Replacement of nitrogen by argon in LNG carriers membrane tanks

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1. Abstract

This paper describes a new concept of insulation for Liquefied Natural Gas (LNG) carriers membrane tanks, based on the use of argon, instead of nitrogen, to fill up with inert gas the insulation spaces.

Argon gas has the advantage of having a much lower thermal conductivity, offering the opportunity of reducing the LNG boil off rate of an existing ship by up to 20 %.

This paper describes this new concepts, and its implementation on board LNG carriers.

Two strategies are considered for the argon supply system, based either on an open either on a closed loop architecture.

The feasibility of the corresponding argon related logistics and operations is confirmed.

2. Description

Presently cargo insulation of membrane type LNG carrier, developed by Gaz Transport and Technigaz, is composed of a first gas tight membrane in direct contact with the LNG, resting on a thermal insulation system made of two layers of foam panels (Mark or CS1 containment systems) or two layers of plywood boxes filled with expanded perlite (NO system), which are themselves separated by a redundant secondary gas tight membrane.

The figures 1, 2 and 3 give overviews of these different types of insulation.

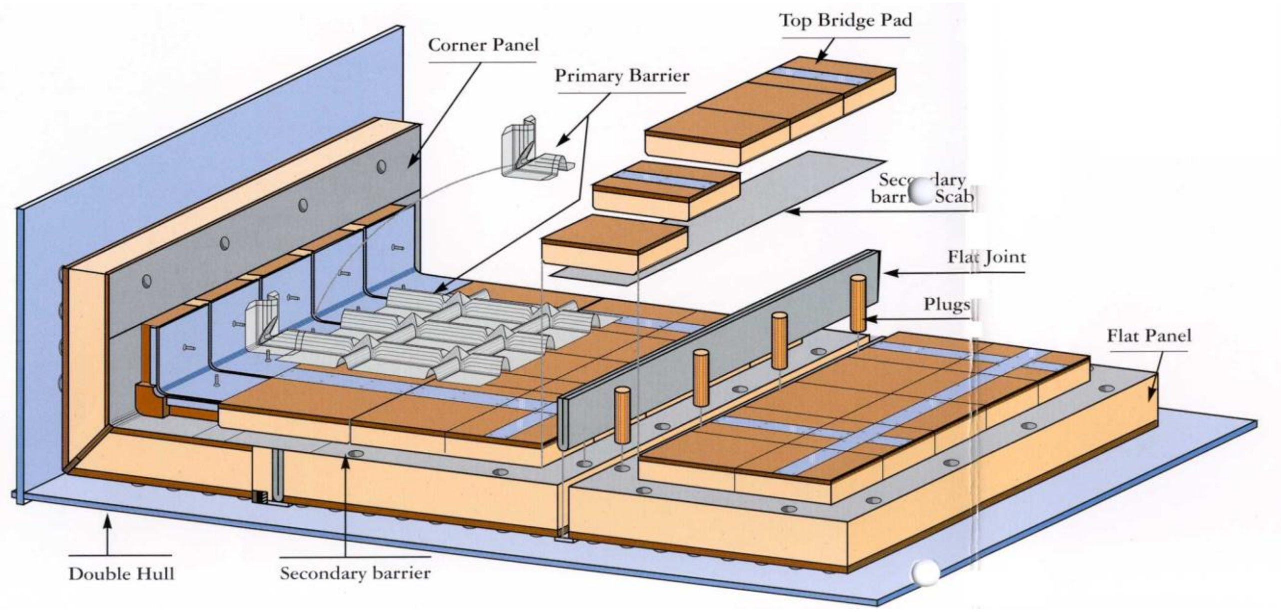

Figure 1 : Mark 3 type foam insulation proposed by Gaz Transport and Technigaz

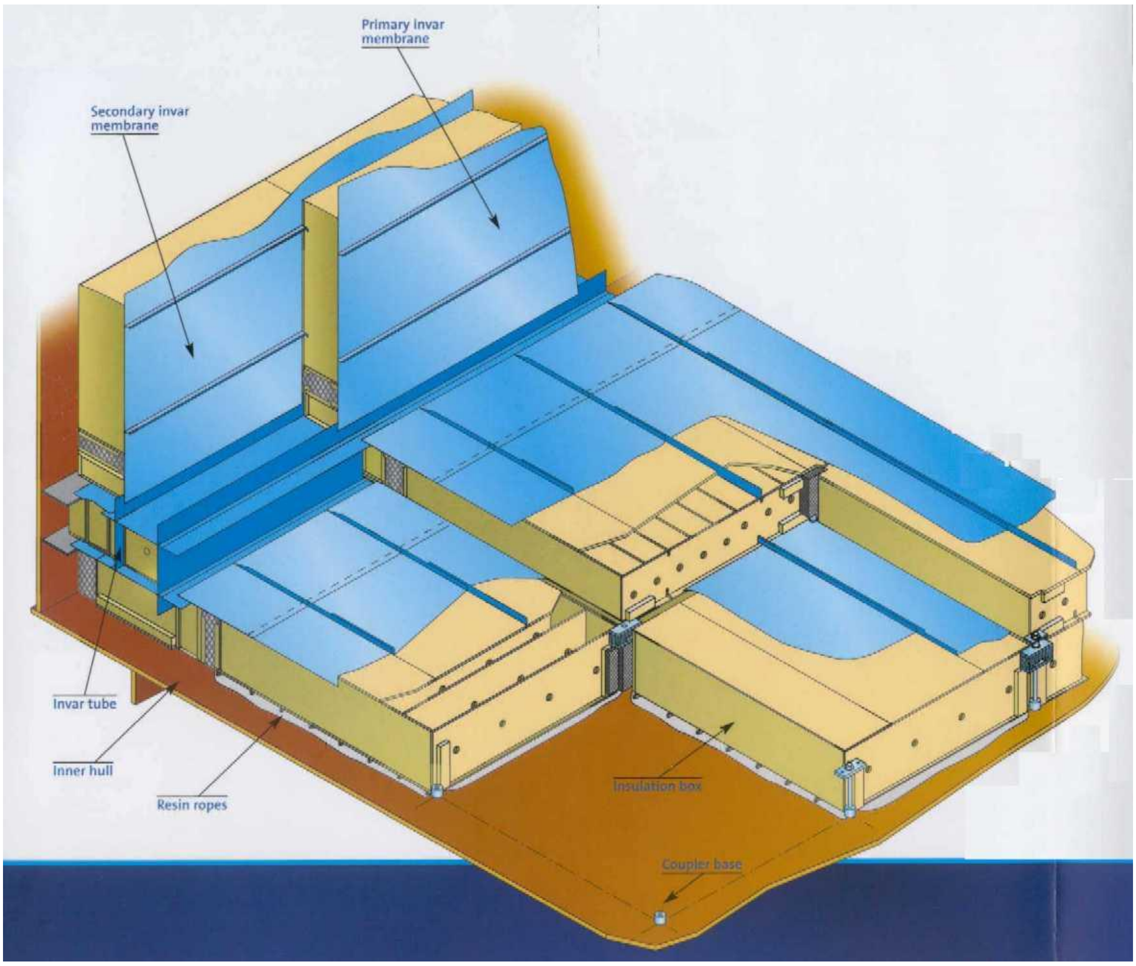

Figure 2: NO 96 perlite insulation by Gaz Transport and Technigaz

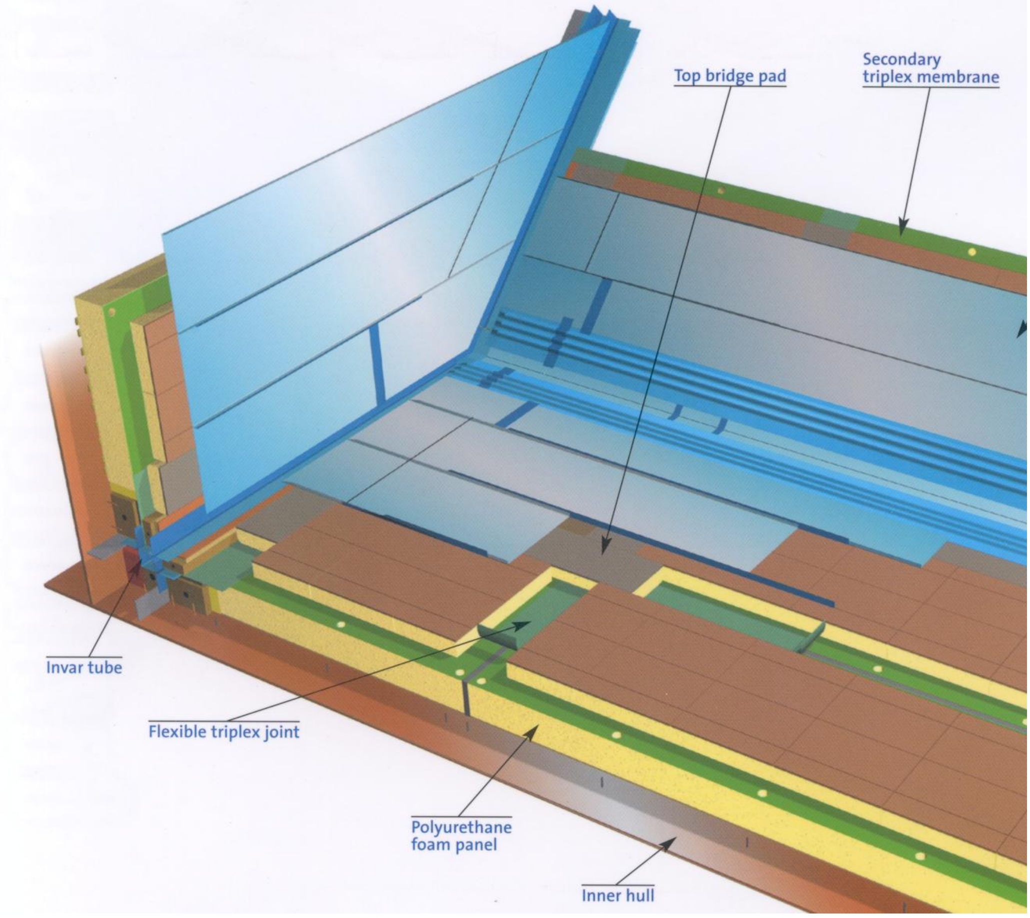

Figure 3 : CS1 foam insulation by Gaz Transport and Technigaz

These two insulation spaces are filled by nitrogen gas which is used to inert them, so that, even in case of leakage of natural gas through either the primary or the secondary membranes, there is no safety hazard.

This nitrogen gas is as well used as a gas carrier to collect, detect and vent out of the insulation spaces, the LNG leaks through the membranes to keep the concentration of methane below 30 % of the limit of flammability, in compliance with the IGC (International Gas Code).

The thermal efficiency, and therefore the thickness of this insulation, is driven by the two following main requirements :

1) protect the ship's double from cold temperature which would make it brittle;
2) reduce the thermal heat leaks through the insulation toward the cargo to avoid excess cargo boil off.

In practice, the reduction of heat leaks is the main driver, and insulation thickness is optimised to keep the boil off within acceptable limits, typically between 0,15 to 0,2 % per day.

This acceptable value for the boil off rate is directly derived from the fact that at least part of the ship's energy requirements is met by using, as fuel, the boil off vapours coming from the cargo tanks

The insulation thickness is therefore optimised so that the boil-off rate from the cargo is slightly below, when fully loaded, the fuel consumption of the ship when it is on its way at nominal speed. This way, the boil off gas is directly valorised by using it for the ship propulsion during most of the ship's operations.

When the ship is operating at low speed or during harbour manoeuvres, it has to flare (or vent to the atmosphere) the excess boil off gas to keep the pressure in the cargo tanks within acceptable limits.

The same applies when the sea conditions, (storms or heavy swells) generate a lot of sloshing in the cargo tanks , increasing the boil off rate by up to 0,05 % per day, while, at the same time, the ship has to reduce its speed, and, therefore its power consumption, to avoid excessive slamming.
In the same way, decrease of the atmospheric pressure on the way may generate additional boil ff of the cargo.

This quantity of excess boil off flared or vented during operations at low speed or at anchor depends therefore on the LNG routes considered.

For short LNG routes (North Africa/Southern Europe, Norway / Northern Europe, Trinidad / North America trades…), excess boil off during harbour operations can become quite significant, and economical and, and more recently, environmental (reduction of CO_2 emissions) issues provide an incentive to reduce them as much as possible, even on an existing ship.

For longer LNG routes, such as the transatlantic routes, it is the combination of heavy swell and stormy conditions which may make the excess boil off quite significant while the ship is at sea.

Natural boil off reduction can be therefore an interest either as a retrofit action on already built ships.

For new built ships, improving the performance of the insulation of the cargo containment system can either be used to :
- either reduce the boil off rate
-either to allow , with the same boil off rate, to reduce the insulation thickness and therefore, for the same hull shape, increase the shipping capacity and reduce the volume of insulation materials.

Of course, to be economically feasible, especially in case of a retrofit action, any improvement should minimise impacts on existing hardware and technology, especially on the containment system.

We propose therefore to improve drastically the thermal performance of existing LNG carrier containment system by simply replacing the inert gas used to fill these insulation spaces by argon instead of nitrogen.

As the most common inert gas present in ambient air (0,934% in volume), after nitrogen , argon provides the same inerting capabilities as nitrogen with, as well, the same non corrosive and non toxic properties.

The thermal conductivity of argon is significantly lower (up to 39 %, see table 1) than the one of nitrogen (this property is the reason why argon is used in the building industry to fill in the inner space of double glass windows to increase their thermal performance).

Temperature (°C)	Nitrogen conductivity (mW/mK)	Argon conductivity (mW/mK)	Difference (%)
-163	10,5	7,3	31
-123	14,0	9,7	31
-73	18,3	12,5	32
-3	26,2	16,2	39
27	28	17,6	38

Table 1: Heat conductivity of argon and nitrogen versus temperature

This allow to reduce drastically the overall thermal conductivity of the insulation which is a combination of :
- the thermal conductivity of the gas trapped in the foam or perlite ,
- the solid and radiative conductivity through the foam or the expanded perlite and the plywood.

If one considers as in reference 7, than part of the heat exchange may come (especially in the perlite case) from slow convective current, replacement of nitrogen by argon should be as well advantageous, as argon has roughly the same coefficient of expansion but is 20 % more viscous.

The influence of the gas filling cryogenic insulation spaces has been identified for years, as explained in reference 1 and 2 and is illustrated for example in figure 4 by the effect of residual gas pressure on effective thermal conductivity of a perlite type insulation.

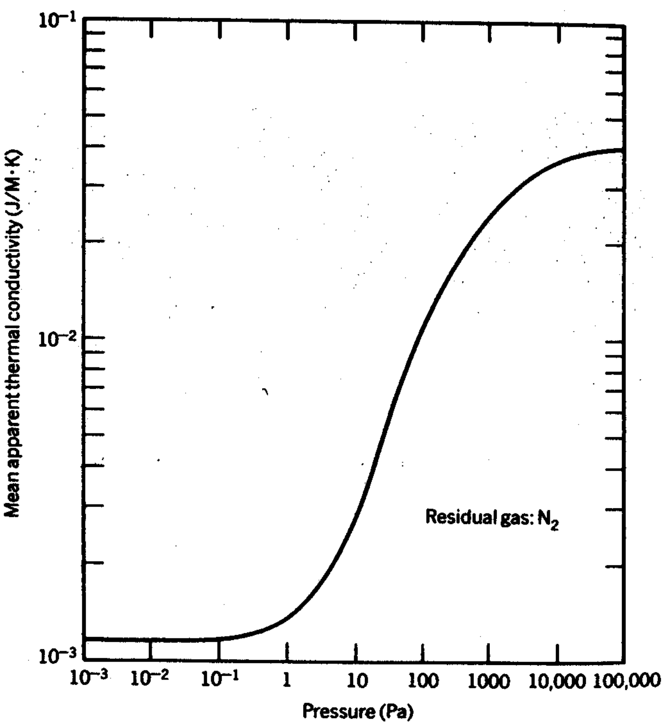

Figure 4 : Effect of residual gas pressure on the effective thermal conductivity of powder insulation perlite, 30-80 mesh, Between 27°C and - 195°C (Leonard A;Wenzel, in Cryogenic systems)

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In this case, the overall conductivity is the sum of the conductivity of the gas trapped in the perlite and the conductivity of the plywood structure, so the reduction of the overall thermal conductivity reduction is expected to be less than the one between argon and nitrogen gas, around 20 % instead of 30%.

In the case of the foam insulation, an estimate of the breakdown of theses different heat conduction modes is given in table 2 for the foam insulation system, where the thermal conductivity of the foam itself is as well quite significant, so the overall reduction of thermal conductivity is expected to be around 20 % as well.

Temperature (°C)	Foam in nitrogen conductivity (mW/mK)	Nitrogen conductivity (mW/mK)	Foam solid and radiative conduction estimate (mW/mK)	Argon conductivity (mW/mK)	Foam conduction in argon estimate (mW/mK)	Overall Loss in thermal conductivity (%)
-160	19	10,5	8,5	7,4	15,9	16
-80	24	17,7	6,3	12,1	18,4	23
0	30	23,9	6,1	16,2	22,3	25

Table 2 : Heat conductivity contribution breakdown and overall thermal conductivity of argon and nitrogen insulation versus temperature

3. Implementation on board

As replacement of nitrogen by argon in the insulation spaces does not require any changes in the containment system technologies, the implementation of this new system is therefore focused on the argon supply system required to provide this argon gas to the insulation spaces.

Two main argon supply strategies have been identified :
- one based **on a open loop configuration**, where the flow of argon gas getting through the insulation spaces is no recycled and is directly vented to the atmosphere, as illustrated in figure 5;
- one based **on a closed loop configuration** where the flow of argon is recycled, as illustrated in figure 8.

In both cases, like the present nitrogen supply system, the argon supply system must be compatible with the following operational requirements :
- use of the inert gas as a carrier gas by providing a flow of gas to continuously vent the insulation space in order to detect and prevent any leakage of LNG though the membranes;
- use of the inert gas to control the pressure in the insulation spaces by providing a flow of gas during the cool down of the insulation spaces when they are brought back to cryogenic temperature when the tanks are filled up with LNG at the loading terminal;
- use of the inert gas to keep the natural gas concentration in the insulation spaces below 30 % of the limit of explosion by providing a flow of gas to dilute possible LNG leaks in case of failure of the membrane.

The flow of inert gas required for these different requirements are respectively in the order of (for a 140 000 m^3 LNG carrier) :
- 20 Nm^3/h for the continuous venting of the insulation spaces;
- 100 Nm^3/h for the pressure control of the insulation spaces during cool down;

- 100 Nm^3/h for the dilution of LNG leaks into the insulation spaces.

3.1. Open loop configuration

The open loop configuration is identical to the one used for the nitrogen supply on the first generation of LNG carriers : for these carriers the inert gas supply is stored on board in a liquefied state at low pressure (several atmospheres), in a cryogenic, vacuum insulated, tanks located on deck, see figure 6.

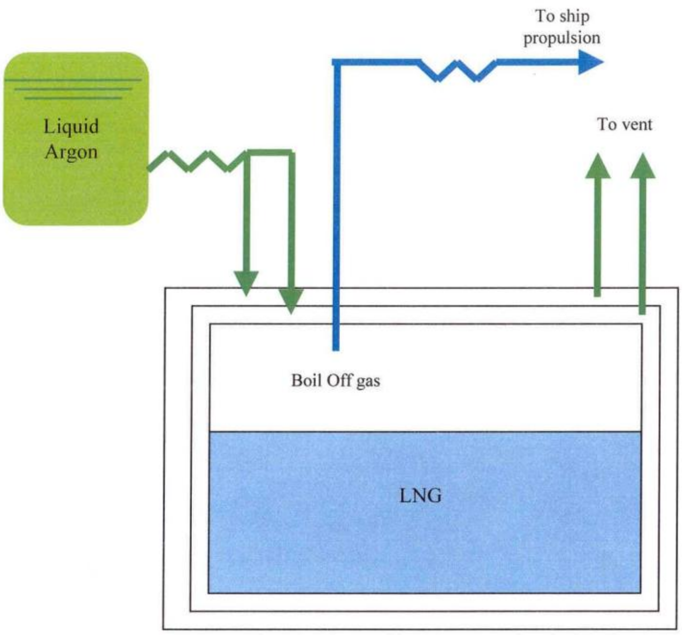

Figure 5 : Open loop argon supply configuration

Figure 6 :Example of on board liquefied nitrogen storage tanks and vaporisers which could be directly used to store liquefied argon.

To fill up these tanks periodically, a liquefied nitrogen logistics has been put in place at most the corresponding loading or unloading terminals, to perform the filling up of these tanks during loading or unloading operations, through a specific, 3 inches diameter, liquefied nitrogen pipe attached to one of the LNG loading arms, see figure 7. This liquefied nitrogen supply is as well used, even for LNG carrier equipped with on board nitrogen generators, to provide the liquefied nitrogen used to check periodically, at cryogenic temperature, equipment's in the cargo room such as boil off heat exchangers..

80 % of present and future terminals are, or will be, equipped with this type of interface, so most LNG routes are already covered with this loading interfaces which could be directly used to load liquefied argon instead of nitrogen, with the same operating procedures for the crew.

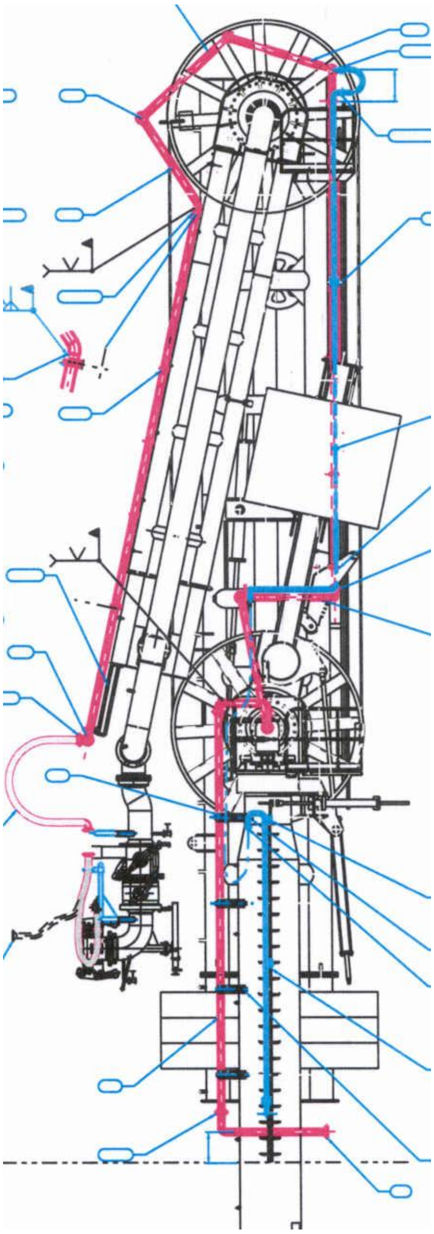

Figure 7 : Example of Liquefied nitrogen loading lines (in red) attached to an LNG loading arm, proposed by FMC loading systems, which could be directly used to supply liquefied argon

To provide a continuous venting of the insulation spaces, the flow of liquefied inert gas coming from the tank is sent through an open air vaporiser, and then to the cargo containment system. At the exit of the containment system, the mixture of argon and natural gas leakage through the membrane system is directly vented to the atmosphere. This open loop architecture requires therefore large quantities of inert gas, which are stored in large capacity (typically two 30 m^3 tanks on a 140 000 m^3 LNG carrier, see figure 6).

Retrofit case on first generation LNG carrier :

In the case of a retrofit case on a first generation LNG carrier, these liquefied nitrogen tanks and associated vaporisers and piping systems are already existing and expected to be directly usable to store and vaporise liquefied argon instead of nitrogen, the only identified limitations being :
1) the mechanical design of the tanks as liquefied argon has a higher specific mass (1392 kg/m^3) than liquefied nitrogen (808 kg/m^3),
2) the thermal design of the vaporisers as for the same volume of vaporised gas, argon requires around 60 % more heat.

If the same tanks are used for the storage of liquefied argon as the one previously used for nitrogen, one benefit will be that they will provide, within the same volume of liquefied gas, a 20 % increased supply of inert gas, as one litre of liquefied argon can provide 835 litres of gas, at ambient conditions, instead of 691 for nitrogen…This would increase therefore the autonomy of the carrier in inert gas by 20 %.

Assuming the existing hardware is readily usable to handle argon instead of nitrogen, the additional Capital Expenses (CaPex) relevant to the use of a liquefied argon instead of liquefied nitrogen inert gas supply on an existing ship are therefore expected to be negligible.

If either the mechanical design of the tanks or the thermal design of the heat exchanger is not compatible, the CaPex will have to include the corresponding upgrading or procurement of tanks and heat exchangers.

Retrofit or new built case on present generation LNG carrier :

The same approach can be used for the present generation of LNG carriers (from inert gas supply point of view) , where the nitrogen supply is provided by an on board system extracting nitrogen from the ambient air.
In this case, as on board extraction of the minute quantities (0,934 %) of argon contained in ambient air is not economically attractive, the replacement of nitrogen by argon in the insulation spaces will require the additional CaPex relative to the implementation of specific liquefied argon tank, vaporisers and piping systems .

Nevertheless, if the nitrogen generator is kept on board, the size of the argon storage tank can be reduced, as the nitrogen supply can be used to provide inert gas :
- to dilute LNG leaks in the insulation spaces in case of membrane failure;
- for blanketing purpose in other areas than the insulation spaces (cargo room ,etc…);
- as a back up source for the blanketing of the insulation spaces, in case of shortage of liquefied argon if the vessel was not able to fill up its liquefied argon tank for any reasons or if a major leak occurs in the cargo containment system.

This should allow, for a 140 000 m^3 carrier, to have only one 30 m^3 liquefied nitrogen tank, instead of two, reducing the corresponding CaPex.

Use of the existing on board nitrogen supply as back up of the liquefied argon supply is feasible as there is no inconvenience (apart with regard to the thermal performance) in a having in the insulation space a mixture of nitrogen and argon gas.

Replacement by one or the other inert gas is reversible and can be performed without impact on the vessel nominal operations.

Replacement of nitrogen by argon in the insulation spaces should not therefore impact on the flexibility of LNG carriers operations, as , in case of shortage of argon, the carrier can switch to its nitrogen supply … and back to argon when this gas is available again!

The sizing of the vaporisers will be driven by the peak demand of inert gas during the cool down of the insulation spaces. These items will be identical to the ones presently used on first generation of LNG carriers. For a 140 000 m^3 carrier, one may consider a vaporiser having a 100 Nm^3/h capability.

Such type of storage and vaporisers equipment's compatible with classification societies requirements are readily available on the market, as illustrated in figure 6.

The additional Operational Expenses (OpEx) relative to this open loop configuration for both first and new generation LNG carriers is expected to be limited to the difference of cost between argon and nitrogen, provided either in liquefied form (for the first generation LNG carriers) either by the onboard nitrogen generator (for the second generation of LNG carriers).

The logistic associated with liquefied argon being essentially identical to the liquefied nitrogen one (argon is a common industrial gas presently used in many process ranging from welding, metallurgy heat treatment and is commercially available in gaseous or liquefied state), it should not be a major constraint.

Liquefied argon is widely available on an industrial basis, just like nitrogen, as a product of the air liquefaction process which is usually primarily aimed at the production of oxygen or nitrogen gas. The fact that argon is a by product of the air liquefaction process means that its production does not generate any significant energy cost and, more importantly, emissions. Production of argon can be therefore considered emission free.
Its price range is in the same order (typically twice as much) as liquefied nitrogen and it can be therefore delivered by truck in most importing or exporting LNG harbours by most gas vendors.

Storage tank	30 m3 , 6 barg Maximum operating Pressure
Vaporisers	100 Nm^3/h
Loading pipe	3 " diameter

Table 3 : Typical open loop components main features for a 150 000 m^3 carrier.

3.2. Closed loop configuration :

Although attractive, due to its limited CapEx, the open loop configuration is not optimised with regard to OpEx , as argon is significantly more expansive than nitrogen (typically two to three times as much) . Furthermore, the logistics associated with the supply of liquefied argon is an incentive to reduce as much as possible argon refilling operations, to maximise the LNG carrier autonomy.

An alternative can be, therefore, considered where the argon circulating in the insulation spaces is recycled in closed loop to reduce drastically the OpEx relevant to argon consumption, as illustrated in figure 8.

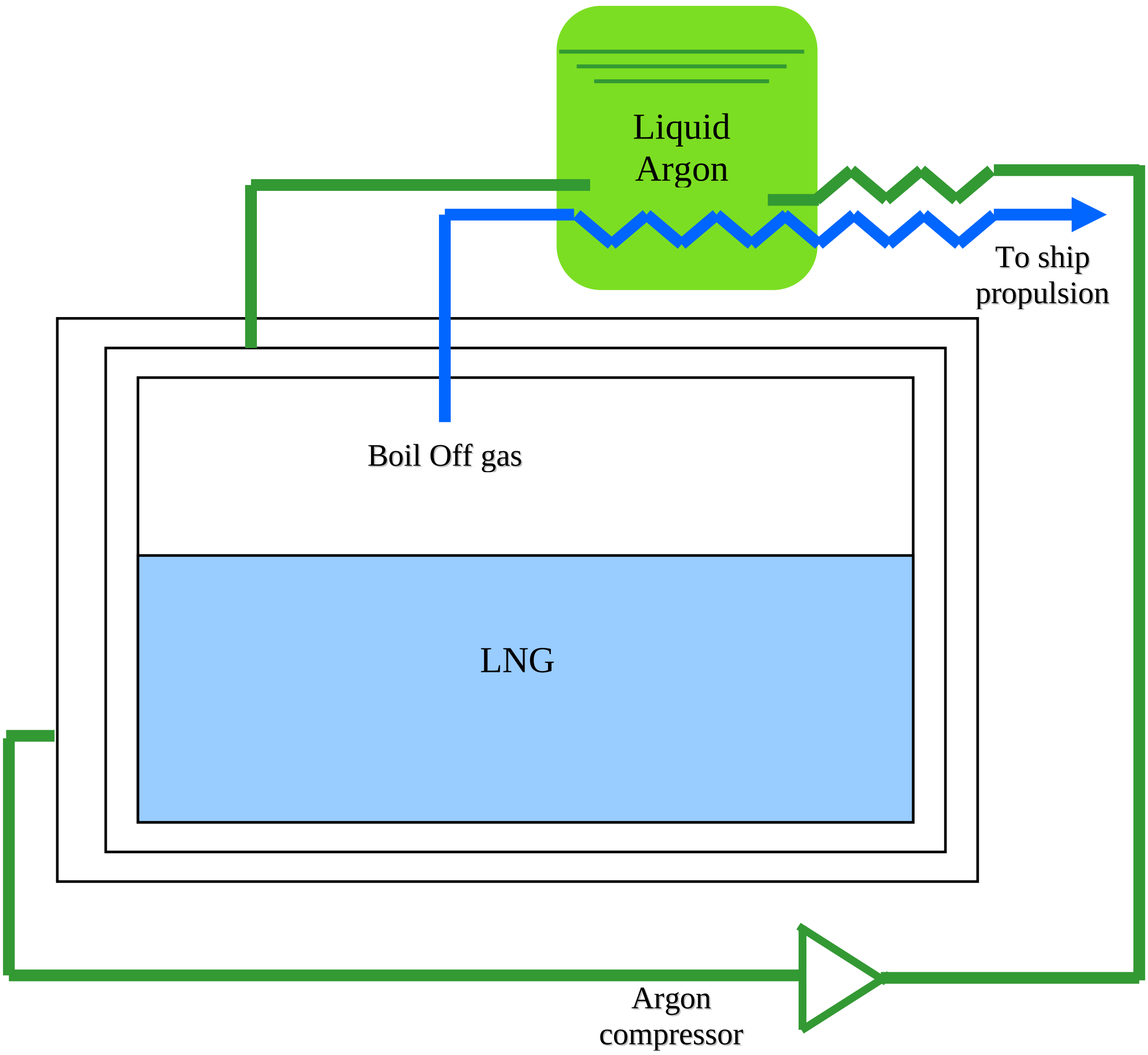

Figure 8: Closed loop argon supply configuration

In the case of closed loop configuration, three main challenges have to be addressed :
1) storing the excess of argon getting out of the insulation spaces after the unloading of the carrier, on the return voyage, when the empty cargo tanks insulation spaces are warming up;
2) meeting the required peak consumption of argon to refill the insulation spaces during their rapid cool down after loading, when the cargo tanks and their insulation are brought back to cryogenic temperature.
3) purifying the argon from contaminants, such as the one coming from natural gas leaks through the membranes, before re cycling it into the insulation spaces.

The first two challenges can be met by storing, in a similar way as for the open loop configuration, argon in a liquefied form, taking advantage, as illustrated in table 4, that the argon saturation curve is just slightly above the methane one.
It is therefore possible, pressurising gaseous argon to around 2 Mpa, to liquefy it by cooling it with a flow of boil off vapours and/ or LNG coming from the cargo tanks, on their way toward the engine room.

Temperature (°C)	Argon saturation pressure (Mpa)	Comments
-186	0.1	Boiling point at ambient atmosphere
-173	0.32	
-163	0,66	Boiling point of methane at ambient atmosphere
-153	1,21	
-143	2,02	Typical BOG exit temperature from tanks
-133	3,16	
-123	4,9	Critical point

Table 4 : argon saturation pressure versus temperature

The storage of the required quantity of argon can be performed with a small cryogenic tank of limited capacities (typically less than 5 m^3), which can be easily implemented on deck .

During the ballast voyage , boil off is reduced, and the ship uses, for its propulsion needs, mostly LNG which can be used to cool down and liquefy the argon coming from the insulation spaces.

When the insulation spaces are cooled down, just prior and after loading, the peak argon demand to keep the insulation spaces at constant pressure can be met by sending the liquefied argon from the storage tank through an open air vaporisers (identical to the one required for the open loop configuration) before sending it to the containment system.

The third challenge can be addressed by implementing a purification process in the loop to separate the argon from the contaminants it has collected in the insulation spaces, as illustrated in figure 9. These are expected to come mainly from the cargo itself and the ballast tanks surrounding the cargo tanks and be composed mostly of water, hydrocarbons and nitrogen.

The approach can be therefore to use the cool down of the argon before its re liquefaction, to remove, the water, the hydrocarbons (which may lead to a safety hazard in the insulation space if the LIE is reached) , as their condensation temperature are higher. So by implementing, in the appropriate locations of the heat exchangers used to cool the argon on its way to the storage tank, purge systems to collect and vent out condensates, these contaminants can be removed.

With regard to the nitrogen contamination which can come as well from the LNG leaks, but does not bring any safety hazard in the insulation spaces , but only an increase in the thermal conductivity of the gas mixture, its effects can be either neglected or, as this gas is more volatile than argon , it can be removed by periodically venting the gas dome of the storage tanks which is filled with argon vapours enriched with nitrogen.

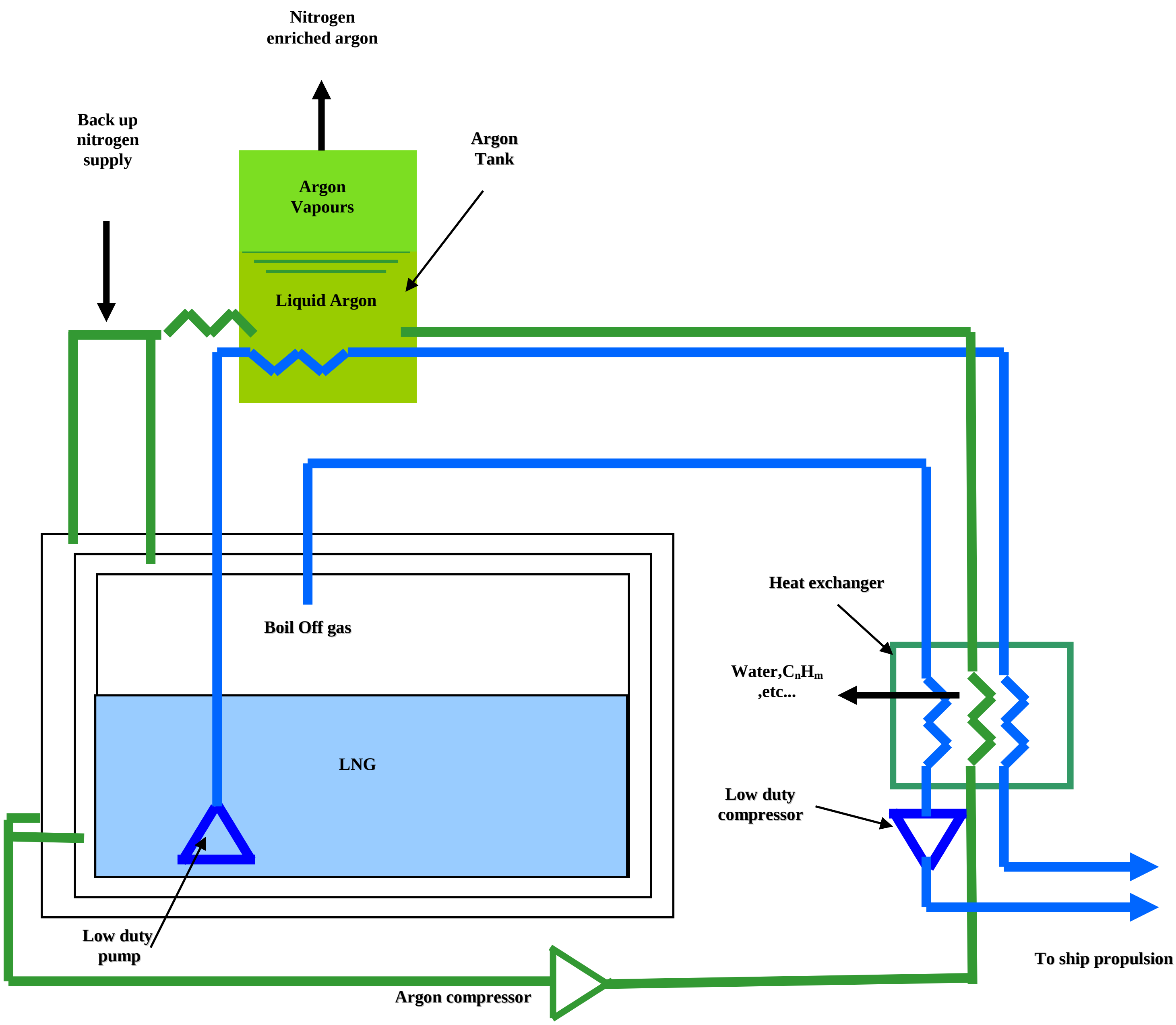

Figure 9 : Argon purification system

For the present generation of LNG carriers, which use on board nitrogen generators, or in the case of the first generation of LNG carriers, if the existing liquefied nitrogen storage tank are not compatible with the required maximum operating pressure, the CaPex required to implement a closed loop configuration is therefore limited to the implementation of a low duty compressor (typically in the 3 MPa/ 20 Nm^3/h range for a 140 000 m^3 carrier), a small size, medium pressure (3 MPa) liquefied argon tank (typically 5 m^3 for a 140 000 m^3 carrier) , a small size heat exchanger (20 Nm^3/h range) and purification system to cool and recycle the argon gas and a small size vaporiser (100 Nm^3/h range) to inject argon at ambient temperature in the insulation spaces.

In any case, impacts are very limited and this additional systems can be easily implemented on deck (for the storage tank and the vaporiser) and in the cargo room (for the compressor), with very small foot prints.

Storage tank	5 m^3 , 30 barg Maximum operating Pressure
Argon compressor	30 barg , 20 Nm^3/h
Argon condenser	30 barg , 20 Nm^3/h
Vaporisers	5 barg , 100 Nm^3/h
Loading pipe	3 " diameter

Table 5 : Typical closed loop components main features for a 150 000 m^3 carrier.

4. Difference of behaviour between insulation using foam or perlite

The behaviour of the argon gas in the insulation spaces will be quite different, depending on the type of insulation material used, especially with regard to the rate of replacement of the nitrogen gas initially contained in the system by argon.

4.1. Behaviour of argon filled perlite insulation

In the case of Perlite insulation, the plywood boxes containing the argon have venting holes which allow direct replacement of the nitrogen, just by gravity effect (argon is 1.4 times heavier than nitrogen). As the inert gas inlet are located in the lower part of the insulation spaces, so that the heavier LNG leaks will be naturally pushed by buoyancy effect toward the outlet located on top, replacement of nitrogen by argon gas is expected to be very fast.

The only effect which could delay it could be nitrogen adsorption effect on the perlite itself. In a first approximation the rate of replacement should be therefore close to the rate of venting of the insulation spaces.
As an example, if we consider a venting flow rate of 20 Nm^3/h for an LNG carrier with 10 000 m^3 of insulation spaces, argon will have replaced the nitrogen within 20 days…

If furthermore, the nitrogen replacement operation is performed just at the end of a dry docking activity, the replacement of nitrogen by argon can be reduced to few hours only, if the insulation spaces are first vacuum pumped to evacuate air or nitrogen before the injection of the argon gas.

In any case, by switching to argon an LNG carrier should be able to replace the nitrogen gas filling the insulation space by argon within a single rotation…

4.2. Behaviour of argon filled foam insulation

In the case of foam insulation, the replacement of nitrogen by argon is expected to be much slower as the inert gas is trapped in the closed cells of the foams. Gas exchange is therefore limited by the permeation rate of argon and nitrogen through the foam cells walls.

For a given foam, permeation rates depends on the gas nature and more precisely its molecular shape and size. As argon molecule size is very similar to the one of nitrogen (3.8 A instead of 3 to

4.1 A) this rate is expected to be very similar for both gas, and the gas initially trapped in the foam cells can be expected to be replaced by argon within several weeks.

5. Safety aspects

The § 9.2.1 of the IGC stipulates that : *"Interbarrier and hold spaces associated with cargo containment systems for flammable gas requiring full secundary barriers should be inerted with a suitable dry inert gas and kept inerted with a suitable dry inert gas provided by a shipboard inert gas generation system, or by a shipboard storage which should be sufficient for normal consumption for at least 30 days."*

The proposed replacement of dry nitrogen by another inert dry gas, **argon is therefore compliant with the IGC**. For ship equipped with an on board nitrogen generator able to back up the supply of inert gas in case of failure of the argon supply, the autonomy of the argon storage may be less than 30 days.

From biological and inerting point of view, argon and nitrogen are identical, both described (see ref 5) as : *"Physiologically, inert, non toxic gas. By displacing the oxygen in the air, it may have harmful effect on the organism, by reducing the partial pressure of oxygen and acting as an asphyxiant."*

With regard to the capability of carrying the natural gas leakage out of the insulation spaces, as argon is 2,4 times heavier than methane compared to nitrogen which is only 1,8 times heavier, the corresponding 30 % increase in buoyancy effect should speed up detection and collection of any natural gas leaks through the membrane, increasing the safety of the cargo containment system.

6. Identification of main economical and environmental benefits

The main economical and environmental gains brought by the replacement of nitrogen by argon in the insulation spaces are the following depending whether the increased performance of the insulation is used to reduce either the boil off rate, either the insulation thickness.

6.1. Benefits from reduced boil off rate, keeping the same insulation thickness

These benefits are considered when the replacement of nitrogen by argon is made for the same insulation thickness. **It does, therefore, apply more specifically to retrofit activity on existing LNG carriers.**

Reduced of excess boil off gas flaring or venting

Reducing the BOG rate will allow to reduce the corresponding quantities of loaded gas which has to be flared or vented to avoid cargo tank pressure build up when the carrier energy needs are lower than the one which can be provided by the gas boiling out of the tanks.

The gains in extra LNG unloaded at the importing terminal depends on the given LNG route, as an example :
- shorter routes, mean that the vessel will spend a very significant part of its time operating at low speed or even waiting to get authorisation to proceed…

- open sea routes, in adverse sea conditions such as North Atlantic, mean that the vessel will have to face BOG rate increase due to heavy internal sloshing in the cargo tanks, combined with the need to reduce speed to avoid structural damage…

Another benefit is environmental : Reduced excess BOG, means reduced emissions. As part of the general trend to reduce green house effect gas emissions, international and local regulations are expected to get more and more stringent. Replacing nitrogen by argon in the insulation spaces will allow to reduce drastically these LNG carrier emissions, especially during harbour operations..

Reduced re cooling heel

The reduction of the thermal heat leaks in the cargo tank during the ballast voyage can increase very significantly the shipping capacity by reducing the LNG "heel" required to re cool the tank prior loading.
The volume of this re cooling heel depends on the length of the LNGF route considered. Typically, for a 140 000 m^3 carrier it varies between 1000 to 2000 m^3.
Any reduction of this volume of LNG will be directly transformed extra unloaded LNG quantities...

Reduced LNG fuel consumption

Reduction of the BOG rate allows to use more HFO or MDO instead of boil off vapours to meet the ship propulsion needs.
All the LNG which is not used as fuel will be directly transformed in extra unloaded quantities…

Access to longer LNG routes

LNG carriers are required to have a minimum filling ratio, typically 90 % , in order to keep sloshing effect in the tank within acceptable limits.

For the longest LNG route, such limitation can become critical, for example, assuming an initial filling ratio of 98 % and a boil off rate of 0,2 %, an LNG carriers will reach this limit within 40 days. This can become a limiting factor for very long routes, such as the one which may be especially used or the LNG "spot" market, for example to deliver an LNG cargo from Algeria to Korea…The same could apply, in case of a major crisis in the Middle East, leading to the closure of the Suez canal, which would force LNG carriers to go around the cape of Good Hope to deliver LNG cargo towards Europe or the United States..

If nitrogen is replaced by argon in the insulation spaces, and reduces the boil off rate to 0,16%, this limitation is pushed upward to 48 days and the carrier become compatible with these extra long LNG routes..

Increased optimised speed domain

Most existing LNG carriers have been designed with a specific route and speed in mind, leading to a given optimisation of the insulation thickness to provide the appropriate BOG to the ship propulsion system. With the present increase of the LNG "spot" market, these LNG carriers may have more various shipping opportunities, albeit with different, slower, operating speeds

In this case the reduction of the boil off rate offered by the replacement or nitrogen by argon in the insulation spaces may allow to take advantage of the corresponding, fuel consumption reduction.
As an example, let's consider a ship designed initially to operate at a given speed, matching its boil off rate of ,let's say, 0,2 % per day.

If the ship is used on another route at a slower speed, let say for example 17 knots instead of 19, its boil off rate will exceeds its fuel needs by 20 %, typically, and the corresponding excess boil off will be lost.

But, if nitrogen is replaced by argon in the insulation spaces and reduces the boil off rate to 0,16%, the reduced boil off rate will match this fuel consumption reduction, avoiding excess boil off, making the carrier energy efficient for this route.
Excess boil off savings can be quite significant : 0,04 % per day of boil off reduction on a 140 000 m^3 LNG carrier, means, at the end of the trip, 50 extra cubic meters of unloaded LNG per sea day!

Reduced cargo room power consumption

Increase use of HFO or MDO for propulsion will reduce the power consumption required for the warming up and pressurisation of the boil off vapours before using them as fuel in the engine room.

For the Dual Diesel Electric carrier which uses mostly natural gas as fuel, and get it both from the boil off compressors and dedicated submerged pump,a reduced boil off leads to an higher portion of the natural gas to be taken from the cargo tanks in a liquefied form rather than gaseous.
This means a significant power reduction as pressurising LNG at the level required by the propulsion systems (typically 0,5 Mpa) requires much less power than pressuring boil off gas (typically 1,2 kJ/kg instead of 160). The corresponding savings assuming that 1ton/hour of extra LNG is pumped that way, 150 days per year leading to 150 000 kWh less power consumption per year. Considering the cost of on board power at 0,06 $/kWh, this means an extra saving of 9500 $ per year.

Reduced bulkhead power consumption

Reduced heat leaks in the bulkheads will reduce the power consumption require to keep them at ambient temperature

Reduced maintenance

By reducing the amount of excess boil off, the replacement of nitrogen by argon in the insulation spaces will reduce the wear and the risk of damage of such equipment as the boiler and steam condenser on a steam driven LNG carrier or as the gas combustion units or on board liquefier used on Diesel driven ones.

Reduced liquefaction plant and GCUs size, mass and power consumption

The present paper has been mostly aimed at retrofit activities on existing, LNG carriers, but it can be applied as well on the ship which are presently built around Dual Fuel Diesel electric propulsion systems or Low speed Diesel coupled with on board re liquefier.

For Dual Fuel Diesel Electric carriers, the economical assessment is very much the same as for steam propelled carriers, except that the boil off reduction will allow to reduce the size, mass and cost of the required GCUs (Gas Combustion Units) used to flare the BOG when it is not used by the Dual Fuel Diesel engines.

Based on reference 3, the cost of the GCU plant required to treat 100 % of the boil off is 500 000 $, excluding installation. With replacement of nitrogen by argon the BOG reduction of 20 % will allow to reduce accordingly the size of the GCU. Typically the cost of GCU will follow as well, being reduced by 10 %, i.e. 50 000 $.

For Low Speed Diesel coupled with on board re liquefier, the economical assessment will be performed by estimating the gains linked to the reduction of mass, size and cost of the GCUs (used to flare the BOG when the re liquefaction plant is out of order) and the re liquefaction plant, as well as the year round reduced power consumption of the latter.

Based on reference 4, one can estimate that the cost of power on board is around 0,063$ per kWh and the on board liquefaction plant will require, respectively, 1600 and 3000 kW of input power during the ballast and fully loaded voyage, i.e. 2300 kW on average, 350 days per year…

Replacement of nitrogen by argon will reduce these power consumption. If we consider a 20 % heat leaks reduction in the cargo tank, this would generate a saving of 3 864 000 kWh, or 243 000 $ per year…

Based on reference 3, the cost of the onboard liquefaction plant required to treat 100 % of the boil off is 6 000 000 $, whereas the CaPex to implement an argon insulation reducing the boil off to be treated by 20 % is lower than 500 000 $, even if one consider a redundant, closed cycle, argon installation : this means that from CapEx point of view, the replacement of nitrogen by argon is around 2,4 times more efficient than a on board liquefaction plant, so the cost of the argon installation will certainly be directly balanced by the reduced cost -(typically 10 %) of the liquefaction plant whose required capacity will be reduced by 20 %.

Table 6 summarise the corresponding estimates of CapEx and OpEx for a slow speed engine / on board liquefaction plant configuration for a 140 000 m^3 LNGC. Here again, replacement of nitrogen by argon in the insulation spaces is something to look at , as even from CaPex point of view, use of argon is less costly!

	Nitrogen insulation	Argon insulation	Comments
GCU	500 000	450 000	
Liquefaction plant	6 000 000	5 400 000	10 % cost reduction due to 20 % reduced required capacity
Argon installation	0	500 000	Assuming redundant closed loop architecture
Capex ($)	**6 500 000**	**6 350 000**	
Power consumption	1 215 000	972 000	Assuming 0,06 $/kWh and a 20 % boil off reduction
Argon/nitrogen consumption	90 000	10 000	Assuming 3 % loss of argon due to recycling porcess
Opex ($/year)	**1 305 000**	**982 000**	

Table 6 : CapEx and OpEx comparison for a Slow speed engine / liquefaction plant LNG C configuration

6.2. Benefits from increased shipping capacity , keeping the same boil off rate

Of course reduction of the heat leaks in the cargo tanks, keeping the same insulation thickness is expected to be already attractive, but **for new build LNG carriers one may take the opportunity of the replacement of nitrogen by argon to reduce the insulation thickness (and cost) and at the same time, increase the shipping capacity**, keeping the same boil off rate.

Depending on the required boil off rate, decreasing the insulation thickness by 20 % would increase the shipping capacity by several hundreds m^3…

7. Conclusion

This paper demonstrates clearly the technical and operational feasibility of replacing nitrogen by argon in LNG carriers insulation spaces. To assess its economical viability, thermal conductivity test are on going, as part of the European Commission funded project, NG^2ShipI/F and should be completed first quarter of 2005. If an LNG carrier can be made available to perform it, a full size test is foreseen in 2005-2006.

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