recently, the direct gas injection engines (ME-GI), pioneered by MAN Diesel & Turbo. The ME-GI type engines require fuel gas supplied at a pressure of 300 bar.

Overall vessel configuration
Irrespective of the type of propulsion, a primary requirement on board any LNG carrier is the tank pressure control. For vessels with membrane type containment systems, the tolerances are relatively small to ensure a safe operation of the tanks.

Cryostar’s solution for ME-GI engines
Cryostar performed a study of the alternatives to ME-GI engine applications, based on a 170,000 m3 LNGC hull configuration.

The study took account of the thermal power required to operate the system. It was noted that most vessels are designed to suit the conditions for 100% MCR operation. It is clear that if the vessel is operated at low load, the power consumption drops significantly. With the ME-GI engines being more fuel efficient than both steam and DFDE propulsion, the issue of surplus BOG becomes significant.

With the 300-bar fuel gas supply pressure, a centrifugal compressor is uneconomical. It makes sense to use a positive displacement pump to increase the pressure to 300 bar. By comparison, the power required in liquid state is almost negligible (less than 1/6th). This led Cryostar to offer a high-pressure liquid pump solution, which is then fed by condensate from a reliquefaction plant, returning any surplus condensate to the cargo tanks.

Cryostar’s EcoRel reliquefaction plant, together with its HP pump and vaporizer system, provides a well-balanced solution.

EcoRel reliquefaction plant configuration
Cryostar’s proven EcoRel reliquefaction plant consists of a nitrogen-filled refrigeration loop with a compander as the main component. This machine combines three compressor stages and a single expander stage on a common gearbox. This configuration was a Cryostar world-first, and it was utilised on a machine delivered as early as 1996. The nitrogen loop also incorporates a counter-current heat exchanger, which improves the efficiency of the N2 loop.

After leaving the expander, the cold nitrogen enters the BOG condenser, where the BOG is condensed.

The BOG loop receives gas from the tanks, compresses it in a BOG compressor with intercooling, and passes it through a desuperheater that precedes the BOG condenser.

This desuperheater is a key component in the EcoRel system. It protects the delicate plate-fin construction of the BOG condenser from damage due to rapid temperature changes. This unit is also a major contributor to the fast start-up times achieved by the system. See also Fig. 10.

The high-pressure pump and vaporizer system
The skid-mounted HP pump is driven by either a gearbox or a simple belt-drive. The low-friction crank drive is connected to one or more pumping chambers where multiple seals ensure efficient pumping of the cryogenic liquid to these high-pressures. Pressures of over 400 bar are common for this pump design, see Fig. 11. The pump-
ing chamber is vacuum insulated to reduce the heat inleak and promote constant priming. Vapour return lines allow simple return of any vapour to the supply vessel. Starting is simple, with protection interlocks to ensure safe operation. A wide flow range is possible by use of a variable speed drive and pressure is achieved promptly, allowing the system to easily follow engine load requirements.

A typical skid is fitted with three pumping chambers to smooth out the flow. In addition, a pulsation damper is fitted to avoid any issues with downstream pulsation in the fuel gas lines. Simple control loops are used to maintain a constant fuel gas pressure irrespective of the flow.

Integration of reliquefaction and fuel gas supply
Cryostar has designed a simple interface between the two systems to allow simple operation of the fuel gas supply, either by reliquefaction or independently if required. The liquid supply to the HP pump is from the flash drum where the condensate is separated after the BOG condenser. This vessel acts as a holding vessel, which allows condensate to be led to the engines or returned to the tank. In addition, if the reliquefaction plant is not operating, then liquid may be pumped from the cargo tanks to provide LNG for fuel. In this way, complete versatility is maintained.

The fuel gas supply system consists of the high-pressure liquid pump together with a vaporizer system to ensure that the gas enters the engines at an acceptable temperature, see Fig. 12.

Experience base
Cryostar has over 30 years of experience with reciprocating pumps, and the reference list comprises many thousands in daily operation worldwide. The vast majority of these cryogenic pumps operate in conjunction with vaporizers for high-pressure gas filling operations. This experience with the supply and control of high-pressure gas means that the technology is well established and suitable for this application.

In addition, Cryostar EcoRel reliquefaction plants were specified by Qatargas for the entire fleet of Q-Max vessels.

Special benefits
Below are listed special cases where HP pump and EcoRel reliquefaction plants offer significant benefits thanks to their ability to adequately handle surplus BOG without burning it in the GCU (gas combustion unit):

- Vessels likely to be laden and idle for any length of time (such as lying in wait before a Suez canal transit)
- Long periods of slow speed operation
- Spot trading if cargo is to be maintained for extended periods
- Particularly long trading routes, where maximum cargo delivery is paramount
- Either BOG or liquid fuel can be used whenever economically advantageous
- Thermal power consumption is lower for a combination of HP pump and EcoRel
- The system offers full fuel flexibility to use the cheapest fuel available – either gas or HFO.
Cryostar system philosophy

Recent developments in LNG carrier propulsion and cargo handling include low speed diesel engines (burning HFO) linked to reliquefaction plants and, more recently, the direct gas injection engines (ME-GI), pioneered by MAN Diesel & Turbo. The ME-Gi type engines require fuel gas supplied at a pressure of 300 bar.

Overall vessel configuration

The typical LNG carrier with ME-GI propulsion can be fitted with a reliquefaction plant to:

- control the tank pressure on short or long voyages
- control the tank pressure during idling if spot trading

A by-product from the reliquefaction plant is liquid condensate, which can either be returned to the tank or consumed as fuel in gaseous form.

To be able to burn the condensate as fuel on an ME-Gi engine, the pressure must be increased considerably and the temperature must be controlled within a certain range.

A typical equipment arrangement is shown in Fig. 12. As it is more efficient to increase the pressure by use of a positive displacement pump, rather than vaporize the LNG and compress the gas in a multi-stage compressor, Cryostar proposes a high-pressure pump followed by a vaporizer to convert the liquid to a supercritical fluid suitable for injection into the engine. This system of liquid compression and vaporization has been used for decades in the industrial gas sector with colder and more volatile compounds than LNG. Typically, oxygen cylinders for oxy-acetylene cutting and medical gases are filled using identical technology. Thousands of operating references exist with Cryostar cryogenic pumps.

The application of this technology for fuel gas supply is not more stringent than any of these other uses.

Fuel gas pressure control

Suitable measures are required to keep the pressure within tight limits so as to avoid undesirable pulsation. As the pump is a reciprocating unit, there are unavoidable pulsations due to each delivery stroke. In order to smoothen (and almost eliminate) these pulsations, a damper is fitted to each pump skid to absorb these fluctuations. This, together with the gas volume downstream the vaporizer, results in almost negligible changes to the pressure in steady-state operations.

The pressure in the system is a function of the liquid flow at the pump discharge and the consumption by the engine/s. Therefore, the primary pressure control is done by adjusting the pump speed to meet the consumption of the engines. Since the engine cannot operate with pressures below 150 bar, the initial fuel gas pressure should be attained before changing over to gas.

Because the pump is controlled by a variable frequency drive and the action of the pump is immediate, it will take very short time to pressurise the system by filling the downstream volume with fuel gas at the correct pressure. If this pressure is achieved and if engine consumption is low, excess fuel gas will be returned to the tank by a pressure control valve.

Fig. 12: Combined reliquefaction plant and HP LNP pump supply system delivering high pressure fuel gas to the ME-Gi engine.
The drawing in Fig. 13 shows the liquid feed from the flash drum of the reliquefaction plant. Surplus condensate is returned to the tanks and any shortfall of liquid can be made-up using an intermittent supply from the spray pumps to maintain the necessary buffer level in the flash drum.

**System safety**

Sequences already exist for the cool down, degassing and starting of the reciprocating pump. Likewise for shut-down, depressurisation sequences are also required. These can be automated, as is done on some land-based applications.

According to the pipework layout, purging sequences will be required before maintenance. These will be developed according to the actual installation.

---

**BOG Reliquefaction System from Hamworthy**

The principle of the boil-off gas compression in the Mark III version will be different compared with previous generations of LNG reliquefaction systems. Boil-off gas (BOG) is evacuated from the LNG tanks by a three-stage centrifugal type BOG compressor with subsequent cooling after each stage, see Fig. 14.

The BOG with vapour header temperature is preheated up to near ambient temperature in a heat exchanger upstream the BOG compressor. This allows application of conventional compressors, since there is no requirement for cryogenic materials. This cooler configuration ensures that the heat from the compression work can be water-cooled in the intermediate stage – and in the aftercoolers. The BOG is preheated in a heat exchanger utilising the high-pressure nitrogen stream taken downstream the nitrogen compander after the cooler. A patent is pending for the Mark III system with preheater and ambient BOG compression.

At this pressure, vapour is cooled to about $-160°C$ in a cryogenic platefin heat exchanger downstream the BOG compressor. This ensures condensation of hydrocarbons to LNG.

A special feature of the Hamworthy reliquefaction process is that for LNG with a high content of nitrogen, not all the nitrogen is condensed at $-160°C$.

Nitrogen gas is compressed in a compander unit (3-stage centrifugal compressor and single expander on a common gearbox).

After the third-stage cooler, the stream is split into two different streams. One stream is used to preheat the BOG in a separate heat exchanger (preheater), and the other is led to the “warm” part of the cryogenic heat exchanger. After heating the BOG, the two streams are mixed again and reintroduced into the cold box core. If the fuel gas supply system is integrated with the reliquefaction plant, a third nitrogen stream is taken out after the cooler.

In the cryogenic heat exchanger, the nitrogen is pre cooled and then expanded to almost compressor suction pressure. The gas leaves the expander at a temperature below $-160°C$ and is returned to the “cold” part of the cryogenic heat exchanger.

The cold nitrogen continues through the “warm” part of the cryogenic heat exchanger, see Figs. 14 and 15.
Fig. 14: Process description of LNG liquefaction system (Mark III, 3rd generation)

Fig. 15: Process integration between the LNG liquefaction system and fuel gas supply system for dual fuel ME-GI engine
LNG High-pressure liquid pump system

Condensate from the BOG re liquefaction system or LNG from the cargo tanks supplied with the cargo pumps is sent to the fuel gas supply system. This system consists of a booster pump, a high-pressure pump and a heater unit.

After pumping LNG to the pressure required, LNG above the supercritical pressure is heated in a heat exchanger (LNG vaporiser) to the temperature required. The high-pressure gas is then fed to the dual fuel engine, see Fig. 16. The discharge pressure of the high-pressure pump is 300 bar at 100% engine load.

The system is based on an evaporation of LNG at high-pressure with heat exchanging by means of an intermediate brine loop. Engine jacket water or steam is used as the heating medium. In order to use jacket water or steam from the engine room directly in the heat exchanging with LNG, a closed brine loop is used to heat the LNG. This prevents the risk of getting LNG in the engine room in case of an internal leakage in the vaporiser. The intermediate media is a “brine” mixture. If process water from the BOG compressors or compander is considered, direct heating should be considered to reduce the energy loss in the system. In that case, the process water loop will be considered an intermediate loop.

In the LNG vaporiser, cold duty is removed from the LNG while it is heated up to engine requirement. The cold duty is removed by a heating source and is not utilised. For this reason, Hamworthy has optimised the complete process to a BOG re liquefaction system and a gas supply system to reduce the overall power consumption.

The main objective is to utilise the cold duty taken out, before the LNG reaches the evaporator, and use it to cool the BOG re liquefaction system. This heat exchange is performed in a unit referred to as the optimiser, which operates in parallel to the cold box. This has the effect that part of the nitrogen, from the nitrogen cycle and at ambient condition, is cooled by heat exchanging with the pressurised LNG. This is all done in the optimiser. The nitrogen stream is cooled to about the inlet expander temperature, and is mixed with nitrogen from the cold box.

The optimiser can only be in operation when the BOG re liquefaction system is working and the engine is being fuelled with LNG. If the re liquefaction system is stopped or the optimiser is not heating the LNG sufficiently, the standalone vaporisation system will heat the gas sufficiently before entering the engine.

By installing the gas supply system in the cargo compressor room together with the BOG re liquefaction plant, makes a very compact installation.

Fig. 16: High-pressure gas supply system from Hamworthy, including 2 x LNG pumps and a vaporiser. Size 7 x 3 x 2m
Laby – GI Compressor from Burckhardt Compression

The ME-GI propulsion engine together with a compressor gas supply system will utilise the BOG (boil-off gas) coming from the ship storage tanks. The key component of the fuel gas supply is the Laby®-GI fuel gas compressor from Burckhardt Compression. The pressure range of 150-300 bar will cover the main operating range required by the ME-GI dual fuel engines from MAN Diesel & Turbo.

Design concept

Various design options have been evaluated during the last four years of compressor and system development. The concept described here is based on the installation of two Laby-GI fuel gas compressors each capable of handling 100% of the emerging BOG. Thereby, the diesel engines themselves will consume 50% each of the compressed gas. The main compressor will be operating continuously to ensure full redundancy and the second unit can be started manually in case of a malfunction. We will focus on this design in the following description. Other design options are explained in a later chapter.

There are many parameters influencing the design of an efficient fuel gas supply system. For example, the total amount of BOG is highly dependent on the ship operation cycle (laden or ballast voyage) and the tank pressure level. This may result in extreme operating conditions for the fuel gas compressor, from ultra cold to warm start-up temperatures. Other factors can be the gas composition, handling of forced or natural BOG (fBOG or nBOG), the simultaneous delivery of low-pressure gas to the gas combustion unit (GCU), Dual Fuel gensets, parallel reliquefaction of BOG and many more.

Laby®-GI key components

Handling of cryogenic natural gas with suction temperatures below ~160°C in the pressure range of 10 to 50 barg (1.0 to 5.0 MPa g) is a common application in many on and offshore LNG or LPG facilities worldwide. With its unique labyrinth sealing technology, the Laby-GI compressor design has demonstrated a performance that is second to none in this field.

The Laby-GI fuel gas compressor is designed for the same low suction temperatures as the Laby-GI. The only difference is the extension of the pressure range up to 300 bar. Therefore, the three oil-free labyrinth-sealed, low-pressure stages are complemented with two stages of piston ring sealing systems, comparable to the proven API 618 design. All five stages are combined in a vertical crank gear and form the six-crank Laby-GI fuel gas compressor. As a result of mass balancing, the compressor will be free from vibrations and moments, see Fig. 17.

The optimised piston sealing technology – a combination of labyrinth sealing and piston ring sealing of the five-stage compressor, results in ultralong lifetime of the sealing elements. Careful thermal design and material selection means that it is not necessary to precool the compressor or to heat the gas prior to startup. The rugged design in combination with the well-proven equipment

Fig. 17: Compressor cross-section
stands for longest meantime between overhaul (MTBO) for this and related applications.

Fuel gas compressor engineering

The engineering of the compressor plant is a very important issue when it comes to optimum performance and reliability. Static and dynamic mechanical analysis, analysis of thermal stress as well as pulsation and vibration issues of the compressor and related equipment such as gas piping, pulsation vessels, gas coolers, etc., are standard procedures when it comes to an evaluation by Burckhardt Compression.

Each compressor stage is followed by an intercooler to fully control the inlet temperature of the following stage. Fig. 18 shows a simplified P&I diagram of the compressor. Bypass valves are provided over stage one, from stages two to three, and from stage four to five. These valves will regulate the flow of the compressor according to the engine set pressure within the defined system limits. The entire plant layout is designed towards a zero vent philosophy. Any BOG in the compressor will be led fully controlled back to the cargo containment system.

Compressor safety

Safety relief valves are provided at the discharge of each compression stage to protect the cylinders and gas system against overpressure. Stage differential relief valves, where applicable, are installed to prevent compressor excessive loading.

Pressure and temperature instrumentation for each stage is provided to ensure adequate system monitoring alarm and shutdown. Emergency procedures allow a safe shutdown, isolation and venting of the compressor gas system.

The safety of the entire system has been proved by various HAZID/HAZOP studies performed by such shipyards as Daewoo Shipbuilding and Marine Engineering, Samsung Heavy Industries and Hyundai Heavy Industries, and by fleet operators like Nakilat, ExxonMobil, Shell, Chevron, BG and Conoco Philips and, furthermore, by certification societies like DNV, ABS and Lloyd’s Register. The results of these studies have been fully implemented in the control concept.

Control requirements for the fuel gas system

The primary function of the compressor control system is to ensure that the required discharge pressure is always available to match the demand of the main propulsion diesel engines. In doing so, the control system must adequately handle the gas supply variables, such as tank pressure, BOG rate

![Fig. 18: Simplified P&I compressor diagram](image)

Legend
- PCV01: Bypass control valve for ME-GI supply pressure and tank pressure
- PCV02: Side stream control valve to limit discharge pressure 1st stage (delivery to GCU and Reliquefaction)
- TCV01/02: Temperature control valve to limit suction temperature 2nd stage
- PCV03: Bypass control valve to limit discharge pressure 3rd stage
- PCV04: Bypass control valve to limit discharge pressure 5th stage

**P range:** 3.5 to 6.5 bar  
**T range:** -45 to +45 °C
(laden and ballast voyage), gas composition and gas suction temperature.

If the amount of nBOG decreases, the compressor must be operated on part load to ensure a stable tank pressure or fBOG must be added to the gas supply. If the amount of nBOG increases, resulting in a higher than acceptable tank pressure, the control system must act to send excess gas to the gas combustion unit (GCU).

The main control variable for compressor operation is the feed pressure to the ME-GI engine, which may be subject to controlled or instantaneous change. An adequate control system must be able to handle such events as part of the “normal” operating procedure. The required gas delivery pressure varies between 150 and 300 bar, depending on the engine load. The compressor must also be able to operate continuously in full recycle mode with 100% of delivered gas returned to the suction side of the compressor.

Power saving mode
Economic regulation of a multi-stage compressor is most efficiently executed using gas recycle around the first stage of compression. The ME-GI required set-pressure is therefore taken as control input directly to the compressor first stage bypass valve, which will open or close until the actual compressor discharge pressure is equal to the set-pressure. With this method of control, BOG delivery to the ME-GI is regulated without any direct measurement and control of the mass flow delivered. If none of the above control limits are active, the controller is able to regulate the mass flow in the range from 0 to 100%, see Fig. 19.

Simulation and test
The concept ME-GI engine and relevant propulsion components, including the entire fuel gas system, was successfully tested in a combined process simulation by Kongsberg Maritime.
Reliquefaction system and Laby-GI compressor integration

Burckhardt Compression and Hamworthy Gas Systems have developed a solution that integrates the Laby-GI compressor in the reliquefaction Mk III system from Hamworthy Gas Systems (see Fig. 20). The Laby-GI compressor will substitute the normal BOG low-duty compressor upstream the Mk III system. After the first or second stage, at 56 bar, the gas can be partly – or fully – diverted to the reliquefaction system. When the ME-GI engine is running in gas mode, the BOG is sent directly by the compressor to the engine, thereby bypassing the reliquefaction system. This bypassing of the reliquefaction system is expected during operation in ballast condition and when there is too little BOG for fuelling the ME-GI engine.

TGE’s Cascade Reliquefaction System

TGE’s cascade type reliquefaction system for LNG BOG on LNG carriers has been developed in cooperation with MAN Diesel & Turbo and Burckhardt with focus on high efficiency and, therefore, low operating costs. The goal is to reliquefy excess BOG which is not used for propulsion especially during times of low fuel consumption. Fig. 21 below shows a comparison between the existing plants of full reliquefaction with a high-pressure pump fuel gas system, excess gas reliquefaction with a nitrogen cycle and excess gas reliquefaction with using the cascade technology.

As described in the previous chapter the cascade technology is based on two refrigerant cycles. The BOG is liquefied against ethylene, which in turn is liquefied against propylene.

A unique design feature of the system is the integration of the ethylene compression into the BOG compressor. The first and the second stages are used for refrigerant (ethylene) compression, making use of the existing compressor stages.

The energy efficient mass flow control concept of the Laby®-GI has been adapted to the combined duty of ethylene and BOG compression. The balanced frame design guarantees with the possibility to operate the compressor in flow range 0-100% with any suction condition and supply pressure to consumers. The excellent capacity control of the screw compressors adds further comfort to the operability of the system.

The high efficiency and compact design further achieved by the use of a cold box, combining all streams of the cascade cycle.

The main advantages of a cascade reliquefaction system are:

- High efficiency of refrigerant due to phase transition
- High liquefaction pressure
- BOG and ethylene compression in one compressor
- Standard oil injected screw compressors for the propylene cycle.
The use of oil-lubricated screw compressors is part of the philosophy to use proven components to the benefit of the owner and operator. Being the world market leader in the supply of cargo plants for ethylene carriers, TGE has vast experience and know-how in the design and application of cascade liquefaction systems, which have been a standard technology on such carriers for decades, see Fig. 22. The upgrade of this technology for excess BOG liquefaction of large LNG carriers to provide an efficient and reliable solution has been a logical step.

Sub-conclusions

The market demands a highly reliable gas supply system with individual design flexibility. Sizing options such as 50%, 75% or 100% fuel gas system, based on the engine demand in combination with alternative liquefaction solution can easily be integrated into the Laby-GI design. This compressor is therefore the most adaptable solution for the ME-GI propulsion system when it comes to fuel flexibility.

High reliability and low maintenance add to keep lifecycle costs on a very low level. Preventive maintenance and service work can easily be done by the crew, as the Laby-GI compressor system is the simplest and non-complex fuel gas system available. The complete system is inhouse engineered and customised to fit the ME-GI propulsion system from MAN Diesel & Turbo. It is also the only gastight design on the market that can avoid gas losses and pollution. The possibility to retrofit the Laby®GI as a fully skidmounted unit (see Fig. 22) makes the system very interesting, not only to newbuilt carriers, but also for the existing fleet. The first Laby-GI compressor was installed on a floating storage and regasification unit (FSRU) in 2009.

Fig. 22: Cascade liquefaction plant for LNG carriers developed by TGE and Burckhardt Compression.
ME-LGI – use of LPG or Methanol “MeOH” as fuel

The ME-GI has mainly been considered for LNG carriers, but recent years’ fluctuation in energy prices and the evertighter requirements for lowering engine emissions have increased the interest for using gas as fuel on other ship types, and LPG as the fuel on LPG carriers and other ships types are also a possibility.

The high-pressure gas injection system used on the ME-LGI engine has the advantage of being insensitive to the gas composition as well as the variation in the gas composition. It is well known that the engine can burn lean gas and also gas containing higher hydrocarbons.

The LPG normally consists of higher hydrocarbons like propane and butane, and these can therefore be used as fuel without changing the engine’s performance in terms of speed, thermal efficiency and power output, while maintaining the same rating as for the fuel oil burning engine.

The basic ME engine series applies to the ME-LGI as well, and the new components and auxiliaries remain unchanged in scope when compared with the ME-GI engine type designed for NG (natural gas), see also the section on ME-GI engines for LNG carriers. Some design changes to auxiliaries and components are of course necessary, because the density of LPG fuel is higher than the density of NG. As a result of this difference, the LGI components can be designed much smaller, however, the LPG needs to be pressurised to a pressure of 550 bar instead of 300 bar for NG. This pressure is necessary to achieve a full atomisation of the liquid in the nozzles of the injection valves. In comparison, HFO, which has a slightly higher density, requires an injection pressure of 600-800 bar. The temperature has to be controlled as well, and the engine requires a temperature of approx. 35°C, see Fig. 23.

Hamworthy Gas System (HGS), and now also TGE, have participated in the development of a gas supply system for LPG carriers. Both HGS and TGE are a “natural” supplier of such a system, since they have a long experience in designing regiuefaction plants for LPG carriers. They both have detailed knowledge on this ship type.

On LPG carriers, the LPG is stored in cargo tanks. The cargo is normally owned by the shipowner, while the operator is responsible for the operation of the ship. Under these circumstances, both parties normally want to have a separation of the cargo and the fuel. MAN Diesel & Turbo therefore expects that it will probably be preferred to have an additional installation of an LPG fuel pressure tank on top of the deck, which is fully separated from the cargo. However, an LPG booster pump submerged in the LPG cargo tanks is of course the most feasible option in terms of installation cost.

The gas supply system developed, see Fig. 24, offers the possibility of using the fuel directly from the cargo or from the fuel tank on deck. If a fuel tank is installed, it is recommended to insulate the fuel tank and control the tempera-

![Figure 23: Example of supply pressures and temperatures](image)
ture and pressure in the tanks. From the fuel tank, the LPG is transported via a low temperature/low pressure pump, in which the normal temperature for propane in the cargo is around −42°C. After the low-pressure booster pump, the LPG is liquid and is heated or cooled to 20-25°C. Normal cooling water can be used for this purpose. Finally, the LPG is pressurised in a high-pressure pump to the required injection pressure of 550 bar. The amount of energy used by the pumps is quite small and corresponds to an approx. 0.5-% reduction in efficiency of the engine.

We have estimated the additional cost of including a gas supply system and the additional GI components on the engine, and we have found the price increase to be around 20-60% of the engine price, depending on engine size. The shipyard installation cost comes on top of this figure. However, propane/butane prices can fluctuate greatly depending on, i.e., unforeseen economic, political and climatic factors. With the gas option, it is possible to gain profit both at times where gas prices are low compared with HFO and also when the opposite is the case. For ships operating most of the time in ECA zones, LPG is a cheap alternative to MGO, since the price of LPG price has been seen to be around 20% lower than the price of MGO.

With the ME-LGi engine, the most cost-effective fuel operation solution can be chosen whenever there is a shift in the prices of HFO and LPG.

The comparison of emission levels shows that there are benefits in the full range when using LPG as fuel, i.e. a 17% reduction in CO₂, 12% reduction in NOx, 95% reduction in SO₂ and 37% reduction in particulates, see also Table II.

**Methanol as a fuel**

Methanol as a fuel for ships could become interesting in the future because MeOH does not contain any sulphur. For ships operating in IMO emission controlled areas (ECA), MeOH could be

---

**Table II**

<table>
<thead>
<tr>
<th></th>
<th>Estimated emissions HFO 3500 S.RW 1 6K50MC-C</th>
<th>Estimated emissions 8% pilot oil - 46% propane &amp; 46% butane 6S50ME-GI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load 100%</strong></td>
<td>CO₂ (g/kWh)</td>
<td>CO₂ (g/kWh)</td>
</tr>
<tr>
<td></td>
<td>O₂ (%)</td>
<td>O₂ (%)</td>
</tr>
<tr>
<td></td>
<td>CO (g/kWh)</td>
<td>CO (g/kWh)</td>
</tr>
<tr>
<td></td>
<td>NOx (g/kWh)</td>
<td>NOx (g/kWh)</td>
</tr>
<tr>
<td></td>
<td>HC (g/kWh)</td>
<td>HC (g/kWh)</td>
</tr>
<tr>
<td></td>
<td>SO₂ (g/kWh)</td>
<td>SO₂ (g/kWh)</td>
</tr>
<tr>
<td></td>
<td>PM (mg/m³)</td>
<td>PM (mg/m³)</td>
</tr>
<tr>
<td>Load 100%</td>
<td>556</td>
<td>469</td>
</tr>
<tr>
<td>O₂ (%)</td>
<td>1223</td>
<td>1255</td>
</tr>
<tr>
<td>CO</td>
<td>0.71</td>
<td>0.89</td>
</tr>
<tr>
<td>NOx</td>
<td>11.97</td>
<td>10.51</td>
</tr>
<tr>
<td>HC</td>
<td>0.28</td>
<td>0.57</td>
</tr>
<tr>
<td>SO₂</td>
<td>10.57</td>
<td>0.85</td>
</tr>
<tr>
<td>PM (mg/m³)</td>
<td>0.49</td>
<td>0.31</td>
</tr>
</tbody>
</table>

**Fig. 24: LPG gas supply system**
a feasible solution to meet the sulphur requirement. But there are also other issues that could increase the interest for new fuels. Already from 2013, IMO has decided to adopt the EEDI (Energy Efficiency Design Index) as a mandatory piece of information for ships built after January 2013. This could influence the engine market and technical solutions faster than first anticipated. Here, alternative fuels such as NG, LPG and MeOH could quickly become serious candidates to fuel oil as a means to reduce the EEDI. By nature, NG, LPG and MeOH generate less CO₂ emissions during combustion than fuel oils. MeOH is furthermore interesting because bio-

MeOH can be produced from a vast variety of biomasses and mixed with MeOH produced from fossil fuels. MeOH is an Otto fuel, which is characterised by having a low Cetane number, see Table III.

For LPG, the injection pressure has been found to 550 bar. For MeOH, this pressure has been estimated at max. 400 bar. MeOH is a liquid at ambient temperature and pressure so, according to pump manufacturers, MeOH can be pressurized in a single pressure step, on the condition that the MeOH tank can be arranged so that the MeOH can be taken from the bottom of the fuel tank. Otherwise, a small booster pump will have to be established.

Other considerations when using MeOH as fuel.

We have not yet made any estimation of the emission data for combustion of MeOH, and we will not be able to come up with reliable estimations before we have conducted a performance test on our test engine, especially NOₓ figures are difficult to estimate. But to meet Tier III, it is already concluded that it is mandatory to have an EGR system installed. We do not foresee that we can achieve NOₓ figures that can meet Tier

<table>
<thead>
<tr>
<th>Property</th>
<th>DME</th>
<th>Methanol</th>
<th>Ethanol</th>
<th>Diesel</th>
<th>HFO 45</th>
<th>Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td>CH₃-O-CH₃</td>
<td>CH₃-OH</td>
<td>C₃H₇-0H</td>
<td>C₈-C₂₅</td>
<td>-</td>
<td>C₄-C₁₂</td>
</tr>
<tr>
<td>Fuel carbon (wt%)</td>
<td>52.2</td>
<td>38</td>
<td>52</td>
<td>85</td>
<td>-</td>
<td>86</td>
</tr>
<tr>
<td>Fuel hydrogen (wt%)</td>
<td>13</td>
<td>12</td>
<td>13</td>
<td>15</td>
<td>-</td>
<td>14</td>
</tr>
<tr>
<td>Fuel oxygen (wt%)</td>
<td>34.8</td>
<td>50</td>
<td>35</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Molar mass (kg/kmol)</td>
<td>46</td>
<td>32</td>
<td>46</td>
<td>Ca. 183</td>
<td>-</td>
<td>Ca. 114</td>
</tr>
<tr>
<td>Liquid density (kg/m³)</td>
<td>660</td>
<td>798</td>
<td>794</td>
<td>840</td>
<td>982</td>
<td>740</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg)</td>
<td>22.8</td>
<td>20.1</td>
<td>27.0</td>
<td>42.7</td>
<td>40.9</td>
<td>-</td>
</tr>
<tr>
<td>Boiling temperature (°C at 1 bar)</td>
<td>-24.9</td>
<td>65</td>
<td>78</td>
<td>180-360</td>
<td>-</td>
<td>27-245</td>
</tr>
<tr>
<td>Vapour pressure (bar at 20°C)</td>
<td>5.3</td>
<td>0.13</td>
<td>0.059</td>
<td>+1</td>
<td>-</td>
<td>0.25-0.45</td>
</tr>
<tr>
<td>Critical pressure (bar)</td>
<td>53.7</td>
<td>81</td>
<td>63</td>
<td>30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Critical temperature (°C)</td>
<td>127</td>
<td>239.4</td>
<td>241</td>
<td>435</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Kinematic viscosity (cSt at 20°C)</td>
<td>0.19-0.25</td>
<td>0.74</td>
<td>1.2</td>
<td>2.5-3.0</td>
<td>-</td>
<td>0.6</td>
</tr>
<tr>
<td>Surface tension (N/m at 20°C)</td>
<td>0.012</td>
<td>0.023</td>
<td>0.022</td>
<td>0.027</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bulk modulus (N/mm² at 20°C 2MPa)</td>
<td>1,549</td>
<td>823</td>
<td>902</td>
<td>553</td>
<td>-</td>
<td>1,300</td>
</tr>
<tr>
<td>Cetane number</td>
<td>55</td>
<td>&lt;5</td>
<td>8</td>
<td>38-53</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Octane number</td>
<td>Low</td>
<td>109</td>
<td>109</td>
<td>15-25</td>
<td>-</td>
<td>90-100</td>
</tr>
<tr>
<td>Auto ignition temperature in air (°C)</td>
<td>350</td>
<td>470</td>
<td>362</td>
<td>250-450</td>
<td>-</td>
<td>250-460</td>
</tr>
<tr>
<td>Heat of vaporization (kJ/kg at 1 bar)</td>
<td>467</td>
<td>1,089</td>
<td>841</td>
<td>250</td>
<td>-</td>
<td>375</td>
</tr>
<tr>
<td>Minimum ignition energy (mJ at φ=1)</td>
<td>0.33</td>
<td>0.21</td>
<td>0.65</td>
<td>0.23</td>
<td>-</td>
<td>0.8</td>
</tr>
<tr>
<td>Stoichiometric air/fuel ratio</td>
<td>9</td>
<td>6.5</td>
<td>9.1</td>
<td>14.6</td>
<td>13.5</td>
<td>14.7</td>
</tr>
<tr>
<td>Peak flame temperature (°C at 1 bar)</td>
<td>1,780</td>
<td>1,890</td>
<td>1,920</td>
<td>2,054</td>
<td>-</td>
<td>2,030</td>
</tr>
<tr>
<td>Flamability limits (vol%)</td>
<td>3.4-18.28</td>
<td>6-36</td>
<td>3-19</td>
<td>0.5-7.5</td>
<td>-</td>
<td>1.4-7.6</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>-41</td>
<td>12</td>
<td>14</td>
<td>52</td>
<td>-</td>
<td>-45</td>
</tr>
</tbody>
</table>

Table III
III without the use of any abatement system. So the engine room design will have to be made with adequate space for putting up the EGR system including a scrubber water treatment system.

We do not expect problems with the generation of formaldehydes from the combustion. MeOH will burn with a temperature of up till 2600 °F and, consequently, all MeOH molecules will be burned. Formaldehydes are generated at a temperature of approx. 400-600 °C, however, because our engines have no fuel slip, formaldehydes will not be generated in the exhaust gas system. For engines with fuel slip, such as four-stroke engines using the Otto cycle, it is much more likely that problems with formaldehydes generation in the exhaust gas system will occur, since they have a high fuel slip range. But for two-stroke engines using the diesel principle, we do not foresee the need for preparing for any after-treatment system in the exhaust gas system, besides the EGR system.

ME-GI for Container Ships, Tankers and Bulk Carriers

In recent years we have seen an increase in fuel prices, and soon we may see a situation where it is economically feasible to fuel a container vessel with LNG instead of conventional HFO. If the propulsion power of the vessel is delivered by an ME or ME-C engine, then it is also possible to convert it to run on gas.

The system used on the LNG-fuelled car ferry, the M/F Glutra, has shown that solutions do exist for fitting in an LNG tank system. However, a number of studies have already been made by all the major yards and classification societies, and designs therefore exist for almost all types of ships. Basically, the space required for the LNG tanks is almost 2.5-3 times the size of an HFO tank system due to the lower heating value and the heavy insulation required to keep the LNG cold.

The GI engine requires pressurised gas at a max. pressure of 300 bar. The technology to pressurise the LNG and evaporate it at this high pressure is available, and solutions have been developed by HGS, TGE, DSME, Cryostar, HHI and now also MHI.

Common for these systems is that they comprise the following:

- Reciprocating LNG pump to generate the high pressure
- Automatic pump control system to control the pressure according to the engine delivery pressure
- Heat exchanger to heat LNG according to the required engine temperature
- Buffer volume to dampen out pulsations from the pressure generation.

The gas supply system utilises a Cryostar LNG pump fed by the LNG spray pumps placed in the LNG tank, and with a head sufficient to be used as booster. The Cryostar HPP reciprocating pumps are driven through Variable Frequency Drives (VFD), so that the pump speed can be adjusted to follow the engine load diagram that reflects the fuel demand of the engine.

At this time, it is expected that one high-pressure pump is installed, no redundancy is necessary, but this can be discussed with the shipowner. Redundancy in the fuel choice already exists with the ME-GI.

The Cryostar high-pressure LNG pump will be used to increase the pressure to a maximum of 250-300 bar and pass the LNG through a heliflow heat exchanger. The gas is evaporated and transferred to a 300 bar buffer capacity system. The buffer system is needed to dampen out pulsations in the system.

Depending on the layout of the system, the buffer volume could also be included in the high-pressure pipe volume. The heliflow heat exchanger, also called the HP vaporizer, requires a heat source to vaporise the LNG, and this can be taken as hot water directly from the cooling system of the ME-GI. Alternatively, steam can be used to heat the LNG. It is also possible incorporate an
intermediate heating loop using either brine or glycol water if requested.

The energy required by the HPP LNG pump is very low, and corresponds to less than 0.5% reduction of the efficiency of the ME-GI engine compared with an ME-C type engine.

LNG tank systems

For merchant ships, several possibilities of equipping the ship with an LNG tank are available. For smaller ship sizes, prefabricated vacuum-isolated cryogenic tanks can be found in a wide range of sizes with an allowable working pressure of up to 10 bar, which is the maximum allowable according to the preliminary IGF Code. Some of these tanks have been installed and are already in operation on ferries and supply vessels.

For bigger ships, several other possibilities exist, some of which are listed below:

- Membrane tank design. Dominating for LNG carriers, but vulnerable to sloshing BOR range 0.14-0.2%/day.

- Spherical tanks, i.e. Moss type. Self-supporting and invulnerable to sloshing, but space problems and very few manufacturers. BOR 0.14-0.2%/day.

- Type B tanks from IHI or others. Self-supporting and invulnerable to sloshing. Low-pressure tanks, and built on a licence in some yards. BOR 0.14-0.2%/day or higher for smaller tanks.

- Type C tanks from TGE or others. Single or bilobe design. Pressure range 3 to 10 barg, depending on tank size, material and operational requirements BOR is unfortunately higher for the «small» fuel tanks: 0.2 to 0.6 %/day (up to 50 travelling days is possible), self-supporting and invulnerable to sloshing.

The IHI B-type tank design and the C-type design from TGE seem to be the most promising for larger conventional ships. Common for both tank designs is that it is possible to operate the ship with a partially filled tank, which is a basic requirement when the tank is used for fuel storage. Both of the designs can be used for LPG fuel as well.

The above tank designs have advantages and disadvantages. For instance, in the IHI design it is possible to adapt the tank form to follow the shape of the ship, see Fig. 25. Practically any tank size can be chosen. In the TGE design, on the other hand, the hull form can only be followed to some extent if the bilobe design is used, see Fig. 26. The max. tank size in the bilobe design is in the range of 20,000 cum.

Another advantage of the TGE tank design is the ability to accumulate the BOG in the tank during operation, thanks to its allowable working pressure of up to 9-10 bar. If a tank design without this possibility is used, an alternative method to handle BOG has to be incorporated in the fuel gas supply system. A list of alternative possibilities in combination with the Cryostar gas supply system is shown in Fig. 27.

With this in mind, it can be concluded that the technology for a gas driven two-stroke ME-GI engine is available. What is needed is a visionary pioneer within the transport business to take the lead.

Requirements for classification

When entering the LNG market with the combined two-stroke and reliquefaction solution, it was discovered that there is a big difference in the require-
HAZOP investigation are therefore found to be the only way to ensure that all situations have been taken into account when using gas for propulsion, and that all necessary precautions have been taken to minimise any risk involved.

Since 2005, more than 10 HAZID and HAZOP studies have been performed with different yards, classification societies, owners, engine builders, and manufacturers of gas supply systems.

Main engine room safety

In 2006, DNV and MDT finished a safety investigation, initiated by a group of players in the LNG market, questioned the use of 300-bar gas in the engine room which, moreover, is located under the wheel house, where the crew is working and living.

Even though the risk of full rupture of both the inner and outer pipe at the same time is considered close to negligible and, in spite of the precautions introduced in the system design, MAN Diesel & Turbo found it necessary to investigate the effect of such an accident, as the question still remains in part of the industry: what if a double-wall pipe fully ruptures and gas is released from a full opening and is ignited?

As specialists in the offshore industry, DNV was commissioned to simulate such worst case scenarios, study the consequences and point to the appropriate countermeasures. DNV’s work comprised a CFD (computational fluid dynamics) simulation of the hazard of an explosion and subsequent fire, and an investigation of the risk of this event ever occurring and at what scale.
As input for the simulation, the volume of the engine room space, the location of major equipment, the air ventilation rate, and the location of the gas pipe and control room were the key input parameters.

Realistic gas leakage scenarios were defined, assuming a full breakage of the outer pipe and a large or small hole in the inner fuel pipe. Actions from the closure of the gas shutdown valves, the ventilation system and the ventilation conditions prior to and after detection were included in the analysis. This action limited the amount of gas in the fuel pipe and limited the duration of the leak. Ignition of a leak causing an explosion or a fire is furthermore factored in, due to possible hot spots or electrical equipment that can give sparks in the engine room.

Calculations of the leak rate as a function of time, and the ventilation flow rates were performed and applied as input to the explosion and fire analyses.

The conclusion was that it is not the high pressure that is of concern, but the total amount of energy contained in the gas piping system that constitutes the risk. On low-pressure systems, the pipe diameter is much wider, and the gas volume per pipe metre is the same for the high-pressure system as for the low-pressure system. So the amount of energy contained is the same for a low-pressure system as for a high-pressure system.

### Concluding Remarks

To enter the market for a demanding application such as an LNG vessel calls for a high level of knowhow and careful studies by the shipyard, the engine builder, and the maker of the gas supply system as well as the engine designer.

Many alternative tailormade ME-GI propulsion solutions and fuel gas supply system are now available from a variety manufactures. HAZOPs have been completed for almost all available systems, and many different ship types. For newbuild LNG carriers, the boil-off rate has been lowered from 0.15%/day to 0.10%/day by increasing the insulation layer on the LNG cargo tanks. This has resulted in that excessive BOG are gone when the two-stroke ME-GI engine is operating at normal ship speed. This makes the basic Laby-GI compressor solution very economically attractive for owners considering use of only gas as fuel on their LNG carriers.

Thus, for LNG carrier owners interested in full fuel flexibility, a gas supply system combined with a full reliquefaction plant is recommended.

For LPG carriers and other ships types, an ME-L-GI solution for LPG fuel is also available, including a developed gas supply system from Hamworthy Gas Systems and now also from TGE. This solution offers such major benefits as lower emission levels and lower fuel costs by utilising the heavy fluctuation between LPG and FO prices.

Also for other ship types, technical solutions exist to use gaseous fuel. At present, the lack of LNG bunkering facilities seems to be the biggest hurdle to overcome. Projects are ongoing to establish LNG facilities. Therefore, in some parts of the world, e.g. Stockholm and the port of Zeebrygge, LNG is already available and, in the coming years, LNG will be available as fuel for ships on many other locations.
All data provided in this document is non-binding. This data serves informational purposes only and is especially not guaranteed in any way. Depending on the subsequent specific individual projects, the relevant data may be subject to changes and will be assessed and determined individually for each project. This will depend on the particular characteristics of each individual project, especially specific site and operational conditions. Copyright © MAN Diesel & Turbo. 5510-0063-04pr Aug 2012 Printed in Denmark.