Guidance on the Operation of Membrane LNG Ships to Reduce the Risk of Damage due to Sloshing

Lloyd’s Register

January 2012
The front cover shows the membrane LNG ship Excelsior at the Teesside GasPort, north east England. Equipment type approval and operational risk analysis and simulation studies were performed by Lloyd’s Register.
Section 1. Purpose of this Guidance Document

This document offers practical guidance to Masters of Lloyd’s Register classed membrane tank LNG ships on minimising the risk of sloshing damage. As it includes consideration of cargo tank filling levels, it will also be of interest to Owners, Operators and Charterers planning cargo movements and to LNG Terminal management in cases where emergency departure of a partly loaded ship is being considered.

Background is provided on the design of membrane tank LNG ships in relation to sloshing. In addition, shipboard arrangements are described which may help to prevent a ship getting into situations where sloshing could pose a risk to the ship.

Section 2. Introduction

2.1 The Nature of Sloshing

The term sloshing describes the motion of a liquid inside a tank as a consequence of a ship moving (rolling, pitching, etc) in a seaway. Except when a tank is full, sloshing waves can be generated which impact against the tank boundaries.

Sloshing is a “stochastic” phenomenon which means that sloshing impacts cannot be predicted with certainty and the impact magnitudes for apparently similar sloshing motions can vary quite widely.

However, the factors influencing the severity of sloshing response are well known and these include:
- tank shape, size and local surface geometry
- tank filling levels
- loading condition of the ship
- sea conditions
- seakeeping characteristics of the ship.

The first and second factors are considered in the design of the ship and in the setting of filling limits, see Section 2.3. The severity of sloshing response is affected by the remaining
factors above which concern the operation of the ship. These are discussed in Sections 3 and 4.

Sloshing impacts can induce very high peak pressures concentrated over a small area (of the order of cm²) as well as high average pressures spread over a larger area, of the order a 1m² or more. Hence the local detail arrangements, the more general structural arrangements at or near the surface of the cargo in the tank, and the inner hull strength all need to be considered in the design for resistance against sloshing.

### 2.2 Sloshing Incidents

A review of historical occurrences of sloshing is valuable to augment and calibrate theoretical/experimental evaluation and has provided the impetus for design changes in the past.

There have been a few instances of sloshing damage on ships with early versions of the Gaz Transport NO containment systems (late 1970’s) and one recent case in 2006 on a modern NO 96 ship. The 1970’s incidents involved damage to the primary insulation boxes in the upper regions of the cargo tanks. This led to:

1) the incorporation of reinforced insulation boxes in the upper regions of all more recent NO type ships  
2) the standardisation of the size and shape of the cargo tanks including their characteristic chamfered topside shape in the upper region and hopper shape in the lower region, see Figure 2.

The 2006 damage was discovered on the covers of standard primary insulation boxes on a conventional size NO 96 ship on the side of the tank just above the upper knuckle of the lower hopper. In this case, the tank filling was at a height equal to approximately 10% of the tank length and the damage was caused by sloshing waves impacting against the tank vertical sides (inner longitudinal bulkheads) a few metres above the filling level, see Figure 3.

The single plywood covers of the standard NO 96 primary boxes were found to have bending and shear failures due to sloshing impacts. The primary membrane was intact although deformed and as a consequence there was no cargo leakage through the primary barrier and minimal risk of leakage developing in the short term.
No sloshing damage has ever been reported on ships fitted with the early Mk I version Technigaz containment system, however from 2008 many Mk III ships have been found to have deformed primary barrier corrugations in the following areas:

- on the tank vertical sides above the upper knuckle of the lower hopper (the same region as described above for the NO 96 box damage) and on the transverse bulkheads near to the upper knuckle of the lower hopper
- in the four corners (port forward, starboard forward, port aft and starboard aft) of the tank crown and in the corners on the other adjacent tank surfaces

The locations of the observed deformations are shown in Figure 3.

The extent and severity of the deformations in the lower part of the tanks on the vertical sides above the upper knuckle of the lower hopper, and on the transverse bulkheads close to the intersection with the lower hopper and vertical side, approximately correlates with the maximum amount of LNG heel carried. The deformations on the transverse bulkheads have been associated with a tank filling approaching 10% of the tank length.

The deformations in the four corners of the tank crown are associated with normal full loading and the slight reduction in fill levels due to boil-off during the voyage. The deformations have been found to be more pronounced in the forward and aft cargo tanks in many cases.

For the Mk III system, the cargo containment system foam panels including plywood, secondary barrier and mastic beneath the deformed parts of the primary membrane have been inspected and so far no damages to these parts have been observed, except for a single instance of foam crushing in way of a severely deformed corrugation. The primary membrane has in all cases been intact, although deformed, and as a consequence there was considered to be negligible risk of cargo leakage in the short term.

The overall theoretical sloshing capacity of the Mk containment systems is of the same order as the NO systems, noting that there are variants to both (NO 96 is available in standard, reinforced, super and ultra strength versions; Mk III is available in standard and strengthened versions involving reinforcement of the corrugations). Therefore, similar precautions to both the design of the tanks and the operation of the ships need to be taken to avoid sloshing damage. See 2.4 for the distinction between superficial deformation due to sloshing, and sloshing damage.
2.3 Tank Design and Barred Fill Ranges

Sloshing is generally most violent when the natural period of the liquid in the tank is fairly close to a ship motion period (usually roll or pitch). When the sea conditions are such that there is significant wave energy near one of these periods, i.e. waves of a similar encounter period (referred to as resonant wave conditions later in this guidance), then significant liquid motion is possible which can lead to high sloshing impact loads.

For high fill levels the decreased free surface area inherent in the chamfered topside arrangement reduces the natural period of the free surface of the LNG cargo to a value which is significantly less than the ship motion rolling period in most sea conditions. This shape is also beneficial in altering the characteristic of the sloshing motion and in reducing the impact loads.

For low fill levels the lower hopper arrangement provides a similar shape benefit. For low fill levels the LNG natural period is generally greater than typical ship motion rolling period.

At mid fill heights the ship and LNG natural periods may be close to each other, in addition there is the greatest tank width available for sloshing waves to build up momentum. As a result highest sloshing impact loads are expected at mid fill heights and hence mid fill heights are not permitted for most standard designed membrane LNG ships.

Based on experience and analysis, the minimum high filling level and the maximum low filling level have been set. In the most recent LNG ships of conventional size (up to 155,000m³ capacity) filling is permitted only as follows:

- 70%H and above for higher filling levels (H is the internal tank height), see Figure 4
- 10%H (which is approximately 2.75 metres, which is how this limit is described for Mk III ships) and below for lower filling levels/heels

Hence the usual barred fill range is from 10%H to 70%H.

The 10%H (2.75 metres) lower filling level arises from investigations which have been carried out following the recent experiences described in 2.2, and is a reduction from 10%LT (where LT is the internal tank length) which was the original permitted filling level.
Some older ships were designed with an upper filling limit of 80%H. Recent ships of greater than 155,000m³ have had permitted fill levels defined on a case-by-case basis. Reference should be made to the ship’s approved Loading Manual or Cargo Operations Manual for the applicable values for a specific ship.

It is emphasised that these are not cut-off values at which sloshing activity becomes negligible. Significant sloshing may still occur:

- in severe or moderate seastates if fill levels are close to the permitted limits and
- the ship speed and heading result in resonant ship rolling.

However the severity of sloshing which occurs on ships operating inside the presently permitted filling levels is considered unlikely to cause damage, see also 2.4.

Operating within the barred fill range is not normally permitted, however exceptional circumstances may arise in which doing so is the most appropriate way of avoiding a potentially more hazardous situation, see Section 5.

2.4 Containment System Deformation and Damage

From extensive investigations involving detailed structural analysis and testing of the Mk III primary barrier, it has been shown that deformations of the Mk III primary membrane corrugations up to certain values will not impair the efficiency of the primary membrane in containing the LNG, nor affect its long term performance. Deformation up to a defined criteria arising out of these investigations is regarded as "superficial" and does not require repair.

For the NO systems primary barrier, moderate bending of the raised edges is similarly regarded as superficial, not requiring repair, provided that the welding remains sound.

However, any deformation of the Mk III primary barrier which exceeds the defined criteria, or any failure of the insulation system supporting the primary barriers (insulation panels on Mk systems, or insulation boxes on NO systems) is regarded as damage, and requires repair. See 7.2 for inspection for sloshing damage and deformation.

2.5 Difficulties in Detecting when Sloshing is Occurring and if Tanks have been Damaged

Sloshing is different from some other potentially damaging phenomena such as slamming at the fore end, because there may be no obvious feedback that sloshing is occurring. Severe sloshing may be audible from nearby outside the tanks, but it can be difficult to hear from the bridge and accommodation areas, unless it occurs in the adjacent tank.

Some measure of sloshing activity may be obtained from monitoring boil-off rates which can increase measurably during periods of severe sloshing, although this does
not provide sufficient real-time correlation to be a useful indicator of the occurrence of potentially damaging sloshing impacts.

As stated in 2.2, in the 2006 case of sloshing damage on the NO 96 ship, the primary barrier was not breached even though the primary box covers beneath were damaged. Similarly with the recent deformations on the Mk III ships there has been no failure of the primary barrier. Consequently there has been no indication to the ship’s crew that sloshing deformation has occurred and nothing was found until the next planned entry into the cargo tanks. Therefore, the absence of any increased gas concentration in the inert gas monitoring system can not be relied on as an indicator that the tank is undamaged.

Section 3. The Relationship between Filling Levels and Sloshing

3.1 Typical Operating Practice – Normal Filling Levels

In most circumstances, LNG ships deliver close to the maximum quantity of cargo for which they have been designed to carry and, even allowing for boil-off over a typical loaded voyage, this equates to approximately 95%H full or greater. On the return ballast voyage, LNG ships normally carry a heel of cargo not exceeding approximately 5%H, see Figure 4.

Many thousands of voyages have been made by ships loaded in this way in all sea conditions, and this service experience confirms that the risk of sloshing damage is minimised for membrane tanks filled in this way.

3.2 Evaluation of Sloshing at Different Filling Levels

The prediction of accurate sloshing pressures inside LNG tanks is very complex and model testing continues to be the best practice for evaluating sloshing pressures at the design stage, see Figure 1. This is despite having some limitations which include the impracticality of representing the local surface profile of the primary barriers (corrugations in Mk III, raised edges in NO 96) which are also believed to influence flow and create pressure concentrations.

Model tests have been supplemented by the analysis of in-service Mk III deformations and NO 96 box damages to evaluate the sloshing pressures which have been experienced in service using reverse engineering techniques. In addition, one NO 96 ship has been instrumented in the upper regions of one of its cargo tanks as part of a joint industry project involving LR, GTT and others, and the results of this full scale measurement campaign are assisting in calibrating the sloshing pressures seen in practice.

Figure 5 gives an indicative assessment of the effect of fill height on the sloshing pressure.
3.3 Lower than Normal High Fill Levels during Loaded Voyages

The predominant form of sloshing activity in the upper regions of the tanks results in localised direct LNG impacts or high velocity jets of LNG travelling rapidly over the tank surface causing very high localised pressures.

Model testing programmes have shown that sloshing pressures at fill heights around 95%H can be as high as at slightly lower fill heights, see Figure 5. It should be noted that one of the early incidents of sloshing damage occurred at a fill height of 95.5%H, although the strength of the insulation boxes in the upper region of that ship was lower than the strength of boxes fitted nowadays and the upper region of the tank was of a different shape.

Most of the recent Mk III tank crown deformations are believed to have occurred at fill heights of around 95%.

It should be noted that there have been no reports of damage to NO 96 ships associated with high fill heights, one possible reason for this being that reinforced boxes are normally fitted in these parts instead of standard boxes.

Loaded voyages with the tanks filled less than around 95%H are rare. Filling below 95%H and above 70%H may slightly increase the risk as the sloshing pressures are predicted to be greater again towards 70%H, however the increase in risk is considered low, especially if the ship operation measures described in 4.2 are followed.

3.4 Higher than Normal Low Fill Levels (Heels) during Ballast Voyages

The trend in the low fill range is for sloshing pressures to increase with fill height, see Figure 5. Up to a filling level of approximately 5%H the sloshing pressures are low and it is considered that the risk of sloshing damage on both NO 96 and Mk III is correspondingly very small, and that there will be few if any superficial deformations on Mk III. The pressures increase markedly above a fill height of approximately half the height of the lower hopper and are more significant at the upper limit of the lower filling level permitted for the ship depending on the seastate, ship heading and ship speed.
Section 4. Ship Operation

4.1 General

If any of the cargo tanks are filled outside the normal operational zones, i.e. above about 5%H on ballast voyages and below about 95%H on loaded voyages, the ship’s Master should be prepared to take action to avoid the type of ship motions which could give rise to more severe sloshing loads. In making changes to course and/or speed, it is considered that a change of course is likely to have more effect and probably should be made as the first action. Altering speed should then be considered if the change of course alone does not have sufficient effect in reducing potentially damaging regular rolling or pitching ship motions. This information is summarised in Appendix A.

4.2 Ship Motions to Avoid when Carrying Lower than Normal High Fill levels during Loaded Voyages

The aim should be to avoid regular rolling, especially when this is combined with regular pitching. This is particularly applicable for fill levels near and below 95%H. If this occurs, then the Master should consider changes of course and/or speed to minimise these motions.

4.3 Ship Motions to Avoid when Carrying Higher than Normal Heels during Ballast Voyages

Design evaluations, investigations and experience all indicate that the containment system is most at risk from rolling motion, particularly regular large roll angles in beam seas. If these conditions occur, changes of course and/or speed should be taken by the Master to reduce the large roll angles and the regularity of the roll motion.

A study has been undertaken for a typical conventional sized ship to investigate the combinations of heading, ship speed and wave period which may result in enhanced sloshing activity for a range of filling heights around the permitted limit and within the barred fill range, see Appendix B.

Section 5. Occasions when the Ship is Forced to Leave a Terminal when Tanks are Loaded outside the Permitted Fill Ranges

5.1 General

There may be instances when the ship is forced to leave a terminal before the planned cargo operations have been completed. For example, if an emergency condition occurs on the ship or in the terminal at a stage where the tanks are loaded outside the permitted fill ranges. In this case, it is most important to take suitable action to protect the cargo tanks from the risk of sloshing damage.
Unless there is a sheltered anchorage in the vicinity which can be reached via sheltered waters (see 6.1 for definition of sheltered), it is recommended that these scenarios should be assessed in advance by means of a Risk Assessment. The Risk Assessment needs to be specific for each combination of ship design and terminal and may include consideration of the actions described in 5.2 and 5.3. The Risk Assessment can be undertaken by Lloyd’s Register or by competent consultants.

The Emergency Plan arising from the Risk Assessment study may include changing the loading/discharge pattern to limit the number of partially filled tanks when severe weather conditions are forecast and recommendations on the route to the anchorage depending on the current and forecast weather conditions. It may also contain sloshing risk diagrams similar to those in Appendix B.

Lloyd’s Register’s advice must be sought on the acceptability of the proposed deviation from the approved filling limits. If the Emergency Plan involves the ship operating outside of its approved filling and strength limits, then Lloyd’s Register should be consulted.

The Emergency Plan should be included in, or referenced by, the ship’s Safety Management System. All the ship’s staff should be made aware of the actions to be taken by carrying out drills or similar training methods.

5.2 Actions prior to the Unplanned Departure

In the event of an unplanned departure from a terminal, any time remaining whilst the ship is still alongside should be used to redistribute the LNG between the cargo tanks to avoid any of the tanks being filled within the barred fill range.

If there is insufficient time to achieve this, or the amount of LNG on board is not commensurate with such a re-distribution, filling levels in the barred fill range may be contemplated provided that the likelihood of the ship being exposed to poor weather conditions or resonant wave conditions is minimised, as described in the first paragraph of 2.3 and Section 4. For conventional LNG ships, fill heights between 15%H and 40%H are to be avoided. There is evidence to suggest that there may be less risk at fill heights in the range of 60%H to 70%H than at other fill heights within the barred fill range.

5.3 Actions after Unplanned Departure

Following departure, the ship should be operated with a view to avoiding potentially damaging ship motions, see Section 4.

After the situation has stabilised, it is preferable that the ship returns to the same terminal to complete the loading/unloading operation to achieve normal filling levels.
before departing on the next voyage, rather than proceeding on the next voyage with unusual fill heights.

If this is not possible, the ship may proceed to the next available terminal if the LNG can be distributed between the cargo tanks within the permitted fill ranges and providing the ship is operated as described in Sections 3 and 4.

If, for any reason, the only available course of action is to proceed to another terminal with cargo loaded in the barred fill range, Lloyd’s Register’s advice must be sought before sailing.

Section 6. Terminals in Exposed Locations and Floating LNG Terminals

6.1 General

A location may generally be considered as being “sheltered” if the extreme significant wave heights (based on a 25 year return period) for the location are less than 2 metres, though it should be noted that even 2 metre seastates can cause significant sloshing if they induce resonant wave conditions, see 2.3. An example of a sheltered terminal is shown in Figure 6.

Locations which are not sheltered should be considered as “exposed”.

Exposed terminals include those at the end of extended jetties and floating LNG terminals unless they are sited in sheltered locations such as protected estuaries.

It is expected that all terminals will have anchorages nearby which can be used in case there is some incident at the terminal or on the ship. Sheltered terminals with sheltered anchorages which can be reached via sheltered waters are considered as “safe havens” for the purposes of this document.

6.2 Operation at exposed terminals

Operation at exposed terminals will result in the LNG fill level being taken through the barred fill range during the alongside loading or unloading operations which may result in severe sloshing if the seastate is sufficiently adverse.

As a consequence it is necessary to assess the sloshing pressures which will occur for the full range of sea conditions applicable to the terminal location and for all fill heights
in the barred fill range. This sloshing assessment is to be conducted to the satisfaction of Lloyd’s Register. The purpose of this study is to assess whether the barred fill range can be eliminated or reduced for this terminal.

In the event that the barred fill range can be eliminated, then the ability of the ship to be loaded/unloaded at the exposed LNG terminal will be recognised in the approved Loading Manual by means of a statement such as:

“The permissible filling levels for operation at sea are less than 10% of the tank height or greater than 70% of the tank height. There is no restriction on the filling level when operating at the exposed terminal at XYZ.”

If it is found that the seagoing barred fill range can only be reduced (not eliminated), then it will be necessary to establish a practical window of operation and further studies may be necessary to refine the combinations of fill levels and significant wave heights which will avoid sloshing problems at the terminal.

In this case, this would be recognised in the Loading Manual by a statement such as:

“The permissible filling levels for operation at sea are less than 10% of the tank height or greater than 70% of the tank height. There is no restriction on the filling level when operating at the exposed terminal at XYZ provided that the significant wave height is less than 3m”

or

“The permissible filling levels for operation at sea are less than 10% of the tank height or greater than 70% of the tank height. There is a restriction on the filling level which is dependent on the wave height when operating at the exposed terminal at XYZ in accordance with the following table” (and a table similar to Table 1 below would be included.)

<table>
<thead>
<tr>
<th>Fill level</th>
<th>Maximum allowable significant wave height</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%H</td>
<td>No limit</td>
<td></td>
</tr>
<tr>
<td>70%H</td>
<td>No limit</td>
<td></td>
</tr>
<tr>
<td>60%H</td>
<td>4m</td>
<td></td>
</tr>
<tr>
<td>50%H</td>
<td>3m</td>
<td></td>
</tr>
<tr>
<td>40%H</td>
<td>2m</td>
<td>Mean hourly wind speed of 30 knots</td>
</tr>
<tr>
<td>30%H</td>
<td>1m</td>
<td>Mean hourly wind speed of 20 knots</td>
</tr>
<tr>
<td>20%H</td>
<td>1m</td>
<td>Mean hourly wind speed of 20 knots</td>
</tr>
<tr>
<td>15%H</td>
<td>2m</td>
<td>Mean hourly wind speed of 30 knots</td>
</tr>
<tr>
<td>10%H</td>
<td>No limit</td>
<td></td>
</tr>
</tbody>
</table>
In the event that cargo operations are dependent on stated maximum sea conditions, the provisions for ensuring that these are not exceeded should also be included in the Cargo Operations Manual, and it is the owner’s responsibility to ensure that these are not exceeded.

It is an assumption inherent in classification that a ship will be traded to terminals which can be regarded as safe havens. It is necessary to consult Lloyd’s Register in advance of trading to fixed or floating LNG terminals which are not regarded as safe havens in order to obtain approval for operation at the specified exposed fixed or floating LNG terminal. Specific approval for operation at each terminal needs to be obtained for classification purposes.

6.3 Operation at terminals which are not considered as safe havens

Whilst the terminal may be in a sheltered location, the anchorage may not be sheltered or the route to the anchorage may not be sheltered, see 5.1. The recommended Risk Assessment, see 5.1, should include an assessment of sloshing taking into account the appropriate environmental conditions and hence propose acceptable filling levels and other control measures for the emergency departure from the terminal to the anchorage.

Section 7. Survey for Sloshing Damage and Deformation

7.1 Situations Indicative of Possible Sloshing Damage.

If increased gas concentrations in the interbarrier space are recorded following a period of sailing in moderate or severe weather, especially if the fill levels at that time were outside the normal filling levels, see 3.1, one possible reason might be sloshing damage and precautionary checks should be carried out at the earliest opportunity.

If the ship has had to sail with the cargo tanks outside the permissible filling levels, for instance if it has been asked to leave the terminal prematurely as mentioned in Section 5, or has exceeded the conditions allowed for at an exposed terminal as described in Section 6, then sloshing damage should be considered as a possibility. In this event, a tank inspection should be undertaken at the next available opportunity, even if there is no detectable increase in gas concentrations in the interbarrier space.

It is recommended that a record is maintained in the Ship’s Log or similar document of voyages during which moderate or severe weather is encountered when the ship is sailing with cargo levels outside the normal filling levels, see Figure 4.
7.2 Inspection for Sloshing Damage and Deformation.

Major sloshing damage should be obvious on entry to the cargo tank under the vacuum conditions applied to the insulation spaces according to standard procedures, including Lloyd’s Register’s Periodical Survey Regulations. Closer inspection under these conditions may reveal less obvious damages such as:

- **NO (Gaz Transport) Systems:**
  Any sign of the membrane being locally “set in” is indicative of insulation box damage beneath. As the spacing between internal partitions inside the primary boxes is typically 125mm in the horizontal direction on transverse bulkheads and in the fore/aft direction for all other tank boundaries, damages to the box top panels may occur in a pattern with this same spacing, see Figure 7. Any indenting of greater than around 1mm is evidence of sloshing damage.

  Any bending of the invar raised edges may indicate that significant sloshing pressures have occurred. However, Lloyd's Register might considered such bending as superficial, not as a damage requiring repair, provided that the welding remains sound.

  **All such damage indications are to be reported to Lloyd's Register and Lloyd's Register’s advice sought.**

- **Mk (Technigaz) Systems:**
  The corrugations in the primary barrier are susceptible to deformation under high sloshing pressures, see Figure 8, therefore inspection for this form of damage needs to be carried out. Methods for carrying out this inspection (visual inspection, photography/photometry, gauging and laser scanning) are described in detail in a procedure available from GTT, which (at the time of writing) deals with standard corrugations. Requirements for inspection of reinforced or wedged corrugations are not currently included as no deformations of these have been observed.

  As described in 2.4, investigations into Mk III corrugation deformations have shown that there is no loss of performance (safety or longevity) of the primary barrier up to the large deformation values which were tested, provided the membrane and especially the “knots” (at the intersections of the corrugations) remain fully supported by the insulation system.
However, it has been found that the insulation beneath may be damaged (crushed or cracked) at pressures significantly lower than those which would damage the primary barrier. Because the magnitude of the deformations is an indication of the sloshing pressure which has been experienced, it can be used to predict if the insulation beneath may have been overloaded locally.

Consequently two sets of acceptance criteria have been defined and included in the procedure available from GTT. The lower set specifies deformations which can be accepted provided there is no damage to the insulation beneath. The higher set specifies the deformation level at which the primary barrier needs to be replaced irrespective of the condition of the insulation foam and secondary barrier underneath. Whenever the primary barrier is removed for this reason the condition of the insulation panel should be thoroughly inspected and recorded, and replaced as necessary.

Damage should be considered to have occurred only when the higher set of deformation criteria have been exceeded or when the insulation beneath has been found to be damaged. Otherwise the deformations may be allowed to remain in the cargo tanks without repair and should be regarded as superficial, see also 2.4.

At the time of writing, procedures are being developed to detect whether there is damage to the insulation beneath without removal of the primary barrier.

Investigations have shown that other forms of damage, such as failure of the “back plywood” between the insulation and the inner hull, would normally occur only at greater pressures than would cause failure of the insulation in way.

It is important to record the state of the primary membrane each time the tank is entered. This should be done using photographic and/or laser measurement records, as well as tabulated data of any deformations that have been observed, in accordance with the GTT procedure. Such records should be kept with the other ship (maintenance) records.

• **Pump Tower:**
  Although it is outside the main scope of this Guidance document, the pump tower is also subjected to sloshing loads and should be examined whenever a tank is entered. Particular attention should be given to the strut connection welds and the securing and fastening arrangements of the cargo pumps, instrumentation sensors and cable trays. The lower guide system, which allows for the contraction of the pump tower, should also be closely examined.

  If any components of the pump tower, such as small nuts, become detached then local indenting may be caused to the primary barrier in the lower regions of the tank. If local indenting is observed then any loose items should be found and refitted to the Lloyd's Register's satisfaction and the membrane repaired in accordance with the repair procedures.
7.3 **Inner Hull Failure under Sloshing Pressures.**

Despite no known occurrences, structural damage to the inner hull is a possibility, either in combination with failure of the containment system or in its absence. If the primary barrier is observed to be indented or raised over a large area, then deformation of the inner hull may have occurred and needs to be investigated.

Leakage of water into the secondary barrier space will indicate cracks in the inner hull which may have been caused by sloshing pressures or by structural loads not associated with sloshing. Loss or gain of pressure in the secondary barrier space may indicate cracks in the inner hull. This should be investigated by entering the adjacent ship spaces and checking the steelwork for cracks or deformations.

7.4 **Reporting Suspected Sloshing Damage**

Any evidence of sloshing damage of any kind must be reported immediately to Lloyd’s Register in order to obtain advice on further investigation and repair.

(The distinction between superficial deformations on the Mk III primary barrier which can be tolerated and damage, as referred to here, is described in 2.4 and the guidance in 7.2 should be noted.)

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**Section 8. Designing the Ship to Avoid Sloshing Problems**

8.1 **Extending Areas of Reinforced Containment System**

If an Owner’s intention is to carry LNG near to or outside the standard permitted fill ranges, this should be stated in the Building Specification. It may be possible to reduce or perhaps even eliminate the normal barred fill range by applying the strengthened versions of the containment systems in the areas of the tank which would experience greater sloshing pressures as a result of the change in the barred fill range.

As well as the containment system, the pump towers may also need to be strengthened if non-standard fill ranges are contemplated or higher than normal heels are to be a frequent occurrence.

8.2 **Design Provision to avoid Unplanned Departures from LNG Terminals**

One of the most likely reasons for unplanned departure from an LNG terminal is uncontrollable venting of natural gas brought about by leakage through the primary barrier. Because the strength of the containment system is low in its ability to resist positive pressure in its interbarrier and secondary insulation spaces, controlling the venting by shutting off the interbarrier space (IBS) relief arrangements is not
recommended, even for a short period.

A method of avoiding or stopping uncontrollable venting is to make provision to connect the IBS to the cargo tank vapour space. When this interconnection is made and the IBS vents are shut off, there is no differential pressure between the IBS and the cargo tank vapour space and therefore pressure damage will not occur. Such interconnection can be facilitated by having the piping systems for each tank arranged in close proximity to each other so that a specially made joining piece can be fitted to replace adjacent blank flanges, see Figure 9.

This procedure would only be permitted with the ship at a terminal to enable the completion of cargo operations. The IMO Gas Code requires a functioning system for inerting and leak detection of the IBS in normal operation, hence this interconnection should only be undertaken in an emergency situation.

Any action taken to avoid actual or possible uncontrollable venting should be reported immediately to Lloyd’s Register in order to obtain advice on further investigation and repair.

8.3 On-Board Real Time Measurement or Indication of Sloshing

Lloyd's Register is currently taking part in a JIP which has had strain gauges fitted to a primary and secondary box in both the forward upper corners of No 2 hold of a NO96 ship. The local hull structure in way has also been instrumented. The JIP partners include DNV, GTT, BWG, Teekay and DSME. The real time measurements have been recorded now for a couple of years and work is ongoing to post process the measurements. The post-processed data is being compared with results from sloshing model tests, from Computational Fluid Dynamics (CFD) analyses and finite element analysis results in order to improve the understanding of real sloshing issues. From this we aim to improve methods for the evaluation of sloshing pressure for use in future ship design.

Hopefully from this study and some other measurement projects, it will be possible to develop real time measurement systems capable of determining the severity of the sloshing impacts occurring on a ship. With suitable equipment on the bridge, this would provide the ship’s Master with guidance on the most effective changes of course and/or speed to control sloshing motions, as described in Section 4.

A simpler but potentially effective means of obtaining some indication of the severity of sloshing may be to incorporate microphones adjacent to the containment systems and
to monitor the sound levels recorded, although there are as yet no known plans to do this on any particular ship. There is a question as to how well the sound characteristics of potentially damaging levels of sloshing would be distinguishable from lesser levels of sloshing, although just knowing the frequency of impacts would be useful feedback. Despite its apparent simplicity, the arrangement of such a system would require careful consideration by acoustic specialists before fitting.

Fitting of any measurement system is likely to require changes or additions to the approved arrangements of the containment system or hull structure and would require approval by Lloyd’s Register.
APPENDIX A

Guidance diagram for a typical modern conventional size membrane LNG ship to reduce the risk of sloshing-related damage

Table 2 Guidance diagram on allowable filling heights

<table>
<thead>
<tr>
<th>Fill Height</th>
<th>Description</th>
<th>Operational Notes</th>
<th>Section Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Full” 95%H</td>
<td>Normal Operation</td>
<td>All ship motions can be tolerated</td>
<td>3.1</td>
</tr>
<tr>
<td>70%H</td>
<td>Permissible Fill Range</td>
<td>Avoid regular rolling to large angles, especially when combined with regular pitching. If this occurs, then the Master should consider changes of course and/or speed to minimise these motions.</td>
<td>3.2 and 4.2</td>
</tr>
<tr>
<td>10%H</td>
<td>Barred Fill Range</td>
<td>Not permitted except in exceptional circumstances and only with the prior agreement of Lloyd’s Register – in which case ship is to be operated as advised.</td>
<td>5 (If unavoidable following unplanned departure from loading terminal)</td>
</tr>
<tr>
<td>5%H</td>
<td>Permissible Fill Range</td>
<td>Most risk is from rolling motion, particularly regular large angle rolling in beam seas. If these conditions occur, changes of course and/or speed should be taken by the Master to reduce the large roll angles and the regularity of the roll motion.</td>
<td>3.3 and 4.3</td>
</tr>
<tr>
<td>Empty</td>
<td>Normal Operation</td>
<td>All ship motions can be tolerated</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Note - The same general principles apply for all membrane LNG ships, but the approved filling levels may be different, see the approved loading manual or operations manual for specific ships.
APPENDIX B

Example of sloshing risk diagrams to indicate when more severe sloshing activity is likely for various filling levels

Introduction

This appendix is provided as an example of the kind of information that could be provided to the Master of a ship to enable him to minimise the risk of severe sloshing in the event of an emergency situation that requires him to leave a sheltered location with tank fillings within the Barred Fill Range. Diagrams of this kind may be a requisite part of a Risk Assessment document as recommended in 5.1.

This appendix presents a series of diagrams that illustrate the risk of sloshing for a range of wave headings relative to the ship’s course and tank filling levels. These diagrams include the effect of ship speed.

Ideally these diagrams should also take account of the following:
- Wave height: for this example assessment, it is assumed that the seastate is severe enough to cause significant sloshing motions within the tank. Note that significant sloshing can occur in significant wave heights of as little as 2 metres if the peak ship motion responses are close to the peak of the wave energy spectrum and close to the tank natural period for that filling level; especially for filling levels in the lower part of the Barred Fill Range
- Loading condition: this affects the GM of the ship and hence the natural roll period.

Sloshing risk diagrams

In the example sloshing risk diagrams, the expected degree of severity of the sloshing is indicated by the colour shading, with Red indicating that severe sloshing would be expected, Green indicating that little or no sloshing would be expected and Yellow indicating that a moderate amount of sloshing would occur.

Each diagram is presented as a polar plot which presents the comparative risk (as colour shading) versus “ship heading relative to the wave direction” on the angular axis and ship speed from 0 knots to 20 knots on the radial axis.

Risk diagrams are given for the following combinations of filling height and wave period:
- Figure 6 is for a filling of 30%H
- Figure 7 is for a filling of 20%H
- Figure 8 is for a filling of 10%H
Each figure gives four polar plots, each for a different seastate

The seastates are characterised by the actual wave period. The wave period used is that reported in meteorological ocean wave data. Note, this is different to the encounter wave period which roughly correlates to the wave period observed by the ship.

Sloshing risk diagrams are given for “zero crossing” wave periods of 6, 8, 10 and 12 seconds, hence it is possible to see the effect that different wave periods have on the risk of sloshing.

It should be noted that these diagrams are included only for general illustration purposes of what could be done for particular ships. The diagrams in this document should not be referred to for decision-making purposes at sea.

Notes on interpretation of the sloshing risk diagrams

This study has been undertaken for a typical conventional sized LNG ship. The study is based on a simplified assessment of when the expected tank resonant period will be close to the expected wave encounter period and/or close to the ship natural roll period. It is not based on model tests and hence is only indicative.

The indication that significant sloshing (Red region) could take place does not mean that damage due to sloshing will automatically result, conversely the indication that moderate sloshing (Yellow region) could take place does not mean that sloshing damage would not result. However, there is very little risk of sloshing damage in the Green Regions. Consequently the recommendation from the sloshing risk diagrams is that the Red and Yellow areas should be avoided by adjusting heading and speed.

Note that the sloshing risk diagrams presented for 20%H and 30%H filling levels are within the normal barred fill range, hence these filling heights are not acceptable for normal operation. It should also be noted that model tests have shown the sloshing pressures at these filling heights are in excess of the containment system capability in some seastates.

Furthermore at 10%H filling levels, a highish sloshing risk is indicated for beam seas, this is consistent with the recommendation in 4.3 to take action to avoid regular large angle rolling motions with fill heights of this order. However for this fill height, sloshing model tests and in service experience show that high sloshing pressures are not generated at this fill level.

Calculation notes

The example sloshing risk diagrams have been produced to demonstrate a simplified method for providing masters with guidance on how to reduce the risk of sloshing in
the event of emergency conditions when they might be forced to sea with cargo tanks filled within the barred fill range.

The sloshing risk diagrams have been based on the following principles:

- The risk of significant sloshing occurring within a particular tank is considered to be moderate when the roll natural period of the ship is close to the tank natural period at that filling height.
- The risk is moderate when the wave encounter period is close to the tank natural period.
- The risk is moderate when the wave encounter period is close to the roll natural period.
- The risk is high when the wave encounter period is close to both the roll natural period (producing the largest motions) and the tank natural period.
Figure 6 Sloshing Risk Diagrams for different seastates for a 30% fill level
Figure 7 Sloshing Risk Diagrams for different seastates for a 20%H fill level

Wave Period = 6.0s

Wave Period = 8.0s

Wave Period = 10.0s

Wave Period = 12.0s
Figure 8 Sloshing Risk Diagrams for different seastates for a 10%H fill level

- **Wave Period = 6.0s**
  - Ship GM = 3.77 m
  - Ship T<sub>R</sub> = 13.45 m
  - TK No Filling
  - TK Period
  - TK 1 10.0 %H 12.5 s

- **Wave Period = 8.0s**
  - Ship GM = 3.77 m
  - Ship T<sub>R</sub> = 13.45 m
  - TK No Filling
  - TK Period
  - TK 1 10.0 %H 12.5 s

- **Wave Period = 10.0s**
  - Ship GM = 3.77 m
  - Ship T<sub>R</sub> = 13.45 m
  - TK No Filling
  - TK Period
  - TK 1 10.0 %H 12.5 s

- **Wave Period = 12.0s**
  - Ship GM = 3.77 m
  - Ship T<sub>R</sub> = 13.45 m
  - TK No Filling
  - TK Period
  - TK 1 10.0 %H 12.5 s

Legend:
- Lowest Risk
- Highest Risk