New Developments in Piston Compressor Technology Applied to Gas-Fueled, 2-Stroke, ME-GI and X-DF Engines for LNG Carrier Propulsion

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1 Introduction

The performance of dry-running, oil-free, sealing systems for use in high-pressure compression applications, has improved considerably over the last few years. As a specialist in reciprocating compressor technology, Burckhardt Compression is proud to be leading the innovation in non-lubricated seals, which has centered on the development and testing of heterogeneous sealing ring assemblies coupled with alternative, tailor-made ring materials.

Utilizing the advantages of completely oil-free gas delivery, a non-lubricated, high-pressure, 300 bar fuel gas compressor design is introduced and now available. The oil-free, multi-stage Laby®-GI Non-Lube Compressor utilizes a combination of labyrinth piston sealing and proven, dry-running, ring sealing technology. Sealing system component lifetimes are in-line with routine maintenance intervals and offer ship owners a highly interesting alternative to conventional lubricated designs. Gas systems within the compressor package are simplified since oil separation equipment is no longer required. This exclusive compression technology results from continuous research into dry-running sealing systems for reciprocating compressors and confirms the supplier's leading position in high-pressure, oil-free applications.

This paper also reviews recent developments of the conventional Laby®-GI fuel gas compressor and introduces new cylinder configurations based on the successful LP250 unit. A new modular design of low- to medium-pressure compressor cylinders, allows application for fuel gas supply to both high-pressure MAN ME-GI as well as low-pressure WinGD X-DF engines. This flexibility permits the robust, slow-speed reciprocating technology, with more than 50 units operating, to be applied to the full range of 2-stroke dual-fuel diesel engines. The paper also looks at the operating history of the Laby®-GI Compressor LP250 and the updates which have been made over the last 2 years resulting in stable operation, prolonged maintenance intervals and higher reliability.

2 Application of reciprocating piston compressors for fuel-gas supply

The application of reciprocating piston compressors to refrigeration and fuel gas compression on marine offshore installations and shipping, has seen rapid growth over the last 5 – 10 years. On the one hand, this is a result of increased exploration of offshore oil and gas reserves, but also due to the substantial growth in the use of liquid natural gas (LNG) as an alternative fuel for shipping, specifically on liquid gas carriers. The demand for dual-fuel propulsion has been driven by the substantially improved efficiency (fuel economics) of dual-fuel diesel engines compared to previously installed steam turbine propulsion. Further incentive for change to natural gas as fuel was given by the International Maritime Organization's regulations for emission reduction of sulfur (SOX) and nitrous oxide (NOX), through its marine pollution protocol MARPOL and even lower limits imposed by Emission Control Areas (ECA).

3 Review of reciprocating compressor application matrix

Reciprocating compressors are employed today across a very wide range of liquid gas carriers including large (174k LNG carriers) down to medium and small LNG distribution ships (3k – 45k), Floating Storage Regasification units (FSRU) and LNG bunker ships. There is also a rapidly growing market for natural gas as fuel to many different types of commercial ships such as cruise ships, container ships, bulk carriers, barges etc.

Ship Type	Conventional LNG Carriers (typically 170 – 210k)		LNG Bunker Vessels & Small-Scale LNG Carriers (typically 5 – 80k)	
BOG Mass Flow	2'500 – 7'000 kg/h		200 – 2'500 kg/h	
	 Laby®-GI	 Laby®	 Laby®	 MHP
MAN ME-GI 2-stroke / 300 bar	●			○
WinGD X-DF 2-stroke / 13 bar	●	●	○	
DFDE/TFDE 4-stroke / 6 bar			○	

Figure 1: *LNG shipping application matrix*

Ship Type	Container Ship		Bulk Carrier		Car Carriers Ro-Ro & PCTC		Cruise Ships
BOG Mass Flow	300 – 1'500 kg/h		300 – 1'500 kg/h		300 – 1'500 kg/h		300 – 1'000 kg/h
	 Laby®	 MHP	 Laby®	 MHP	 Laby®	 MHP	 Laby®
MAN ME-GI 2-stroke / 300 bar		●		○		●	
WinGD X-DF 2-stroke / 13 bar	●		○		●		
DFDE/TFDE 4-stroke / 6 bar							○

Figure 2: *Commercial shipping application matrix*

The LNG fleet size has more than doubled during the past 10 years, growing to a total of 525 active ships by the end of 2018. But why has there been the rapid adoption of reciprocating compressors compared to other designs? The answer to this question lies partly in the individual compression duty requirements but more importantly, to the greater acceptance of qualified, proven compressor designs for highly demanding marine fuel gas applications.

Traditional marine industry guidelines prefer not to approve the specification of reciprocating compressors for critical rotating machinery applications on board ships, floating storage and offshore structures. Fear of vibration and low frequency resonances resulting from unbalanced forces and moments is common among marine architects. But surprisingly, there is a very long history of application of reciprocating compressors for LPG carriers, based on the rugged design of the labyrinth compressor. This experience goes back to the advent of LPG ship transport over 50 years ago. Many thousands of Laby® compressors are installed on a wide range of LPG carriers, giving unparalleled reliability for difficult gases in boil-off gas re-liquefaction processes.

***Figure 3:** Laby® Compressor system installed on an LPG carrier*

4 Compressor selection according to dual-fuel engine technology

In an ideal world, large volumes of gas are economically compressed at low to medium pressures (2 – 12 bar) by centrifugal compressors. Reciprocating or screw compressors are applied to medium volumes of gas for medium discharge pressures (4 – 40 bar) and reciprocating compressors are the natural selection for medium to low volumes of gas, for compression to high pressures (50 – 500 bar).

Having a closer look at the application-specific requirements, no compression duty is quite that simple. For example, 3'000 – 4'000 kg/h natural BOG typical for a 174k LNG carrier, can be classified as a medium flow. Reciprocating compressors are also commonly applied at low discharge pressures in the range of 5 to 15 bar. Other factors must also be considered such as:

- Quality of delivered gas (cleanliness, dew point, etc.)
- Oil-free or oil-lubricated gas compression
- Variations in gas composition
- Changing process conditions (e.g. suction pressure and temperature, discharge pressure)
- Operational restrictions: start-up with cold gas, repeated start-stop-cycles, etc.
- Continuous, step-less capacity control variation
- Flexibility in control of capacity as well as suction and/or discharge pressure
- Vibration to ship structure
- Available installation space
- Energy efficiency
- High reliability and availability
- Simple maintenance
- Total cost of ownership

For boil-off gas applications, required in the transport and storage of low temperature liquid gases, labyrinth reciprocating compressors are the ideal solution to the above evaluation.

5 Containment system and re-liquefaction – influence of BOG and flash-gas

The choice of the containment system including quality of insulation and the type of re-liquefaction system installed on the ship, have a direct impact on the total amount of boil-off gas and hence sizing of the low duty fuel gas compressor. The determination of specified "design" capacity is highly important for economic ship operation.

The most common containment technology installed in LNG carriers today are membrane tanks, using thin, flexible membranes supported only by the insulated hull structure. A large share of the carrier fleet today is using the tanks designed by Gaztransport and Technigaz (GTT). Earlier membrane tanks were designed with a boil-off rate of 0.15% of the cargo capacity per day. The later GTT Mark III Flex design, introduced in 2011, reduced the boil-off rate by one third to 0.1 –

0.085% per day. New storage tanks designed for the market today (Mark III Flex+) have reduced boil-off rates at around 0.07% of the cargo per day.

In most cases LNG carriers are additionally equipped with onboard re-liquefaction systems to handle excessive but valuable boil-off gas. The market can select between active, energy consuming but high-efficient nitrogen expansion and mixed-refrigerant full re-liquefaction systems, or the passive, energy efficient, Joule-Thompson based, high-pressure partial re-liquefaction process. As the partial re-liquefaction process creates larger amounts of flash gas as a process byproduct, the required compressor design capacity can increase by as much as 30 – 40%. As a result, compressor volumetric flow, power consumption and size of machinery are increased. It is clearly very important to get this calculation right.

6 Overview of dual-fuel propulsion systems available on the market

6.1 MAN ME-GI engine

The introduction in 2010 of MAN Energy Systems slow-speed, ME-GI dual-fuel engine employing the 2-stroke diesel cycle, gave the market a very welcomed alternative to the 4-stroke dual fuel diesel-electric (DFDE) propulsion system. The MAN ME-GI engine promised higher overall efficiency using the diesel cycle and considerably lower maintenance due to the reduction in the number of installed cylinders. This led to substantial growth in the use of LNG as an alternative fuel for shipping, specifically on liquid natural gas carriers. Fuel gas is injected at a pressure between 260 – 300 bar directly into the cylinder after the compression stroke. Reciprocating compressors, such as the Laby®-GI, with a multi-stage design are successfully employed to deliver such high pressure. The detail design of the Laby®-GI Compressor and a review of design updates together with operational history and lessons learned is given in chapter 9.1.

6.2 WinGD X-DF engine

Introduced in 2013, this is the latest engine technology to enter the market for LNG carrier propulsion. The 2-stroke, slow-speed engine uses the Otto cycle and requires a gas supply pressure of 13 bar or lower at reduced loads. At this intermediate pressure level, the reciprocating compressor for fuel gas supply to the WinGD X-DF engine starts to become very attractive in terms of efficiency, performance flexibility, reliability and cost of ownership. Compressor solutions for large LNG carriers with WinGD X-DF propulsion are discussed in chapter 9.2. WinGD X-DF references, employing the reciprocating Laby® Compressor, are already available for smaller LNG distribution and LNG bunker ships.

6.3 Dual- or Tri-Fuel Diesel Electric

The first dual-fuel LNG ships, which came into service in the early 2000's, were supplied with 4-stroke engines using the Otto cycle when operating in gas mode. Fuel gas is supplied to the dual-fuel diesel electric (DFDE) engines by 2 to 4 stage centrifugal compressors at a pressure of approximately 6 bar. Control of the discharge pressure proved being difficult under varying suction conditions. The 4 – impeller / stage alternative was introduced to compensate. This duty would however also be possible by a reciprocating compressor, for reasons explained above.

7 More than 50 years of experience with Laby® Compressors on ships

LPG carriers fitted with vertically aligned labyrinth compressors for boil-off gas handling on semi-refrigerated and fully-refrigerated ships, have long been the preferred specification for many ship owners and operators. Although relatively moderate discharge pressure in the range up to 18 – 35 bar g are required for re-liquefaction, the compression duty is surprisingly very demanding. A wide range of alternative liquid petroleum cargos, ranging from heavy liquid VCM, butadiene, through LPG and propane to toxic ammonia, ethane and ethylene must be managed, with boil-off gas temperatures ranging from +30 to –104 °C. A simple and reliable, highly robust compressor design is called for, with low footprint due to minimal space availability common to all ships. The compressor must furthermore be designed to minimize or eliminate leakage of the process gas, which in many cases for LPG transport, represents a dangerous toxic, hazardous and environmental unfriendly substance. Oil-free compression is required for LPG shipping to avoid contamination of the transported liquid and is mandatory for the compression of low temperature gases below –40 °C, where lubricating oils no longer provide satisfactory protection against cylinder and piston ring wear.

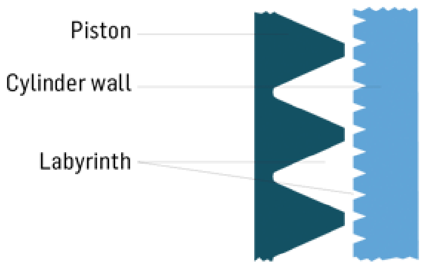

Figure 4: *Wear-free labyrinth cylinder sealing technology*

The labyrinth compressor meets entirely these requirements. The oil-free, contactless labyrinth sealing employed both for piston sealing in the cylinder and the piston rod packing (piston rod gland), is the most reliable sealing method in the compressor industry. The absence of friction in the sealing elements ensures an extremely long lifetime of sealing components. The heavy-duty, robust crankcase is uniquely provided with mechanical sealing where the crankshaft leaves the casing for connection to the motor drive. The complete casing assembly comprising motion work, cylinder and distance piece is designed as a hermetically sealed, gas-tight unit. The design pressure of this sealed unit may be set at settle-out pressures from 2 bar g up to as much as 15 bar g. The design without traditional piston ring sealings on the piston wall, together with ring sealings for the piston rod, results in a design with long periods between overhaul (MTBO).

The compressors run at comparatively low speeds (typically running between 500 and 1'000 rpm), in comparison to other designs, which leads to reduced maintenance of wear and tear parts, particularly valves. Process control for discharge pressure, capacity regulation and operating compressor start-up, is considerably simpler with positive displacement reciprocating compressors compared to centrifugal designs. The required discharge pressure is always automatically available independent of gas composition and temperature.

The reasons for the tremendous success of Laby® compressors in the marine LPG application are in summary:

- Unique, contactless, oil-free, labyrinth sealing system for both cylinder and piston rod
- Reduction of regular wear parts, such as piston and packing rings, significantly reduces maintenance and stoppage
- Gas-tight crankcase saves gas loss and reduces hazard and operator risks
- Robust, vertical design crankcase and cylinder arrangement: low installation footprint
- Low speed, well-known and understood design and technology
- Maintenance procedures require only basic mechanical skills and may be executed by the ship's crew

Figure 5: *LPG BOG Laby® Compressor 2K160-2A*

Innovation and development for new applications draw on a long tradition of high-quality compression machinery design, manufacture and services. The basic design principles of the labyrinth compressor have been adopted to the development of the Laby®-GI fuel gas compressor for MAN ME-GI engines. As a new development, the Laby®-GI Compressor is now also available as fuel gas compressor for WinGD X-DF propulsion (see chapter 9.2).

8 Fuel gas compression – a very demanding machinery application

Natural gas compression is typically required for pipeline pressure boosting and onshore fuel gas supply to combined cycle power plants. The main application variable for pipeline compression is the suction pressure which changes according to the demand and available inlet pipeline pressure.

The most demanding application however, is fuel gas supply to dual-fuel engines on LNG carriers. Here, the suction pressure remains practically constant and limited by the narrow range of LNG tank pressure. All other boundary conditions are subject to change, such as wide-ranging suction temperature, incoming gas composition, compressor load which may be subject to rapid change, and variable discharge pressure. Clearly, a robust design with simple and effective control possibility is required.

Irrespective of requested discharge pressure, either 13 bar or 300 bar, fuel gas applications demand the highest requirements concerning, availability, reliability, maintenance and operational costs. The piston compressor does have distinct advantages for both, high- and low-pressure applications, such as operational simplicity and flexibility. The latest reciprocating compressor developments for supply of natural BOG to dual-fuel, 2-stroke engines type MAN ME-GI and WinGD X-DF, dominating today's market for LNG ship propulsion, are explained in chapters 9.1 and 9.2.

9 Laby®-GI Compressors for MAN ME-GI and WinGD X-DF applications

The updated compressor family comprises 6-,5-,4- and 3-cylinder versions for application to both MAN ME-GI and WinGD X-DF dual-fuel propulsion engines. The units comprise a common fixed LP250 fully balanced frame, fitted with the required number of cylinders according to specified flow capacity and delivery pressure.

The Laby®-GI Compressor versions designated 6LP250, 5LP250, 4LP250 and 3LP250, cover normal and forced boil-off gas flows ranging from 6'000 to 3'000 kg/h, or lower. This relates to BOG percentage rates of 0.15 to 0.08 % of cargo per day. The actual frame size selection depends on the specific engine fuel gas pressure and the type of BOG re-liquefaction system (if any) employed. For MAN ME-GI ship propulsion, the Joule-Thompson based partial re-liquefaction system uses the cold energy of the BOG as heat sink to re-liquefy a certain amount of the normal BOG. Doing so, the suction temperature of the BOG is increased from cargo tank conditions up to temperature levels above 0 °C. Warmer suction gas corresponds to a higher actual suction volume flow rate, and results in the larger frame and cylinder size. Typically for a 174k LNG carrier with MAN ME-GI engine and partial re-liquefaction system (PRS), the 5LP250 is applied (refer to Figure 6). The unit comprises five cylinders, five stages of compression and a stroke of 250 mm.

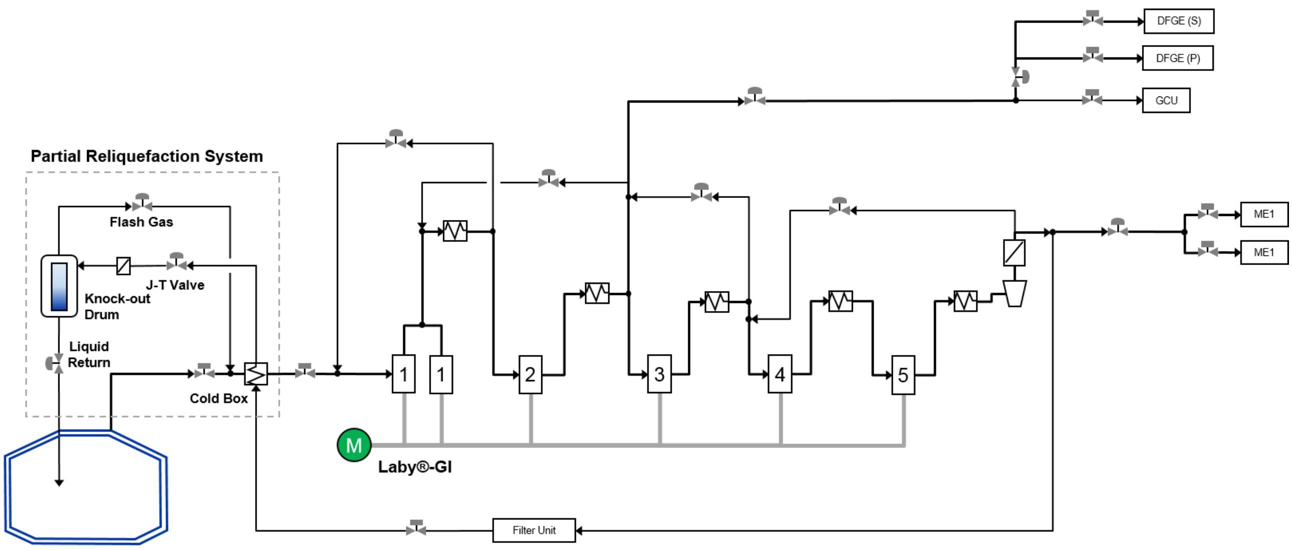

Figure 6: *Single compressor unit with partial re-liquefaction system (typically 5LP250, 5-stages)*

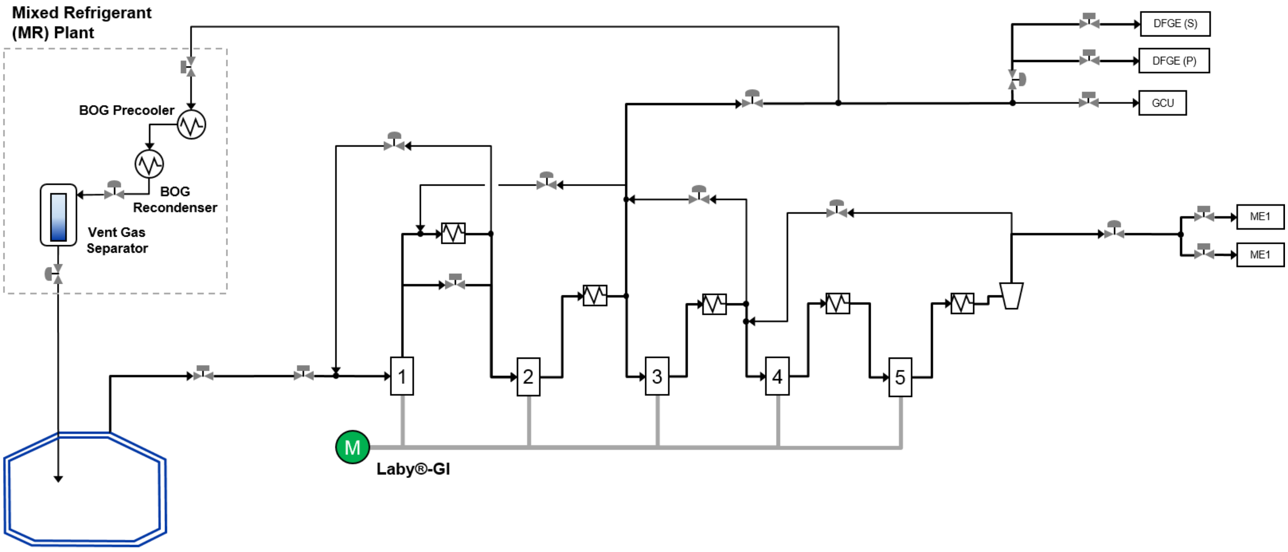

Figure 7: *Single compressor unit with full re-liquefaction system (side stream to re-liquefaction system from the 2nd stage)*

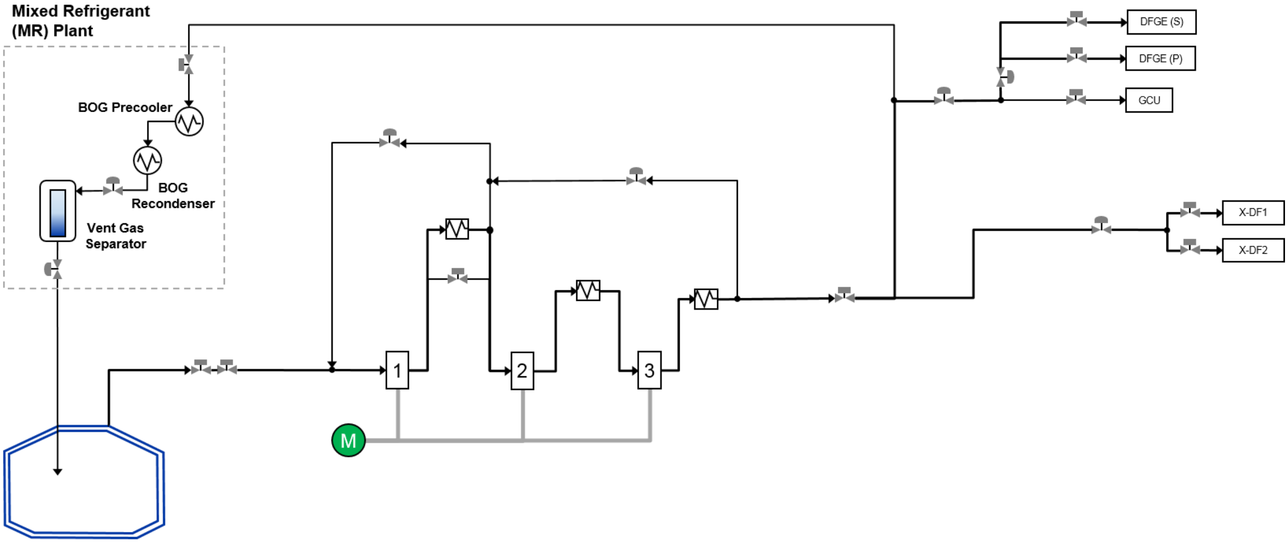

Figure 8: *X-DF 3DL200 (typical)*

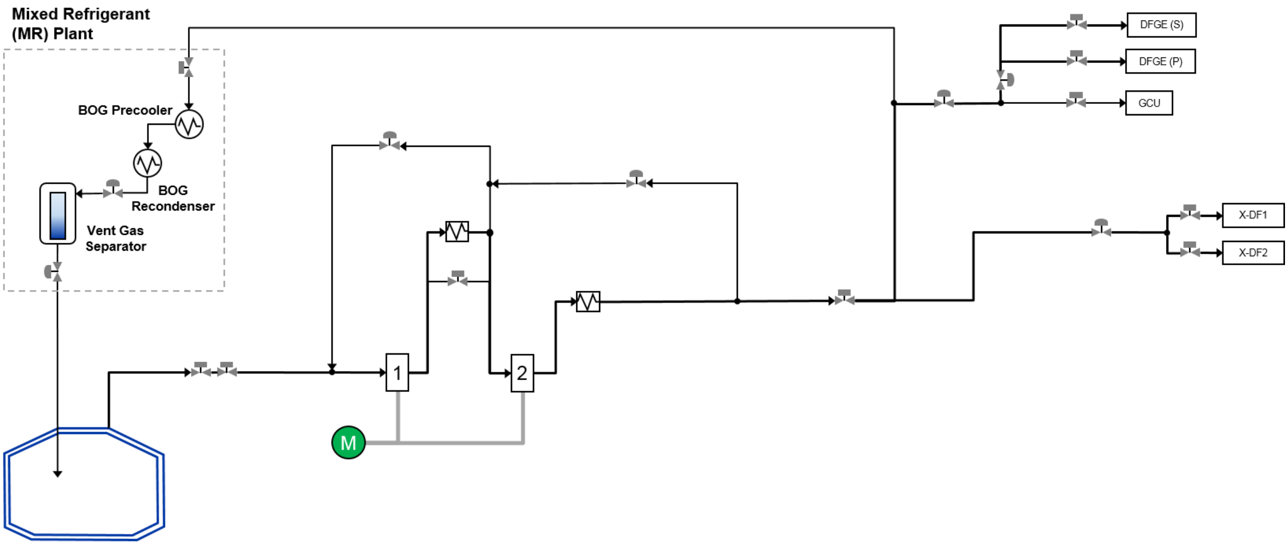

Figure 9: *X-DF 3LP250 (typical)*

MAN ME-GI powered LNG ships without re-liquefaction system or employing a separate dedicated re-liquefaction system (Brayton, cascade or mixed refrigerant) are fitted with the smaller flow 4-cylinder design 4LP250 frame size (refer to Figure 7). Mass flow range for this compressor is 3'000 – 4'000 kg/h.

The 3LP250 is designed to handle BOG amounts typical for conventional LNG ships and carriers sizes up to 260k, equipped with WinGD X-DF propulsion and (if applicable) a partial reliquefaction system. Two stages of compression are required with three cylinders sharing the total discharge pressure in the range 14 – 16 bar. Having only two stages, the 3LP250 is considerably less complex than the 5-stage unit. The control system requirements are similar to the LPG Laby® Compressor, on which the technology is based.

9.1 Laby®-GI fuel gas compressor for high-pressure ME-GI dual-fuel engines

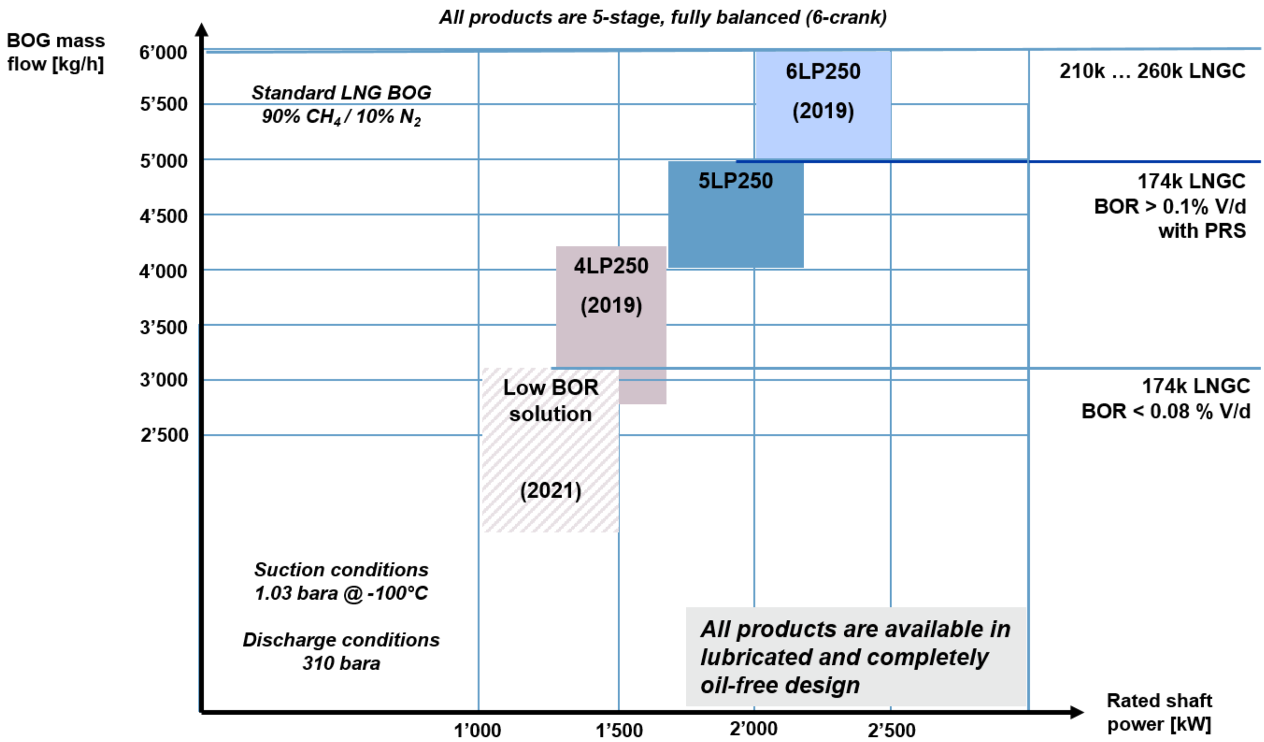

Figure 10: *Compressor solutions for ME-GI engines*

The MAN ME-GI engine has accumulated more than three years of successful service in the propulsion of large LNG carriers. The engine requires a fuel gas supply pressure of 260 – 300 bar. Multi-stage piston compressors of the type Laby®-GI are employed to deliver boil-off gas for injection into the engine cylinders. They supply high-pressure fuel gas not only to the main engines, but also to the dual-fuel generators, re-liquefaction system and gas combustion unit. It forms the key component of the ship boil-off gas handling and management system. With a total of 40 large 174'000 m^3 LNG ships running with MAN ME-GI propulsion and 56 compressors in service (status July 2019), the Laby®-GI Compressor has now collected more than 400'000 operating hours.

9.1.1 Laby®-GI – basic design features and compressor designation

The Laby®-GI Compressor comprises a 6-throw, vertically arranged motion work or crankcase, much like a conventional ship diesel engine. Cylinders are mounted on top of the crankcase in 4-, 5-, and 6-cylinder configurations, according to the specific compressor design volume and capacity. The individual cylinder sizing and selection for each designation allows the construction of five compression stages, the final 4th and 5th stages being contained in one of the compressor throws. The cylinders are different sizes, since multi-stage compression takes place, unlike a diesel engine, where each cylinder is the same size. Cylinder material is selected according to individual stage design pressure and temperature, from atmospheric suction pressure, first stage, low temperature, LT casting (–160 °C boil-off temperature), to final stage, forged steel, designed for 300 bar and +160 °C.

Compressor Designation 5LP250-5B	
5	number of cylinders employed (options are 4, 5 and 6)
LP	Laby® and process design compressor design pedigree (fully balanced)
250	compressor stroke
5	number of compression stages (for 300 bar duty, five stages are always required)
B	cylinder diameter selection according to specified design condition

Figure 11: *Compressor designation 5LP250-5B*

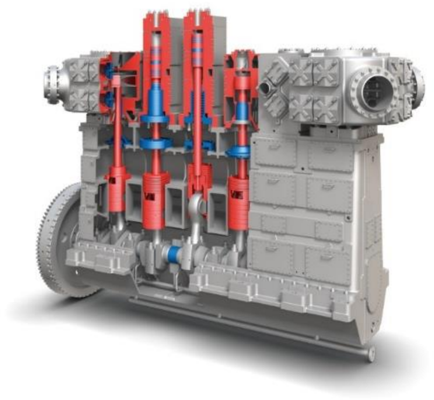

Figure 12: *Cut-view of the Laby®-GI Compressor*

Each throw is carefully provided with balancing weights, as necessary to eliminate unbalanced forces and moments caused by oscillating masses.

Cylinders are double-acting, compression on top and bottom. Conventional plate valves are used at suction and discharge ports. Cylinder sealing technology is applied according to stage gas temperature and pressure, with low-pressure, low-temperature stages 1 – 3 employing labyrinth seals in oil-free design, and high-pressure stages using ring-sealed, lubricated cylinders, or alternatively an oil-free design.

9.1.2 Process flow and control – multi-functional, fully integrated, BOG management

Compression of BOG from atmospheric tank pressure to 300 bar is made in five stages. Heat of compression is removed after each stage by provision of conventional shell and tube heat exchangers. The interconnecting gas system between stages, external to each stage cylinder block, is provided with adequate pulsation dampers to ensure piping vibration within the compressor complete module package conforms to marine industry requirements and is free from resonances.

Intermediate side streams after the 2nd or 3rd compression stage are available for integration of the compressor into the ship gas processing, power generation and re-liquefaction systems. The basic package design provides high flexibility to adapt to individual yard requirements.

Through the above mentioned, fully integrated control concept, the Laby®-GI Compressor takes over a central element in the ship boil-off gas management.

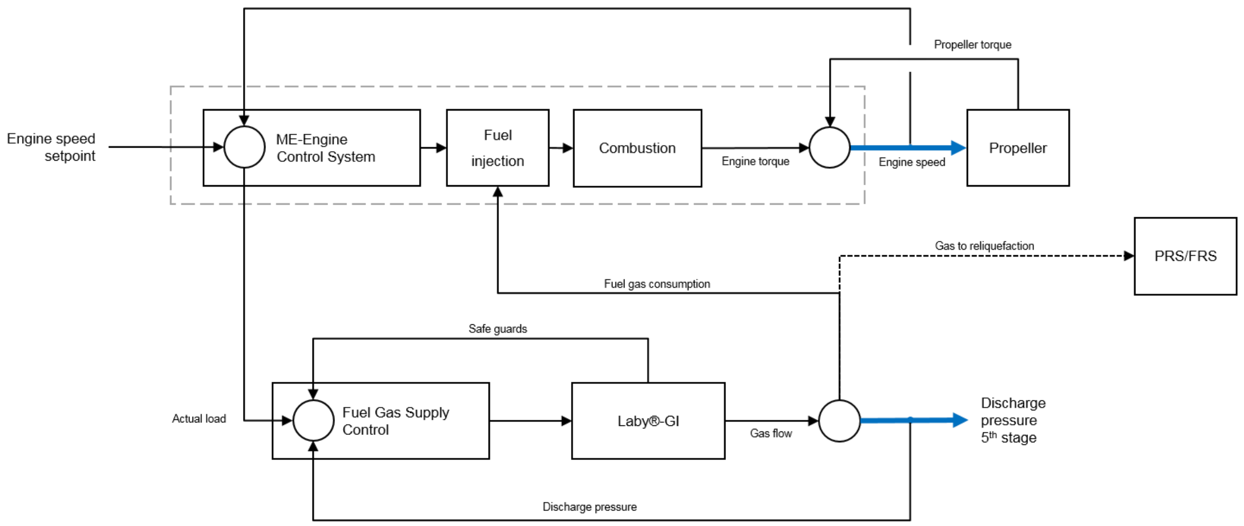

***Figure 13:** Control of Laby®-GI fuel gas compressor for MAN ME-GI engines*

9.1.3 Cylinder lubrication – final discharge oil filtration and removal

The high-pressure 4th and 5th compression stages of the Laby®-GI Compressor in the basic design execution are oil-lubricated. Oil lubrication of high-pressure cylinders is standard in the processing industry where small amounts of residual lubrication oil carried over to the gas stream are acceptable. Various stages/types of liquid separation may be provided in series in the module discharge line or additionally downstream of the compressor, to remove oil down to micro level. Removal of all but very small traces of oil from the final gas stream is therefore possible. The base Laby®-GI design complies with the specified requirements of residual oil acceptable to the main engine. However, additional separation may be requested where re-liquefaction is executed by the partial re-liquefaction system.

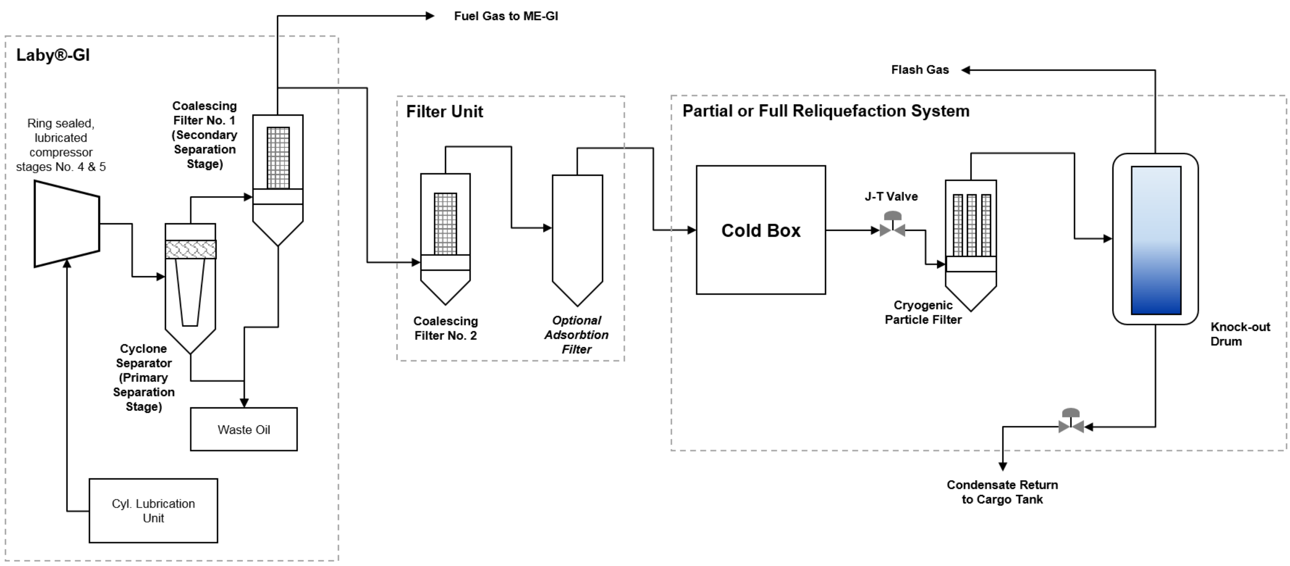

***Figure 14:** Partial reliquefaction system with high-efficiency oil removal system*

9.1.4 Oil-free Laby®-GI Non-Lube – now available

Burckhardt Compression's leading technology position in the development of high-pressure, oil-free, sealing systems for reciprocating compressors is confirmed by the market introduction of the Laby®-GI Non-Lube Compressor in completely oil-free cylinder execution for delivery pressures of up to 300 bar. This design is now available as an option for ship owners which prefer to dispense with the oil separation equipment required for the oil lubricated design. The Laby®-GI Non-Lube Compressor uses proven sealing technology developed by Burckhardt Compression's world class sealing technology team which has more than 30 years of experience with research, manufacturing and application across a wide range of industries.

The first compression stage of the Laby®-GI Non-Lube Compressor is oil-free, by the labyrinth design principle as applied to very low temperature boil-off gas compression. By employing latest in-house developed ring sealing technology on the following stages 2 to 5, boil-off gas can now be delivered at pressures higher than 300 bar in completely oil-free condition, for direct injection into the MAN ME-GI engine or to an auxiliary re-liquefaction system. Additional oil separation equipment normally installed at the compressor discharge is no longer necessary. The simplified process design results in a significant improvement of delivered gas quality, while maintaining unimpaired system availability. The multi-stage compressor gas system benefits from having substantially reduced complexity.

Research into the tribology of oil-lubricated and oil-free reciprocating sealing systems, is one of Burckhardt Compression's leading, well-documented, development activities. With applications requiring effective and reliable sealing at pressures up to 3'000 bar, as used for production of low density polyethylene, the correct selection of seals and sealing materials is critical to successful plant operation. Burckhardt Compression is at the forefront of this technology in developing tailor-made sealing elements for demanding applications.

Many gas compression applications specify a delivered gas which is free from contamination by cylinder lubricating oil, such as compressed air and hydrogen used in food production, or processes with sensitive catalysts (plastics such as LLDPE and PP). Oil separation systems have also made significant improvements in recent years, however still bearing the potential risks of failures, resulting in loss of product and considerable cost for gas system clean-up.

Without oil lubrication, conventional sealing ring designs are exposed to high temperatures due to friction, which can reduce their lifetime significantly, particularly at high discharge pressures. Limits for successful operation were typically 100 to 150 bar. The challenge has been to extend the maximum operating pressure of sealing designs for discharge pressures up to 350 bar. Operating results from oil-free sealing designs based on the Redura® principle, working at this pressure have shown considerable resistance to wear and much improved sealing efficiency.

Sealing systems normally must withstand both dynamic and static pressures during the compression stroke. Dynamic pressure is the pressure difference between suction and discharge pressure, whereas static pressure is the pressure difference between the suction pressure of the stage in consideration, and the constant pressure at the end of the stage's last sealing ring.

Investigations have shown that these two pressure components have significantly different effects on the behavior of the entire sealing system. With Burckhardt Compression's Redura® sealings, heterogeneous sealing systems are applied consisting of a combination of different designs, each optimized for the stress from the respective pressure component **(***Heterogeneously designed sealing systems based on the Redura principle*, COMPRESSORtech2, March 2015**).**

In the cylinder, retained piston rings have long been used on oil-free sealings. These have been developed and provided with a slope angle (alpha) to self-lock the ring and prevent it from fluttering during compression. The retained rings are mounted in series with friction rings (see Figure 15). The retained rings allow pressure distribution over several sealing components. They are up to six rings or more and act to shelter the friction sealing rings from the dynamic pressure component tight, but work as a contactless seal after running-in. The friction rings therefore are under less stress and can be designed with priority on sealing effectiveness, rather than being rigid and robust. Material selection can therefore be optimized for sealing efficiency and wear durability.

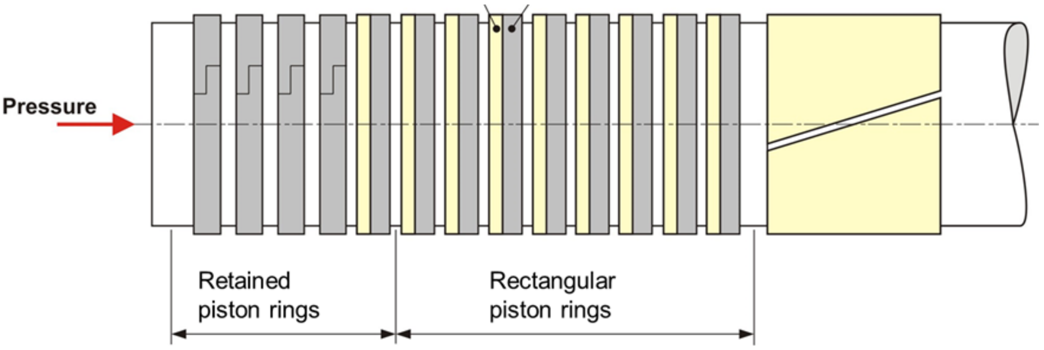

Figure 15: *Heterogeneous piston design for dry-running high-pressure applications*

In the packing, so-called "TriSemic" packing rings are being used to handle the dynamic pressure component. As seen in the picture below, each TriSemic ring comprises three components:

- Two serially arranged endless rings, which move from opposite directions toward the rod by a spring actuator
- A bronze anti-extrusion ring

Importantly, TriSemic ring wear is compensated by a shift in ring components rather than ring wear.

Figure 16: *Components of a TriSemic packing ring*

In addition to the "TriSemic" pressure breaker, a special packing ring design called Multi Piece (MP) is being used to handle the static pressure component. MP rings are designed to permit wear without increasing the flow area. This is achieved by a special segment design which width at inner and outer diameter is identical (see Figure 17).

Figure 17: *Multi-piece ring with eight pressure-relieved segments*

This geometric design allows unimpeded wear compensation without the need for gaps between the individual segments. The simple segment contour also allows easy implementation of a pressure relief groove to reduce pressure load.

Not only the ring designs but also their materials are of high importance for challenging high-pressure applications. Burckhardt Compression utilizes custom-made compounds for their compressor sealing systems which may be differentiated from common standard materials by the Persisto® brand name. Matrix materials, fillers and ratio of components were chosen so to optimally fulfill the individual sealing function within a Redura® system. Burckhardt Compression produces its own plastic billets and has the full range of production know-how from powders to sealing elements.

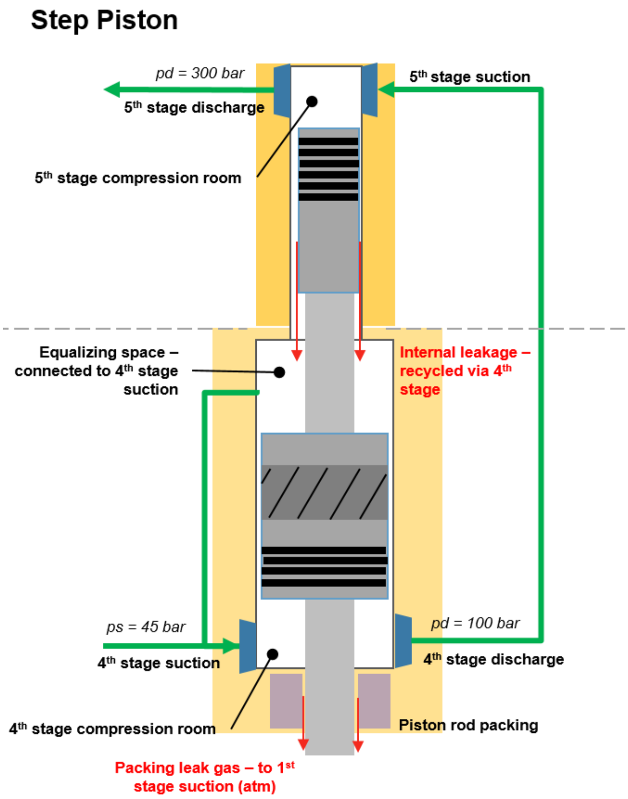

Figure 18: *Step piston design*

In summary, the sealing package system is optimized for each compression stage resulting in significantly improved performance, reliability and lifetime between overhaul. The fourth and fifth compression stages of the Laby®-GI Compressor are configured in a step piston design (see Figure 18). The key piston rod sealing system is thereby not exposed to the final delivery pressure of 300 bar, but the 4th stage discharge pressure of 150 bar (suction pressure to the 5th stage). This lower pressure combined with the specifically selected ring combination, provides an optimal condition for reliable low wear operation.

9.2 Fuel gas supply for WinGD X-DF propulsion systems

The WinGD X-DF, low-speed, 2-stroke, dual fuel engine is developed as a gas engine and operates based on the lean-burn Otto cycle. Gas supply to the engine is introduced at low pressure, in mid-stroke at a pressure of 14 bar. Ignition is done by pilot fuel burning in a pre-chamber.

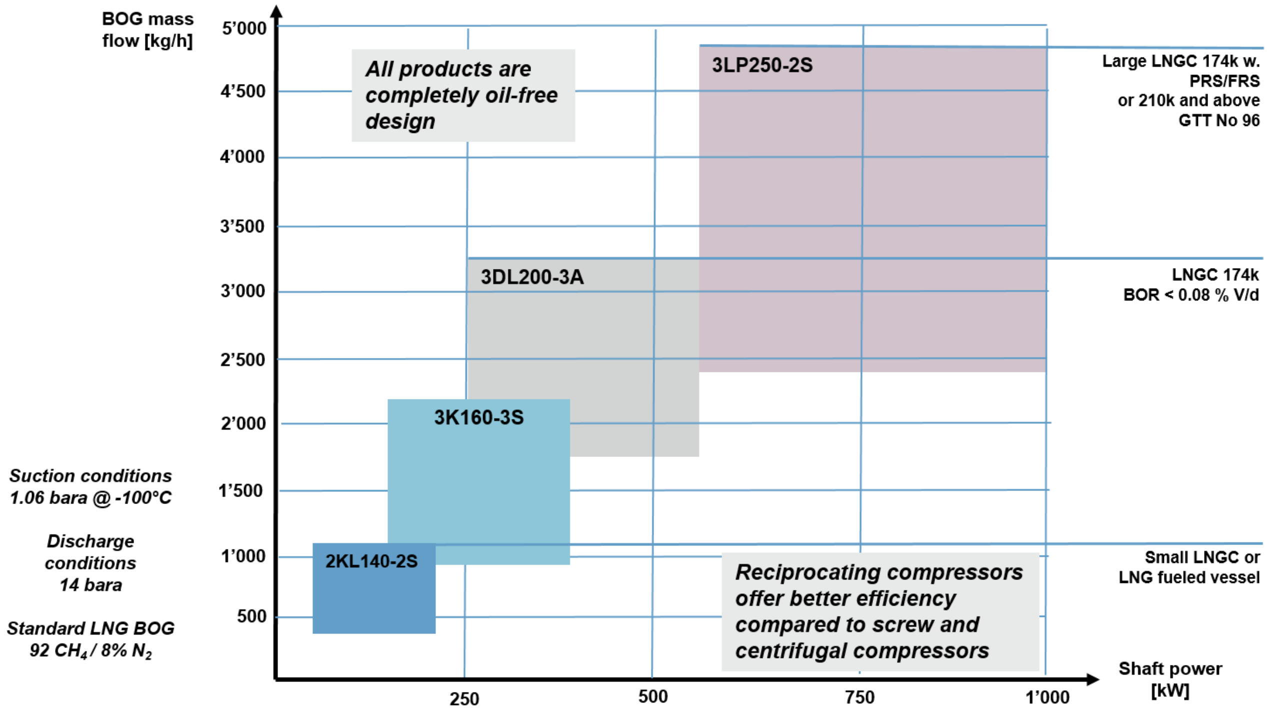

Figure 19: *Compressor solutions for X-DF engines*

The fuel gas supply system has, to date, been equipped with either centrifugal or screw type compressors. An alternative reciprocating piston compressor, based on Burckhardt Compression's contactless Laby® labyrinth sealing technology, offers distinct advantages and is now available for order for fuel gas supply to the WinGD X-DF engine. The design draws directly on the well-known Laby® Compressor, used extensively in LPG shipping and refrigeration applications.

LPG containment systems are typically designed for liquid storage temperatures down to –40 °C. For large LNG ships with membrane tanks and liquid storage as low as –160 °C, obviously different materials are applied for LNG. Low temperature casting materials, analogue to the Laby® and Laby®-GI Compressors, are again used and provide a well-proven and robust cylinder for the wide range of operating temperatures and pressures experienced.

A discharge pressure of 14 bar normally requires two stages of compression for cold BOG compression. Intercooling is provided between stages and an aftercooler at the 3rd discharge stage. Since the compressor can operate over the full range of suction temperatures, a suction line pre-heater is not required. This item is normally necessary for screw compressors, where the suction temperature is limited due to constructional restraints. A pre-heater however, acts to reduce the density of the inlet gas at the compressor, thereby, for a given mass flow rate, increases the actual volume flow to be compressed. This in turn increases the shaft input power of a screw compressor.

Capacity control for the reciprocating compressor is facilitated by a bypass line around the first stage. This process flow arrangement, including 1st and 3rd stage bypass lines, results in a compression system which is fully flexible in all possible modes of operation from start-up with warm gas to full load at cold, maximum flow, capacity turndown. The power requirement at full load and part load is the lowest available for WinGD X-DF fuel gas supply. Combined with simplicity in design, operation, and control of capacity and pressure, makes the Laby® Compressor a highly attractive alternative for the fuel gas supply to WinGD X-DF engines.

A wide range of frame sizes is available covering ship sizes from 5k – 210k. A first Laby® Compressor reference for WinGD X-DF ship propulsion is soon in operation.

10 Laby®-GI Service Experience

In November 2015, a team of experienced and carefully selected Burckhardt Compression service specialists joined the first ever gas trial on a MAN ME-GI propelled LNG carrier, with a Laby®-GI fuel gas supply compressor system installed. In the meantime, up to date a fleet of 40 LNG carriers have entered operation. 56 compressors are in service and 400'000 operating hours have been accumulated.

A number of compressors completed the regular maintenance after 20'000 operating hours. Concerned machines have undergone precise inspection. Replaced parts have been examined closely to determine rates of wear and as a consequence, expected lifetime and service intervals for key compressor components could be prolonged.

Compressor parts	See manual chapter	Regular maintenance action required	Overhaul interval (hours) - as per manual status 2014	Overhaul interval (hours) - as per manual status 2017	Updated inspection interval (hours) - as per Service Experience	Updated expected service life time (hours) - as per Service Experience
Crank gear						
Crankshaft	8.8.1	Check deflection	-	-	-	-
Main bearings and connecting rod bearings	8.8.2	Check clearances w/o removing	16'000	18'000 →	20'000	80'000
Main bearings and connecting rod bearings	8.8.2	Remove some bearings, spot check	24'000	-	cancled	80'000
Crankshaft seal	8.8.3	Replace if required (depending on leak rate)	-	30'000	continuous	40'000
Crosshead	8.8.5	Check clearances w/o removing	16'000	18'000 →	20'000	80'000
Crosshead pin bearing	8.8.6	Check clearances w/o removing	16'000	18'000 →	20'000	80'000
Guide bearing 1st to 3rd stage	8.8.7	Check clearances	8'000	18'000 →	20'000	80'000
Oil scraping 4th/5th stage	8.8.8	Replace when piston rod is removed	-	18'000 →	20'000	20'000
Wiper elements 1st to 3rd stage	8.8.9	Replace when piston rod is removed	-	18'000 →	20'000	20'000
Cylinder						
Piston rod	8.9.1	Remove piston, check surface quality	16'000	18'000 →	20'000	40'000
Piston rod gland 1st to 3rd stage	8.9.2	Replace if required (depending on leak rate)	-	-	20'000	40'000
Piston rod packing 4th/5th stage	8.9.3	Replace (inner parts)	16'000	18'000 ←	16'000	16'000
Cylinder liner 4th/5th stage	8.9.5	Check diameter and surface quality	16'000	18'000 →	20'000	60'000
Labyrinth piston	8.9.4	Check pretension	16'000	18'000 →	20'000	40'000
Ring sealed lubricated piston	8.9.5	Replace piston rings and guide rings	16'000	18'000 →	20'000	20'000
Piston clearance measurement	8.9.6	Check clearances TDC/BDC	16'000	18'000 →	20'000	-
Cylinder clearance measurement	8.9.7	Check clearances TDC/BDC	16'000	18'000 →	20'000	-
Suction and discharge valves	8.10	Check valves	8'000	6'000	cancled	cancled
Suction and discharge valves 1st to 3rd stage	8.10	Replace valves - installed valves can be refurbished	8'000	18'000 ←	16'000	16'000
Suction and discharge valves 4th/5th stage	8.10	Replace valves - installed valves can be refurbished	8'000	18'000 ←	12'000	12'000

Figure 20: *Guiding overhaul intervals for Laby®-GI compressors (reference type 5LP250-5B_1). Prolonged intervals are indicated with green arrow*

Apart from available learnings coming from routine inspections, large knowledge was acquired from daily operations. As for every new technology being introduced - tuning, adjustment and modification of the system and its key components is required to achieve target performance and reliability of the product.

A number of major milestones in the learnings and developments of the Laby®-GI fuel gas supply compressor systems based on gathered service experience shall be reviewed within this chapter.

10.1 Availability and reliability

During the development phase of the application, yards and owners predicted a utilization of 6'000 hours per year for the Laby®-GI fuel gas supply system. Actual service experience however displayed that single compressor systems are accumulating much more than 7'000 hours per year. In average, compressors are up 24/7 when sailing in laden conditions (740 hours per month) whilst during ballast conditions the utilization is reduced to 500 hours per month. This experience is reviewing the conditions when sailing between U.S. hub Sabine Pass to terminals in Japan, China or Korea.

Since the systems do not ask for maintenance for a period of 16'000 hours, the general availability is high. Unexpected stops for component replacement or repair however are reality but are considered as manageable. Reviewing the present experience of 300'000 operating hours on the compressor type 5LP250, the majority of experienced downtime can be assigned to the later described failures of the high-pressure packing, compressor valve failures and a number of issues mainly related to failing instrumentation and controls.

The high-pressure packing issue is considered as resolved. With an extensive replacement campaign, new packings for all concerned compressors have been made available within the period of mid-2018 to mid-2019.

Analyzing the total of more than 300'000 operating hours accumulated on compressors of type 5LP250-5B_1, the reliability of the product is calculated to above 98%.

10.2 Compressor Valves

Compressor valves are commonly known as the no. 1 reason for downtime of reciprocating compressors. A failure statistic reviewing the service history of all Laby®-GI compressors of type 5LP250-5B_1 counts a total of 936 valves installed. A total of 50 valves had to be replaced during the complete operating period of 300'000 hours. At a first glance, this number appears to be high. However, it must be considered, that whenever valves are installed in pairs, many times they will also be replaced in pairs, even though only one of the two valves is defect. This is mainly related to the fact that once the compression room housing the defect valve is identified, it is difficult for the crew to distinguish which of the valves is finally accountable for the poor compressor performance. Thus, in most of the cases both valves are replaced at the same time. Taking this fact into account, it must therefore be assumed, that the number of failed valves is not identical with the number of valves replaced.

Investigating the reason behind the early failing of the valves, it was recognized that especially valves in the high-pressure section of the compressor are concerned (stages 4 and 5). Dismantling inspection of the valves displayed that the valves were found excessively covered by oil. The presence of lubricant in the valve is generally considered as undesirable and harmful. Reduction of lubricating rates already decreased the oil feed rate to the cylinders to a minimum. Therefore, the performance of the compressor valves in the lubricated high-pressure stages of the compressor is still under investigation.

It is needless to say, it must be expected that by the introduction of dry-running ring-sealed technology for the next generation of Laby®-GI compressors the lifetime of the high-pressure compressor valves will benefit as well from the absence of the oil.

Overall, it must be recognized that the present service experience with valve failures is insufficient to conclude on a root cause. This, since valves of different types and sizes (suction, discharge, various stages) are involved. Since a larger number of issues was experienced during the first 8'000 operating hours of the compressors, it must be expected that failures are related to the common "shakedown" of the system after commissioning. In this period, valves have been subjected to unstable commissioning activities and foreign matters and particles remaining from piping and pressure vessel fabrication processes (e.g. residues of blasting material).

Proper analysis and record keeping for systematic study of occurred issues is a part of the ongoing improvement campaign. All valves affected from pre-mature wear are sent back for detailed inspection to a Burckhardt Compression valve service center.

10.3 Pressure relief valves

Every compressor stage must be equipped with a pressure relief device on the discharge side. Typically, spring loaded safety valves in accordance with API 526 standard are applied. Proper selection of the set pressure of each relieve valve is paramount to allow ideal system protection on one side (maximum pressure permitted by the weakest component in the system), but also to avoid undesired opening of the safety valve during dynamic pressure fluctuations in the system during short-term upset conditions.

Especially for safety valves located in the high-pressure system of stages 4 and 5, defining the correct set pressure must consider the typical characteristics of API pressure relief valves. If only normal operating conditions are considered when defining the set pressure, safety valves might start leaking or even completely relief in case of short-period pressure peaks occur. Due to the high dynamic nature of the fuel gas consumption of the MAN ME-GI propulsion system under certain load conditions, experiencing pressure peaks in the fuel gas supply however is unavoidable.

The dynamic response of the system during operation can hardly be simulated for all possible operating scenarios in advance. Present service experience has displayed that it is essential to provide an adequate span between calculated maximum operating pressure to the set pressure of the safety valve.

The set pressure of the 5th compressor stage is pre-defined at 330 bar by general design restrictions within the fuel gas supply system. This conflicts with the above stated recommendation for an adequate span between the operating and set pressure, as the maximum operating pressure in the gas delivery to the MAN ME-GI engine can reach a level up to 315 bar. In such cases, where the offset between the maximum expected operating pressure is less than 10% of the set pressure, pilot operated valves must be applied.

To further protect installed safety relief valves from undesired opening and gas relief, optimization of the control of the system was required. Analysis of events causing inadvertent relief of valves in the high-pressure section of the system displayed, that the event causing the relief is not located inside the compressor system itself, but in the downstream fuel gas supply system. So-called "gas trips" - immediate shut-down of the fuel gas supply to the MAN ME-GI engines - might occur due to a number of reasons not related to the compressor. If, however, the compressor system is not able to respond timely to a gas trip, discharge pressures inside the compressor system are in a sudden burst reaching the set-pressure level of installed safety relief valves (keep in mind: there is no buffer volume installed in the downstream fuel gas supply system).

Remedy on this issue was found by improvements on linking the both control systems for the downstream fuel gas supply and the engine control to the Laby®-GI compressor control respectively. Instead of solely relying on the fuel gas supply pressure signal, inputs from the external fuel gas supply system have been directly implemented to manipulate the compressor capacity control.

Close cooperation between involved parties - crew, the engine maker, yard, IAS supplier and compressor maker - is indispensable for proper analysis and system improvement as exemplary displayed on this issue. Each party supported the problem analysis, solution finding, and implementation process based on the jointly collected service experience. It must be mentioned, that the key role is assigned to the ship crew, having the most difficult task to report experienced incidents in a detailed and self-explanatory way to the supporting teams ashore. Well-trained and excellently educated, highly motivated chief and cargo engineers have displayed this capability many times.

10.4 Lubricant selection

Lubrication of Laby®-GI Compressors must be divided into two sections: crankgear lubrication and cylinder lubrication. For gas-tight Laby®-GI compressors it is essential that the applied lubricant for the crank gear is carefully selected, as the process gas (methane) is in direct contact with the lubricant.

Low solubility of the gas in the oil drives the selection of the correct lubricant for the crankgear lubrication. For the lubricant applied to the cylinder lubrication, low solubility of oil in the gas must be considered. When discussing solubility issues between lubricants and process media, process pressures and temperatures play a major role. This must be especially considered for the lubrication of the high-pressure stages 4 and 5, where lubricant is in contact with methane at pressure levels up to 300 bar and temperatures around 150 °C.

Synthetic lubricants of type PAG (Polyalkylene Glycol Lubricants) offer best characteristics to be applied for hydrocarbon applications at high pressures. The synthetic nature of the lubricant reduces the solubility with the natural hydrocarbon to a minimum. At the same time, vapor formation of the lubricant at supercritical conditions is low, compared to mineral oils. Both factors play an essential role when it comes to the separation of the cylinder lubricant from the gas.

As the boil-off gas is not exclusively used as fuel and Laby®-GI Compressors are commonly applied to partial re-liquefaction systems, the cylinder lubricant must be removed from the gas to the maximum possible degree. Oil carried within the gas to the re-liquefaction system will cause fouling in the heat exchanger (cold box) and cause clogging of equipment in the liquid section of the re-liquefaction unit. Intensive research and testing has revealed, that PAG oil offers the best characteristics to allow stable and efficient separation of the oil from the gas.

The use of synthetic lubricants for the crankgear lubrication however is not mandatory. Mineral oils show very low solubility with methane under the given process conditions inside the compressor crankgear.

10.5 Reduction of cylinder lubrication rates

Cylinder and packing lubrication are applied on the high-pressure stages 4 and 5. Lubricating feed rates are pre-calculated as per detailed engineering guidelines during the development process of the product.

Cylinder lubricant however is a costly utility to the operator of the system. Optimizing the oil consumption is therefore in the focus once first operational experience is available. The optimal cylinder lubrication rate was determined for first Laby®-GI Compressors after around 4'000 operating hours, after completing the running-in period of sealing rings and cylinder liner.

To determine the grade of lubrication, wetting of the liner surface is checked by visual inspection. A special wipe test applying absorbent paper provides the required information for excessive lubricant on the cylinder liner. In case of the Laby®-GI, a series of field test allowed to reduce the cylinder and packing lubrication rates by 25% for compressors of type 6LP190 and by 40% for compressors of type 5LP250.

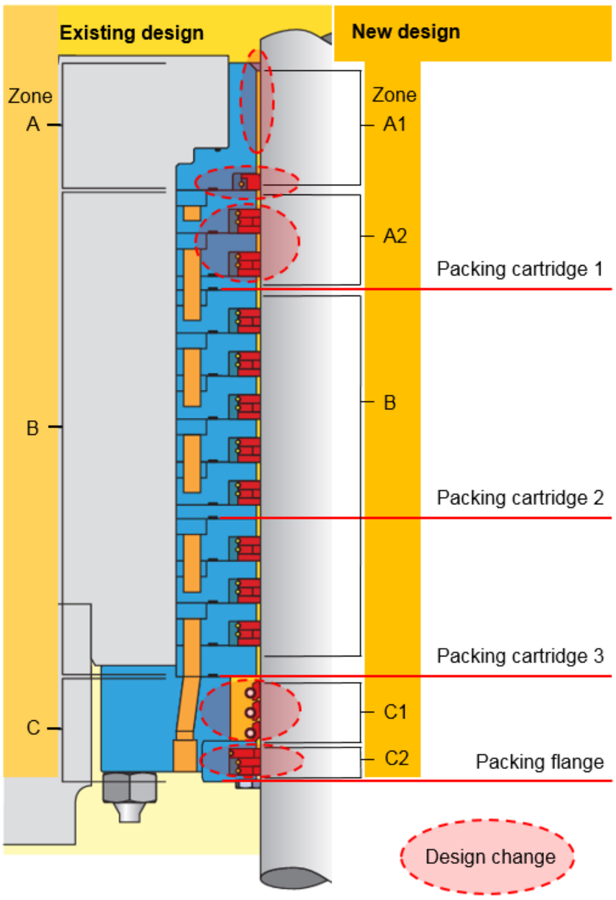

Figure 21: *Piston rod packing (typical view)*

10.6 Development of a new high-pressure piston rod packing

The high-pressure piston rod packing installed on the dual-piston high-pressure stage of the Laby®-GI Compressor seals the compressor system with a dynamic pressure of 300 bar and a static pressure of 105 bar against almost atmospheric conditions. Accordingly, the mechanical load on the rings in the upper area of the packing arrangement is high.

A number of high-pressure packing failures due to mechanical fatigue of sealing elements were recorded after an operating period of approximately 4'000 to 8'000 hours. The analysis of the packing failures and its related consequential harm to the compressor system revealed, that a change of both applied sealing element technology and packing bush design was required.

The high-pressure piston rod packing configuration consists of three different zones. Zone A houses the so-called pressure breaker elements. These elements are directly exposed to the dynamic pressure of the 5th stage. Zone B is housing a number of sealing elements, followed by Zone C – the lower section of the packing where the leak gas is collected and led away to the leak gas recycling system.

The failure modes of examined packings displayed, that the 3-segment pressure breaker rings in Zone A collapsed, releasing their tension spring towards the oscillating piston rod. The fragments of the collapsed rings and the spring travelled into the compression room, where subsequent damages to piston rings and compressor valves where caused.

After a detailed root cause analysis of experienced, early packing failures, the following changes have been implemented:

- Pressure breaker design was changed from 3-segment to single-piece design
- Pressure breaker Zone A was extended (Zone A2)
- Sealing elements in Zone A2 are new hold together by solid tension rings instead of tension springs
- Packing bush Zone A inner diameter was reduced (blocking loose parts from travelling into the compression room)

The new packing design was released after a series of tests and a large replacement campaign was initiated by mid-2018. Up to date, due to the pro-active campaign, no further down-time due to high-pressure packing issues was recorded.

10.7 Development of a multi tool

In combination with the service activities around the replacement campaign of the high-pressure piston rod packings, a demand for a tool allowing removal of the high-pressure piston rod packing without opening of the compressor room hatch and use of the deck-crane was discovered. The

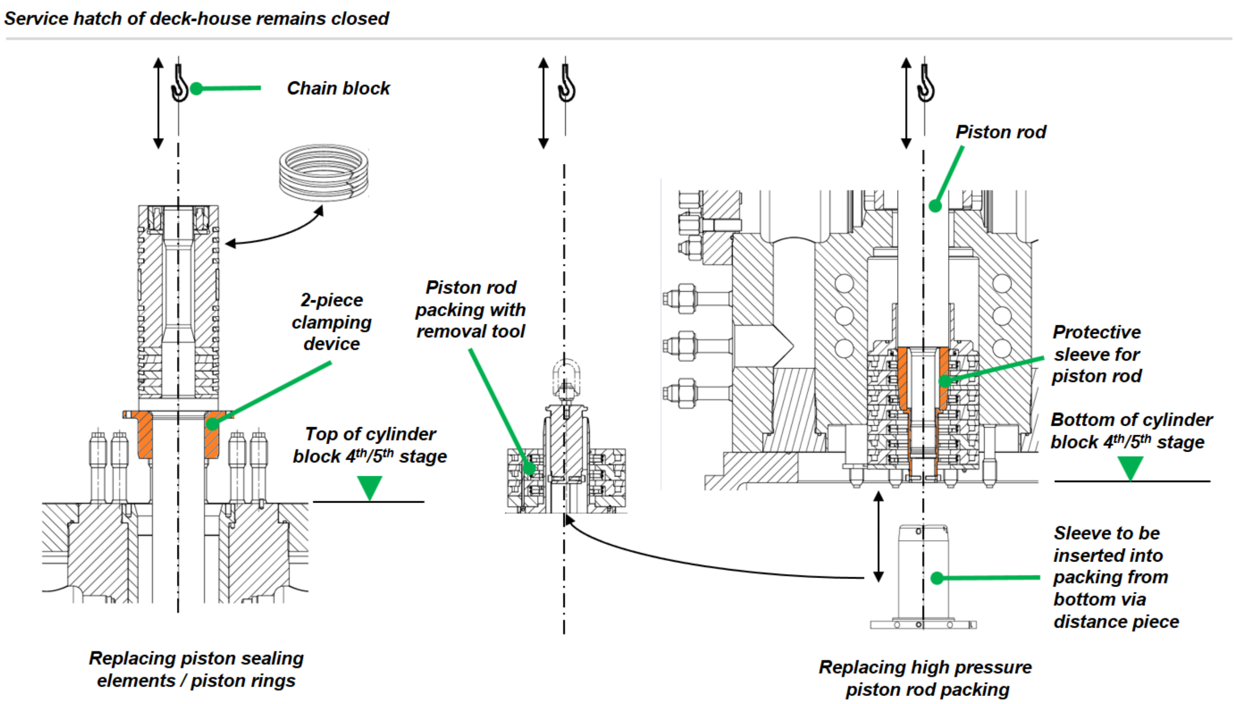

***Figure 22:** Multi tool for piston ring and packing service*

requirement for hatch opening makes every service intervention dependable on weather conditions. To allow service on the compressor pistons at every time, independently from the weather, a solution for lifting the piston of the high-pressure stage with a chain block mounted on lifting eyes located on the ceiling of the cargo compressor room was required.

The developed tool simplifies the maintenance activities on the high-pressure stage in two ways. For replacement of the sealing elements on the piston, the piston assembly can be fixed on top of the cylinder bore with a 2-piece clamping device, allowing safe access to the piston area without removing the piston assembly from the compressor. To remove the high-pressure packing from the cylinder block, a tool was developed allowing to lower the packing segments by utilizing the piston rod itself. Figure 22 illustrates the two maintenance activities applying the developed multi tool.

10.8 Aspects of vibrations

Reciprocating compressors are commonly known as the source for vibrations. The fully mass balanced design of the Laby®-GI Compressor series reduces the source of vibrations to pressure pulsations. Sophisticated, in-house pulsation and vibration studies and optimization of both structure and piping layout reduces the level of vibration to a minimum. Avoiding natural frequencies within the piping system and for structural members is a key factor to success.

Installed on a ship deck structure, the compressor is not the only source of vibration on the LNG carrier. 4-stroke diesel generators, 2-stroke engines and the propellers cause additional impact on the system.

Whilst ship structure, sensitive membrane cargo containment systems, cargo and fuel gas piping systems remained unharmed by fatigue cracking, it was recognized that especially process instrumentation and control electronics located within the compressor system are the source for downtime based on vibration issues.

Process instrumentation sensors are provided with test certificates for vibration resistance. However, whilst sensors themselves remained unharmed by vibration levels, especially the instrument mounting for standard temperature sensors displayed weakness in design. The same was experienced for communication processor modules (CPM) and remote I/O modules installed in local cabinets.

Temperature sensors fractured on the connection of the sensor housing to the thermowell. Electrical modules became loose and lost connectivity. Both issues resulted in line fault errors in the IAS and consequentially led to an uncontrolled compressor shut-down.

Close cooperation with related component makers was required to improve the given design and increase the robustness of the installation. Various tests were required to conclude on the final solution.

In the meantime, all Laby®-GI units are provided with vibration-proof sensors and electrical systems. Comprehensive vibration analysis of the compressor systems revealed that all vibration levels are within common limits.

10.9 Global service network

Being a well-known and experienced service provider with more than 750 service employees worldwide for stationary onshore installations in the industrial, petrochemical and refinery industries is a fair starting point to establish services in the marine industries. But to provide good service to marine customers, it takes much more: 24/7 callable support engineers, global coverage of services at most frequented shipping routes and LNG hot spots, prompt availability of spares for compressor and accessories, skilled and seamanlike thinking service engineers and last but not least the endurance and attitude it needs to cooperate in such a demanding and highly dynamic business environment.

Starting with a selection of a handful of people, Burckhardt Compression has established a global network of more than 60 specially selected and trained service engineers. Specialized service hubs have been set up at striking locations such as Busan (yard commissioning activities, Asia/Pacific region), Singapore (Asia/Pacific region), Dubai (mid-East area), UK (Northern Europe), Spain (Southern Europe, Mediterranean Sea) and Panama (Gulf of Mexico).

Close cooperation with the engine maker's service department MAN PRIMESERV additionally strengthens the position of Burckhardt Compression as a service provider.

Emergency spares are kept in service hubs close to marine traffic routes, a large spare parts center was set up and keeps further growing at Burckhardt Compression headquarters in Winterthur, Switzerland. Local logistics at the hub Winterthur allow fast and efficient dispatch of parts via the closely located Zurich airport to any destination worldwide. Having the expertise of being well-trained in fast-track shipping of parts to all regions of the world, Burckhardt Compression can benefit from its existing shipping and logistics network. Close cooperation with ship owner's agents however is unavoidable to finally launch the parts to the final destination onboard.

11 Conclusions

A new compressor family based on Laby®-GI Compressor frame size LP250 is introduced to the market. Both MAN ME-GI and WinGD X-DF ship propulsion systems are considered in the individual package designs. The compressor packages have been simplified and improved, based on experience from more than 400'000 hours of operation. For ships employing WinGD X-DF propulsion, the well-known Laby® Compressor design is applied and is already referenced on small scale LNG shipping. The benefits for the ship owner of selecting the Laby® Compressor package type 3DL200 for large 174k WinGD X-DF powered ships without PRS and 3LP250 for vessels with PRS, are very compelling, and based on the well-proven design of the already applied K-type Laby® Compressor units.

A completely oil-free, Laby®-GI Compressor for 300 bar fuel gas supply to MAN ME-GI propulsion is now available. Oil separation and removal equipment in the compressor discharge and the reliquefaction system is no longer necessary, resulting in substantial savings in system complexity, maintenance and CAPEX.