In proceedings of “Design, Construction and Operation of Natural Gas Carriers and Offshore Systems”,
ISCOT 2006 / The Royal Institution of Naval Architects - RINA, Busan, Korea

GAS CARRIER DEVELOPMENT FOR AN EXPANDING MARKET

S. Valsgård, T. K. Østvold, O. Rognebakke, E. Byklum, and H. O. Sele, Det Norske Veritas, Norway

SUMMARY

The paper describes the work carried out in DNV to meet the new challenges facing the Gas Carrier industry, emphasising sloshing loads and tank system strength for normal tank fillings as well as reduced tank filling operations of membrane type LNG carriers. The current applicability of Computational Fluid Dynamics (CFD) computer codes in sloshing analysis is discussed. Results from scaling of model tests results between different model scales are shown and it is concluded that a full scale sloshing impact measurement campaign is necessary to better understand the model scaling issue. Short-term expected extreme as estimate for lifetime expected extreme sloshing loads is discussed and some remarks are given on sloshing loads at low filling ballast operation as compared to high filling full load operation. Due to the current shortcomings in the CFD analysis tools DNV has concluded that sloshing load determination has to be based on model testing. As uncertainties still exists in the determination of absolute values of sloshing impact loads, a comparative approach has been selected for the containment assessment procedure in the new DNV guideline on “Sloshing Analyses of LNG Membrane Tanks”.

The status of the emerging CNG shipping industry is outlined. Work is in progress for establishing a common basis for steel tank system design. Several CNG proponents are working with prototype testing of tank system designs. The main results from a specific full scale prototype testing campaign is reviewed highlighting fatigue testing, burst testing and live gas cool-down testing of a particular steel tank concept.

1. INTRODUCTION

The world use of natural gas is increasing. For long distance seaborne transportation of natural gas LNG represents today the most efficient commercial alternative, but economically competitive systems for smaller volumes and shorter distance trades like Compressed Natural Gas (CNG) are emerging.

1.1 GAS CARRIER DEVELOPMENT

From the very beginning of the gas carrier industry great care has been taken to include all relevant failure modes in the design of the tank systems and fatigue, buckling and sloshing loads have been important design parameters.

The seaborne transport of liquefied gases in bulk is older than often realised. Already in 1949 the first dedicated liquefied gas carrier was delivered with DNV class. This was a vessel with fully pressurised cargo tanks for transport of LPG/Ammonia. The vessel, named Herøya, had vertical cylindrical tanks and was built at the Horten Navy Shipyard in Norway. DNV, therefore, became involved very early in the setting of safety standards, and was in 1962 the first classification society to publish comprehensive rules for gas carriers

A research team on LNG was established in DNV in 1959. A membrane tank system was developed and tested successfully in 1962. The system used double corrugated aluminium sheets as the primary barrier. This system was later taken over and further developed by Technigaz in France.

The Moss spherical tank design was developed by the Kvaerner Group in Norway during 1969-1972. Basic design criteria for type B tanks were formulated by DNV in the 1972 rules. In order to confirm compliance with the design criteria comprehensive R&D programmes were carried out in DNV, e.g. sloshing loads from liquid movement inside the cargo tanks, crack propagation, fatigue characteristics and buckling strength.

The idea of shipping gas on keel without a costly liquefaction process is equally old as the LNG industry, but have until recently been no success due to the heavy gas containment systems if the tanks (cargo cylinders) were to be designed according to conventional pressure vessel codes or the international Gas Code (IGC). This leads to heavy containments systems with virtually no lifting capacity left for cargo unless unreasonably large and costly ships are to be used.

Most CNG concepts apply high pressure (130-250 bars) in a semi-chilled or at ambient temperature condition in order to keep the gas in a gaseous state with basically no liquid hydrate fall-out. CNG tanks are mostly based on the use of cylindrical bottles or pipes with diameters up to 48 inch being designed according to modern limit state pipeline or pressure vessel codes. For such tanks *fatigue becomes the driving design parameter*, ref [8].

1.2 NEW OPERATIONAL CHALLENGES

The consumption of natural gas is projected to increase by nearly 70% between 2002 and 2025 [1] and the market for seaborne gas transport is increasing at an unprecedented pace. The latter is characterised by rapid increase in the carrier fleet, spot trading, speculative ordering, increased carrier size, a move away from the traditional one propeller steam plant towards diesel propulsion and two propellers, more cross Atlantic trading, partial load trading (milk runs) and an emerging market for cold climate (Artic) operation. Fatigue considerations and tank sloshing loads are becoming more important design parameters.

Offshore receiving/storage terminals and regasification and discharge terminals will in some parts of the world be the preferred future option due to safety considerations and environmental concerns. Floating units for receiving, storage, regasification and export (FSRUs) of natural gas as well as units for offshore production (FPSOs) are emerging markets. For these new applications safe operation with partial tank fillings has to be carefully studied on a case to case basis. Sloshing loads and tank system strength are therefore key issues in the design and operation of such systems.

Seaborne LNG transport has historically been a high standard, low accident operation. Damage statistics from DNV in-house studies indicate an average accident rate in the range 30-80% lower than for average shipping operations. It is a challenge for everyone involved to maintain this favourable situation in order to further develop the industry.

The larger sizes of carriers and the new operational profiles outlined above make relying on past experience for structural performance of the vessel hulls and containment systems rather uncertain. *Hence, the use of state-of-the-art design for ultimate strength and fatigue will be essential for safe and trouble free operation.*

2. SLOSHING LOADS AND STRENGTH

Sloshing can induce various types of loads. Motions and/or more rapidly varying motions, causing higher accelerations, induce dynamic effects. The pressure fields inside the tanks can still be described by smoothly varying pressure distribution functions and the structural response can be calculated in a quasi-static manner. In case of more frequency content around sloshing resonance the fluid behaviour becomes violent, causing breaking waves and high velocities of the fluid surface. In this case the fluid can cause impact loads on the containment system. These loads can be characterised by a high pressure load with short duration acting on a limited area.

Violent sloshing can be characterised by various fluid flow phenomena illustrated in Figure 1. In the high filling range >90%H (H denoting the tank height) the impacts typically occur on the tank roof at the connection with the transverse bulkheads. Typically a 'flat' fluid surface hits the roof at high velocity causing the impact.

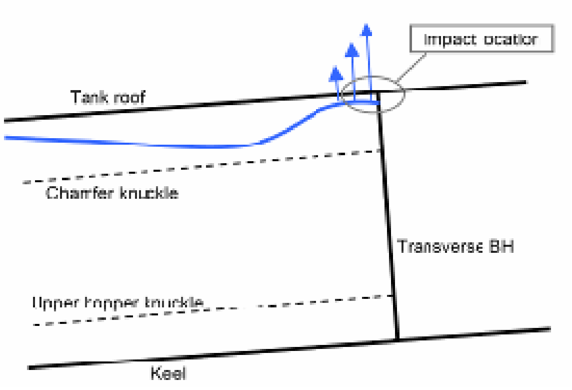

Figure 1: Typical high-filling (>90%H) impact in near head sea conditions

For fillings in the range of ~60% to ~80% the largest impacts occur in the corners and knuckles of the chamfer. These impacts can be caused by run-ups against the longitudinal or transverse bulkheads or by a 'flat' fluid surface impact.

For fillings in the range of ~20%H to ~40%H the largest impacts occur at the longitudinal and transverse bulkheads due to breaking waves, Figure 2.

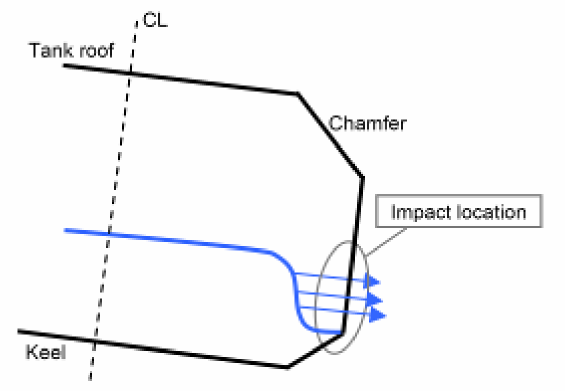

Figure 2: Schematic illustration of a hydraulic jump or hydraulic bore

A characteristic phenomenon, which can occur at lower fillings is the so-called *hydraulic jump* or *bore*. This wave phenomenon is characterised by a 'jump' in the free surface level, which travels at high speed, and can cause a large impact. Sloshing model experiments are required in order to assess the violent sloshing causing impact loads.

The sloshing loads vary in size, duration and load area. In addition, the containment system and hull structure have different failure modes. Consequently, a careful analysis of the structural response and strength needs to be conducted for the various loads to assess the structural integrity.

2.1 LNG CARRIER DEVELOPMENTS

Many of the current developments in the LNG shipping industry affect ship classification. R&D is a key element to develop the required competence to adapt classification rules and guidelines to new ship designs and operations. DNV therefore applies a significant amount of resources to R&D and has defined a specific R&D portfolio for gas carriers - LNG as well as CNG. Some of the key elements in these efforts related to gas carriers are:

- LNG sloshing in membrane LNG tanks
- Alternative propulsion arrangements
- Vibrations
- Hull fatigue
- Operation in cold climate

The last three items are not only related to gas carriers, but are of major importance to all types of ships. The two last items are organised in separate R&D programmes on “Hull Loads and Strength” and “Cold Climate” respectively.

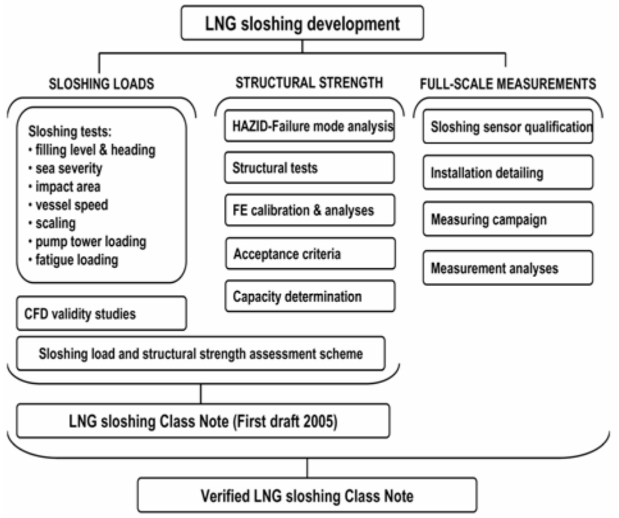

Figure 3: Integration of sloshing load and response projects for membrane LNG carriers

Three Class Notes are under development and are expected to be issued in 2006. One is focussing on the hull and tank support design of membrane tankers, excluding the containment system, the second is focussed on sloshing loads and strength of membrane tanks [3] and the third one is concerned with the design and analysis of the hull and tank system of spherical type LNG carriers.

Industry co-operations complement the pure internal R&D work. Joint Industry Projects with yards and ship owners are important for DNV in order to improve knowledge sharing and competence exchange.

Most attention in the LNG R&D portfolio has been paid to the first item in the list - LNG sloshing in membrane tanks. This R&D work is divided into four projects:

- Sloshing loads
- Sloshing structural response and strength
- Sloshing guideline
- Full-scale sloshing measurements onboard an LNG carrier

Prime activities within these projects and the structure in which these projects are linked are illustrated in Figure 3. More details can be found in ref. nos. [6] and [7].

The first two listed projects are primarily focused on competence development in order to support DNV classification. All the knowledge and competence gained are used to develop a load and structural strength assessment scheme. This forms the basis for a dedicated Class Note (Guideline) on sloshing in membrane LNG tanks [3].

Sloshing is a highly complex phenomenon and despite the huge R&D efforts some aspects are still under discussion or difficult to put down in a practical guideline. Based on this and as a response to market requests a sloshing full-scale measurement campaign has been designed by DNV. This measurement campaign is intended to provide a validation database for sloshing loads and structural responses.

2.2 MODEL TESTS OR COMPUTER SIMULATIONS?

Computational fluid dynamics (CFD) software has found many engineering applications enabling designers to simulate fluid flow, heat and mass transfer, and a host of related phenomena involving turbulent, reacting, and multiphase flow. Hence, CFD has been considered a potential tool for sloshing impact analyses in LNG tanks and much effort has been made to adapt CFD tools for such applications.

DNV is using the ComFLOW CFD software developed by University of Groningen in Holland [4], and has evaluated the programme for simulation of sloshing phenomena in LNG tanks. The present version is simulating one-phase flow only, but does have facilities for random 6 d.o.f. motion time series input to the programme. Presently work is underway in a Joint Industry Programme (JIP) aiming at implementing two-phase capabilities which will be essential for possible future applications to LNG sloshing phenomena. In this connection large 1:10 scale sloshing tests of a transverse cross-sectional cut of an LNG membrane tank has been carried out in the DNV laboratories at Høvik using water and air at atmospheric pressure in order to provide a verification data base for further development, Figure 4.

Figure 4: Test rig with 1:10 scale model for the ComFLOW 2-phase JIP

Previous model tests [7] have shown that ullage gas depressurisation according to the linear Froude scaling law and tests with heavy gas aiming to have a correct gas to liquid density ratio gives quite different sloshing test results, the latter giving the lower measured pressures, Figure 5. Hence, for approaching an absolute sloshing impact load assessment with a CFD code a two-phase simulation capability for simulating both the liquid and the gas is essential.

Another challenge is the correct mathematical modelling of the gas/liquid interface. In an LNG tank continuous phase transition from liquid to gas (boil-off) takes place due to the heat influx through the insulation system. The motion of the LNG creates gas bubbles and turbulence effect on the gas/liquid interface. Also, when the liquid hits the sharp knuckles and corners of the tank wall cushioning effects may occur caused by entrapped gas and the increased flexibility of the fluid/bubble mixture. Being able to capture the local compressibility effect of the fluid/bubble mixture which varies in time and space is therefore important for determining cushioning effects. In order to simulate these effects very small meshes have to be used (in the order of 1 mm). This is prohibitive for CFD calculations.

Harmonic model test have shown that sloshing impact pressures is a highly stochastic process. Consecutive tests with the same harmonic input signal do not give the same result and statistical treatment of the results can be done in the same way as for tests with randomly generated input signals. CFD codes may not have implemented such facilities in their solution schemes – the same input gives the same results.

For these reasons Det Norske Veritas has concluded that for the time being the only viable and practical approach to determining sloshing loads in LNG tank systems is to perform model tests. We are then faced with the pressure scaling issue which has been a continuous question mark in the LNG industry. This will be discussed later in the paper.

However, liquid motions can be modelled in a CFD programme using much coarser meshes than necessary for impact pressures. Hence, pipe tower loads, i.e. drag forces from liquid motions, as well as inertia load effects can be modelled adequately with today's CFD codes. This also means that simulation of global sloshing loads for sloshing-ship motion coupling is possible.

2.3 SCALING OF MODEL TEST RESULTS

For the sloshing experiments there has been quite some discussion about the scaling of the impact pressure and the properties of the ullage gas. The Froude scaling is a well known scaling law used in fluid mechanics. This scaling law is valid for inertia dominated fluid behaviour. But for compressibility, surface tension & viscous effects other scaling laws apply. DNV has studied this further and have earlier (1970s/1980s) recommended a reduction in the ullage gas pressure according to linear scaling. The ullage gas pressure was reduced linearly with the same factor as the geometric scale factor. This was based on experimental sloshing investigations with water and air which showed that the measured extreme pressures are highly sensitive to the variation of ullage pressure when depressurised to lower than approximately 100 mbar [5]. This also had implications on the selection of model scale as the uncertainties increase with reduced model scale.

The validity of this was checked by DNV in 2004 when impact pressure result for roof impact at 90% filling level were compared between two tanks at different scale. A range of different ullage gas densities and pressures were tested. One tank had a scale-ratio of 1/70 and the other a scale-ratio of 1/20.

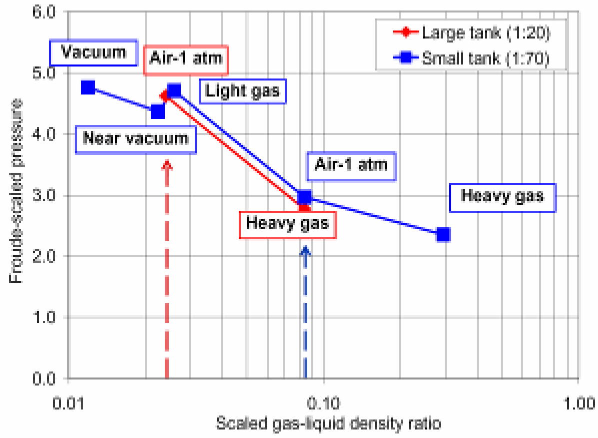

Figure 5: Froude scaling of sloshing impact pressures

The following effects were observed:

- The impact pressure was dependent on the ullage gas density and gas pressure.
- A reduction in the ullage gas density was needed in the small tank by a factor close to the scale-ratio to predict the large tank impact pressure.
- The effect was important for single sensor loads and not that pronounced for a larger area (average pressure for a cluster of sensors)

The implications of these issues are that questions still may be asked if single sensor measurements might be non-conservative if they are scaled directly by Froude scale without modifying the ullage gas density. Figure 5 illustrates the observations. The results from the large (1/20 scale) tank and the small (1/70 scale) tank are compared in the same figure. Both the horizontal and vertical axes are scaled linearly. Then the graphs match. If the ullage pressure in the small tank is scaled down according to the scale ratio, as recommended by DNV from earlier work, the impact pressure follows reasonably Froude scaling.

An example:
The vertical dashed arrows show the points where the air at 1 atmosphere (atm) is tested. The dimensionless impact pressure in the small tank with air at 1 atm is 3.0. If the same gas condition (air 1 atm) is tested in the large tank, the result is 4.6. This leads to an under prediction of the large tank impact pressure by the small tank impact pressure tests by the ratio $4.6/3.0 \approx 1.5$.

However, the following remarks should be made:

- The amount of data is limited.
- There is an uncertainty in the motion due to the large rig and small tank (1/70 scale)
- A validation with full scale measurement should be carried out.
- For some of the points, both the ullage gas density and pressure is changed. Thus it is not only one parameter which is changed.

A final conclusion cannot be drawn as the quality of the tests is not found sufficient. However, the various test cases indicate a trend/direction, which seems to confirm the recommendation given previously by DNV, [5].

2.4 FULL SCALE MEASUREMENT CAMPAIGN

As concluded above a full scale measurement campaign onboard a membrane LNG carrier need to be carried out to be able to get a better background for understanding the scaling issue.

Hence, DNV has together with industry partners designed a full-scale sloshing measurement program in order to obtain a full-scale sloshing measurement validation database.

The objectives of a full-scale measurement program are:

- Development of a full scale LNG sloshing measurement system
- Obtain full-scale validation data
- Validate sloshing assessment procedures

Of prime interest is of course the measurement of sloshing pressures. Traditional pressure sensors cannot be used inside the containment system; hence a new sensor has been developed and qualified. The newly developed sensor is based on fibre-optic measurement technique and is mounted in the insulation system under the primary membrane.

The sensor has been developed by a Norwegian supplier of fibre optical hull monitoring systems with assistance from DNV. A test program consisting of static and dynamic functional tests has been carried out in a pressure test tank with a steel membrane between the sensor and the pressure transmitting liquid. The sensor is capable of measuring dynamic responses with rise time down to 0.5 ms and has a working pressure range up to 40 bars. The sensor has been verified for use with both the No 96 system and the Mk III system.

The sensor has been qualified and approved by DNV for mounting onboard LNG carriers and will be connected to a commercial fibre optical hull monitoring system. A typical installation lay-out will comprise at least a set of instrumented containment boxes/insulation panels inside tank no. 2 at positions likely to encounter the highest sloshing loads.

The main objective with a full-scale measurement program is to obtain validation data. It is therefore of vital importance to integrate full-scale measurements of sloshing load and structural response assessments. Hence, simultaneous measurements of environmental data, ship motions and strains in the supporting insulation system and the supporting hull structure will be carried out to complement the sloshing pressure measurements.

A measurement campaign was initially agreed upon between DSME, DNV, Bergesen Worldwide Gas ASA, Golar Management and STASCO in August 2005. The initiative was well received in the market and several other players in the LNG industry have shown interest in participating.

2.5 LONG TERM AND SHORT TERM LOADS

In standard wave load analysis a wave scatter diagram is used to describe the long-term wave environment. Using linear response transfer functions a complete wave scatter-diagram can be assessed and the long-term response amplitude distribution can be calculated. From this distribution, the lifetime expected extremes can be determined, e.g. corresponding to 10^8 wave encounters in North Atlantic environment as given in the IGC [10] or to a certain return period and probability level.

Another approach is to determine the most critical sea state from the scatter-diagram and assess only the short-term statistics for that sea state. For linear responses these typically give short-term expected extremes some 10% to 20% lower than the long-term expected extreme. However, for nonlinear responses the response behaviour may be characterized by response amplitude distributions having more “flat tails” (i.e. Weibull fitted function with

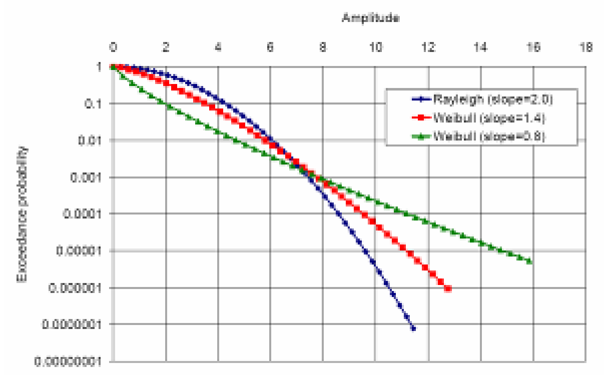

Figure 6: The effect of different Weibull slope factors

low values for the slope factor). Figure 6 shows some example curves with varying slope parameters. For linear responses the amplitude distribution is given by the Rayleigh distribution. However, when the response is characterised by more "flat tails" the difference in determining a short-term or a long-term extreme is larger than 10% to 20%.

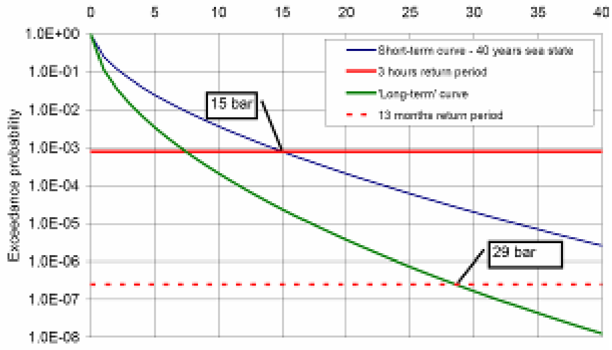

Figure 7: Short–term and "long-term" exceedance probability curves (Weibull slope=0.6)

Figure 7 shows an example based on use of the IACS North Atlantic scatter diagram (recommendation 34) and a Weibull slope factor equal to 0.6 that can typically be observed from sloshing tests. For simplicity 3165 observations of duration 3 hours at a wave period of 8.5 seconds (H_s=5.5–12.5 m) is used for a 40 year period. This corresponds to a return period of 13 months. Consequently, by testing only the worst sea state the short-term expected extreme is not representative for the lifetime expected extreme but significantly lower.

For completeness an additional example is shown, where the Weibull function is modelled with a slope factor β=2.0, which corresponds to the Rayleigh distribution as usually applied for linear ship responses. Figure 8 shows results from which it can be seen that the 'long-term' extreme is only slightly larger than the short-term extreme (1.04).

In order to study this effect experimentally and mainly to be able to determine a first estimate of the long-term distribution for sloshing-impact fatigue considerations DNV has conducted a sloshing experimental program by carrying out a number of tests for a range of sea state combinations. From this study a *very crude* estimate of the long-term distribution indicated a difference factor between the short-term extreme and a lifetime extreme of 1.8 but with a large uncertainty. Most importantly from this study it was seen that the slope parameters for lower significant wave heights remained similar.

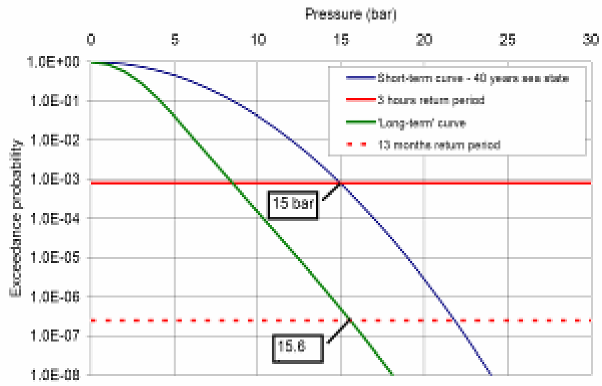

Figure 8: Short–term and "long-term" exceedance probability curves (Weibull slope=2)

In principle LNG carriers sail fully loaded or in ballast. Partially filled trading, i.e. tank filling between 70%H and 90%H, may appear only occasionally. It is therefore an important question how to compare a high filling sloshing case, e.g. ~95%H, versus a lower filling, e.g. ~80%H, when both are analysed for the worst short-term 40 years sea state or how to treat the short-term loads in a long-term absolute load-strength assessment. From the discussion above it is clear that the actual lifetime expected extreme for the high filling case is much larger than the short-term value whereas the lifetime expected extreme for the partially filled case (70-90%H) is presumable only slightly larger.

Hence the analysis (both *comparative* and *absolute*) must account for this difference. Roughly speaking it might be stated that:

- > 90%H filling – representative for normal operation over the lifetime of the vessel – 3hr expected extreme value is not representative for the long term expected extreme.
- < 90%H filling – rare or very rare occasions – 3 hour expected extreme for a sea state with 1 year return period may possibly be representative for the long term expected extreme.

2.6 LOADS AT HIGH AND LOW FILLINGS

Many of today's LNG receiving terminals may have a marginal capacity for serving the growing fleet of LNG carriers of sizes larger than the 138 000 m^3 reference size.

Also, in cases where the terminals have not been able to make available sufficient storage capacity in time for the arrival of the next unloading carrier, the ship may be forced to carry more than the normal heel on the return ballast voyage.

The current maximum low filling height for all DNV classed membrane carriers is <10%L up to 155 000 m^3 in size and <10%H for all larger carriers.

Sloshing impact loads for high and low fillings are sketched in princilpe in Figure 9 as functions of loaded area. The high filling load curve is associated with the situation shown in Figure 1 whereas low fillings are illustrated in Figure 2. The latter is often associated with a hydraulic jump which generates a larger impact pulse acting over a larger area than is the case for high fillings, ref. [6] and [7]. Hence, the low filling impact pulse may be more demanding on the strength of the insulation system [6]. The situation can be summarised as follows:

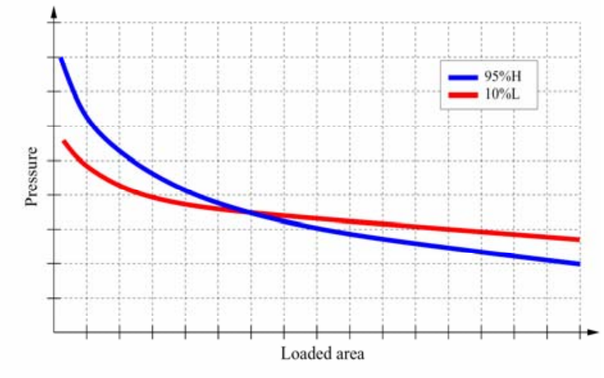

Figure 9: Principle sketch of sloshing loads vs. load area at high and low fillings

- At low tank fillings (<10%L) sloshing impact footprints are larger than at high fillings (~ 95%H) due to "hydraulic jumps/breaking wave" effects.
- The sloshing impact loads at large areas may in general be higher at the low 10%L filling level than the high 95%H filling pressures.

If enhanced safety of low filling operations is an issue basically two options are available:

- Operate with lower fillings at the ballast voyage, i.e. reduce maximum allowed filling height from 10%L to 10%H.
- Reinforce the insulation system to withstand 10%L fillings; vertical sides above upper hopper knuckle and transverse bulkheads up to the same level

Altenatively, apply a combination of the above measures.

In general little attention has been paid to the low filling issue by the LNG industry. Sloshing loads at low fillings therefore need to be more thoroughly investigated.

2.7 TESTING AND ANALYSIS OF MEMBRANE SYSTEM RESPONSE AND STRENGTH

The new market demands have identified the need for a methodology for strength assessment of membrane insulation systems under the action of sloshing loads. Experiments have shown that changes in design and operation not only affect the magnitude of the sloshing loads, but that large variations also can be observed for its spatial extent and the time history. Since the time and spatial distribution of the sloshing impact has significant impact on the response of the containment systems, the various sloshing events can only be *compared in terms of structural response and strength* of the systems. In addition, a rational strength assessment methodology is required to identify the necessary strengthening and design improvements to maintain the required safety margins during the new operation.

A significant amount of work has been done over the years to study both the static and dynamic impact response and strength of the entire system under certain loading conditions. However, in order to construct analysis models for structural response and strength also information on material properties and representative failure modes are needed.

DNV has during the last years carried out R&D work with the aim of developing a methodology for capacity assessment of membrane containment systems. The objective has been that the methodology should be sufficiently general to allow for assessment of strength changes caused by moderate structural modifications such as

- Change of plate thickness
- Modified distance between lateral supports
- Other minor modifications expected to be proposed to add strength to the systems

The scope of the development work includes:

- Identification of critical failure modes.
- Experimental and analytical investigation of the identified failure modes.
- Gathering, developing and/or selection of representative stiffness and strength properties of the materials used in the insulation systems.
- Specification and development of requirements and procedures for structural response assessment.
- Formulation of strength criteria including dynamic and low temperature effects.

Examples from this work have been published in ref. [6] and [7] and will therefore not be repeated here. Testing has been carried on both single components and system sub-assemblies. Further, the experimental studies have been complemented with the development of dynamic non-linear FE response models that has been tested against, and validated by, the experimental results. Based on this quasi-static and dynamic response models for use in design have been established and implemented into the new sloshing guideline [3]. Here the dynamic response is determined by a simplified method using dynamic amplification factors specified as functions of the ratio between pulse rise time and system natural period.

Most of the work has been focused on ultimate strength (ULS) behaviour of the systems. However, the international gas code (IGC) [10] and the Classification Society rules [2] require also the fatigue endurance to be evaluated. Hence, some work has also been done on fatigue and the conclusions have been incorporated in the new guideline. Figure 10 illustrates the findings.

- The number of sloshing impact fatigue cycles is less than the number of sea loads with a factor of 100.
- The Weibull shape factor of the long term response distribution curve is in the order of 0.6.
- This indicates that high cycle low impact loads are not important for the insulations system.
- However, the damaging effect of a limited number of repeated high impact loads may need to be considered.
- Only the 10-50 highest low frequency load cycles contribute to the fatigue damage resulting in an accumulated damage effect (Miner sum) < 0.1.

2.8 THE SLOSHING CLASS NOTE

Due to uncertainties in the sloshing impact load assessment a *comparative approach* is used for assessing the strength of the containment system and the supporting hull structure. This is contrary to traditional direct wave load and strength analysis of ships where an absolute approach is used. However, for the pump tower structure an absolute approach may be used, [3].

In the *comparative approach* the sloshing load and strength of a new LNG carrier design or a new operation of an LNG carrier is compared with the sloshing load and strength of the existing fleet of membrane type LNG carriers that have traded in a safe and damage free operation. The former is referred to as the *target* vessel, whereas the latter is referred to as the *reference* case.

2.8 (a) Design Safety Format

The safety format used is a partial safety factor format which allows uncertainties to be defined and associated with the actual load response and strength effect rather than combining everything into one common usage factor.

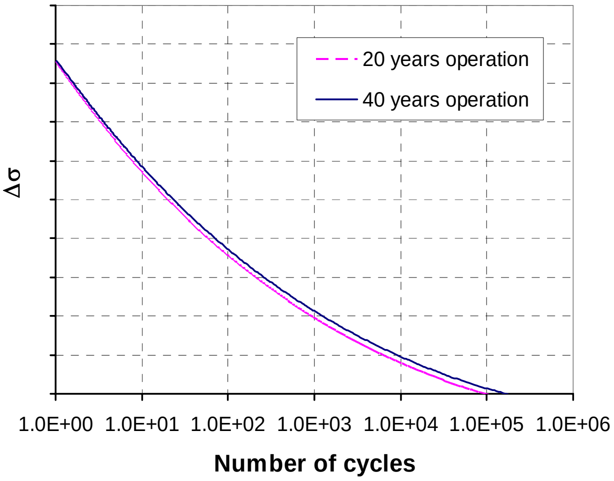

Figure 10: Comparison of scaled long term response distributions for 20 years and 40 years North Atlantic operation.

Load comparative approach:

The following acceptance criterion should be satisfied:

$$p_{tar} \cdot \gamma_F \le \frac{p_{ref}}{\gamma_M}\text{, where} \qquad (1)$$

p_{tar} is the sloshing impact pressure for the target LNG carrier.

p_{ref} is the sloshing impact pressure for the reference LNG carrier.

γ_F is the partial safety load factor

γ_M is the partial safety resistance factor

The criterion should be satisfied for the entire range of load areas relevant for the unit dimensions of the containment system.

Strength comparative approach:

The format is defined as follows:

$$S(p \cdot DAF \cdot \gamma_F) \le \frac{R_c}{\gamma_M}\text{, where} \qquad (2)$$

S	is the structural response, in general a non-linear function of the dynamic load.
p	is the sloshing impact pressure scaled according to the comparative procedure described in the next section.
DAF	is the dynamic load factor.
R_c	is the capacity in terms of the considered response parameter.
γ_F	is the partial safety load factor
γ_M	is the partial safety resistance factor

Pump tower assessment

The strength assessment of the pump tower and supports may be carried out using either a comparative approach or an absolute approach.

The absolute approach will usually be most convenient, since the load and strength need to be calculated for the target case LNG carrier only. The strength is satisfactory if:

$$S\gamma_F \le \frac{R_c}{\gamma_M} \qquad (3)$$

which is a simplification of eq. (2) above

Direct vs. comparative strength assessment

In a direct strength assessment, the absolute magnitude of the loads is of major importance, and a thorough investigation of the loads is necessary. Larger load factors need to be used in the absolute approach than in the comparative approach, in order to account for the uncertainties related to the load level.

If the comparative approach is followed, as recommended for the containment system and the hull strength, the load and strength of the pump tower in the reference case are compared with the load and strength of the pump tower in the target case. The utilization for the target case, multiplied with a safety factor, should be lower than for the reference case. The strength is satisfactory if:

$$\left(\frac{S}{R_c}\right)_{tar}\gamma_{compare} \le \left(\frac{S}{R_c}\right)_{ref} \text{, where} \qquad (4)$$

S is the structural response

R_c is the capacity in terms of the considered response parameter

$\gamma_{compare}$ is a load factor that reflects the statistical uncertainty in the comparative load assessment

In the comparative approach, the uncertainty related to load level is reduced, since the main concern is the load increase from the reference case to the target case, rather than the absolute load level.

2.8 (b) Strength Assessment Methodology

The methodology can be summarised as follows:

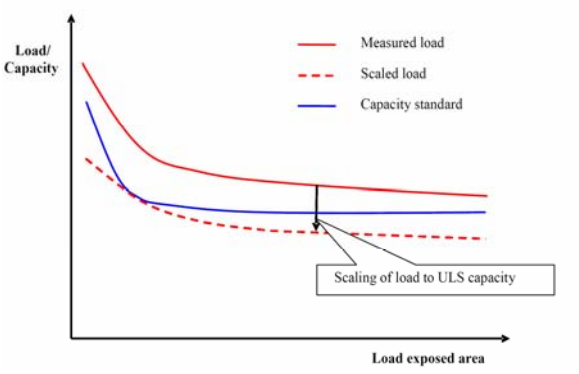

Figure 11: Scaling of loads for the reference case to the ULS capacity.

Reference case, Figure 11:

1) Establish a curve relating sloshing impact pressure and sloshing exposed area based on experimental results. Load factors to be disregarded in this step.
2) Establish a curve relating the impact load capacity of the insulation system and the sloshing exposed surface area of the structure. Resistance factors to be disregarded in this step.
3) Establish the ratio between the load and the capacity for the entire range of load areas, and identify the maximum ratio between load and capacity. Denote this ratio by α_{comp}.
4) Scale the load uniformly for all load areas using the maximum identified ratio between the load and the capacity. The scaled load will now for any load area size be lower than the ultimate capacity of the insulation panels. This step is motivated by the damage free operational experience with the membrane type LNG carriers.

The resulting load curve is now the basis for the strength assessment of the insulation system and its supporting hull structure.

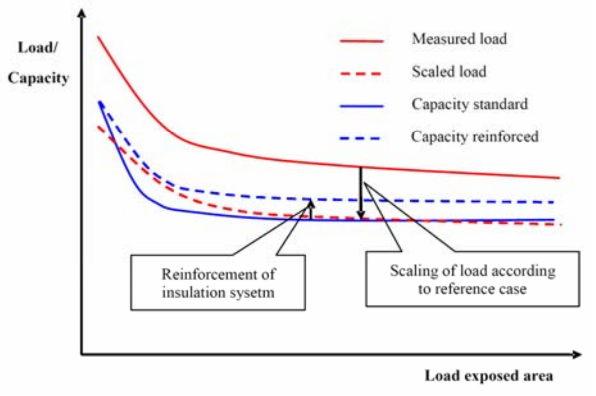

Figure 12: Scaling target case with same load factor as for reference case. Strengthen containment system according to scaled load curve.

Target case, Figure 12:

1) Establish a curve relating sloshing impact pressure and sloshing exposed area based on experimental results.
2) Scale the load using the maximum ratio, α_{comp}, between load and response determined from the reference case.
3) Carry out a strength assessment of the insulation.
4) Carry out the necessary reinforcement of the insulation system so that the load for any load area is lower than the ultimate capacity of the insulation panels.
5) Carry out a strength assessment of the supporting hull structure.

The comparative strength assessment should be carried out for all insulation structure elements that will experience sloshing impact loads in the cargo tank. In practice this means the dedicated transverse and longitudinal corner/knuckle structure and standard flat wall structure adjacent to the corner/knuckles. The specific locations are determined by the applicable tank filling limitations and the operation of the vessel.

A single comparative load scaling factor, α_{comp}, representative for the weakest element of the considered insulation structures should be applied in the assessment of all relevant insulation structures of the target vessel. This means that potential strength margins determined for the reference case can be utilised in the target case.

2.8 (c) Application of the sloshing guideline

The main focus of the Classification Note 30.9 [3] is to provide guidance to assess sloshing for:

- Increased size LNG carriers
- Offshore loading/unloading
- Partially filled LNG tanks on a particular trade route

However, the class note provides detailed information on the specification, execution and analysis of sloshing experiments. Consequently, it may be used to assess other applications than the specific applications listed above.

3. THE CNG ALTERNATIVE

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 and LNG storage tanks, nor will LNG storage and regasification at the discharge location be necessary. A fleet of CNG ships may 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.

3.1 CNG SYSTEM DESIGNS

Table 1 Example of CNG Systems

System	CNG Tanks	Design condition	
		[bar]	[°C]
Coselle (SeaNG)	Horizontal steel coils	240	Ambient
Knutsen PNG®	Vertical steel pipes	250	Ambient
EnerSea VoTrans	Vertical Steel Pipes	130	-30
Trans Ocean Gas	Vertical composite pipes	250	Ambient
CETech	Horizontal steel pipes	250	Ambient

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 like the International Gas carrier Code (IGC), leads to heavy containment 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 design codes that offer the same system safety, but with the use of smaller nominal safety factors on the structural design. A typical example is the DNV Standard for Submarine Pipeline Systems, OS-F101, ref. [9] that for the X-80 standard pipeline steel allows for a 50% reduction in wall thickness of the containment cylinders as compared to the IGC. This weight reduction is the essential door opener for realization of steel based CNG systems onboard ships.

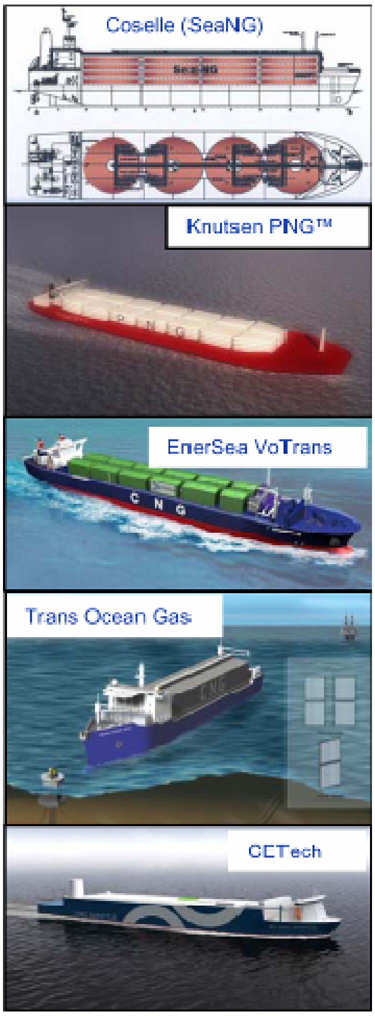

Figure 13: CNG Designs

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 selected examples are shown in Table 1 and Figure 13.

The CNG concepts apply high pressure in order to keep the gas in a gaseous state with basically no liquid hydrate fall-out. Concepts with such high pressure (250 bars) are far beyond the scope for pressure vessel type C tanks defined in the IGC. This gap has been filled by the new DNV Class Rules for Compressed Natural Gas Carriers [8] following an equivalent Formal Safety Assessment (FSA) approach according to IMO MSC 72/16, [11] and MSC 74/19, [12].

The Trans Ocean Gas design is based on use of 12 m long gas bottles built in composite materials. This is well proven technology from the aerospace industry and has several advantages;

- Good track record from the aerospace industry since 1960 and now also successfully being used in CNG powered buses since 1995
- Better rupture characteristics than steel
- Corrosion resistant
- Lighter than steel (about 1/3 of the weight for comparable configurations)
- Excellent low temperature characteristics

As for cost comparisons, both steel tank designers and composite designers maintain that their system is the best and the most cost effective. However, both types of systems have their advantages and drawbacks. They are all technically feasible, but only the future will be able to judge on the cost effectiveness.

3.2 CNG TRANSPORT ECONOMY

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 rather than LNG. Figure 14 shows an example case worked out for the Knutsen PNG® system. The figures are based on

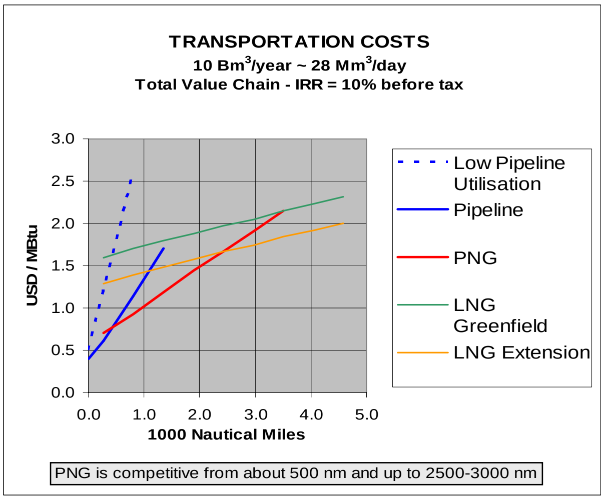

Figure 14: Competitive range for Knutsen PNG®

- 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.

3.3 CNG RULE DEVELOPMENT

Since the IGC never was intended to cover compressed natural gas cargo containment systems, no existing rules were previously available for such concepts. However, according to IMO, Formal Safety Assessment (FSA) principles can be applied where existing rules do not cover new applications ref. [12].

3.3 (a) The DNV rule development

Rules for classification of ships, Part 5 Chapter 15 for Compressed Natural Gas Carriers were issued for the first time by DNV in January 2003, [8]. This was the first time a complete set of rules has been issued for CNG Carriers. The rules are to some extent generic and apply to ships carrying gases in the superheated phase above the critical temperature. The scope covered steel pipeline designs, including PNG®, but did not apply for all proposed CNG concepts. In the January 2005 issue design requirements for composite pipes and composite wrapped steel pipes were introduced.

Technical background documentation started in the summer of 2000. The rule development was initiated early December 2001, and the first draft was available on February 14th 2002. Internal and external hearings took place from July through October 2002. The new rules that were issued in January 2003 came formally into force by July 1rst 2003. During that time frame the rules had been presented to and discussed twice with the Norwegian Maritime authorities (NMD) and the US Coast Guard (USCG). Also the Norwegian Petroleum Directorate (NPD) had been informed about the development. Valuable input and comments were received throughout this process.

3.3 (b) Rule Harmonization

At the “2nd International Marine CNG Standards Forum” at St. John’s Newfoundland in August 2005 it was decided that the Classification Societies that had issued rule or guidelines (DNV and ABS) or were in the process of doing so (Bureau Veritas) were to meet to work out a common set of basic design requirements applicable to steel CNG cylinders. Secretary for the work was to be the Centre for Marine CNG at St. John’s. So far one meeting has been held at ABS premises in Houston and the work is in progress.

3.4 VERIFICATION TESTING

An essential part of the verification of the safety of the containment cylinders is to carry out full scale prototype tests in accordance with the testing requirements set fourth in the DNV CNG rules, [8]. For steel cylinders the requirements are:

Figure 15: Full scale end-capped test pipe at Europipe's test site

a. Full scale fatigue tests of two end-capped pipes. The fatigue capacity to be at least 15 times the number of design life pressure induced stress cycles.
b. Burst test of one full scale end-capped pipe after 2 times the number of design life pressure induced stress cycles.
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 cylinders.
e. Verification that the loading/unloading process works as intended, by full scale process prototype testing, small scale model testing or numerical simulations

The factor of 15 times the design life rather than 10 times is applied to account for system effects by testing only 2 randomly selected pipes out of more than the 1000-3000 pipes in an actual ship.

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

3.4 (a) Full scale prototype tests and fatigue tests

In order to document that the requirements to burst and fatigue for the PNG® system were complied with tests were carried out by Europipe GmbH at their Mannesmann Research laboratory in Duisburg, Germany.
A series of small scale fatigue tests of longitudinal welds and circumferential welds were made together with full scale burst and fatigue tests with end-capped pipes. The following tests were carried out:

- One full scale burst test where the requirement was to maintain full burst capacity after fatigue cycling to two times the design lifetime, 4 000 cycles.
- Two full scale fatigue tests with a required safety factor of 15 to the design life which results in 30 000 cycles.
- The creation of an individual S/N curve at mean value minus three standard deviation (m-3s) probability level for the special product and applied production methods.
- Proof of statistical safety of the (m-3s) S/N curve between test results from small sample testing and the required limit. The requirement for the statistical testing was a safety factor of ten leading to a minimum required number of cycles of 20 000.

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.

The smaller samples were cut out across the welds from the full scale fabricated pipes. Hence, thickness and welding properties were correctly represented. These tests were therefore representative for the actual production quality and production control standards at the steel mill.

The tests demonstrated fulfilment of the CNG rule requirements with ample margins. No trace of brittle behaviour could be seen - the material behaviour proved ductile, [13], [14].

3.4 (b) Live Gas Cool-down Testing

Prior to the gas leak testing Europipe prepared the X-80 test cylinder with a semi elliptical through thickness fatigue crack with a crack length close to the estimated critical length (150 mm at the outside), [15]. The crack was positioned in the base material as close as practically possible to the long seam and was made by notch grinding, spark erosion and hydraulic fatigue cycling.

Figure 16: Test arrangement

The gas leakage test was carried out in full scale with live gas at the Advantica Spadeadam test site in Cumbria in Great Britain. Figure 16 shows the arrangement at the test site. The end-capped cargo test cylinder (vessel) was positioned horizontally and was supported and secured on a concrete pad. A second cylinder section from the same pipe used for the vessel was placed horizontally in front of the test vessel in line at a distance of 300 mm to the vessel to represent the cylinder spacing onboard a PNG® carrier.

This pipe section had one temperature gauge on the inner surface directly in line with the centre of the release from the test vessel. This instrument was aimed at providing information on the cool-down effect of the adjacent vessels in case of a direct gas impingement.

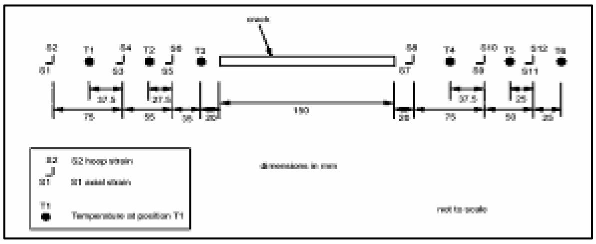

Figure 17: Positioning of temperature and strain measurements on the vessel

To be able to pressurize the vessel without prematurely cooling the pipe wall the crack was sealed by a rubber padded steel bar pressed to the crack by a hydraulic cylinder which could be released by remote control.

Temperature gauges were fixed on the outside surface of the cargo containment cylinder close to the crack at six locations shown schematically in Figure 17.

The strain on the vessel wall close to the crack was measured at six locations in longitudinal and transverse direction. The pressure in the vessel was measured with a gauge placed directly at the gas inlet into the vessel. The test vessel was pressurized with natural gas (96% Methane/4% Ethane) to a pressure level of 250 barg. Some leakage was experienced from 140 to 250 bars at the tips of the seal. In order to place the thermocouples as close to the crack tip as possible not enough rubber material was present to seal the crack completely. The pump rate had therefore to be increased to reach the target pressure of 250 barg. Due to this mishap the gas flow from the leakage passed thermocouple T3 and the temperature in the gas jet could be measured.

After reaching 250 bar the sealing mechanism was released to allow the gas to escape while monitoring temperature and strain response. The pressure level of 250 bars was maintained by pumping for 15 minutes during free gas flow through the crack. Then the pumping was stopped and the pressure in the vessel dropped to a pressure of approximately 180 bars over a period of about 30 minutes. After this the vessel was vented through the pipework. *During the test the crack was stable and no indication of fatigue crack growth could be seen.*

Prior to the testing DNV had calculated the temperature profile through the leaking crack [15]. By comparing the test results with the theoretical predictions the following could be observed:

- The lowest gas temperature predicted at the crack exit was -70 °C and the lowest gas temperature measured was -68 °C.
- At a distance of 20 mm from the crack an outside temperature of -24 °C was measured. The predicted temperature at the same location was ~ -30 °C.
- At a distance 120 mm from the crack an outside temperature of -0 °C was measured. The predicted temperature at the same location was ~ -5 °C.
- The temperature at the inside of the adjacent pipe was measured to -16°C. The predicted temperature was ~ -10 °C.

After testing the crack surfaces were examined in an electron microscope and no indication of crack growth could be seen. This means that leak-before–failure had been demonstrated. This is a very important result that enhances the safety of the system and simplifies the in-service monitoring arrangement. The test also showed that gas impingement onto a neighbouring cylinder will not be critical.

4. THE WAY AHEAD

As outlined previously the future will see increased demand for gas carriers able to operate under more severe environmental conditions - cross Atlantic trading and operation in cold climates. Due to the trend towards offshore storage and discharge gas carriers able to operate with reduced tank filling levels is, and will be, in demand.

In general most independent tank systems can be designed to operate at any tank filling for any fraction of their design lifetime, whereas membrane carriers normally will have to operate inside a carefully determined site specific operational envelope of significant wave heights and heading angles.

In order to participate in the transportation of natural gas out of the vast gas fields in the Russian arctic the carriers have to be able to operate under extreme cold and darkness, with icing from sea spray and fog and under adverse ice load conditions. This requires carriers specifically adapted to the intended trade and with hull constructions providing adequate protection of the containment systems, the people onboard as well as the environment.

For membrane type carriers more work will be needed on part loaded and low filling operations, sloshing loads and strengthening of the containment system. Full scale sloshing load and response measurements need to be carried out to better understand the load scaling issue in order to move into an absolute sloshing assessment methodology.

To meet these challenges, the future may see a renewed competition between independent tank systems and membrane tank systems.

On the CNG carrier side the systems closest to realization appear to be the steel tank systems and composite wrapped steel tank design. Pure composite based CNG designs are under development and depending of costs the future may see more CNG composite solutions.

5. CONCLUSIONS

The paper describes the work carried out in DNV to meet the challenges from the expanding gas transport market, emphasising sloshing loads and tank system strength for normal tank fillings as well as reduced tank filling operations of membrane LNG carriers.

An overview of the LNG R&D efforts related to membrane carriers is given outlining the work on sloshing loads, system response and strength and full scale measurements/verification. These are important milestones in developing a sloshing analysis guideline. The first version was issued in June 2006 [3].

Work on the further development of Computational Fluid Dynamics (CFD) tool for liquid motion analysis and two phase analysis capabilities is ongoing, both testing and programme development. However, due to the shortcomings in the present CFD analysis tools DNV has concluded that for the time being sloshing load determination has to be based on model testing.

This makes a proper understanding of model test scaling laws vitally important, and a full scale test campaign is set up aiming to get better insight into these matters. Model testing in different model scales (1:70 and 1:20) indicates that quite different results are obtained depending on test conditions, e.g. ullage gas Froude scaling gives considerably higher pressures than gas density scaling.

An example is shown highlighting that the 3 hour expected extreme sloshing load which is usually determined from sloshing model tests is not representative for the long term expected extreme for high filling, >90%H, but may possibly be so for lower filling levels.

Due to the hydraulic jump effects sloshing loads at low filling ballast operation (10%L) may in some cases be larger than the reference case high filling loads (95%H). This may need special consideration either in terms of reduced filling height and/or strengthening of the containment system in the lower parts of the tanks.

Work with the aim of developing a methodology for capacity assessment of membrane containment systems has been carried out and is implemented into the new sloshing guideline [3].

Some of the background for, and the basic principles behind, the sloshing guideline are described. Due to uncertainties in the sloshing impact load assessment a *comparative approach* is used for assessing the strength of the containment system and the supporting hull structure. However, for the pump tower structure an absolute approach may be used.

The emerging Compressed Natural Gas (CNG) technology offers interesting possibilities for handling of associated gas and for exploitation of marginal gas fields (stranded gas). Examples of CNG designs are shown; both steel based and composite solutions. Compared to pipeline and LNG transport, an example of transportation costs for the Knutsen PNG® system indicates that CNG can come in as an interesting supplement in the transport range from 500 – 2500/3000 nautical miles.

In order to provide a common basis of design criteria for CNG, DNV, ABS and BV are working on rule harmonization together with the Centre for Marine CNG at St. John's, Newfoundland.

Full scale prototype verification tests of CNG containment cylinders have been done/are underway for several of the CNG systems. For the PNG® design successful tests at ambient temperature have been reported in ref. [13] and [14]. Further, a full scale leakage test with live gas has been carried out at the Advantica Spadeadam test site in Cumbria in Great Britain [15]. The outcome of the test was that even when exposed to the cooling effect of the leaking gas (down to -70 °C) the crack was stable and no indication of crack growth could be seen. The test also showed that gas impingement onto a neighbouring cylinder was not critical.

6. ACKNOWLEDGEMENTS

The work on LNG development presented in the present paper is the joint efforts of the DNV LNG R&D team. Valuable input and comments have been given by Jens Bloch Helmers, Øyvind Lund-Johansen and Thor Hysing. Thanks also go to our previous DNV collegues Trym Tveitnes and Wouter Pastoor.

On the CNG part thanks go to Kim Mørk, Erling Fredriksen, Morten Lerø, Kjell Olav Halsen and Lars Even Torbergsen.

7. REFERENCES

1. Energy Information Administration (EIA): "International Energy Outlook 2005"
2. Det Norske Veritas: "Liquefied Gas Carriers ", *Rules for Classification of Ships Pt 5 Ch 5*, July 2005
3. Det Norske Veritas: "Sloshing Analysis of LNG Membrane Tanks", *Classification Note 30.9*, June 2006
4. Kleefsman, K.M.T, Fekken, G., Veldman, A.E.P., Iwanowski, B. and Buchner, B.: "A Volume-of-Fluid based simulation method for wave impact problems", *J. Comp. Phys.* (2005) **206** 363-393.
5. Berg, A.: "Scaling Laws and Statistical Distributions of Impact Pressures in Liquid Sloshing", *A.S Veritas Research, Report no. 87-2008*, (1987).

6. Pastoor, W., Tveitnes, T., Valsgård, S. and Sele, H. O.: "Sloshing in Partially filled LNG Tanks – an Experimental Survey", *OTC 16581*, May 2004

7. Pastoor, W., Østvold, T. K., Byklum, E. and Valsgård, S.: "Sloshing Load and Response in LNG Carriers for New Designs, New Operations and New Trades", *GasTech 2005, Bilbao, Spain*, March 14-17, 2005

8. Det Norske Veritas: "Compressed Natural Gas Carriers", *Rules for Classification of ships Pt.5 Ch.15, January 2006*

9. Det Norske Veritas: *"Offshore Standard – Submarine pipeline Systems", DNV-OS- F101*, January 2000

10. International Maritime Organisation (IMO): "International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk - IGC Code", 1993 Edition

11. International Maritime Organisation (IMO): "Formal Safety Assessment. Decision parameters including Risk Acceptance Criteria", *Maritime Safety Committee, MSC 72/16*, 14 February 2000 (Submitted by Norway).
12. International Maritime Organization (IMO): "Guidelines for Formal Safety Assessment (FSA) for use in the Rule-Making Process", *MSC/Circ.1023, MEPC/Circ.392, 5* April 2002

13. Valsgård, S., Reepmeyer, O., Lothe, P., Strøm, N.K. and Mørk, K.: "The Development of a Compressed Natural Gas Carrier", *The 9th International Symposium on Practical Design of Ships and other Floating Structures (PRADS 2004), Lübeck-Travemünde, Germany*, September 12-17, 2004

14. Valsgård, S., Mørk, K.J., Lothe, P. and Strøm, N.K.: "Compressed Natural Gas Carrier Development – The Knutsen PNG Concept", *SNAME Annual Meeting, Washington DC,* September 29th - October 2nd , 2004

15. Reepmeyer, O., Lothe, P, Valsgård, S., Erdelen-Peppler, M. and Knauf, G.: " Full Scale Gas leak Test at a Large Diameter X-80 DSAW Pipe", *Proceedings of IPC 2006, 6th International Pipeline Conference, Calgary, Canada,* September 25-29, 2006.

8. AUTHORS' BIOGRAPHIES

Sverre Valsgård, Ph.D., is a Senior Principal Engineer and focus responsible for gas carrier development on the maritime side of Det Norske Veritas. He has more than 30 years experience from DNV on R&D and consultancy on ships including gas carriers and offshore structures as well as from management positions.

Tom Klungseth Østvold, M.Sc., is a Senior engineer at Det Norske Veritas. He is mainly working on development projects to improve calculation procedures and acceptance criteria for ultimate strength assessment of (ship) structures. Currently he is working as task leader on strength assessment of LNG cargo containment systems and tank structures exposed to sloshing impact loads. Other activities include strength assessment consultancy studies on behalf of clients and DNV Classification.

Olav Rognebakke, Ph.D. is a Senior Engineer in Det Norske Veritas. He has five years of working experience from Marintek and DNV with focus on R&D activities and commercial model tests. Main competence areas are hydrodynamic theory, experimental techniques, analysis methods and seakeeping issues relevant for sloshing in membrane type containment systems for transportation of Liquified Natural Gas (LNG).

Eirik Byklum, Ph.D., is a Senior engineer at Det Norske Veritas. He is mainly working with development of procedures and calculation tools for ultimate strength assessment of marine structures. Currently he is working on strength assessment of LNG cargo containment systems and tank structures exposed to sloshing impact loads. He is also involved in strength assessment consultancy studies on behalf of clients and DNV Classification.

Hans O. Sele, M.Sc., is a Project Engineer in Det Norske Veritas. He has 5 years experience from DNV on hydrodynamics and structural analyses and R&D on LNG sloshing.