ON-BOARD RELIQUEFACTION FOR LNG SHIPS

by

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1 Introduction

Liquefied Natural Gas (LNG) is transported at near atmospheric pressure and low temperatures (approx. -160 °C) in carriers over long distances. During the voyage a proportion of the LNG is vaporized by heat ingress in the cargo containment system. The cargo tanks are well insulated with, typically 270mm cryogenic insulation, but some heat inleak producing boil-off gas (BOG) is inevitable. Typical values are about 0.1 to 0.15% of the full contents per day, which over a 21 day voyage, becomes a significant amount. Hitherto, ships have employed gas compression and use of the boil-off gas as fuel for the propulsion systems. Until now LNG carriers have been equipped with steam turbines powered by heavy fuel oil (HFO) and/or LNG BOG. However, designers of new larger ships are seeking more economic propulsion solutions which offer further economic advantages when combined with of a BOG re-liquefaction facility on-board LNG carriers.

This paper describes the process concept for a BOG re-liquefaction system developed by Tractebel Gas Engineering (TGE), the operating experience of such a process and preliminary economics of implementing the scheme on board a ship having a capacity greater than 200,000 m³ LNG. The process described in this paper considers BOG re-liquefaction with a capacity of approximately 6,500 kg/h of BOG which is sufficient to maintain tank pressure for a carrier of 228,000 m³ capacity. In reality, the boil-off gas rates are somewhat smaller, but the unit must be able to deal with peak rates to bring the tank pressure down and also be able to deal with LNG cargoes having relatively high nitrogen concentrations.

2 History of Small-scale Liquefaction Technologies

Natural gas liquefaction has been in operation for many decades and from the 1970s, single train plant capacities have steadily climbed to 100 times the capacity being considered for BOG re-liquefaction process in this paper. These processes use mixed refrigerant cycles of various types to achieve a very low specific power to liquefy LNG. Typically this power may be in the region of 0.25 – 0.3kW/kg LNG into the storage tank. Power consumption is very important in such large facilities.

However, the 1970s were also a time when peak shaving applications were implemented in many countries including, USA, UK, Holland, Belgium and Germany. This was a time when cryogenic experience was applied from the air separation industry to optimise cycles for LNG liquefaction, and although the mixed refrigerant process emerged even earlier than this, other processes were considered for peak shaving. These included methane expander cycles, cascade cycles and closed loop nitrogen cycles. Their choice was determined based on the number of days these liquefiers were expected to operate in each year. In some cases the hours of operation were quite low and thus power consumption was less important. In such cases the capital cost was an extremely strong driver for the choice of process.

Other drivers for process selection were:

- rapid start & stop requirements for peak shaving applications;
- greater availability of high efficiency machinery for inert gas applications;
- no particular requirement for high turndown ratio (the units generally run at 100% capacity).

These liquefiers were generally in the 100 to 300 tonnes/day capacity range which fits well in the tanker boil-off re-liquefaction. This case is about 150 tonnes/day.
One such example was a 240 tonnes/day liquefier in Belgium engineered and constructed by Tractebel for Distrigas. Figure (1) below illustrates the overall plant including the LNG storage. The liquefaction part is the small processing unit in the centre of the picture.

Figure (1) LNG Peak Shaving Plant in Belgium

The plant was more complex than is required for the ship boil-off re-liquefaction because of a number of reasons including:

- The gas was wet and required mole sieve driers.
- The gas contained 14% nitrogen which required removal.
- The customer requirement included liquid nitrogen.

Therefore, the process route included a pre-treatment section and the cryogenic unit included a double column distillation process which separated the nitrogen from the methane.

The nitrogen cycle was chosen for this process because of the reasons given above and also the fact that nitrogen could be sourced from the process. The actual liquefaction part was contained in a small cold box which enclosed plate fin heat exchangers, piping and controls in an insulated environment.
The nitrogen cycle compressor was located in a compressor house whilst the expansion turbine was located outside near the cold box. The de-nitrogenation column was located outside as shown in the centre of the picture.

There was a second plant built using the nitrogen cycle concept in the UK which used a very similar cycle arrangement and having a capacity of 200 tonnes/day of LNG. At the time of intense competition for the various liquefiers, a considerable amount of optimisation was done on the cycle operating pressures, temperatures, the arrangement of the compressor and the expander as well as the inlet temperature of the expander. This resulted in a consistent optimum for the liquefaction cycle which was a success factor for these plants. The authors were successfully involved in this optimisation and subsequent design, building and start-up of the nitrogen cycle concept. This concept was examined in considerable detail in order to arrive at the scheme for ship boil-off re-liquefaction presented in this paper.

Since then the LNG liquefaction business has gone in the direction on base load plants and the use of complex mixed refrigerants and cascade processes in order to significantly reduce the specific power. Consequently, the nitrogen cycle process has been little used in the LNG industry, though it is being considered for floating LNG plants. It has, nonetheless, been continuously improved for the air separation industry. The Tractebel scheme is based on the above mentioned optimisations and also takes account of modern machinery and exchanger improvements.

It is worthy to note that boil-off gas re-liquefaction has been considered for LNG ships as early as the 1970s. However, due to economics, it had not been implemented till now. Boil-off handling and re-liquefaction has been implemented on many other applications over the past 20 years in refrigerated LPG and ethylene ships. TGE has over 60% of the market share in re-liquefaction of boil-off in ethylene carriers. To achieve this, TGE utilises the cascade cycle for the refrigeration. With respect to energy consumption a cascade cycle would also be the preferred solution for boil-off re-liquefaction onboard LNG carriers, but because of the different temperature levels the plant would be more complex than on an Ethylene carrier. Hence such system for LNG would require very qualified operators and the investment cost would also be relatively high. Therefore the much simpler closed nitrogen Brayton Cycle has been chosen for LNG boil-off re-liquefaction.

3 Process Route Selection

For small liquefaction units and in particular, ship mounted units, several issues become dominant in the decisions taken during process selection. These include:

- Previous experience in such technologies.
- Rapid start/stop and flexibility.
- Plant simplicity.
- Ability to operate during voyages with pitch and roll.
- Space on board may be limited.
- Low cost.
- Easy installation.
- Safe – low amounts of hazardous inventory in plant.

Each of these pushes the designer to a closed loop nitrogen cycle. In selecting optimum process conditions, there are several parameters that are important including:

- BOG liquefaction pressure (the higher the better)
- BOG temperature (the lower the better)
- Gas composition.

Unfortunately, the more one compresses the BOG, the more expensive the compressor capital cost, and the warmer the BOG gas becomes. So the first two parameters work against each other. The third parameter, is determined by the cargo being transported. Therefore, a simple, single stage BOG compressor was selected for the TGE process. The refrigeration that must be provided to cool, condense and sub-cool the LNG is thus needed at mostly below -50^{o}C and down to -170 ^{o}C. Since the BOG pressure is low, the condensing is done over a narrow temperature range which makes the liquefaction cycle, thermodynamically, less efficient. This can be seen in Figure (2), below, where the temperature differences are high at the cold end (bottom left) of the heat exchangers carrying out the liquefaction, with 30 – 35 ^{o}C differences near the cold end.

Given the above, it becomes necessary to design a nitrogen cycle as efficiently as possible in order to provide the most advantageous economics. Therefore, the experience of nitrogen cycles of the 1970s and 1980s has been revisited and further optimized to provide a modern solution to BOG re-liquefaction.

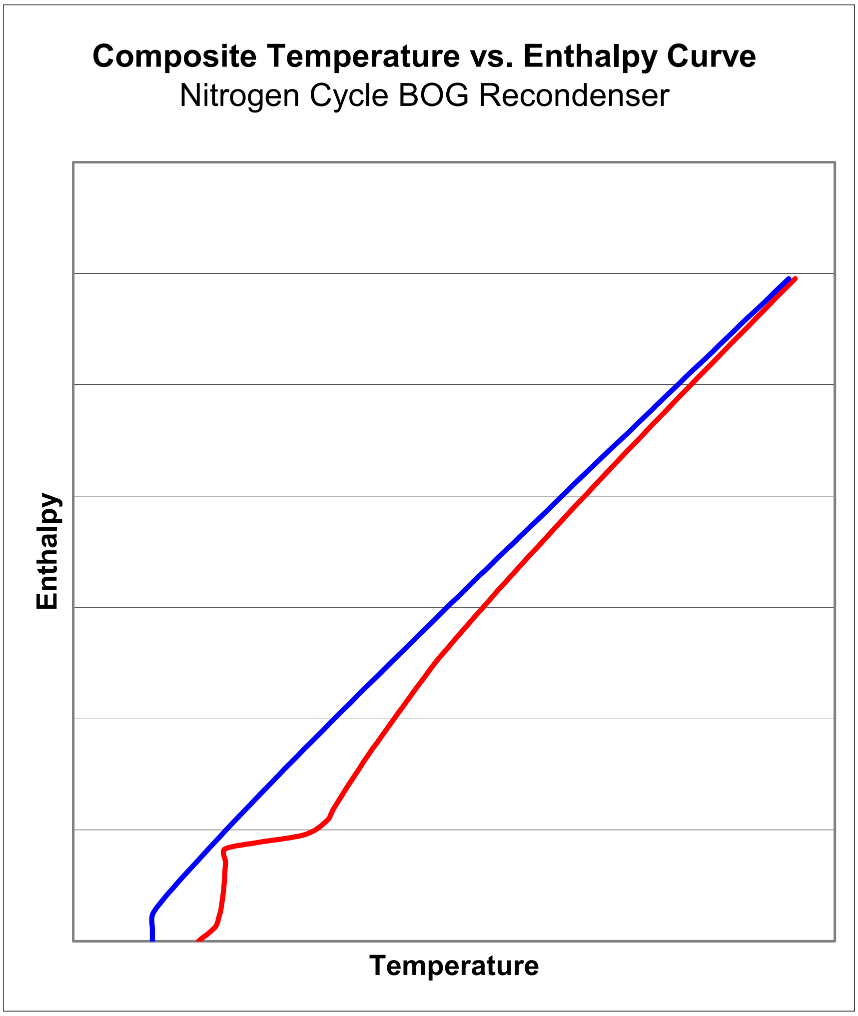


Figure (2) Composite Curve

The selection of an optimum cycle configuration needs an appreciation of a number of heuristics including:

- High temperature differences mean high exergy loss.
- Large circulation of refrigerant means high pressure drop losses and hence high exergy losses, unless very large equipment is used to reduce pressure drops in heat exchangers and piping.
- High capacity machinery, generally has higher efficiency.
- A gas expander has an optimum pressure ratio for high efficiency.
- A compressor wheel coupled to an expander generally has a maximum pressure ratio of about 1.4.
- Compressor stages generally require cooling after a pressure ratio of about 3.5.

The above heuristics guide the designer to select an optimum and by applying these "rules" one can carry out an optimisation sequence which eventually arrives at the preferred solution. This was done by TGE taking into account our experience in design and operation from the 1970s onwards. Figure (3) shows a qualitative representation of the optimisation carried of for the BOG re-liquefaction process showing that there was a minimum value for power consumption to liquefy BOG which concurred with the peak shaver liquefier experience. Valuable comparison points for optimisation were nitrogen cycle system pressures.

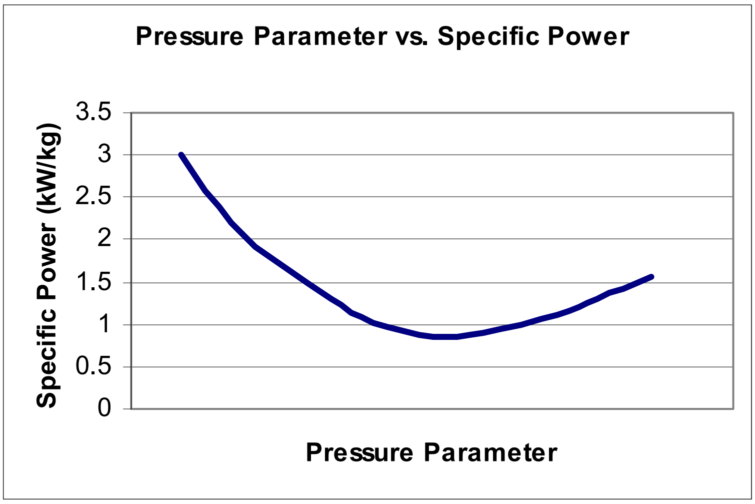


Figure (3) System Pressure Optimisation

4 Process Description

The TGE process concept for the re-liquefaction of Boil-Off Gas (BOG) is based on the classical Brayton Cycle. BOG is withdrawn from the cargo tanks and compressed to an intermediate pressure of about 3 – 6 bar a. It is then liquefied in a main process exchanger (BOG Liquefier). Liquefied BOG is flashed down to tank pressure in a separate valve and sparged into each of the cargo tanks on the ship. The process is designed to achieve 100 % liquid BOG at tank pressure. The cooling and liquefaction of the BOG is done in exchange with cold, gaseous nitrogen.

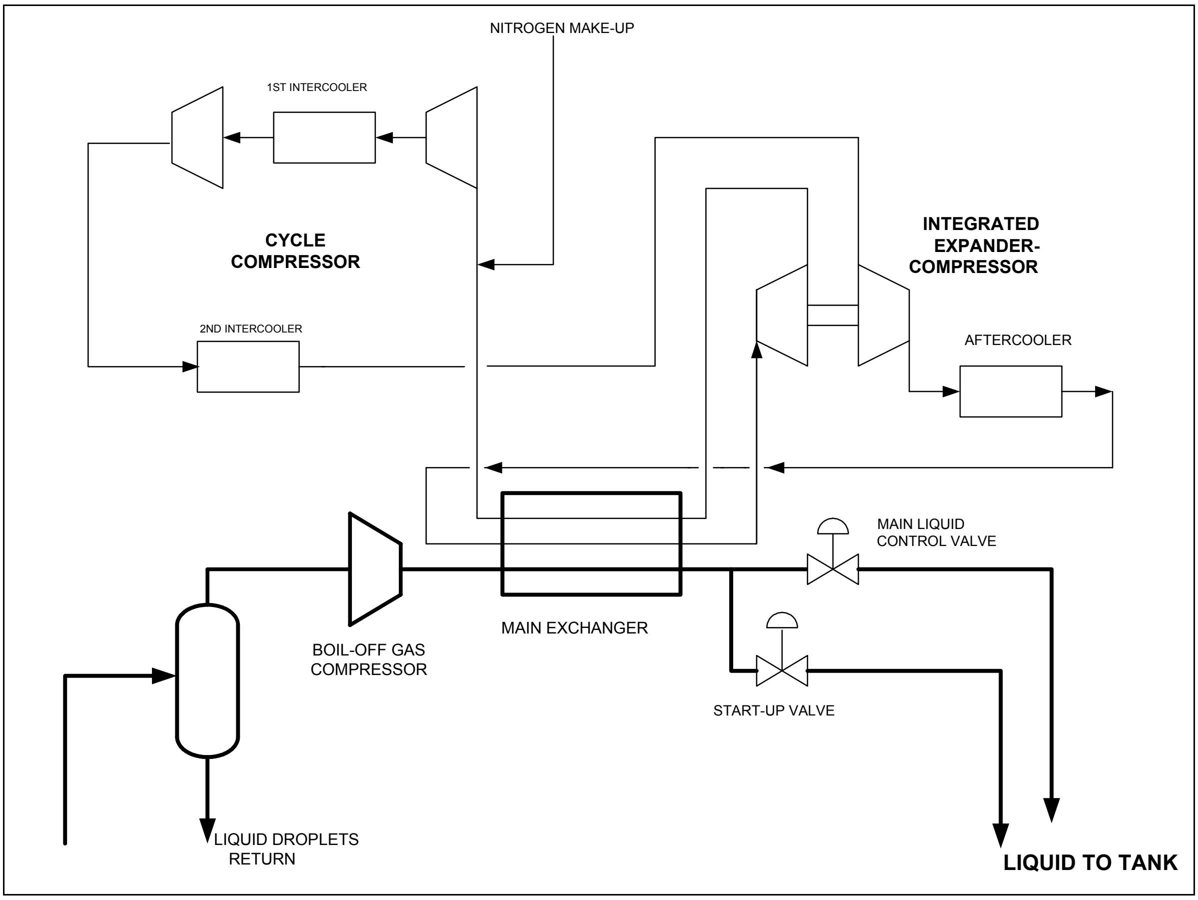
The main heat exchanger assembly is an aluminium plate fin type exchanger which has 3 streams. The BOG is cooled in one of the streams whilst HP nitrogen is cooled in the second stream. The third stream is the cold, low pressure nitrogen, which provides the refrigeration for the process. In the TGE system, this heat exchanger is a single block, but attention has been paid to the configuration of the BOG inlet location to avoid large thermal stresses, which would otherwise occur with superheated BOG present during ballast voyages.

Nitrogen is compressed in a three stage turbo compressor to a high pressure. It is cooled after each stage in a shell & tube heat exchanger to ambient temperature using seawater as coolant. Seawater temperature is typically, 0°C to 32 °C. The pre-cooled high pressure nitrogen is then fed to the BOG liquefier and cooled down to approx. – 80°C to -110 °C.

Cold high pressure nitrogen is fed to an expander which is directly coupled to the third compressor stage to form a "Compander". Outlet temperature of the low pressure nitrogen is approx. -170°C to -180°C. The cycle temperatures and pressures have been optimised to provide the lowest practical power consumption. This optimisation is based on similar land-based cycles on LNG peak shavers that have been in operation over the last 25 years, and much longer in the air separation industry.

Nitrogen is circulated in a closed circuit with minimal losses. The seal losses are made up with a high purity supply from a ship-based production unit. The refrigerant nitrogen must be of high purity and dryness to avoid blockage of exchanger passages during operation and must also have a low oxygen content.

The combination of three-stage compression with high efficiency turbo expansion using the appropriate pressure levels ensures a high efficiency of the overall process. The overall energy consumption is approximately 0.75 kWh/kg. A simplified process flow-scheme is shown in figure (4).



BOG FEED

Figure (4) – Process Flow-scheme of Boil-off Re-liquefaction Unit

5 Design Parameters

The plant has been designed for installation on a 228,000 m³ gas carrier vessel which is designed for the storage and transportation of Liquefied Natural Gas (LNG).

Table (1) – Typical Cargo Composition

Composition	Range (Mole %)
Nitrogen	0.01 – 1.00
Methane	86.0 – 95.0
Ethane	4.00 – 8.50
Propane	0.05 – 3.10
Butane	0.0 – 1.5
Pentanes and Heavier	0 – 0.10
Density Range, kg/m3	420 – 470

The above cargo composition range was used for designing the process cycle and equipment. The calculation of the plant performance has assumed that there will be some enrichment of the boil-off gas during the voyage, though this is minimised as far as possible when the LNG product stream is injected into each of the liquids in the cargo tanks. Nevertheless, the plant performance has been based on the following "worst case" calculated conditions.

Table (2) – Boil-off Gas to Liquefier.

Component	*Composition*
Nitrogen	max. 9.0 % (mol)
Methane	Min. 91.0 % (mol)
Ethane	max. 0.01 % (mol)
Propane +	traces
Suction Temperature, °C	-140
Suction Pressure, kPa	107.3
Molecular Weight of vapour	16.205
Mass density of vapour, kg/m³	1.67
Heat of vaporisation at 450 kPa, kJ/kg	470
Design Boil-off Rate, %/day	0.14
Typical Boil-off Rates, %/day	0.1 to 0.15

Given a cargo capacity of 228,000 m3 and a maximum specific gravity for LNG of 470 kg/m^3 and a boil-off rate of 0.14%, leads to a capacity of **6250 kg/h**. In reality, the boil-off rate will be somewhat less, perhaps in the region of about 5500 to 5800 kg/h depending on the LNG cargo composition.

Design margins have been carefully addressed in this process. The main cryogenic exchanger has a 25% thermal design margin which is normal practice for high efficiency exchangers in the cryogenics industry where small temperature differences are expected. The machinery will have approximately 5% capacity margins with no negative tolerance. It is important to add only small margins to the machinery since the design BOG rate is taken conservatively. If we add large margins to the machinery, the operating point will be far from the optimum giving high specific powers and the capital cost will be high.

Equipement sparing has also been considered in the TGE design. Two BOG compressors are assumed in the design. A single cryogenic exchanger has been assumed since this is a very clean service and similarly for the cycle machinery. The reliability of turbo-machinery in nitrogen service, both expanders and compressors, is good enough to justify the use of a single machine concept for both of these machines.

If the liquefaction plant is shut down for any reason, then a thermal oxidiser is used as back-up to dispose of the BOG that would then build up in the tanks.

The LNG product emanating from the main heat exchanger will have a very small amount of flash gas which will contain a substantial amount of nitrogen. This should be injected into the bulk of the LNG in each of the cargo holds to ensure that it is re-absorbed by the bulk liquid. This prevents any enrichment of the LNG and the development of a high nitrogen boil-off gas, thereby, maintaining the composition of the LNG relatively constant throughout the voyage. Hence the composition of the liquefied boil-off is the same as that in the feed to the liquefier with a flow of 6250 kg/h.

6 BOG Reliquefaction Plant Description

A single packaged reliquefaction has the following major components.

Boil Off Compressor (2x105%)
Boil off compressor duty :

- To supply the boil-off to the cryogenic heat exchangers
- To send boil-off gas to thermal oxidizer (in case of failure of reliquefaction plant)

Nitrogen Expander/Compressor Unit (1x105%)
Nitrogen expander/compressor system consists of three (3) compressor stages driven by a single electric motor and one (1) expander stage:

- Compressor type: Horizontal, three stage, centrifugal with inter & after coolers.
- Expander type: Horizontal, single stage, single shaft turbine coupled directly to a compressor which is used as a brake for the expander.

This is an integral multi-wheel compressor with the 3rd stage compressor wheel attached to the main compressor bull-gear, but assisted by the turbo-expander. Expansion from high pressure to low is realised in the expander stage. The expander produces about 1200kW of energy which is absorbed by the "brake" which is the 3rd stage. It is this energy which is extracted to provide the necessary cold for the liquefaction process.

The compressed Nitrogen is cooled in three gas coolers against seawater. Approximately 700 m³/h seawater with inlet temperature of 32°C is required and has a 6°C rise through the coolers. The Gas Coolers are Shell- and Tube-Type with seawater on the tube side and gas on the shell side for easy cleaning. Tubes are of fin-type with materials of construction compatible with the seawater environment. These are likely to be admiralty brass or titanium.

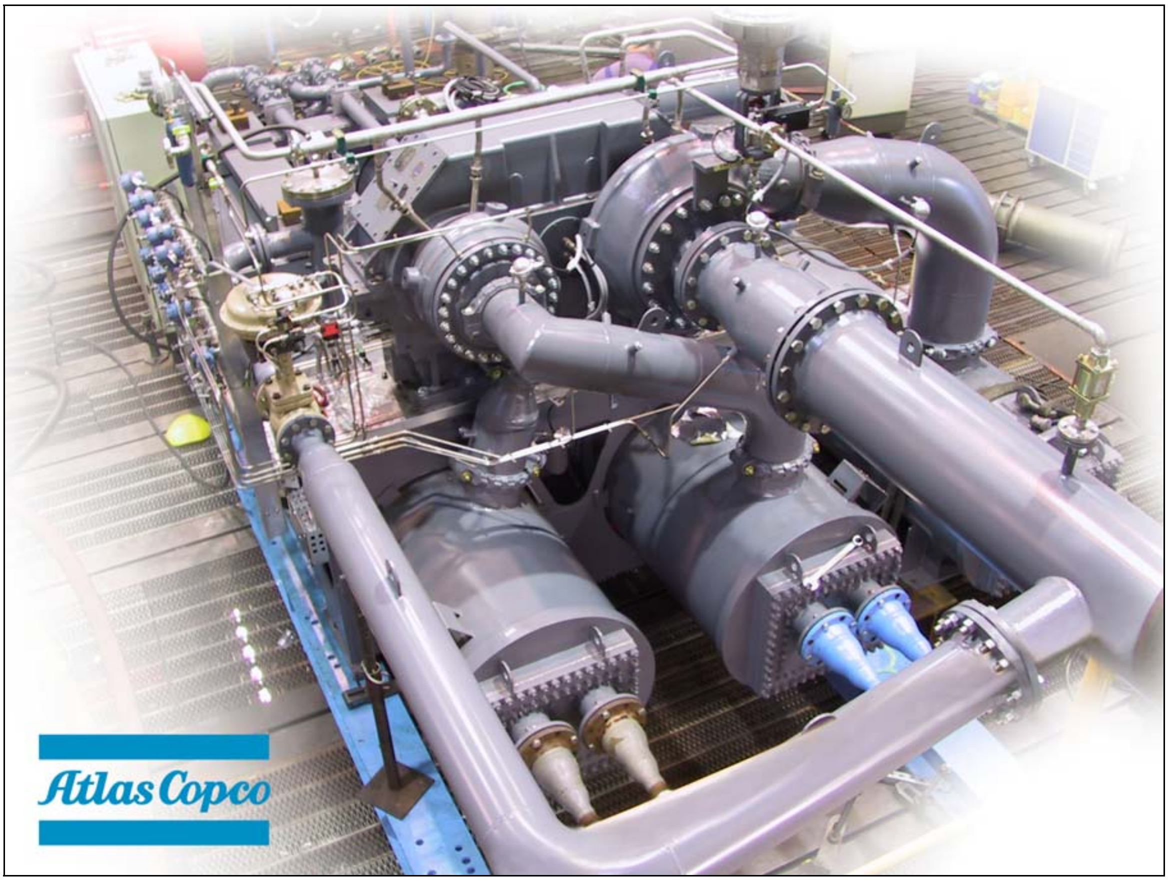


Figure (5) – Nitrogen Expander/Compressor Unit (Example: Atlas Copco)

Cryogenic Heat Exchanger (1 x 125%)
One plate-fin type cryogenic heat exchanger is used for condensing the compressed BOG by indirect heat exchange using cold nitrogen after turbine discharge as heat exchange medium. This is a three stream exchanger housed in a carbon steel plate and frame construction. Before entering the expansion stage of the Compander, Nitrogen is passed through the Main Heat Exchanger counter current to the expanded cold Nitrogen. This way the cold low pressure Nitrogen at the same time cools down the warm high pressure Nitrogen and condenses the BOG.

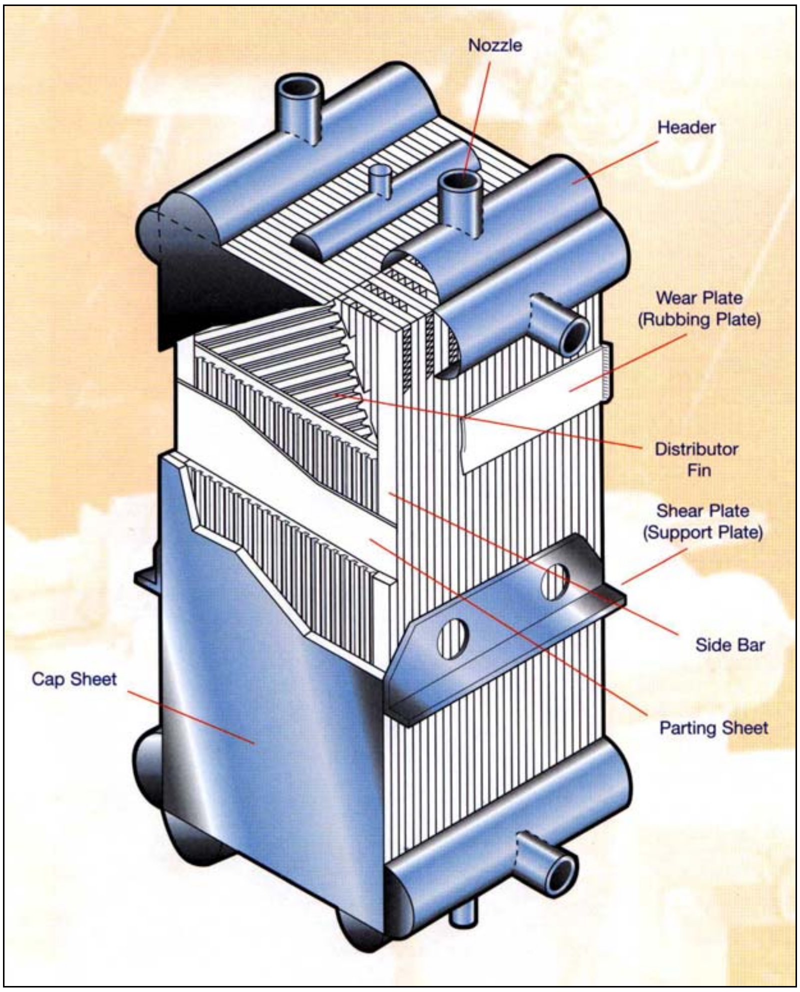


Figure (6) – Cryogenic Heat Exchanger (Example: Chart Industries)

Piping and Ancillaries.
In addition to the above main items of equipment, a separator is shown in the above flow-scheme. In reality it may be a piping arrangement that ensures no liquid carry-over. The injection of the LNG product is done using a piping arrangement which ensures good distribution of liquid into the bulk LNG and also allows re-absorption of any light flash gases.

BOG Collector System
BOG is collected at the vapour connection of the cargo tank dome and routed to the boil-off compressor. To control suction temperature liquid from the LNG product produced by the liquefaction unit may be injected. However, this will only be required in extreme cases and at start-up.

Condensed LNG Return System
Liquids from the flash valve are fed back to the cargo tank via a condensate header. During start-up, a separate route is used since the control valve needs to be larger when it expands vapour. Once the proper operating conditions are reached, the smaller valve route is used. LNG is routed to each of the cargo tanks to balance out the re-liquefied flows evenly. Any incondensable gas from the liquefaction process is routed to each of the tanks into the body of the LNG to allow for some re-absorption of the gas in the 4 LNG cargo tanks.

The unit is controlled by a PLC type. The Unit PLC is normally integrated in the ship and cargo control system's architecture. Unit control is complete including all necessary safety and process controls and vibration monitoring for rotating equipment. All instruments used for the gas plant, its machinery (e.g. surge control) are for marine application and shock proof. Compressor control is based on vendors preferred standard controls. The control rack is normally designed to IP 54 for mounting in a safe location.

The BOG Re-liquefaction system is designed for use in a compressor house with process compartment and gas-safe machinery room. The system is made up of four packaged units:

- BOG compressors, gearbox , motor , oil system each on a common base frame
- Refrigerant Compressor / expander, gearbox/bull gear, motor, intercoolers, oil-system on a common base frame.
- Main Exchanger assembly insulated and clad in stainless steel.

It is assumed that the combined nitrogen cycle compressor and turbo-expander are located is a safe area, thereby allowing for the use of lower cost machinery as applied in the mature air separation industry.

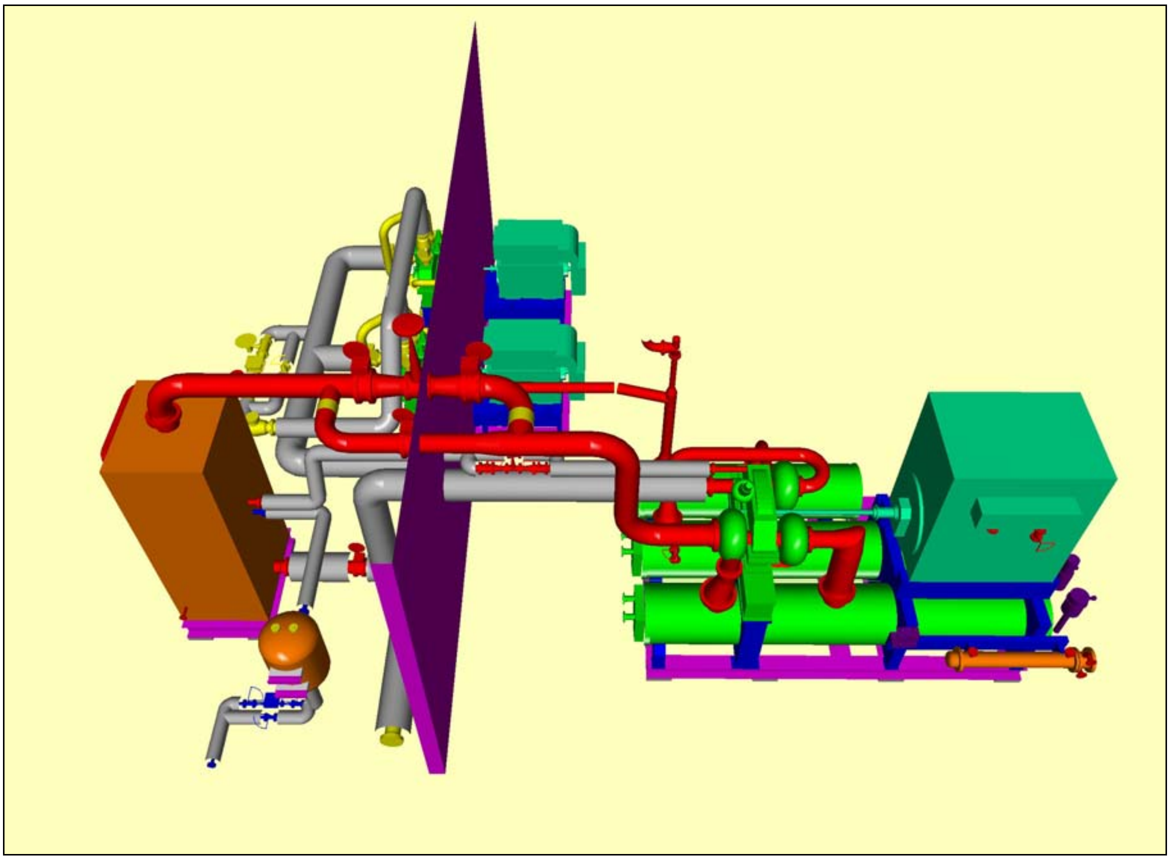


Figure (7) – 3D Model of Nitrogen BOG Re-liquefaction System

Table (3) – Preliminary process package dimensions

	BOG Comp Each	Ref. Comp & Expander	Main Exchanger
Length:	4,900 mm	7,100 mm	1,800 mm
Width:	3,500 mm	4,000 mm	2,200 mm
Height:	2,800 mm	3,000 mm	4,800 mm
Weight:	25t	45 t	16t

7 Modes of Operation and Standby Systems

The BOG re-liquefaction unit will be required to operate at say 60 – 90 % of its design capacity most of the time in the ships' life. There will be BOG produced during the "loaded" voyage as well as the "ballast" voyage when the ship has a small "heel" of LNG in the cargo tanks and is returning for the next cargo. At times when the pressure rise in the vapour space is slow, during the "ballast" voyage, the unit can start/stop relatively frequently. For example, assuming a pressure range differential of about 100mbar in the cargo tanks, the BOG re-liquefaction unit can start/stop daily running for say 9 – 12 hours bringing the pressure in the cargo tanks down and then stopping.

The nitrogen cycle process is very forgiving in this kind of start/stop cycle since it is easy to operate. The cycle is first charged up with nitrogen to an intermediate pressure of say 8 - 10 bar g, since the nitrogen unit can supply this without further compression. The unit can then be started up by starting the cycle compressor. The turbo-expander is coupled to the main compressor via the "bull-gear" and thus rotates but uses the motor power to raise the pressure of the nitrogen. The inlet guide vanes are then opened slowly using a pre-programmed sequence to ensure that cool-down is not too rapid as to impose a thermal shock on the system. As the guide vanes on the expander open, the cooling effect increases and the main exchanger cools significantly at the cold end. This process can be controlled using a pre-programmed sequence to achieve the correct operating temperatures within max. 2 hours. Then the unit can liquefy at full capacity, if required. Once cold, the unit can be started and stopped within one hour in a pre-programmed sequence.

The nitrogen make-up is carried out using a pressure controller taking a signal from the suction of the cycle compressor (or the expander outlet). This is used as the cycle pressure optimiser to ensure the power consumption is minimised.

As the unit cools down, nitrogen make-up is required, for two reasons:

- There is a net compression and cooling which increases the net density of the nitrogen.
- There is a loss of nitrogen through the compressor and expander seals.

At steady state, nitrogen make-up is only for the seals, which amounts to about 60 – 100 Nm^3/h of pure nitrogen. The quality of the nitrogen is important, since the cycle will reach temperatures below -170°C requiring "bone-dry" nitrogen. TGE experience has been based on the supply of cryogenic sourced nitrogen, but some packaged nitrogen generators can also produce very dry nitrogen.

The economics of seal compression has been evaluated and the use of a nitrogen generator proves to be the better option.

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Boil-off gas needs to be disposed of during power outages. This is done either by an incinerator or, if available, by feeding to a dual fuel propulsion engine. The capacity is sufficient to treat the complete BOG quantity in case of a failure of the refrigeration/liquefaction system.
The Re-liquefaction unit ESD system should normally be integrated into the ship ESD system. The emergency shut down system is hydraulically operated and should be automatically activated on:

1. Fire alarm - low pressure in ESD-piping loop, via thermal fusible plugs.
2. Gas alarm - activated by Gas Detection System.
3. Compressor or Expander Malfunction.
4. Manual call points.

8 Utility Requirements

Power will be required for one large driver and several small ones. The installed drives will be divided as follows:

- The Cycle Compressor.
- The BOG Compressors.
- Compressor Lube circuit will need 2 pumps.

Table (4) – Power Users for BOG Re-liquefaction.

Typical electrical power supply	6.6 kV / 450 V, 60 cps
Cycle Compressor @ power 6.6 kV	4,700 kW installed
BOG Compressor @ power 6.6 kV	2 X 330 kW
Minor lube circuits @ power at 450V	2 X 10 kW
Control power	24V, 60 CPS

The ship facilities normally include both nitrogen and instrument air systems. Instrument air is required at a pressure of about 8 bar a and a water dew-point better that -40 deg C. The amount of air is small at about 30 – 40 Nm^3/h. The two nitrogen generators located on the ship should provide nitrogen of quality as follows:

- Capacity 150 Nm3/h per unit.
- Discharge pressure 8 - 10 bar g
- Dew point -100°C or better
- Purity : 99%

About 80 – 120 Nm3/h will be used by the seals and cold box purge. This is easliy handled by one of the nitrogen generators. The second unit can be used to speed up the start-up sequence of the liquefaction unit after it has bee shut down for a long time and the settle-out pressure has declined significantly.

9 Economic Aspects of BOG re-liquefaction

The buoyant LNG market has widened the differential cost between fuel and the use of BOG on-board ship. The Henry-Hub price has recently risen to well above 5$/MMBtU and the HFO prices are relatively static as opposed to LNG. Hence there is a rising differential between HFO and LNG making the use of BOG re-liquefaction more attractive on ships which utilize HFO.

The situation with marine diesel, MDO, is quite different. In recent months the price of this has risen sharply to over 400US$/tonne. Table 5 shows how the various fuels compare over the last 2 years.

Table (5) – Fuel Prices and Lower Heating Values.

Year & Source		MDO	LNG	HFO
2002	US$/tonne	210	156	135
2004, Rotterdam	US$/tonne	365 - 370	-	146 - 150
2004 for LNG	US$/tonne	-	250 - 270	-
2004, Suez, Singapore	US$/tonne	375 - 380	-	174 - 178
	LHV, MJ/kg	41.8	49.2	40.4

Based on the use of HFO in low speed 2-stroke drives on board ship, the economics look very favorable for the implementation of BOG re-liquefaction yielding savings of over 2 million US$, based on 150$/tonne HFO cost and an LNG price of 5$/MMBtU. Typical paybacks of about 3 – 5 years are expected. Referring to Henry Hub prices LNG has been slightly cheaper than HFO until 2002, while it is now approx. 15…20% more expensive (based on the heating valve). When the fuel is diesel, the picture is less clear because of the very high price of MDO.

10 Conclusions

The use of BOG re-liquefaction processes based on the classical Brayton cycle has been considered for LNG ships over many decades. The process technology has been in operation on many land-based LNG liquefaction plants and air separation facilities giving it an excellent platform for application on board LNG carries.
The economics of BOG re-liquefaction looks very attractive when considering the use of HFO as the basic fuel on board LNG carriers.

Based on a process technology which is well-known in the industry and on long-term in-house experience, Tractebel Gas Engineering has developed a BOG re-liquefaction system for modern large LNG carriers, which offers superior energy efficiency and hence optimized economics.

11 References.

1. Kuver, Dr. M, et al, "Evaluation of Propulsion Options for LNG Carriers", Gastech 2002.