In proceedings of “The 9th International Symposium on Practical Design of Ships and Other Floating Structures”, PRADS 2004, September 12-17, 2004, Lübeck-Travemünde, Germany

The Development of a Compressed Natural Gas Carrier

Sverre Valsgård [1], Oskar Reepmeyer [2], Per Lothe [3], Nils Kristian Strøm [3] and Kim Mørk [1]

[1] Det Norske Veritas, Norway
[2] Europipe GmbH, Germany
[3] Knutsen O.A.S. Haugesund, Norway

Abstract

The paper outlines the operational and economic aspects for CNG carriers in general and the Knutsen PNG carrier designs in particular and continues with a description of the Knutsen PNG vessel development and the CNG rule development process. Key design aspects and safety/risk aspects considered in the process are described together with new design criteria and the qualification process for the containment cylinders.

Keywords

Compressed Natural Gas; Ship development; Containment; Pipeline; Risk Assessment; Qualification testing

Nomenclature

PNG (Pressurised Natural Gas) is a Knutsen OAS Shipping Registered Trade Mark for their CNG concept. The gas is stored under normal temperature in 42” vertical pipes onboard the vessel.

Hifa Pipe (high fatigue resistant pipe) is Europipe’s Registered Trade Mark for a long seam welded pipe with a specially treated long seam to improve the internal pressure fatigue resistance of these pipes.

Introduction

The demand for natural gas is increasing world-wide as a result of the increase in the world energy consumption and increasing environmental concern. Among the fossil fuels available today, natural gas is by far the most clean and environmentally friendly energy source that is believed to be an increasingly important energy carrier in the next 20-30 years.

The natural gas resources are to a large extent located far from their markets. Some 30% of the discovered gas is considered stranded. Stranded is defined as reservoir gas fractions that prevent the development or optimal production from an oil or gas field due to their distance from the market, lack of transport economy or lack of conversion technology. To meet the future demand for natural gas, new cost effective solutions for transporting natural gas from the production site to the consumers need to be developed.

The Compressed Natural Gas (CNG) technology offers interesting possibilities for handling of associated gas and for exploitation of marginal gas fields (stranded gas). The system does not require a gas liquefaction plant or LNG storage tanks. LNG storage and regasification at the discharge location will not be necessary. Hence, looking at the complete transport chain from gas well to consumer there is potential for large savings in infrastructure. A fleet of CNG ships will serve as both storage and transport vehicles and can discharge directly into the land based gas grid via an on/offshore discharge terminal, an offshore platform or offshore buoys.

Looking at the energy loss of transport of gas from the gas well to the consumer CNG loses 5-8%, LNG about 15%, Pipeline 3-5% and LPG about 5%. Hence, CNG appears to be a more environmentally friendly way of transport than LNG where additional energy is lost in the liquefaction and regasification process.

Market possibilities for CNG carriers

In numerous instances worldwide, gas reserves are stranded because neither LNG nor pipelines can economically exploit them. LNG generally requires an onshore LNG plant and fairly large volumes making it difficult for LNG to commercially serve offshore reserves, small markets, or small reserves. Pipelines are often defeated by long marine distances, small reserves or difficult marine environments (deepwater, ice scour, or environmental concerns such as fisheries). CNG technology provides an alternate gas transportation system that economically fits between pipelines and LNG.

To mention some possibilities – trades where CNG technology may offer competitive solutions are the South China Sea to Korea and Japan, Sakhalin to Korea, Japan and China, the Middle East to India, Indonesia to India, Eastern Indonesia to Japan and Korea, North Africa to Europe, the North Sea and the Barents Sea to

Europe, Eastern Canada to the eastern US and Canadian seaboards and cross Caribbean trades from Venezuela and Trinidad & Tobago to the US Gulf Coast. All these possibilities are within a transport range of up to about 3000 Nautical Miles (NM), which for the larger CNG Carriers may be within their economic competitive range, Fig. 4.

CNG can also be used in the start-up phase of an LNG train or a pipeline project development and will enable an early gas start-up. This will facilitate a gradual build-up of the export volume without waiting for the large investment necessary for a fully developed export train.

Design challenges for CNG carriers

Methods for shipping gas on keel without a costly liquefaction process have been studied for decades without any apparent success. Design of containment systems using pressure vessel codes, or the International Gas carrier Code (IGC), leads to heavy containments systems with virtually no lifting capacity left for cargo unless unreasonably large and costly ships were to be used.

The key to the realization of the idea is to use modern reliability calibrated limit state design codes that offer the same system safety, but with the use of smaller nominal safety factors on the structural design of the containment cylinder. The rationale is that the CNG cylinders resemble modern pipelines designed against explicit failure modes caused by internal overpressure. A safe and yet optimal CNG tank design is in reality outside the scope of traditional pressure vessel codes. Pressure vessel codes applying implicit acceptance criteria is considered adequate for vessels where the prevailing failure modes are more uncertain due to increased complexity, detrimental effect of nozzles, supports, and manual welding.

A majority of the CNG concepts being proposed or under development are based on using pipelines as the pressure vessels. The steel based systems can be designed using the DNV Submarine Pipeline Standard which has become the "world industry standard" within the pipeline industry. Some examples of CNG concepts are described in Stenning (2000), White (2003) and Valsgård (2003).

Some CNG concepts apply high pressure at ambient temperature in order to keep the gas in a gaseous state with basically no liquid hydrate fall-out. Others use somewhat lower temperature at a reduced pressure. Concepts with pressure in the range 130 – 275 barg are 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 new DNV (2003) Class Rules for Compressed Natural Gas Carriers by following an equivalent Formal Safety Assessment (FSA) approach as defined by IMO (2002).

The Knutsen PNG development strategy

The development strategy selected by the Norwegian shipping company Knutsen OAS Shipping was as follows:

- Apply known design principles as far as possible
- Combine the best from the pipeline industry with the best from the shipping industry
- Use ambient temperature in order to apply standard carbon steel
- Keep the system complexity to a minimum

In order to meet the development strategy above, Knutsen OAS Shipping has developed their CNG system with assistance from a leading ship classification society (Det Norske Veritas of Norway) and a world leading pipeline fabrication company (Europipe GmBH of Germany).

The PNG Concept

In the PNG concept the gas is stored under normal temperature in 42" vertical pipes onboard the vessel. The concept is based on several patents pending solutions.

The Knutsen PNG carrier will not require sophisticated processing to maintain the gas stored in the containment system. Due to the operation under ambient temperatures, no insulation will be required to prevent heating during the voyage.

The vertical cylinders will be prepared according to the principles and requirements laid down in the new DNV rules for CNG carriers (2003).

The vessel itself is a straightforward vessel design looking as a combination of an oil tanker and a container vessel. Some special vessel arrangements are required to ensure maximum safety and functionality for the new application.

Fundamental Design Premises

Based on the stated safety approach in the DNV CNG rules (2003) a set of fundamental design premises were defined in order to simplify the design development of the PNG design.

a. The CNG vessel need not to be designed to survive accidental rupture of cargo cylinder(s), e.g. from collisions. This is equivalent to a case of accidental massive liquid outflow from a conventional LNG carrier which in not designed for.
b. The cargo hold spaces shall be inerted with Nitrogen (N_2).
c. Cargo hold space covers shall remain intact - no fire in hold space due to inert (N_2) atmosphere. Hence, a suitable hold space venting system shall be provided capable of venting off the gas release resulting from one complete cargo tank piping failure.
d. The CNG vessel shall be equipped with a flare mast for controlled blow-down of high pressure gas (cargo containment cylinders) and low pressure gas (cargo hold spaces) - to be cold vented or ignited.

Point a. above means that it has to be demonstrated that the risk of having a collision penetrating the inner hull and starting to push at the gas bottles is sufficiently low, below the design target of annual risk of 10^{-4}, and that the CNG carrier side is capable of absorbing the associ-

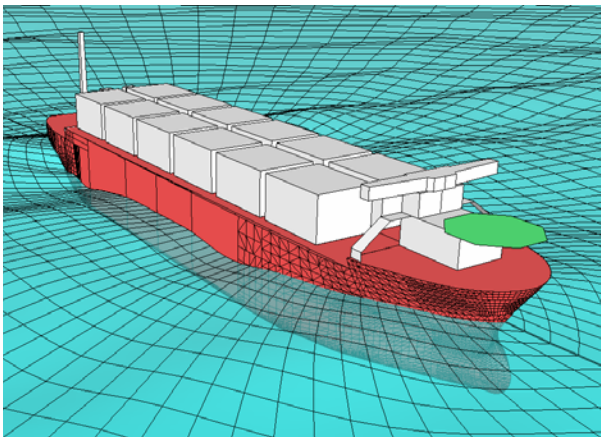


Fig. 1 Offshore loading PNG vessel

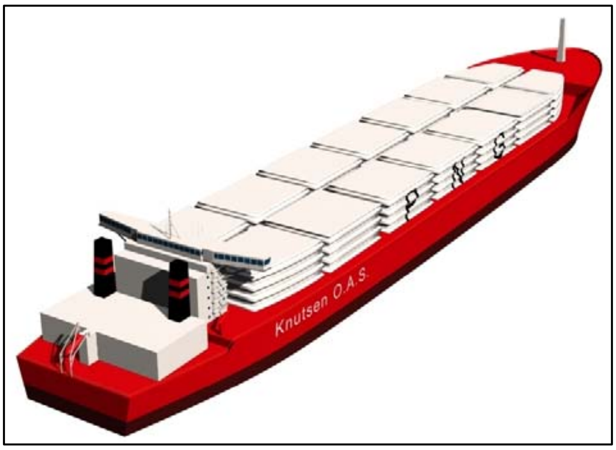


Fig. 2 Terminal to terminal PNG vessel

ated collision energy. This is a *key safety measure* in the design philosophy.

Vessel Designs

Knutsen OAS Shipping has performed the vessel initial design using independent naval architect consultants and input from DNV.

Two different types of vessels have been developed:

- Offshore loading and discharging type PNG vessel
- Terminal to terminal type PNG vessel

The offshore loading type vessel is based on Knutsen OAS Shipping's own experience with similar operation of oil shuttle tankers, Fig. 1. The vessel can apply the well-known Submerged Turret Loading - STL system from APL Loading Systems. Other types of offshore loading systems have also been evaluated and several designs can be adopted for offshore loading or offshore discharging. Area has been allocated for such facilities together with space for process facilities that either could be used for gas polishing or compression.

The standard type offshore loading vessel has the following characteristics:

- Net cargo transportation capacity, 22 to 24 million Sm3 (775 to 850 million Sft3)
- Vessel length, about 260 meter
- Vessel beam, 54 meter

A larger vessel capable of transporting up to 33.5 million Sm^3 of gas has also been developed. This vessel is capable of sailing with a speed of 17.5 knots and is well suited for large volumes and/or long distance gas deliveries, Fig. 2. Similar, smaller vessels can be built tailor-made to the volumes and distances for the actual gas transport trade.

PNG Design features

The PNG designs have number of specific features which are summarised in the following:

Application:

- Terminal-to-terminal gas transport
- Offshore loading of gas using normal offshore procedures
- Direct loading from well stream
- Space allocated for processing facilities

Safety:

- Low complexity improves safety
- Loading and discharge of gas can be performed at offshore terminals
- Risk assessment shows equal or better safety than normal LNG carriers
- Quantitative Risk Assessment Carried out (QRA)

Environmentally favourable:

- Low CO_2 and NOx emissions
- Reduced total energy consumption - no liquefaction and regasification
- Gas used for propulsion
- No ballast water discharge
- Easy to re-use on other projects

Structural feasibility analysis

In order to support the development process DNV carried out initial load, load response and strength analyses of the new concepts. For the offshore loading carrier a direct structural response analysis of the hull in accordance with DNV's CSA-2 procedure for direct load application was carried out in order to properly account for torsion and warping effects. Being an open deck ship very much resembling a container vessel this is an essential analysis in order to being able to assess the fatigue endurance of the deck corners.

The scope of the analyses included the following analyses:

Seakeeping and Wave Load Analysis: Hydrostatic and hydrodynamic loads were transferred to the structural FE model by automatic load transfer of sea pressures. The effect of both speed reduction due to heavy weather, and non-linear loads due to ship form was included, Fig. 1.

3-D FEM Analysis of Ship Hull: The frame and girder stresses were analysed by a Finite Element model of the whole vessel including the containment bottles. Still water and wave loads were combined for the loading conditions being analysed. Both longitudinal bending and torsion were considered.

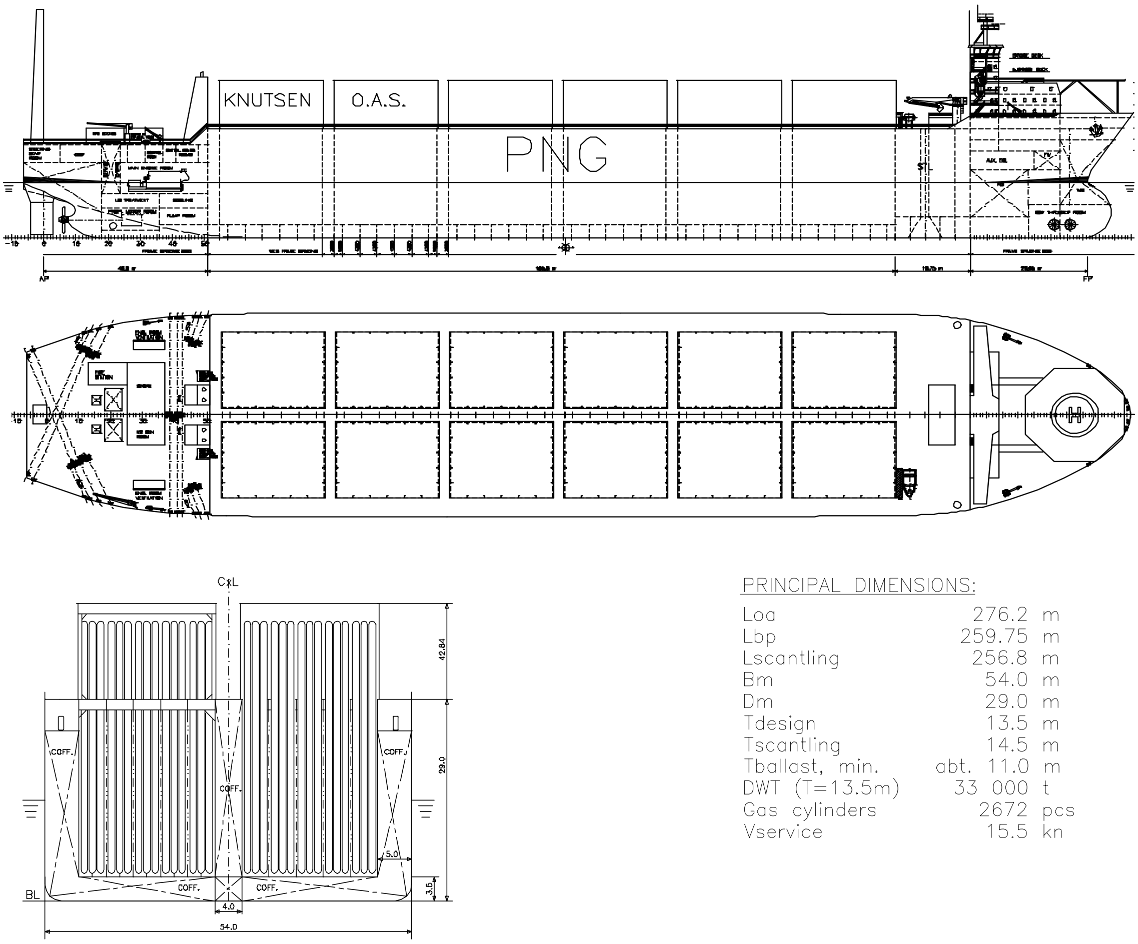


Fig. 3 The Offshore Loading PNG Design as per 1Q 2002

Stochastic fatigue analysis: A fatigue screening using full stochastic (spectral) fatigue analysis was performed in order to map the fatigue strength of the design.

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.

This is a flexible solution that can facilitate gas transport build-up according to actual needs without requiring huge pre-investments in spare 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 richer 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 2500 to 3000 nautical miles it could be more interesting to use PNG than LNG, Fig. 4.

Some examples of PNG transport costs are listed in Table 1.

Table 1 Example of PNG® Transport Costs

Route (Supply MSm^3/d)	Distance [NM]	Annual Volume [BSm^3]	PNG Carrier Size [MSm^3]	No of PNG Carriers	Transp. Cost [USD/ MBtu]
Coastal (3,5)	250	1.3	3.3	4	1.1*
Ex. (3,5)	350	1,3	3,2	4	0.9
Ex. (24)	570	7.8	28.4	5	0.80
Ex. (17)	840	5,9	27,9	5	0.95
Ex. (44)	1400	15.2	27.7	16	1.19
Ex. (28)	1720	9.8	27.5	13	1.46

***Costs for gas storage included**
(Source: Knutsen O.A.S.)

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)

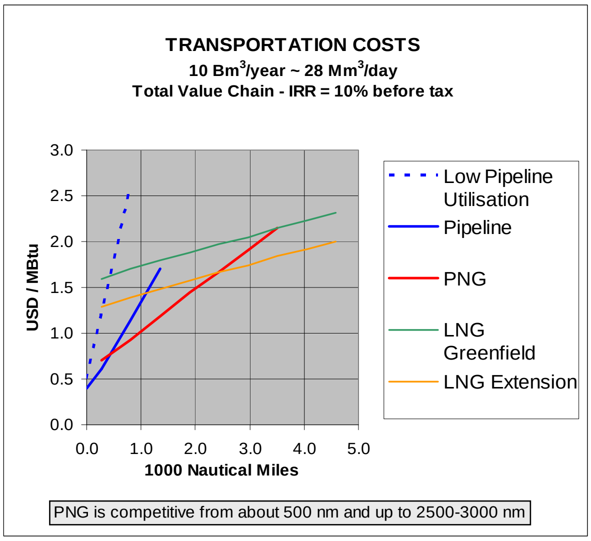


Fig. 4 Competitive range for Knutsen PNG

- Costs not included are gas production costs, entry fees market, possible port charges, and government tax.

Rule Safety Philosophy

The overall safety with respect to life, property and environment shall be equivalent or better than comparable LNG vessels built and operated according to traditional ship rules and industry practices.

For new concepts a Quantitative Risk Assessment (QRA) shall be submitted as a part of the documentation for class approval and be carried out in accordance with IMO (2000) and IMO (2002).

Table 3 Summary of risk targets and risk assessment (per year)

Risk Value	**Historical Data LNG** 1)	**CNG Target risk** 2)	**Risk Result for PNG 1Q, 2002** 3)
Average individual Risk for crew members (AIR)	1.2 x 10^{-4}	1.0 x 10^{-4}	0.7 x 10^{-4} 5)
Total loss due to collision	1.2 x 10^{-4}	1.0 x 10^{-4}	0.2 x 10^{-4} 4)
Total loss due to cargo hazards (fires & explosions)	2.4 x 10^{-4}	1.0 x 10^{-4}	0.9 x 10^{-4} 5)
Individual risk from cargo cylinder failure	-	1.0 x 10^{-5}	< 10^{-5}
Individual risk for public ashore	-	1.0 x 10^{-5}	Recommends offshore terminals

1. *Historical data derived by DNV from the LMIS date base (LNG & LPG)*
2. *Target safety values aimed for in design*
3. *Results from PNG risk assessment as per 1Q, 2002*
4. *Based on generic North Sea route (Norne – NE England/Scotland). May change for actual vessel trade*
5. *Assumes deck piping in inert duct*

Fundamental safety requirements shall be defined taking into consideration safety targets for:

- life (crew and third party personnel)
- property (damage to ship, off-hire)
- environment (oil pollution, gas release to the atmosphere)

The safety level of a LNG carrier represents *the minimum acceptable* safety level for a CNG vessel**.** The targets can therefore be based on historical experience and are shown in Table 3.

Risk Analyses for the offshore offloading version Knutsen PNG® Design

A concept risk assessment was performed to address the cargo containment hazards of the Knutsen PNG ship design as developed by 1rst quarter of 2002, Fig. 1 and Fig. 3.

The objective was to establish the safety feasibility of the cargo containment design for ongoing development, and to propose risk reduction measures to ensure risks to be as low as reasonably practicable - ALARP.

The results of the risk assessment show that nominal risks on the PNG vessel are within the region of, or better than, historical LNG vessels. The risk estimates in Table 3 indicate the cargo containment design is feasible with respect to the applied quantitative risk criteria, provided that acceptable reliability and risk uncertainties for safety-critical items are robustly documented and controlled by, a combination of design, testing, and appropriate consequence reduction measures.

The listed results apply to the preferred design solution in which the cargo deck piping are put in inerted ducts on the deck in order to avoid escalating jet fires from deck piping leaks impairing cargo holds and valves.

The main hazards were catastrophic failure of cargo tank cylinders (13-20%) and failure of cargo tank piping (70%). The percentage figures refer to total risk related to “average individual risk for crew members (AIR)” and “Total loss of vessel due to cargo hazards” respectively. Each scenario may lead to cool down of the cargo cylinders with possible embrittlement and rupture of the X80 pipe material. *Hence, design and testing requirements for mitigating, or altogether avoiding, these scenarios are vitally important.*

Cargo containment design

The basis for the design is the DNV CNG rules (2003) stating that:

- Design, material selection and testing regime for the cargo cylinder wall shall be in compliance with Safety Class High in DNV-OS-F101(2000)
- End-caps are to be designed according to the rules for ships, Ch. 5, (same as IGC).
- The materials used in the cargo containment cylinders and end-caps shall comply with the requirements for manufacture, survey and certification given in DNV-OS-F101 Submarine Pipeline Systems. Due regard shall be given to corrosion protection.

- The materials used in the cargo tank piping, cargo deck piping and all valves and fittings shall be of quality NV316L or equivalent (equivalent with respect to ductility, fatigue and corrosion resistance) and shall comply with the requirements for manufacture survey and certification given in the DNV rules for Classification of Ships Pt. 2 and Pt. 5 Ch. 5.

Why then use a submarine pipeline code in a ship? There are some very compelling reasons:

- To reduce the weight of the containment cylinders
- The prevailing failure modes are well defined (burst, fatigue)
- The cargo containment cylinder wall is similar to a pipeline and therefore a well proven design
- Large diameter (42") high strength steel (X80) is standard industry practice with proven track record
- DNV-OS-F101 is considered to be
  - the state-of-the-art standard for pipeline design
  - it is the reference code for most major pipeline projects and
  - more than 200 pipelines have been built to DNV-OS-F101 and the previous issue DNV'96
- Cylinder wall thickness sizing (burst) in compliance with DNV-OS-F101 gives minor contribution to total risk

In principle, any recognised pipeline code (ISO, API) will yield comparable cylinder wall thickness but DNV-OS-F101 is reliability based with a strict link to material selection, welding qualification, test procedures and production tolerances.

Burst Design

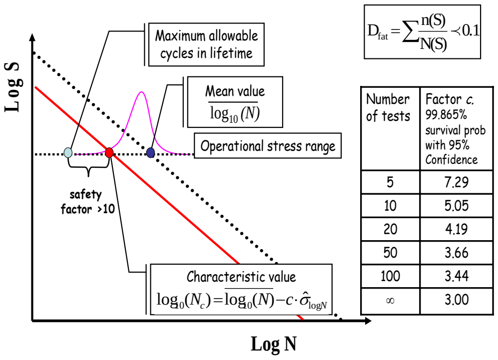
The burst design is carried out according to safety class High in the DNV OS-F101 (2000).

A dedicated calibration study for Grade X80 pipes was presented by Collberg et. al. (2001). For the PNG ship with 130-140 km of pipe the number of independent sections is in the order of 10^4 to 10^5. For such a case the (nominal) failure probability for safety class High was found to be very low, i.e., likely to be below 10^{-6}.

The most controversial part of the DNV Rules is the selection of safety factor for the cargo tanks. The safety factors on tensile strength for pressure tanks are

- USCG:	4.0
- IGC Code:	3.0
- ASME VIII div 3	2.14 (steel grade X80)
- DNV CNG Rules:	1.57

The DNV CNG rules are based on FSA principles using explicit limit state design with qualified safety level rather than "old" implicit experience based criteria. The safety calibration includes the inherent safety benefit from tight tolerances on thickness and material strength, enhanced testing requirements (mill test and system test) as well as the maximum pressure regulation systems (pressure relief valves) used on the tanks. A safety factor of 1.57 is therefore sufficient to ensure a low failure probability.



$$D_{fat}=\sum\frac{n(S)}{N(S)}\prec 0.1$$

Number of tests	Factor *c.* 99.865% survival prob with 95% Confidence
5	7.29
10	5.05
20	4.19
50	3.66
100	3.44
∞	3.00

Fig. 5 Definition and Test Verification of S/N Curve for Cargo Cylinders

Fatigue Design Criteria

The cargo tank cylinder shall be subject to comprehensive fatigue analysis. Model testing of cargo tank details as fabricated may be required to establish the S/N curve. The characteristic S/N curve for use in design is defined as the "mean-minus-three-standard-deviations" curve as obtained from a $\log_{10}S$-$\log_{10}N$ plot of experimental data. This is due to the system effect caused by longitudinal welds of a large number of bottles. This is a significant enhancement compared to traditional maritime and offshore design where "mean-minus-two-standard-deviations" without any specified confidence level is applied. The uncertainty in this curve when its derivation is based on a limited number of test data shall be accounted for as shown in Fig. 5. It is required that the characteristic curve be estimated with at least 95% confidence.

The Miner sum (for both dynamic loads and fatigue loads due to loading and unloading) is not to be higher than 0.1. The minimum calculated fatigue life using the S/N curve approach shall not be less than 200 years.

Additional fatigue analyses using fracture mechanics crack propagation calculations shall be carried out for the cargo tank cylinders. The analysis is to be carried out for defects assumed located in both the longitudinal and circumferential welds of the cylinders.

Assuming an initial crack equal to the largest non-detectable defect during production inspection and testing the calculated crack propagation life for a crack to propagate through the cylinder wall thickness shall be at least 3 times the design life, but not less than 60 years. The applied crack propagation parameters are to be documented for the cylinder base material and its welds.

If the necessary number of load cycles for the crack to propagate through the wall cannot be shown, it is to be documented that *unstable fracture will not occur* in the cylinder from a fatigue crack before a possible leak from the calculated through thickness crack is detected and the tank pressure has been relieved (blown down). The fracture mechanics assessments may be carried out according to e.g. BS 7910:1999. "Guide on methods for assessing the acceptability of flaws in metallic structures." Relevant fracture toughness properties are to be applied for the base material, heat affected zone and weld metal at the minimum design temperature.

Qualification Testing

An essential part of the verification of the safety of the containment cylinders is to carry out full scale tests in accordance with the testing requirements set fourth in the DNV CNG rules (2003).

a. Full scale fatigue tests of two end-capped pipes.
b. Burst test of one full scale end-capped pipe
c. Crack tip cool-down during gas leaks through a fatigue crack at the longitudinal weld seam of a containment pipe.
d. Cool-down testing from gas leaks in cargo piping impinging on the cargo containment pipes from different distances
e. Process prototype testing to document that the system functions as specified with respect to accumulation and disposal of liquids.

The reason for the cool-down testing is to explore if, and under which conditions, the X80 pipe may exhibit brittle behaviour due to the nozzle effect (Joule Thompson) from gas escaping under high pressure.

For the PNG design the following 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.

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 1000-3000 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. Erdelen-Peppler (2004) recommended using these values as the lower bound for a minus-two-sigma-S-N curve.

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.

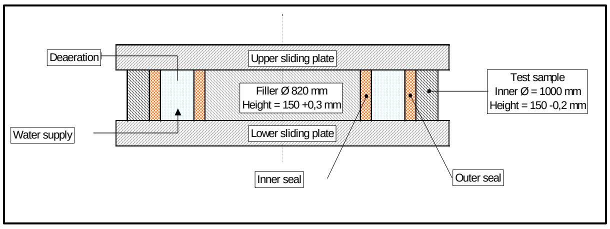


Fig. 6 Scheme for fatigue ring tests

This test seams 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 weld and to investigate the compliance with the minus-three-sigma requirement for the tank cylinder. 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.

Full scale fatigue test results

The results of the full scale tests were already partly described by Erdelen-Peppler (2004) and Valsgård (2003). 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. Assembly of pipes and end caps was performed by automated Gas Metal Arc Welding (GMAW) method and inspected by Automated Ultrasonic Testing (AUT). Each test cylinder was tested with a frequency of 90s per cycle 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. This test result is much in line with the lifetime prediction according to several codes to predict the lifetime for specially selected design elements, DNV (2001), AD merkblatt S2 (1998), DIN 2413 (1993) and GE/TD/1 (2001). Both 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, Fig. 7.

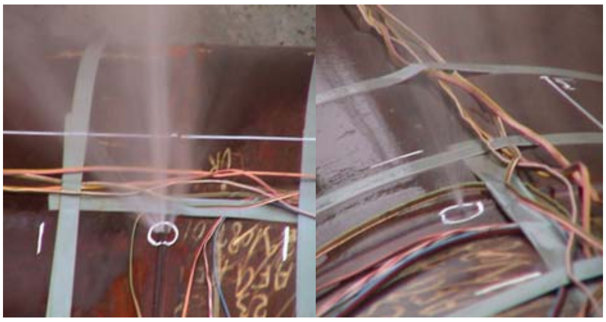


Fig. 7 Fatigue test failures at girth welds

The rejects were not repaired in order to support an Engineering Criticality 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.

Fig. 8 Fatigue failure at corrosion pitting in long seam

The second cylinder failed after 41,000 cycles, Fig. 8. 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.

Full scale fatigue burst test

The cylinder for this test was cycled in the same frequency with water as the fatigue samples
Burst occurred at 472 bars which is 1.8 times the design pressure. In Fig. 9 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 ductile and the cylinder showed circumferential straining of 2.7% in average. The girth weld stiffened the body somewhat and restricted the deformation.

Fig. 9 Full scale fatigue-burst test

Comparison of test results

S/N curves from different codes are outlined in Fig. 10.

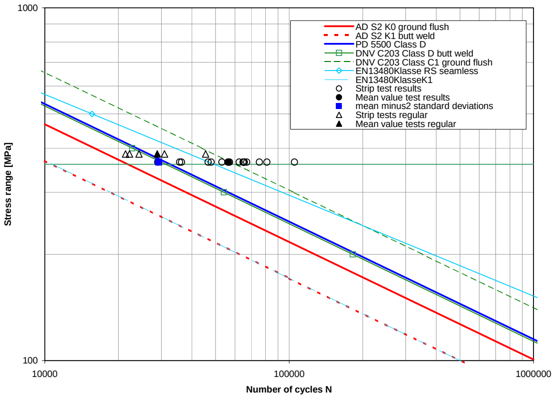


Fig. 10 S/N Curves strip sample fatigue tests

The results of the strip sample testing are marked and compared to the curves from the codes. Based on the strip samples, which provide more lower bound values, the fatigue life of a Hifa® pipe is 2 to 3 times longer than for a conventional pipe.

The mean strip sample value from the treated seam material is in the same range as the DNV C203 C1-ground flush-curve, DNV (2001) and the line for seamless pipes from EN 13480 (2002). The results show a large scatter band of the strip sample results. This might also be an indication that the effect of the flattening process cannot be disregarded. Due to this the flattening does not only provide conservative values but also creates a larger scatter band which results in a bigger standard deviation. Even with these penalties the final result from the strip samples meets the requirement of minus-three-sigma in the DNV CNG Rules.

The results from the ring tests are expected to be more representative for the full scale test than those from the strip sample tests. Fig. 11 shows the results from the three full scale tests and the results from the ring tests.

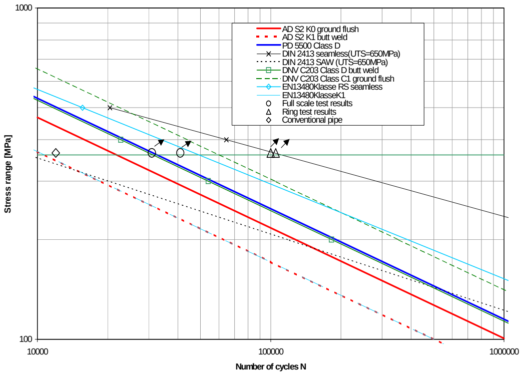


Fig. 11 S/N Curve short ring and full scale fatigue tests

The full scale test result with the conventional Double Submerged Arch Welding (DSAW) pipe is very much in line with the butt weld curves provided by DIN 2413 for Submerged Arch Welding (SAW) pipes with conventional welds and the S2 K1 curve from AD for normal butt welds. The two Hifa® Pipe samples passed the approval limits for PNG. The final lifetime of the DSAW pipes with the treated long seam could not be finally determined but is expected to be in the range of seamless pipe.

The cylinder will most likely fail due to an imperfection in a localised area either in the girth weld or somewhere in the pipe body. *The long seam appears not to the critical element.* In any case the failure will occur for fatigue lives (cycles) much larger than required by the DNV CNG code.

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 2500 to 3000 nautical miles it could be more interesting to use CNG than LNG.

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. Up to now this has not been successful mainly due to the large weight of the containment system since standard design codes have been applied for the containment design. To compensate for the large weight, a combination of cooled gas and pressure has been introduced. This will reduce the containment weight since the required pressure will be lower when the temperature is reduced, but will add extra complexity to the gas handling system onboard the CNG carrier.

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 and Det Norske Veritas. DNV developed throughout 2002 rules for CNG carriers that was issued in January 2003 and came into force July 1rst 2003.

The IGC were not intended to cover compressed natural gas cargo containment systems, and no existing rules were therefore available for CNG carriers. The DNV CNG rules are using the IMO (2002) FSA procedure for assessing the safety of new solutions not covered by current practise. 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. Specific requirements have been defined to determination of collision frequency, collision damage calculations as well as energy absorption of the bottom structure while grounding at rocky sea beds.

Without compromising on safety, the use of the modern risk and reliability based DNV submarine pipeline standard (DNV-OS-F101) reduces the steel weight of the cylinders to 50% of what should have been necessary with the requirements of the International Gas Code. 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 PNG carrier with up to 3900 pipes of a total length of 150 Km (90 miles).

Enhanced fatigue requirements are enforced. Fatigue testing of cargo tank details as fabricated is required to establish the S/N curve. The characteristic curve for use in design is defined as the "mean-minus-three-standard-deviations" with at least 95% confidence. In addition to this a safety factor of 10 on the fatigue life is applied.
In order to qualify the cargo cylinders full scale burst and fatigue tests have been completed by Europipe at the Mannesmann Research institute in Duisburg, The tested cylinders surpassed the expectations for both burst and fatigue and no indications of unstable (brittle) behaviour could be detected.

For the Knutsen PNG® a special treatment for the long seam of the DSAW pipe was developed. This treatment provides lifetimes of the DSAW pipe body in the range of a seamless pipe. Different tests with a higher number of samples were performed to simulate the long seam under internal pressure. The small sample test results provide statistical evidence to the expensive full scale tests and support the final conclusion about the real lifetime of a tank cylinder.

For internal pressure fatigue the long seam of the DSAW pipes is not a critical design element anymore, and enables the DSAW process to provide suitable pipes for CNG carriers.

The design of the containment cylinders is driven by fatigue criteria rather than burst. The burst criteria in the DNV pipeline code have a direct link to material selection, welding qualification, test procedures and production tolerances. The same goes for the fatigue criteria in the DNV CNG rules which are even stricter than those in the pipeline code and require a qualification of the design S/N curve for the actual production line and pipeline supplier.

References

AD Merkblatt S2 (1998), „Berechnung auf Wechselbeanspruchung", Beuth Verlag.

Collberg, L., K. Mørk, K. J. and Marley, M. J. (2001). "Inherent safety level in different pressure containment criteria", ISOPE 2001, Stavanger, Norway

Det Norske Veritas (2000). "Offshore Standard – Submarine pipeline Systems", DNV-OS- F101

Det Norske Veritas (2001), "Fatigue strength analysis of offshore steel structures", RP-C203

Det Norske Veritas (2002). "Rules for Classification of Ships Pt 5 Ch 5 – Liquefied Gas Carriers", January 2002

Det Norske Veritas (2003). "Rules for Classification of Ships Pt 5 Ch 15 – Compressed Natural Gas Carriers", January 2003

DIN 2413 (1993), "Teil 1, Stahlrohre, Berechnung der Wanddicke von Stahlrohren gegen Innendruck, Beuth Verlag

EN 13480 (2002), "Metallic industrial piping – Part 3: Design and calculation".

Erdelen-Peppler, M., Knauf, G., Marewski, U., Reepmeyer, O. (2004). "Longitudinal welded pipes with enhanced fatigue strength (Hifa® pipe)", 4th Pipeline Technology Conference Ostende, 9-13 May

GE/TD/1 (2001), "Edition 4, Steel pipelines for high pressure gas transmission".

International Maritime Organisation (IMO) (2000): "Formal Safety Assessment. Decision parameters including Risk Acceptance Criteria", Maritime Safety Committee, MSC 72/16, 14 February 2000 (Submitted by Norway).

International Maritime Organisation (IMO) (2002). "Guidelines for Formal Safety Assessment (FSA) for use in the Rule-Making Process", MSC/Circ.1023, MEPC/Circ.392, 5 April 2002

Stenning, David G. (2000). "Coselle CNG: Economics and opportunities", GasTech 2000, November 2000, Houston Texas USA

Valsgård, S., Lothe, P., Strøm, N. K., Mørk, K. J., Ng, E. and Roper, N. (2003). "CNG – A Competitive Ship Transport Solution for Natural Gas", 2nd International Conference on Port & Maritime R&D and Technology, Singapore 10th-12th September

White, C., Grossweiler, P., Ha, J. K., Naokawa, S. and McClure, S. (2003). "The Impact of Compressed Natural Gas upon Offshore Gas Development", OTC 15070, Offshore Technology Conference, Houston, Texas, May 2003