**LNG Industry** asked several companies to discuss some issues regarding LNG compressors.

# COMPRESSORS Q&A

## Dominic Sarachine – Product Manager, Engineered and Air Separation
## FS-Elliott

Dominic Sarachine graduated with a BSc in mechanical engineering from Pennsylvania State University, US, and an MSc in mechanical engineering from University of Pittsburgh, US. He joined the FS-Elliott team in 2018. As the Product Manager of Engineered and Air Separation, he is responsible for developing a strategic vision for FS-Elliott's products to meet market demand in these segments, including centrifugal compressor products that support LNG production.

## Jens Wulff – Managing Director
## NEUMAN & ESSER

Jens Wulff, Managing Director of NEUMAN & ESSER Deutschland, is an LNG pioneer at the company, and has sold compressor units for various applications from small scale for trailer evacuation to big systems, as well as working on strategic market development of the $H_2$ economy. Jens has a degree in aerospace engineering from the German Armed Forces University in Munich, as well as an MBA from the University for Economics and Management in Essen.

## Joe Fernandez – Applications Engineering Manager
## Ariel Corporation

Joe Fernandez, P.E. is the Applications Engineering Manager for Ariel Corporation, leading a talented group of engineers tasked with helping customers achieve long-term success. Joe brings a wealth of experience in compressor design, application, optimisation, and packaging. He has helped Ariel build a reputation for developing compressors that maximise performance, reliability, and efficiency.

## Leonardo Baldassarre – Turbomachinery and Process Solution (TPS) Executive General Manager Engineering
## Baker Hughes

Leonardo Baldassarre is Executive General Manager Engineering at Baker Hughes, leading the platform dedicated to the development and enhancement of products, such as compressors, pumps, expanders, and electrical systems. He is actively engaged in energy transition areas, including hydrogen, CCUS, energy efficiency, and decarbonisation. He received a bachelor's degree in mechanical engineering in 1993 and a Ph.D. in fluid dynamics in 1998 from the University of Florence, Italy. He presently holds 15 patents, has authored or co-authored 50+ technical papers, and he is an active member of distinguished energy associations and technical advisory boards.

## Michael Drewes – Onshore LNG Market Manager
## Atlas Copco Gas and Process

Michael Drewes has worked as a professional engineer for more than a decade. In 2011, he joined Atlas Copco Gas and Process and was responsible for individual project proposals and framework agreements in the air separation market. Starting in 2013, he served customers with process gas compressor solutions for worldwide projects in the oil and gas market. In mid-2016, he was appointed Market Manager for fertilizer applications. Since early 2019, he has been responsible for the onshore LNG segment. Michael holds a master's degree in aerospace engineering from FH Aachen University of Applied Sciences, Germany, and has authored multiple conference papers and trade articles in the area of hydrocarbon processing.

## Tyler Rice – Application Engineer
## Mitsubishi Heavy Industries Compressor International

Tyler Rice is an Application Engineer at Mitsubishi Heavy Industries Compressor International (MCO-I). Located in Houston, Texas, US, he focuses on the design and preparation for unique technical solutions for customers on new equipment projects across a variety of process applications involving centrifugal compressors and steam turbines. Prior to his time at MCO-I, Tyler worked at Elliott Ebara for several years as an Application Engineer.

Tyler graduated from Texas A&M University with a BSc in mechanical engineering with a minor in mathematics in 2015, and an MSc in mechanical engineering in 2017. He is a member of the American Society of Mechanical Engineers (ASME) and a licensed professional engineer in the State of Texas.

# Compressors Q&A

## What factors are considered when deciding which compressor technology is needed for an application?

### Dominic Sarachine – FS-Elliott

Choosing the wrong compressor can cost a plant thousands in wasted energy and lost production time. A common misconception is to only consider upfront equipment costs, but many different factors need to be evaluated when determining which compressor technology is best for an application. The most important factors to consider with every new application are the compressed air requirements, flow demand, air cleanliness, maintenance requirements, energy consumption, and environmental regulations. For example, centrifugal compressors are suitable for continuous high-flow applications and provide efficient, oil-free compressed air. When selecting the best technology for an application, it must be kept in mind that while some units may require a lower capital investment, higher maintenance costs may be incurred. An example of this is any compressor that requires a separate oil removal system or a design that requires frequent airend replacements.

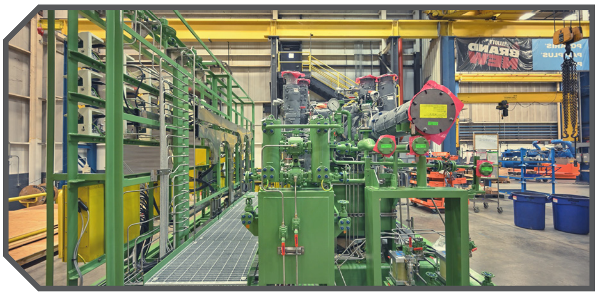
### Jens Wulff – NEUMAN & ESSER

Listed below are the advantages of reciprocating compressors:

- High-pressure ratio per stage.
- Medium to high flows with excellent efficiencies.
- Perfect metering of the flow.
- Perfect adjustment to varying suction and/or discharge pressure without additional measures and without loss of efficiency (by self-actuating valves).
- Perfect options available to control the flow without loss of efficiency.
- Almost no leakage losses.
- Low sensitivity to intermittent operations with many start/stops.

Here are the advantages of centrifugal compressors:

- Small dimensions.
- Huge flows are possible with reasonable compressor dimensions.
- Continuous flow (no pulsations) with low tendency of pipe vibrations.
- No inertia loads (small foundations) with no tendency of compressor and foundation vibrations.
- Very reliable with lowest maintenance effort.



FS-Elliott: This compressor package designed for a Middle Eastern oil refinery features an extensive instrument rack with transmitters for local monitoring and a walkway platform for easy maintenance access. This compressor was also specially designed to use fan-cooled, air-to-air heat exchangers for cooling between each compression stage. This package highlights FS-Elliott's ability to accommodate rigid customer specifications and unique operating parameters.

### Joe Fernandez – Ariel Corporation

The primary considerations in compressor selection are inlet and discharge pressures, coupled with required throughput. These factors will determine the best technology for the project, as well as the size and number of units required. Positive displacement compressors, such as reciprocating compressors, are well-suited for high discharge pressures and moderately high throughputs. Reciprocating compressors are highly efficient and highly configurable, allowing operators to customise their unit for wide ranging flows and pressures. Rotary screws are more appropriate for low inlet pressures and very high throughputs at lower discharge pressures. Dynamic compressors, such as centrifugals, are designed for very high throughputs and moderately high discharge pressures. Axial compressors provide the highest throughput capabilities with considerably lower compression ratios. Another consideration is the type of prime mover needed. Natural gas engines and electric motors are well suited for driving reciprocating and rotary screw compressors, whereas if a turbine is being used, a centrifugal compressor is a better solution.

# Compressors Q&A

**A** **Leonardo Baldassarre** – Baker Hughes

When deciding which compression technology is best suited for a project or specific application within a project, several factors are considered. But two criteria sit at the top of the hierarchy at the same level: efficiency and reliability. This explains the efforts by Baker Hughes to continuously develop new solutions and new aerodynamics to always achieve greater results. These efforts also call for ongoing investments to validate developments while maintaining reliability at the top of the hierarchy. That calls for a deep knowledge of certain aspects related to rotordynamics, operability, etc. that need to be guaranteed here.

**A** **Michael Drewes** – Atlas Copco Gas and Process

There are several kinds of compression technologies, including screw, reciprocating, radial, and axial centrifugal. They all have their own advantages regarding process parameters, such as for pressure, temperature, and flow. There are in addition overlapping areas that allow the use of different technologies for the same applications. Further parameters such as CAPEX and OPEX also come into play, as do energy costs at destination and whether the compressor is OEM standard or highly customised. Atlas Copco Gas and Process advises customers to look for the overall lifecycle costs rather than to just focus on one of the factors. The lifecycle of an integrally geared compressor comes with high efficiency and good maintainability at long service intervals.

Efficiency, footprint, seal-leakage rates, noise emissions, and the gas type are vitally important factors in helping decide which is the right technology type. The reliability of a compressor also plays an important role, simply because downtime is costly. For all the above, integrally geared centrifugal compression technologies are a top choice.

For some customers, the OEM's reference base combined with an appetite to improve can also be a decision factor. Often, early adopters of new technologies are followed by others. Finally, it could also simply be a customer preference for one special type of compression technology.

**A** **Tyler Rice** – Mitsubishi Heavy Industries Compressor International

There are several factors to consider in determining the appropriate compressor technology. The type of compressor is typically decided upon depending on the compressor inlet flow and compressor discharge pressure. For example, screw type compressors are utilised in relatively low-flow/low-pressure applications where centrifugal type compressors are a better fit at relatively high-flow applications.

Equipment speed is another factor that must be taken into account when deciding on technology. For example, when the gas turbine is used as the compressor driver, the gas turbine has its design speed and usually is operated at almost fixed speed (a small percent speed change tolerance). The driven equipment (compressor) speed needs to be aligned with the turbine speed and therefore compressor design needs to be verified to accommodate several operating conditions (e.g., seasonal load change) during the design phase. When an electric motor is selected as the driver, its speed is dictated by the frequency of the grid in general and the compressor is more freely designed to the most efficient speed by introducing a speed increasing gear. Additionally, the process gas in LNG processes usually does not allow for oil mist contamination, although some types of compressors have a chance of oil mist (lube oil) migrating into the process gas. This is another area that needs to be considered when choosing compressor technology.

## Q Different situations release different amounts of BOG. How can compressors handle these changing conditions efficiently?

**A** **Jens Wulff** – NEUMAN & ESSER

Different scenarios of LNG systems cause changing amounts of BOG at varying pressures, temperatures, and changing flows. The most common state-of-the-art compression principles are centrifugal, screw, and reciprocating piston compressors. With piston compressors, as of NEUMAN & ESSER design, there are a wide range of flows covered.

Being sustainable with a compressor unit and flow control means always following the required volatile operation scenarios as efficiently as possible.

It starts with selection of a dedicated number of stages and cranks and an appropriate size and construction type. Typically, a well-designed contact ring piston compressor system offers isothermal efficiencies at approximately the 80% range. On top of that, there is an assortment of capacity control measures available.

Simple ones are bypass and clearance pockets; suction valve unloading in steps is already getting more efficient. Looking at top efficient methods, it ends up at a stepless system via hydraulic or electric actuated valve unloaders. This system allows the flow to be reduced steplessly down to a minimum of 20% partial load, simultaneously reducing the power consumption by a similar amount. In addition, this is independent from actual pressure, temperatures, and pressure ratios in all stages.

So, one of the most sustainable compression principles is a reciprocating compressor combined with a stepless valve unloader system.

To make this even more sophisticated, it is possible to create a hybrid package which combines different compression principles. For example, a centrifugal compressor followed by a reciprocating piston in a send-out application on an FSRU. Or a piston compressor followed by a hermetically sealed diaphragm compressor in high-pressure applications such as MEGI engines in propulsion systems.

### A: **Joe Fernandez** – Ariel Corporation

Several different strategies and systems are used to optimise compressor flexibility when dealing with varying flows and conditions. One of the simplest and most effective ways is to vary operating speed. Electric motors with variable frequency drives are used extensively for this purpose. Natural gas engines also have variable speed capabilities, which are used to handle changes in throughput. Other methods of handling varying gas flow is by using capacity control devices. These devices enable the unit to be sized for the maximum throughput, then employ the device to reduce flow as needed. Reciprocating and rotary compressors both have capacity control capabilities available. A preferred method of capacity control for reciprocating compressors is to use additional clearance to effectively reduce the amount of gas being drawn into the cylinders. This is a very energy-efficient method which provides considerable flexibility for changing flow requirements. Rotary screws use a slide valve, which internally bypasses gas from varying locations along the screws, back to suction, thus reducing the amount of throughput delivered at discharge. This method is also very energy-efficient. Other less efficient ways to handle different volumes of gas include external bypasses and inlet pressure throttling.

### A: **Leonardo Baldassarre** – Baker Hughes

Talking about BOG in particular, rapidly changing conditions are particularly true for these machines. Movement from very cold conditions (significantly below -100˚C) to hot conditions creates challenges either in terms of gas velocities at the inlet (volume flows), impeller mach numbers, and significantly different achievable pressure ratios. Usually, these machines are equipped with variable geometries at the inlet – inlet guide vanes (IGVs)– in order to efficiently adapt volume flows and pressure ratios. In addition, Baker Hughes' impellers and stages are designed to maximise operating range. These rapidly changing temperature conditions also call for a very accurate and proven selection of materials and definition of any clearances inside the machine to avoid potential rubbings and failures.

### A: **Michael Drewes** – Atlas Copco Gas and Process

Atlas Copco Gas and Process engineers have a big toolbox for integrally geared compressors when it comes to the selection of the appropriate control mechanism to fit different BOG flows and usages. A compressor can be selected for IGV control, diffuser guide vane (DGV) control, bypass operation, throttle operation, and speed control. Atlas Copco Gas and Process has also built machines with a combination of different control mechanisms to further widen operating ranges. Together with the customer, the company identifies process requirements, which can vary from single-stage, low-pressure boil-off compression for re-liquefaction up to eight-stage, high-pressure BOGs for use as fuel.

Atlas Copco Gas and Process has supplied BOG machines with suction temperatures down to -251˚C (22.15 Kelvin), which includes workshop cold gas tests. For use as fuel, six-stage compression has been supplied, which combines cryogenic and non-cryogenic stages on one single compressor gear.

Another smart solution to cope with varying amounts of flow is to combine Atlas Copco Gas and Process screw compressors for low-duty BOG needs with a single-stage integrally geared compressor, typically for high-duty needs with LNG carriers.

NEUMAN & ESSER: Piston rod pressure packing by STASSKOL to seal suction and discharge pressures against atmospheric pressure of the distance piece.

## Q: How are compressor lifecycle costs kept to a minimum?

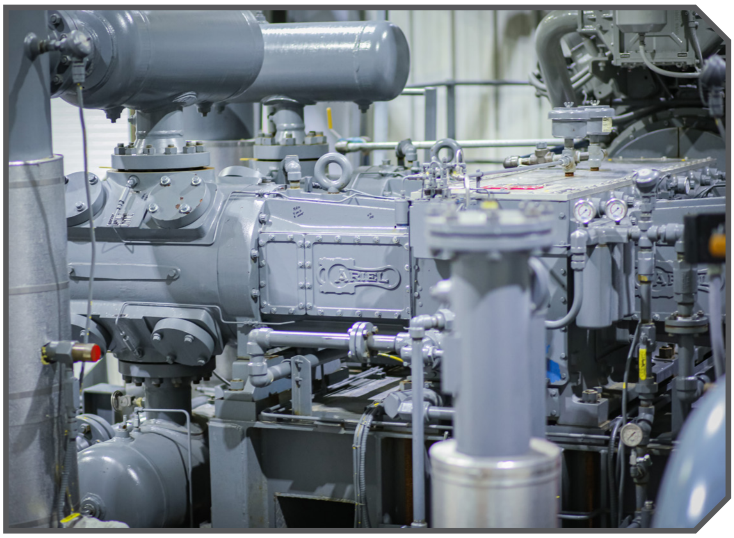
### A: **Dominic Sarachine** – FS-Elliott

Compressor lifecycle costs can be kept to a minimum by following proper routine maintenance recommendations. Many compressors offer optional configurations that allow the end user to perform routine maintenance activities without requiring the compressor to be removed from service, reducing costly downtime. Additionally, there are a variety of key indicators that can be monitored on a compressor to ensure the health of the compressor. Control systems can offer further reliability and lifecycle cost savings while monitoring some of these key indicators. A control system can monitor the most critical parameters and proactively identify when maintenance is required.

## A Jens Wulff – NEUMAN & ESSER

Key to tackle the lifecycle cost is a regular and very qualified maintenance service by the OEM to prevent any unplanned shutdowns or damages. Furthermore, the selection of materials and newest state-of-the-art technology need regular communication with the OEM service team, and the operator therefore will need to always be agile and adaptable. NEUMAN & ESSER can support with a complete maintenance strategy, including remote online monitoring and spare parts management, to effectively reduce the lifecycle cost.

In this context, digital maintenance concepts and respective repair support for compressor plants are becoming vital.



Ariel Corporation: Ariel Compressor in reliable, efficient service.

NEAC Compressor Service together with NEA X Digitals have delivered a digital platform solution that supports service engineers in monitoring and diagnosing machine performance: XPLORE provides instant and quick access to crucial information in a continuous asset health management, and is the core element of NEAC's integrated condition management service strategy.

## A Joe Fernandez – Ariel Corporation

Managing the operating and maintenance costs of a compressor begins when the unit is selected. Ensuring that the unit is conservatively sized to handle all potential operating conditions is the first step, with gas stream cleanliness being the second. For a reciprocating compressor, properly selecting valve springing, lift, and materials is paramount to ensuring maintenance costs are low. The piston rod packing cases must also be prudently selected based on the maximum operating pressures and speeds of the unit to ensure optimal service life can be achieved. Careful selection of lubrication based on operating parameters will also help minimise maintenance and keep operational costs down. After the unit is installed, it is important to have a detailed preventive/predictive maintenance programme to replace wear components at appropriate times before they lead to larger, more expensive problems or catastrophic failures. Onboard monitoring systems also enhance the maintenance programme by trending parameters such as valve and bearing temperatures, and inter-stage pressures, while also alerting operators when anomalous operational changes take place, enabling equipment operators to swap parts before a catastrophic failure takes place.

## A Leonardo Baldassarre – Baker Hughes

There are two main paths to minimise costs. One is through standardisation of components. The second is technological by making compression packages more efficient and compact. At Baker Hughes, this is called power density. To improve the technological cost out, rotational speeds must significantly increase to, in turn, increase the achievable pressure ratio on a single impeller and stage. The combination of both aspects provides on one side an increase in the efficiency of the compressor (related to specific flow increase, particularly true for medium-to-low specific flow applications – on medium-to-low-flow impellers this turns into a major efficiency benefit) and on the other, a reduction of the physical dimensions of the machine, i.e. weight and footprint. By working on power density solutions, Baker Hughes has been able to reduce weight and footprint by 40%+ and increase efficiency by 3 - 5 pts depending on the application.

## A Michael Drewes – Atlas Copco Gas and Process

Atlas Copco Gas and Process' integrally geared compressors are designed for specific jobs: each project receives a customised aerodynamic design to guarantee the best performance at the highest efficiency. This is done with modern design and simulation tools, such as the finite element method (FEM) and computational fluid dynamics (CFD) analysis. Special in-house design tools derived from the company's long experience are also central to building a reliable compressor.

Design features include gearing to allow optimal speeds for each pinion and possible intercooling between stages to allow close to isothermal compression. All this makes the integrally geared compressor one of the best in terms of energy consumption.

In addition, when plants run in off-design conditions, variable IGVs and/or DGVs make sure high performance and efficiency, plus the turn down operation, are kept at maximum possible performance.

An important factor regarding operating costs that is often not considered at the beginning is the loss of inventory out of the process or closed compression loop. When handling toxic or costly blended gas mixtures, ensuring the lowest leakage rates is of utmost importance. For this reason, Atlas Copco uses dry gas seals for shaft seal-leakage reduction.

To sum up, all the above play important roles when designing a new-build compressor. However, to keep performance high during a compressor's lifetime, Atlas Copco also offers TurboLink®, an operating data analysis tool. TurboLink enables customers to perform an initial data analysis when required, and for customers to do so independently. By reducing the onsite service hours required, TurboLink helps ensure a lower $CO_2$ footprint and improved OPEX.

### A **Tyler Rice** – Mitsubishi Heavy Industries Compressor International

The direct contributor to minimise lifecycle cost is the compressor/driver efficiency. High-efficiency equipment helps to reduce fuel cost and carbon footprint consequently. The operational efficiency can be a great tool when studying the costs of equipment over the decades of expected operation. Another key factor that has impact on lifecycle cost is the reliability/availability of the equipment. Unscheduled shutdown of the compressor train can have significant impact on operation. Obviously, it will require root-cause analysis to investigate the reason for shutdown and action is needed to enact countermeasures, thus losing plant production. An indirect impact of these unexpected shutdowns is the requirement to flaring of hydrocarbon gas when the compressor train is shutdown. With the recent considerations to reduce greenhouse gas (GHG) emissions, any unexpected shutdown of the compressor train has impacts to the lifecycle cost that must be considered.

## Q Describe some recent developments in compressor technologies.

### A **Dominic Sarachine** – FS-Elliott

Recent developments in compressor technologies have provided plant operators with improved predictive maintenance capabilities and allow customers to access real-time compressor data through a web-based connection anywhere in the world. The most up-to-date control systems offer energy advisor systems with predictive maintenance notifications to further improve reliability and decrease compressor downtime. Web-based remote monitoring also allows the operator to monitor compressor health and receive maintenance notifications anywhere in the world. These advancements in compressor controls allow the operator to react more quickly to required compressor maintenance, further increasing compressor reliability, resulting in potentially thousands in savings.

### A **Jens Wulff** – NEUMAN & ESSER

NEUMAN & ESSER serves the LNG application mainly through the contact ring technology. The modern sealing ring material technology, developed by the subsidiary STASSKOL, enables a very long lifetime of the wear parts. This is the result of the tribological research and development work on the tribometer and compressor test rig. Due to the low discharge pressures in the LNG application and the tribologically non-challenging gas methane, the contact ring technology reaches similar lifetimes as the labyrinth technology but with almost no leakage losses and thus higher efficiency. For this application, the labyrinth technology should not be the preferred reciprocating compressor technology.

### A **Joe Fernandez** – Ariel Corporation

Recent design and material changes introduced in reciprocating compressor packing cases have improved the service life of the packing as well as greatly enhanced the sealing capabilities, reducing fugitive gas emissions. Advancements in valve technology, including profiled plates, improved materials, and lift optimisation have doubled expected valve life with Ariel's CP technology. Another area of development has been in instrumentation and monitoring of reciprocating compressors. Newer systems, such as the Ariel Smart Compressor, are designed to monitor both the process parameters, such as gas pressures and temperatures, as well as equipment readings for bearing and valve temperatures and vibrations. Any significant changes or values outside of preset inputs will alarm logically and remotely, giving the ability to troubleshoot and correct potential field issues. Advancements in compressor capacity control are also worth noting. Automated variable volume clearance pockets are a significant example. Ariel's electronic variable control pocket (eVCP) allows the compressor to automatically and finely adjust throughput to meet varying conditions, saving energy, while maintaining optimal equipment utilisation.

### A **Leonardo Baldassarre** – Baker Hughes

There has been a focus on the utilisation of more compact compression technology in the area of rotor dynamics, with new machines that incorporate more stages in a more compact envelope. At Baker Hughes, a continuous development process in mechanics and aerodynamics has translated into the development of a new centrifugal stage: the High Mach T5.4 family provides more rigidity for the rotor in order to increase the number of stages or reduce dimensions while still improving efficiency. The T5.2 is a family for solutions with higher peripheral speed. The T5.3 is a solution for high mach number and for medium-to-high-flow applications. They perfectly fit on services such as propane or propylene. Where drivers are mostly aeroderivative gas turbines or electric motors, and when it is possible a direct drive on the compressor, the adoption of active magnetic bearings (AMB) on the compressor is the ideal solution to allow for a weight reduction of up to 10 - 15%.

## A **Michael Drewes** – Atlas Copco Gas and Process

Atlas Copco Gas and Process has recently delivered a cryogenic hydrogen BOG compressor with a suction temperature of -251˚C (22.15 Kelvin). This BOG compressor, now in operation on a vessel, highlights the capability of integrally geared compressors to work in the coldest temperatures. The compressor is a single-stage design, and it is used for reliquefaction of the gas at a low-pressure. In contrast, so called high-pressure BOG compressors can have six to eight stages and they compress the BOG to be further used (such as for fuel in engines). Existing references, including with $CO_2$, have proven the design's success for up to eight stages on one gear and 200 bar (2900 PSI).

For the LNG sector in particular, a high-capacity nitrogen Compander is currently under construction in the workshop at the company's headquarters in Cologne, Germany. Atlas Copco has also built refrigerant compressors with a driver power exceeding 30 MW. And for vessel BOG needs, there are combined low-duty screw compressors, plus single-stage integrally geared compressors for high-duty needs on LNG carriers.

## A **Tyler Rice** – Mitsubishi Heavy Industries Compressor International

MCO-I is pursuing the new type of hydrogen compressor for the future hydrogen society. Mitsubishi Heavy Industries (MHI), parent company of MCO-I, has announced net zero $CO_2$ emissions by 2040. MCO-I set the company's road map to support society as a group company of MHI. Hydrogen and $CO_2$ are the key enablers to achieve net zero and the company is challenging to deploy the new concept compressors by using its inherent technologies proved by experiences. With technologies such as high-speed impellers and a compact IGC design, the company has compressors ready for the energy transition market.

## Q Detail a short case study of a compressor installation at an LNG terminal.

## A **Dominic Sarachine** – FS-Elliott

In 2019, a new LNG plant development in British Columbia, Canada, required continuous, reliable instrument air to meet the demand of the entire plant, including the feed to the air separation unit (ASU). This plant was constructed in a modular design with tight space constraints and other comprehensive site-specific requirements, including human factors engineering (HFE) requirements for operator safety. FS-Elliott designed and supplied three main instrument air compressors and a closed-loop cooling system to support this new plant, with two units in continuous operation to each supply 50% of the total instrument air demand of the plant. The third compressor is a spare, but can also be put into operation quickly to supply additional air at peak demand. This FS-Elliott compressor package was custom designed to meet the strict project space constraints and detailed site-specific requirements while providing continuous, reliable air to the plant in the most extreme weather conditions.

## A **Leonardo Baldassarre** – Baker Hughes

Baker Hughes supplied two game-changing liquefaction mega-trains with an LNG capacity of 7.8 million tpy each – making Qatargas 2 the world's largest by a long shot.

Since the Frame 9E's (gas turbines drivers selected for this application) nominal rotating speed was 3000 rpm, larger compressors were needed to handle higher capacity with lower speed than previous LNG trains. That required unprecedented casing and impeller sizes up to 1800 mm – well within the capabilities of Baker Hughes' Florence, Italy, manufacturing facility that can machine compressor casings with internal dia. up to 12.4 ft (4000 mm), and 3D shrouded impellers with diameters exceeding 6.5 ft (2000 mm) from a single forging. Dry gas seals with internal dia. of 1.14 ft (350 mm) were also qualified. Each Qatargas 2 mega-train included six of Baker Hughes' centrifugal compressors:

- Propane cycle: 3MCL1403 + MCL1402.
- Mixed refrigerant cycle: MCL1805 + 2BCL1006.
- Nitrogen cycle: MCL1402 + BCL1003.

With thousands of running references, the company can ensure the highest availability at best performance. Advanced technologies and optimisation have enabled single-stage efficiency to be increased up to 6% since Qatargas 2. New robotic welding techniques guarantee lower cost, highest quality, and shorter manufacturing lead times.

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Baker Hughes' Power Density programme includes enhanced rotor dynamics and reduced casing sizes. Leveraging the latest manufacturing technologies, the company's new compression trains weigh less and require less raw materials, which reduces $CO_2$ emissions during production by up to 10%. Design improvements also optimise health, safety, and environment (HSE) aspects, simplify maintenance, while the machines' smaller footprint and dia. facilitates installation and maintenance ergonomics.

### A: **Michael Drewes** – Atlas Copco Gas and Process

Atlas Copco's integrally geared compressors and expanders can be used for various applications at LNG import and export terminals. Perhaps best well-known is the BOG compressor that is suitable for cold-suction temperature without pre-heating of the LNG. Variable designs, from one to eight stages, ensure a best fit for process requirements.

For reliquefaction with the nitrogen Brayton cycle, a Compander combines the compressor and expander stages onto one gear, which represents not just a smart solution but one that also provides the smallest footprint.

Another example is a pressure let-down (PLD) expander that can be applied at LNG terminals to produce energy, which is hugely attractive as companies look for efficiency and environmental benefits. This can be either in a separate cold Organic Rankine Cycle (ORC) with a seawater heat exchanger or as direct gas expansion. The first one uses a closed cycle with a turboexpander generator skid and a pump, in which the vaporiser uses the heat of sea water, and the condenser uses the cold energy stored in the LNG. The latter pumps the liquid LNG to an elevated pressure above pipeline pressure, evaporates it by a seawater heat exchanger, and then expands it via a turboexpander generator skid to pipeline pressure while providing electric energy via the generator.

All the above solutions can be applied to new plants as well as for the revamp of existing terminals to reduce its carbon footprint.

### A: **Tyler Rice** – Mitsubishi Heavy Industries Compressor International

Every project has unique backgrounds and considerations such as site location, environmental conditions, availability of labour, proximity to construction resources, local policy and regulations, and more. These all affect the design concept of any LNG project. With all of this in mind, there is no single answer for the best installation approach. MCO-I are seeing an increase in modularisation installations to minimise site activity required, but there are still customers working under the traditional stick build. Another important aspect of compressor installations is cost. A preliminary method to reduce cost is to minimise the number of equipment tags. MCO-I has many case studies using the H-100 gas turbine from the company's portfolio. The H-100 gas turbine is a two-shaft design and has the largest available shaft power as a mechanical drive turbine. Utilising this gas turbine for the LNG liquefaction process is one solution to pursue the economy of scale. While also having the design capability of starting on its own, using the H-100 gas turbine removes the need for electrical starting equipment and minimising the extra equipment needed at site.

## Q: How are compressors designed to minimise leakage and reduce emissions?

### A: **Dominic Sarachine** – FS-Elliott

Certain types of compressor technologies can offer more efficiency, thereby reducing overall emissions. For example, on average, centrifugal compressors are 5% more efficient than other compressor technologies. Although this may sound like a small number, it is critical to minimise harmful emissions as much as possible. The improved efficiency will result in lower energy consumption and less overall emissions.

Baker Hughes: High-pressure single casing motor-compressor skid.

### A: **Jens Wulff** – NEUMAN & ESSER

All potential sealing parts are reviewed by NEUMAN & ESSER for each project and process to prevent or reduce leakages as much as possible. Main influencing parameters are pressures and temperatures for the design of a reciprocating compressor. A contact ring selection reduces the internal leakages and, in addition, requires less power consumption for the same gas volume compressed. Leakages from the piston rod pressure packing should always be routed back to suction side instead of venting or flaring. By increasing the efficiency and minimising the leakage, operating costs are reduced.

### A: **Joe Fernandez** – Ariel Corporation

Reciprocating compressors rely on a pressure packing case which seals around the reciprocating piston rod. A series of segmented and solid rings are

# COMPRESSORS Q&A

used to seal and breakdown the pressure, minimising gas leakage down the piston rod. Despite the best sealing technologies, there will always be some leakage across the packing rings. These emissions can be captured and blended into the engine fuel gas. When that is not practical, the captured emissions can also be blended back into the compressor suction line or into a pipeline. A small pressure booster may be required to accomplish this. Typically these will be small, hermetically sealed compressors. Proper bolting and seal selection are also key considerations in gas containment. Heads, valves, and other critical joints require appropriate fasteners, O-rings, and gaskets to minimise any fugitive emissions.

### A: **Leonardo Baldassarre** – Baker Hughes

Emissions are either related to unoptimised efficiencies or to gas leakages and venting. All the efforts in the direction of maximising compressor efficiency also have a direct impact on emissions. For controlling vent emissions, the efforts are mainly around four directions: use of gas seals with minimum flow to the atmosphere; development of solutions to recover primary vent leakages (for example, zero leakage systems); minimise machine trips (i.e. maximise reliability); as well as new solutions to avoid venting after a trip while minimising loop pressurisation. This last point is connected to a new series of patent applications developed by Baker Hughes and related to a system (package) that allows to liquefy part of the gas in the loop, properly store it in a vessel, and then release it into the main loop once the compressor is started-up (to reduce break-away torques).

### A: **Michael Drewes** – Atlas Copco Gas and Process

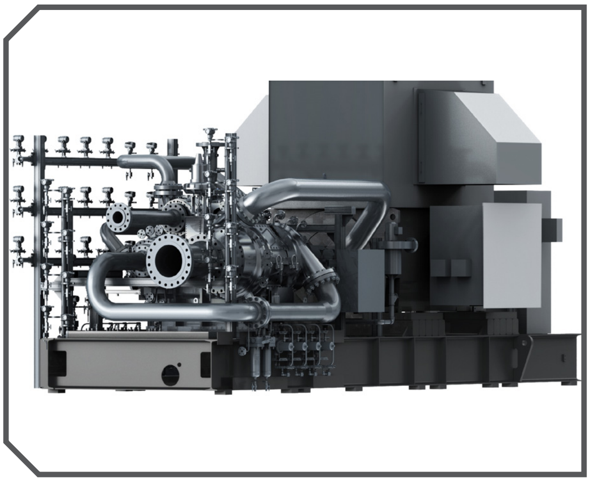
Gas emissions are costly, both financially and environmentally, and this makes a low seal-leakage rate hugely important. Because labyrinth seals and (to a lesser extent) carbon ring seals have a relatively high leakage, Atlas Copco Gas and Process compressors, expanders, and Companders use dry gas seals (DGS) when needed, which have far superior seal-leakage rates. The company's engineers even executed a zero-leakage design by use of a closed-seal system, in which the seal leakage is directed into the oil tank. After extraction of the oil particles in the demister, the clean gas is reinjected into the process.

By allowing the compressor to start from elevated pressures (such as settle-out pressure), incorporated either in the mechanical design or via an optional suction throttle, a potential blow out of process gas is prevented. A dynamic start-up scenario can also be simulated by the use of specially developed in-house tools.

Customised integrally geared equipment designed for specific jobs ensures the best compression and expansion efficiencies. This reduces carbon emissions for power production to the lowest extent possible.

### A: **Tyler Rice** – Mitsubishi Heavy Industries Compressor International

Compressor seal design is an important factor in order to minimise leakage and in turn, reduce emissions. Transitioning to dry gas seal technology from earlier technology oil seals has helped minimise process leakage. Depending on compressor design and process needs, the correct seal types can be selected for optimal performance. Additionally, sealing systems can be designed with vent recovery to help further reduce leakage. To reduce emissions, compressors are designed to operate at high-efficiency in order to lower the equipment power. Properly minimising compressor internal leakage and secondary losses will increase efficiency and help drive down the emissions in the compression process.



Atlas Copco Gas and Process: High-pressure BOG compressor.

## Q: What component of a compressor is most prone to failure and thus requires the most maintenance?

### A: **Dominic Sarachine** – FS-Elliott

The most critical maintenance on centrifugal air compressors is the routine maintenance of the oil lubrication system, including replacing filter elements in the oil and inlet air filter. Although these costs are fairly standard and comparable, certain compressors require airend replacement every three to five years due to the close clearance between the compression elements and subsequent wearing of parts or special coatings. Replacing a compressor airend can cost up to 50% of the original capital equipment cost and require shipping the entire unit back to the factory. However, with proper maintenance to the inlet air filter, oil filter, and regular lubrication changes, the running life of a centrifugal compressor far exceeds that of other compressor technologies and is theoretically infinite since the mechanical parts do not actually touch.

# COMPRESSORS Q&A

## A Jens Wulff – NEUMAN & ESSER

By far the highest uncertainties for the operation of a reciprocating compressor come from the self-actuating valves. Due to impact velocity of sealing elements and tumbling effects which result in high stress zones, it is expected that as a consequence there will be low lifetime and higher maintenance activities.

The second most critical part is the piston rod pressure packing which seals the alternating suction and discharge cylinder pressure against the atmospheric pressure of the distance piece. Dominating factors are the piston speed and the particle contamination of the compressed gas. For particle loaded gases, labyrinth packings are a good solution. As LNG is mostly a very clean BOG, contact ring packings are preferable due to far lower leakages and similar lifetimes. Nevertheless, regular maintenance via well-trained service technicians is essential for the reliability of any rotating equipment.

Mitsubishi Heavy Industries Compressor International: MHI LNG refrigeration compressor train.

## A Joe Fernandez – Ariel Corporation

Valves are the component most prone to failure in a reciprocating compressor. Valves consist of a sealing element, spring, and often damping plates. As a spring mass damped system, the valve motion is optimal at one condition, with fair motion across a small range. The factors defining the range include operating pressure, both suction and discharge, operating speed, gas composition, temperature, and valve design. Gas cleanliness also plays a critical role in valve reliability.

Valve reliability can be optimised through upfront design and then through operational monitoring for changes in condition that may be outside the valves' designed operating window.

## A Leonardo Baldassarre – Baker Hughes

In general, centrifugal compressors are very reliable and robust machines. Certainly, one component that needs more attention is the dry gas seal. This component will not require significant maintenance provided it is developed and supported with a well-designed seal gas system. This is an area where Baker Hughes has put in significant effort over the years to optimise the relevant piping and instrumentation diagrams (P&ID) to guarantee the right conditions in terms of temperatures and pressures in all the duties of the machine, including starts, stops, and transients.

## A Michael Drewes - Atlas Copco Gas and Process

Atlas Copco Gas and Process uses state-of-the-art design tools and sophisticated materials to ensure stable and safe compressor operation, which allows for major overhaul maintenance intervals of beyond five years.

As an OEM not operating the equipment, Atlas Copco does not get all the historical reliability figures for its machines and competing technologies. However, lots of the equipment is under maintenance by the company's service teams and this allows for certain conclusions. Based on an independent market study by *Hydrocarbon Processing*, centrifugal compressors show better reliability and availability figures than other technologies.

In the rare case that an integrally geared or centrifugal compressor in general fails, the auxiliaries tend to fail rather than the compressor core itself. And these auxiliaries, such as instruments, the control system, seal-support systems, and oil system, are common for most equipment. Here, to some extent, equipment redundancy can prevent a shutdown.

## A Tyler Rice – Mitsubishi Heavy Industries Compressor International

Within the compressor, the dry gas seals and bearings are the components most sensitive to failure. This is due to the high contact surfaces between the rotating and stationary parts of the compressor. Proper operation of the compressor within the design parameters will help ensure the operating life of these components. This includes supplying clean gas to the seal system and checking oil quality in the bearings periodically. During turnarounds, these components need to be inspected for any damage. With proper counter-measures and routine maintenance and care, these potential machine troubles and down times can be avoided.

# Compressors Q&A

## Q Detail the process and design behind one of your most popular compressors.

### A Dominic Sarachine – FS-Elliott

FS-Elliott's PAP Plus® compressor is designed to provide optimal accessibility while meeting customer engineered requirements. The compressor gearing, intercoolers, aerodynamic parts, lubrication system, and control system are all independently accessible. Maintenance of any one of these items does not require disassembling other components. Unlike other compressors, the unique PAP Plus horizontally-split design was meticulously engineered to provide quick and easy local maintenance. Overall, PAP Plus owners spend significantly less time and effort on maintenance. The popularity of the PAP Plus compressor is also due to the ability to customise per the customer's engineered requirements. So the compressor is both flexible and low maintenance, resulting in favourable marks from customers.

### A Joe Fernandez – Ariel Corporation

Ariel Corporation has recently introduced improved designs and uprated capabilities in a number of compressors. These new designs began with dialogue and co-operation with the company's valued customers, which was then combined with extensive field experience. This front-end work led to proposed new features and higher ratings on frames with comparable footprints.

The company's design engineers then went to work incorporating proposed features into the various components of the compressors; including increased frame rigidity, increased strength crankshafts, and KB Style angled guides, with through bolting for increased strength and rigidity. Previously discussed technology such as CP Valves, improved packing designs, and increased strength crankshafts come standard, with options such as Ariel Smart Compressor (ASC) technology, and electronic variable capacity pockets (eVCPs) available on all of the company's new frame offerings. Extensive lab testing was performed at Ariel's state-of-the-art R&D facility to ensure the components were capable of providing superior service and reliability than existing compressors. Multi-department teams worked together to make sure the new products meet the demands of the markets, while providing unmatched value to the customer, exceeding equipment uptime expectations.

### A Leonardo Baldassarre – Baker Hughes

Talking about LNG compressors, everything starts during the bid phase in which iterations happen between the compressor designer and the EPC. Iterations are aimed to adjust process conditions and machine selections in order to minimise compression power and guarantee the required operability. Iterations also look to the mechanical configuration and rotordynamics in particular. Once the selection is satisfactory, all the design aspects are looked at in detail. Baker Hughes has a wide and successful experience with compressors for all the different liquefaction processes and possible drivers, such as aeroderivative or heavy duty gas turbines, as well as electric motors.

### A Michael Drewes – Atlas Copco Gas and Process

Atlas Copco Gas and Process has been building its Compander for more than three decades.

This machine combines compressor as well as expander stages onto one gear, and it is not only used for LNG liquefaction but also in various other applications, notably on nitric acid plants, in the chemical/petrochemical sector, and in energy recovery applications.

For a Compander in the LNG sector, the nitrogen Brayton cycle is generally applied in various modified versions, typically with different flows and pressures, and using different stage configurations. Typically, four compression stages and two expansion stages (warm and cold expander), are installed on the gear box. This is all related and customised to the specific plant, its feed gas quality, ambient conditions, and the liquefaction rate. The oil system can be integrated into the base frame, while dry gas seals reduce the leakage rates to a minimum. The Compander is highly efficient, and it is an especially good fit for the small scale range, which reduces both the footprint and lifecycle costs.

Alternatively, when a customer or process requires a mixed refrigerant as a working fluid, Atlas Copco Gas and Process has a wide range of mixed refrigerant compressors in its portfolio. In the mixed refrigerant cycle, in contrast to the Compander, there is no expander stage installed.

### A Tyler Rice – Mitsubishi Heavy Industries Compressor International

MCO-I's solution for ammonia syngas services balances the CAPEX and OPEX criteria that customers use to evaluate equipment. The standard configuration of the syngas compressor train is a both end drive arrangement. This is beneficial for easy maintenance with the unrestricted removal of the cartridge bundles. The compressors are optimised for high performance and reliability through a range of impellers capable of operating at high speed and high efficiency. The high speed reduces the compressor footprint size of the and the high efficiency reduces the power needed to drive the compression. The syngas compressors are a high reliability design with the inclusion of components such as swirl cancellers and overhang dampers for confident rotor stability.

Also, as the capability of gas production facilities continue to grow, MCO-I is continuously improving its compressor technology to meet this demand. Two examples of this are with the super high speed compressor design and high-flow co-efficient impellers for the ethylene market. The high tip speed impellers increase efficiency and decrease the number of impellers required to achieve the increasing discharge pressure needs. In the ethylene market, the capacity of the gas cracker has been increasing. To meet this trend, large flow co-efficient impellers have been a key technology implemented. MCO-I has significant experience with these large flow co-efficient impellers and high-boss ratio impellers for a compact design compressor. **LNG**