PNG, an Innovative System to Transport Gas Economically

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1. Abstract

Natural gas can be brought to the consumer by a fleet of ships with compressed natural gas (CNG) technology. Different proposals for transportation of gas by ship directly from the field to the consumer without the use of costly liquefaction, re-gasification and storage plants have been evaluated for many years. A new type of ship has been introduced having a large number of vertical pipes, designed according to enhanced pipeline design principles transporting compressed natural gas. The weight of the containment system is 50% less of the weight required by conventional pressure vessel design codes, making possible a large storage volume. Ships have so far been designed to transport up to 34 MSm$^3$ gas on each voyage. The presented concept for compressed natural gas was introduced by Knutsen OAS Shipping and has been developed with assistance from EUROPIPE GmbH and Det Norsk Veritas. Economic evaluations show that the new Knutsen PNG® is able to fill the gap in the medium range transportation between pipelines and LNG transport for distances up to 3,000 nautical miles. The advantage is less investment in infrastructure and greater flexibility. This new solution is best suited for so called stranded gas fields which are either to small or to far away from the marked to be connected economically by the so far known technologies, pipe line and/or LNG. The potential market for CNG carriers is large as more than half of the world’s known reserves are associated and stranded gas. These ships will serve as both storage and transport vehicles discharging directly into a land based gas grid via an on/offshore discharge terminal, an offshore platform or offshore buoys. This paper outlines the principles, the development process of the containment design, the qualification testing and the PNG economics for different transport scenarios.

2. Introduction

The demand for natural gas is increasing on a worldwide basis as a result of the increase in the world energy consumption, and increasing environmental awareness. Among the fossil fuels available today, natural gas is by far the most clean and environmentally friendly energy source and will be the increasingly important energy carrier in the next 20-30 years. Natural gas consumption in 2025 is projected to a total of 151 trillion cubic feet, nearly 70% higher than the 2001 total of 90 trillion cubic feet. The natural gas share of the total energy consumption is projected to increase from 23% in 2001 to 25% in 2025 (1).

Differently to the past the natural gas resources are becoming to a large extent more and more disconnected from their markets. This occurs due to large continental distances or by the open sea. Some 30% of the discovered gas is considered as so called “stranded”. Stranded gas is defined as a reservoir that prevents the economical development because of their distance from the market or existing infrastructure and the volume available.

An additional 20-30% of the world’s proven natural gas reserves are found in oil reservoirs as the so called associated gas. Very often the associated gas is uneconomical to commercialize due to the volume. It is flared or re-injected into the reservoir. The disposal of gas by flaring (burning) produces greenhouse gases and a valuable resource is lost. The Kyoto
agreement on reduced CO₂ emissions will eventually lead to reduced flaring of gas. Consequently, flaring is becoming banned in most oil-producing regions.

An alternative to gas flaring is to re-inject the gas into the reservoir. This helps to improve production rates in the beginning but may, in the long run, reduce the oil recovery rate of the oil well. This is becoming a pressing problem in some areas of the world. If a commercial solution for handling the associated gas now being re-injected is not found, the oil recovery rate may in the longer run be seriously impaired.

Hence, there is a clear rationale for finding more cost effective solutions for handling of both associated gas and stranded gas. The idea of being able to transport gas at ambient temperature and high pressure is equally old as the LNG development. The Compressed Natural Gas (CNG) option seemed especially tempting as this would allow for cost-savings in liquefaction, storage and re-gasification installations. Hence, the cost of land based infrastructure could be significantly reduced and also enable more flexibility in the use of the ships as they would not be as dependent on a tailor made infrastructure being in place as is the case for LNG, figure 01.

Figure 01: Value chains LNG versus CNG

A few decades ago the design codes available implied that the thickness and weight of the containment tank cylinders was rather large, leaving little capacity left for carrying gas. This prevented economic solutions for CNG transport. However, important technological developments within high strength materials, welding, non destructive testing and production have taken place during the last decades mainly due to the oil companies requirements to move oil and gas into deeper water areas and over longer distances. The development of reliability based codes and standards based on first principles have been accepted and explicit risk acceptance criteria have been implicitly set.

The new pipeline standards of today are more or less based on the above technological developments improving project economics with equal or even higher safety. By defining the correct failure modes for CNG containment system based on submarine pipeline technology with proven track record, CNG can emerge as an economically viable option.

3. The Pressurized Natural Gas Carrier Concept – PNG®

During the last years several different CNG concepts appeared. Today the Knutsen Pressurized Natural Gas Concept (PNG) is the most advanced technology. PNG is a Knutsen OAS Shipping Registered Trade Mark for CNG transport.

The development strategy selected by Knutsen OAS Shipping has been:
- Apply known design principles as far as possible
- Combine pipeline industry with the shipping industry
- Use ambient temperature in order to apply standard carbon steel pipeline regulation in the cargo containment system
- Minimize ship and cargo system complexity

In order to meet the development strategy above a group out of the Norwegian shipping company Knutsen OAS Shipping, the Norwegian classification society Det Norske Veritas and the large diameter producer EUROPIPE GmbH of Germany has been founded to develop their CNG system. The main reason for this joint working relation is:

- Knutsen OAS Shipping is a Norwegian tanker service company working globally. KOAS is much experienced in the application of state of the art marine technologies including offshore loading. Mainly offshore loading and gas processing lead Knutsen OAS Shipping to the development of the PNG technology.
- Det Norske Veritas (DNV) is one of the leading Classification Societies in the world with special competence on ship design, pipeline design, gas transportation and safety assessment. To succeed with a new ship design, such expertise was absolutely mandatory. Additionally DNV has published and developed the most state of the art pipeline code which has already a large amount of references.
- EUROPIPE GmbH is the leading large diameter pipe fabricator in the world with comprehensive R&D resources. Production capacities and R&D expertise are vital to be able qualify a new Cargo Tank Cylinder (CTC) and to provide the production capacities to deliver the significant amount of such cylinders needed.

In the PNG concept the gas is stored under ambient temperature in vertical positioned Cargo Tank Cylinders (CTC) onboard the vessel.

Figure 02: Cargo Tank Cylinder (CTC) arrangement onboard the vessel

The carrier itself is based on known technology elements arranged in a new manner. The ship is a combination of an ordinary crude oil tanker and a container ship while the containment system is based on standard pipeline fabrication principles. The cargo (tank) piping uses small diameter pipes with material and pressure rating well known from the shipping and offshore industry. Ship delivery is typically within a 24-month period. The first ship in a new series is expected to require 36 months from ordering due to time required for detailed design and engineering.
The system does not require a gas liquefaction plant or LNG storage tanks. A fleet of CNG ships will serve as both storage and transport carriers and can discharge directly into a land based gas grid via an on/offshore discharge terminal, an offshore platform or offshore buoys. The typical PNG value chain consists of the following main elements:

- Gas supply
- Gas drying, compression for loading and metering
- PNG loading system
- Sea transport
- PNG discharging system including unloading compression and metering.

An offshore based PNG value chain is illustrated in figure 03. However, PNG can also provide transportation to-and from jetty based facilities.

For the offshore solution, after metering, the gas is routed via a pipeline system connecting the onshore or offshore facility with the offshore loading buoy, which consists of a riser, swivel and connector. The loading buoy is picked up by the same methods as currently used for offshore oil loading operations. During the initial part of the loading sequence, the gas is heated onboard in order to keep the cargo containment system at ambient conditions. After the loading sequence is completed, the PNG ship disconnects the loading buoy, and commences the sea voyage. In the discharging end, the discharging buoy is picked up and connected to the PNG ship’s loading/unloading manifold system. The discharging buoy is connected to a pipeline system, which again is connected to the onshore or offshore receiving system. This system normally consists of a discharging compressor and gas metering. During the initial phase of the discharging sequence, gas is heated onboard the PNG ship in order to maintain the system temperatures at ambient conditions.

Figure 03: PNG Value Chain for offshore loading

The PNG ship is emptied by way of pressure/flow control without any compression until the system pressure reaches the receiving system pressure, which can typically be around 70 barg. The pressure is then typically let down to approximately 25 to 30 barg onboard the PNG ship, feeding the discharging compressor which is only used for the last part of the discharging se-
For continuous gas deliveries, a system of two or more loading- and discharging buoys are used. As an alternate onshore loading and discharging is possible. In this case instead of loading and discharging via a buoyose system jetties can be used.

4. **Cargo Tank Cylinder (CTC)**

One of the most critical elements in the development of PNG was the CTC. The cylinder is basically a clean line pipe with two hemispherical end caps. The individual elements of the cylinder are assembled with welding technologies applied in pipeline construction with track records of millions of welds. Due to this simple design highly automated manufacturing methods can be applied. The cylinder has become clearly a mass product and not an individually assembled pressure vessel. Due to this the rules of pipeline standards can be fully applied. The details of the CTC design is described in figure 04.

**Figure 04: Details of the CTC**

- Design pressure, 250 bar, ambient temperature
- Height: appr. 13 - 37 meter
- I.D.: 1,000 mm, wall thickness 33.5 mm
- Volumes:
  - Weight of each cylinder: appr. 12–31 to’s
  - No. of cylinders: 500 – 4,200
  - Weight of cylinders: 7,700-129,000 to’s
- Design premises:
  - X 80 line pipe material (LSAW 555)
  - 33 mm W T

The key to the realization of the PNG solution has been the use of modern reliability calibrated limit state design codes for the Cargo Tank Cylinder that offer the same system safety, but with the use of smaller nominal safety factors on the structural design. The rationale is that the PNG CTC resemble modern pipelines designed against explicit failure modes caused by internal overpressure. Pressure vessel codes applying implicit acceptance criteria are considered adequate for vessels where the prevailing failure modes are more uncertain due to increased complexity, detrimental effect of nozzles, supports, and manual welding. The vertical CTC will be prepared according to the principles and requirements laid down in the new DNV rules for CNG carriers (2), which were developed during the work for the PNG CTC approval. These Rules reference the DNV Standard for Submarine Pipelines, DNV-OS-F101 (3). This pipeline standard uses the above mentioned design principles. It also covers state of the art materials which are not referenced in older codes. More than 200 pipeline projects have been built successfully with this standard. For design against burst, the steel weight of the CTC’s may be reduced by 50% compared with the pressure vessel code.

The PNG solution applies higher pressure. The pressure of 250 bar is far beyond the scope for pressure vessel type C tanks defined in the International Gas Carrier code (IGC). This gap has
been filled by the mentioned DNV Class Rules for Compressed Natural Gas Carriers by following an equivalent Formal Safety Assessment (FSA) approach as defined by IMO [4]. EUROPIPE with assistance of the Salzgitter Mannesmann Research Institute performed testing and documentation in order to qualify EUROPIPE as a supplier of the PNG Cargo Tank Cylinders. During the process the following has been performed:

- A trial pipe production according to material specification has been completed
- End cap production has been successfully completed
- Detailed design of the Cargo Tank Cylinder has been completed based on cylinder wall design according to DNV-OS-F101
- Welding procedures and assembly design and plans were prepared and used to fabricate the test cylinders
- Qualification of the cargo containment cylinders according to DNV Rules for CNG Transport has been completed.
- EUROPIPE has received formal approval by DNV that they are qualified as supplier of PNG cargo containment cylinders for PNG ships according to the new DNV CNG Rules.

Without compromising on safety, the use of DNV Submarine Pipeline Standard reduces the steel weight of the cylinders to 50% of what would have been necessary with the requirements of the International Gas Code (X80 pipeline steel). With the use of the pipeline standard it has been shown that the probability of burst is less than $10^{-6}$ per year and the probability of fatigue failure is less than $10^{-5}$ per year for a typical large PNG carrier with a containment system corresponding to a pipeline length of 150 km (90 miles).

On top of the design against burst the DNV CNG Rules enforces enhanced fatigue requirements. An extensive fatigue testing of cargo tank details as fabricated is required in the DNV CNG Rules. These tests are listed in figure 05.

**Figure 05: PNG Cargo Containment Tank Testing**

<table>
<thead>
<tr>
<th>DNV Requirements</th>
<th>Status PNG Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small scale fatigue test</td>
<td></td>
</tr>
<tr>
<td>– longitudinal welds</td>
<td>Successfully Completed</td>
</tr>
<tr>
<td>– circumferential welds</td>
<td></td>
</tr>
<tr>
<td>Full scale (end-capped pipe) fatigue test</td>
<td></td>
</tr>
<tr>
<td>– pressure 20-250 barg (1st cycle 315 barg)</td>
<td>Successfully Completed</td>
</tr>
<tr>
<td>– shall survive 15 times design life cycles</td>
<td></td>
</tr>
<tr>
<td>– fatigue test (+FE) of construction detail</td>
<td></td>
</tr>
<tr>
<td>Burst fatigue test with full scale end-capped pipe</td>
<td></td>
</tr>
<tr>
<td>– test after twice the design life cycles: 4000 cycles</td>
<td>Successfully Completed</td>
</tr>
<tr>
<td>Cool-down verification</td>
<td></td>
</tr>
<tr>
<td>– temperature measurement test with compressed gas in tank piping impinging on pipe section</td>
<td>Successfully Completed</td>
</tr>
<tr>
<td>Crack propagation</td>
<td></td>
</tr>
<tr>
<td>– Full scale test using methane gas to analyse temperature effects</td>
<td>Successfully Completed</td>
</tr>
</tbody>
</table>

These tests have been carried out by EUROPIPE:
- Two full scale fatigue tests with a required safety factor of 15 to the design life which results in 30,000 cycles.
- One full scale fatigue burst test where the requirement is to maintain full burst capacity after fatigue cycling to two times the design lifetime, 4,000 cycles.
- Creation of the individual S/N curve for the special product and applied production methods.
- Proof of statistical safety of minus-three-sigma between test results from small sample testing and the required limit. The requirement for the statistical testing is a safety factor of ten leading to a minimum required number of cycles of 20,000 for the minus-three-sigma criterion.
- Leak before Break (LBF) behaviour of a full scale test body with a through wall fatigue crack present and cool down of the material due to Joule Thomson.

The factor of 15 times the design life rather than 10 times is applied to account for system effects by testing only 2 random pipes out of more than the 1,000-3,000 pipes in the actual ship.

To establish the product related S/N curve, fatigue tests were performed with full scale samples as well as a higher number of smaller samples in order to create statistical back-up for the individual S/N curve.

For the strip testing of the long seam the samples have to be flattened. This leads to a plastic deformation of about 3% which will occur locally in the weld area. On the inside tension will be experienced and on the outside compression. The impact of the plastic straining on the results is difficult to predict, but will most likely provide more conservative results including consideration of the residual stress. These values should be taken as the lower bound for a minus-two-sigma-S-N curve (5).

Considering the plastic deformation on the results for the strip sample testing, additionally tests were performed with pipe rings 150 mm long extracted from the original 42” pipes exposed to internal pressure. The testing of the 150 mm long original pipe ring sections was performed according to the testing scheme illustrated in Fig. 6.

Fig. 6 Scheme for fatigue strip and ring tests

This test seems to be more advantageously because of the testing of the original pipe geometry and the more realistic simulation of the loads. The length of the sample might lead to a relaxation of the residual stresses as observed with strip samples.

Additionally the axial stress component of the full scale body testing is missing. While the
axial stress component relaxes, the most critical stress perpendicular to the long seam, the residual stresses in a full scale sample, will lead to a somewhat lower number of cycles. Comparing strip sample testing to ring sample testing the results from the ring sample test was expected to be in a much better correlation to a full body test than the strip samples.

The main perception for the use of small sample tests is to create statistical evidence to prove the improvement of the lifetime for the specially treated long seam of a Hifa® pipe and to investigate the compliance with the minus-three-sigma requirement for the tank cylinder. Hifa® Pipes is a EUROPIPE Trademark (5, 6). These pipes provide a specially treated long seam in order to provide the fatigue life required by the CNG Rules. The basis is the full scale body providing results very similar to the actual application, but the small samples can support the result of the full scale test.

Two full scale samples were assembled out of two three meters long Hifa® pipe sections and hemispherical end caps, and for one body pipe sections with conventional long seams were used. Each test cylinder was tested with water at ambient temperature. Failures were observed by pressure drop due to water leakage after a crack propagated through the wall. The conventional pipe failed after 12,000 cycles due to a small leak in the longitudinal weld. After the body was opened dye-penetrant inspection exposed indications of fatigue cracks over the entire length of the seam. These cracks propagated 50-80% through the wall thickness and at the point of leakage completely through the wall. The failure was a leak and not a burst proving the excellent toughness of the material in the presence of the seam fatigued over the entire length of the pipe. This test result is much in line with the lifetime prediction according to several codes (7). Hifa Pipes® showed the first failures not in the long seam but in the girth welds at defects in the root pass discovered during the AUT exceeding the UT acceptance level, figure. 7.

Fig. 7 Full Scale Fatigue tests

The rejects were not repaired in order to support an Engineering Critical Assessment (ECA) for the critical defect size for the PNG application. The crack started as expected in the root pass parallel to the pipe axis perpendicular to the main stress direction. After repair the first test was stopped after 31,000 cycles passing the specified limit of 30,000 cycles. Dye penetration of the long seam area showed no indications of any cracks. It took almost three
months testing time for the first full scale body to reach the specified number of cycles of 30,000. In order to support the first result with the second cylinder the test of the first cylinder was terminated after passing the 31,000 cycles without any indications in the long seam area. The second cylinder failed after 41,000 cycles, figure 07 very right position. In this case the fatigue crack started in the bottom of a pronounced pitting created by corrosion which started on the inner surface after the repair of the girth weld after almost three months of testing with inhibited water. No signs of cracks were found during the following dye penetration inspection of the long seam area. Due to a high number of additional pitting corrosion areas also this body could not continue the testing until a regular failure in the long seam. All failures occurred due to defects expected not to be present during the use as PNG tank cylinders for the transportation of dry gas. However the tests demonstrated a lifetime capacity of at least 15 to 20 times the design lifetime of 40 years for the PNG vessels.

The cylinder for the full scale fatigue burst test was cycled 4,000 times which is twice the numbers of the design life time. Burst occurred at 472 bars which is 1.8 times the design pressure. In figure 08 it can be seen that the failure appeared in the base material at the 5 o’clock position considering the long seam being located at the 12 o’clock position. The material failed fully ductile.

Figure 08: Full scale fatigue-burst test

This test was successfully completed and documents that the PNG Cargo Tank Cylinder will give leak before failure and the safety in the PNG design.

Finally a Gas Leak Test was performed to demonstrate leak before failure (LBF) performance of the cylinder with gas leaking through a crack. LBF in such a situation is requested in order to prevent a total loss of a carrier due to a cascading scenario started by the embrittlement of the material due to cool down due to the Joule Thomson Effect of the exiting gas and high thermal induced stresses. The test was conducted in November 2004 at the Advantica Spadeadam Test Site in Cumbria, UK. The vessel was nominally 5 m long. The test set up can be seen in figure 09. To simulate the presence of an adjacent cylinder on a CNG carrier, a secondary pipe was located at a distance of 300mm from test the vessel. All relevant areas were fitted with a temperature sensor with the objective to detect if the temperature would fall below the critical temperature.

In the centre of the vessel, approximately 10 mm from the longitudinal seam weld, a through wall crack had been grown by fatigue from a 150 mm long machined slot, see figure 10.

Figure 09: Set up of full scale gas leak test
The through thickness crack was fatigued from a pre-machined notch with length $2c = 150$ and depth $a = 5$ mm. It was decided to use a fatigue crack instead of a machined notch for two reasons. The first reason is that the stress concentration at the tip of the crack is higher compared to a notch and secondly the flow characteristics of a crack are much different to that in a notch with a significant impact on the temperatures drop reached. The through wall crack in the vessel was closed with a sealing mechanism incorporating a hydraulic ram which could be released remotely. The main findings and conclusions from the full scale leakage test and the evaluations carried out can be summarized as:

- During the full scale leakage test the crack remained stable as the temperature in the pipe wall dropped due to the expanding gas. No evidence was found indicating that the crack had grown.
- It has been considered very likely that the crack subject to the test would have been detected onboard a CNG carrier.
- The measured temperatures correspond very well with the calculated temperatures.
• The crack driving force due to the temperature induced stress caused by the gas leakage is insignificant.
• The cylinder fulfils the leak before break criterion. A rupture due to temperature drop with a following escalation scenario will not happen.

All tests were passed and it was concluded that the risk the cargo tank cylinders contribute to the total risk of the carrier is insignificant compared to those risks being present from normal marine operations.

5. Transport Economics for PNG® Carriers

Gas transport using PNG vessels can be made discontinuous and also continuous if a minimum of 3 vessels is provided for gas transport from the gas source to the gas receiving port. In case of discontinuous deliveries, the gas can be delivered into a gas distribution network which either can accommodate the quantities delivered or alternatively is supplemented with gas storage facilities.

Figure 11: Competitive range for Knutsen PNG

This is a flexible solution that can facilitate gas transport build-up according to actual needs without requiring huge pre-investments in storage capacity before export volumes are being committed.

Another advantage is that the gas quality that can be transported on PNG Carriers is very similar to gas qualities allowed in pipeline systems. In fact, even rich gas could be transported in PNG Carriers than in long distance pipelines, giving PNG Carriers an advantage compared to LNG and even in some cases also to pipelines.

Case studies indicate that for distances from about 500 nautical miles and up to 2,500 to 3,000 nautical miles it could be very interesting to use PNG, Figure 11.

The figures are based on
- Total cost of capital is 10% (Internal Rate of Return - IRR)
- 20 year amortisation
- Costs included are operating & maintenance costs, fuel, loading/unloading facilities (jetties/buoys, compression and heating during discharge)
- Costs not included are gas production costs, entry fees market, possible port charges, and government tax.

6. Conclusions

The Compressed Natural Gas (CNG) technology offers interesting possibilities for handling of associated gas and for exploitation of marginal fields (stranded gas). Case studies indicate that for distances from about 500 nautical miles and up to 2,500 to 3,000 nautical miles it could be interesting to use.

The potential market for CNG carriers is large as more than half of the world’s known reserves are associated and stranded gas. Compressed Natural Gas (CNG) has been evaluated for decades and several concepts have been introduced.

- The Knutsen PNG® vessels are using vertically stacked pipelines as the basic gas storage unit. The concept has been developed with assistance from EUROPIPE GmbH for the tank cylinders and Det Norske Veritas.

- DNV rules for CNG carriers was issued in January 2003 and came into force July 1st 2003. For the design and manufacturing of the cargo tank cylinders the DNV offshore pipeline standard is used with additional comprehensive requirements for fatigue performance. This and the application of higher strength materials lead to a reduction of the cylinder weight of ca 50% compared to the weight in the original concepts several decades ago.

- Formal Safety Assessments in the form of Quantitative Risk Assessments (QRA) have been carried out concluding that the nominal risks for the PNG® vessel are within the region of, or better than, historical LNG vessels and that the containment design is feasible with respect to the applied quantitative risk criteria.

- The DNV CNG rules set stringent requirements to the protection of the cargo tanks from damage from external sources, e.g. from collisions and groundings.

- For the Knutsen PNG®, a special treatment for the long seam of the DSAW Hifa Pipe® was developed. The Hifa Pipe® provides lifetimes of the DSAW pipe body in the range of a seamless pipe.

- In order to qualify the cargo cylinders full scale burst and fatigue tests have been completed by EUROPIPE with the assistance of the Salzgitter Mannesmann Research Institute. The tested cylinders, assembled with Hifa Pipes, surpassed the expectations for both burst and fatigue and no indications of unstable (brittle) behaviour could be detected.

Based on the test results and documentation provided EUROPIPE received DNV’s formal approval that there cargo tank cylinders can be used for PNG applications.

7. References


6 O. Reepmeyer, A. Liessem, M. Erdelen-Peppler, G. Knauf
Enhanced Lifetime for internal Pressure Fatigue of DSAW Pipes
International Pipeline Conference, Calgary 2004

7 Gerhard Knauf, Marion Erdelen-Peppler, Ulrich Marewski, Oskar Reepmeyer
Internal pressure fatigue of pipes, pipelines and Cylinders
TMS (The Minerals, Metals & Material Society) 2006