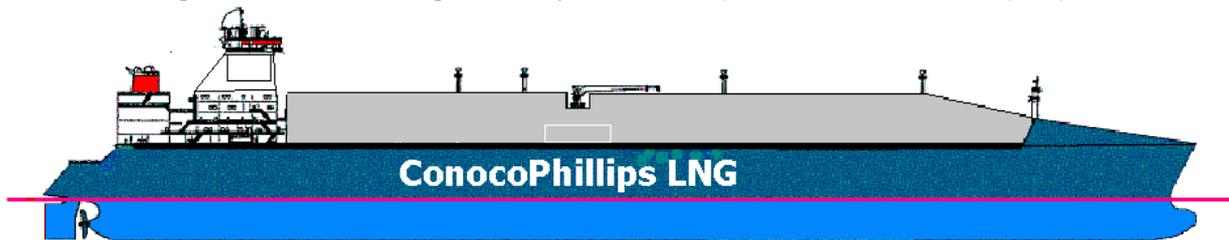


# A Novel LNG Tank Containment Design for Large LNG Carriers

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## ABSTRACT

*A new concept for Large LNG carriers is proposed. This design utilizes membrane tanks with a cross section that reduces the liquid free surface inside the tanks. This reduced free surface results in lower sloshing impact loads on the tank membrane and insulation, extending membrane technology to larger LNG carriers than have hitherto been possible, providing improved costs and fabrication schedules. Further, this concept may extend membrane tank ships to more severe environments than previously thought possible.*

## KEY WORDS:

containment, hydrodynamics, large LNG carrier, membrane tank, model test, prism tank, sloshing

## INTRODUCTION

With the current drive for larger and larger LNG projects, many are seeking ways to improve transportation performance. ConocoPhillips (COP) has been working on a number of areas of technology relating to large LNG ships and one of the first projects to achieve results is the Prism Tank Concept, which has recently received Approval in Principle from the American Bureau of Shipping (ABS).

The key feature of this tank's unique shape is its ability to reduce free surface area, thus reducing high-impact sloshing loads and transverse resonance periods in the tank. This should lead to larger ships with fewer tanks and reduced cost per vessel.

The free surface reduction resulting from the design is important because the impact pressure due to sloshing motion from the cryogenic liquid cargo inside the tanks is one of the most critical loads when designing containment systems for LNG carriers. The magnitude, effective area, and duration of the impact load are all important when considering structural response of the containment system. It is also important to understand the spatial and temporal pattern of the impact load in

concert with structural response of the containment system.

After preliminary in-house engineering design work, COP arranged for model tests on the Prism tank design to be conducted at one of the leading hydrodynamic laboratories in the world experienced in this type of test, the Marine Technology Research Institute (Marintek) in Norway. The critical ship motion responses and sloshing impact conditions were calculated for North Atlantic environment conditions. In conjunction with the model tests, COP arranged for ABS Technology to apply its proprietary numerical simulation tools to predict the dynamic sloshing pressures acting on the membrane tanks in a seaway.

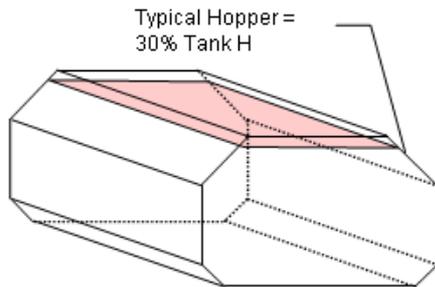
Motion response calculations and tank sloshing tests were performed for a four-tank version of an LNG vessel with cargo capacity of approximately 228,000m<sup>3</sup>. Vessel designs for this size historically have required five or six tanks. Irregular wave conditions were simulated with three different filling levels for the tanks and various ship headings. The results of the tests showed the design was acceptable and the loads on the Prism tank were equal to or less than those experienced on a traditionally designed 138,000m<sup>3</sup> ship.

The paper will describe the Prism Tank Concept, will describe the model tests and the analytical work, and will discuss the next steps in bringing this interesting concept into full commercial development.

## DESCRIPTION OF CONCEPT

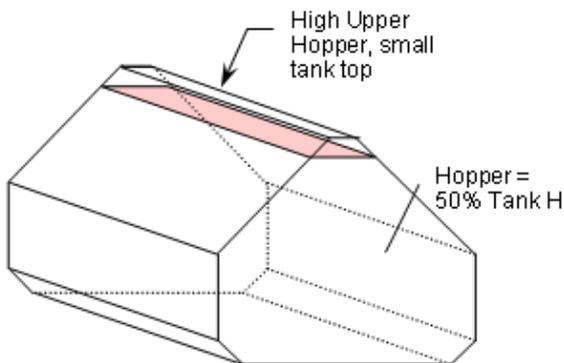
The Prism tanks are similar to conventional membrane tanks with the exception that they are configured with much higher upper hoppers than more conventional tanks that have been built to date, resulting in a long but narrow tank top.

Figure 1 presents a section of a conventional tank. Such conventional tanks are proportioned such that the upper hopper height is approximately 30% of the total tank height.



**Figure 1 - Conventional Tank Configuration**

Figure 2 presents an isometric view of the the Prism tank for comparison. The Prism tanks can have upper hoppers that are 50% of the tank height or higher (i.e. resembling a Prism). For the present design described in this paper, only prismatic tanks were studied; i.e., the cross section does not vary along the tank length, although this is not a limitation of the concept.

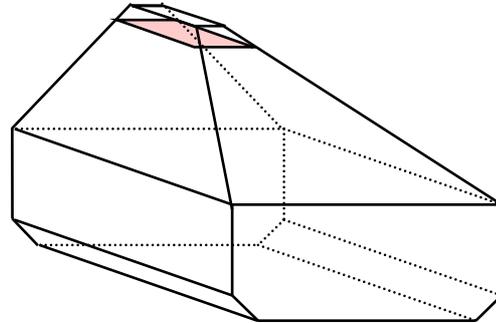


**Figure 2 - Prism Tank Configuration**

The figure shows the features of the Prism tank including its high peaked tank top and its long narrow liquid free surface.

An extreme development of this is the Pyramid tank, so-called because either or both of the fore or aft bulkheads are chamfered resulting in a peaked or pyramid shaped top, with a very small free surface. The Pyramid tank is shown in Figure 3.

Conventional ship designs can accommodate either of these designs, although the Prism tank ship features a conventional trunk deck that is increased in height and reduced in width over present day membrane ships. The hull structure of a Prism tank ship may be designed and analyzed similar to other membrane ships with the trunk deck offering good hull girder stiffness.



**Figure 3 - Pyramid Tank**

The Pyramid tank concept might feature a hull structure similar to a present day large container ship with the pyramid portion of the tank located above the main deck. Some concerns exist regarding global bending and torsional behavior of the hull girder.

Parametric studies show that the ratio of membrane area to the enclosed volume of LNG can be minimized with careful selection of dimensions. This optimization produces economies for the ship overall cost and minimizes the LNG boil-off rate.

## CONCEPT SHIP DESIGN

In the study described in this paper, the design of a 228,000 m<sup>3</sup> capacity ship utilizing the Prism tank concept was carried through to the concept level to determine its feasibility and economic viability. Comparison was made to a concept ship design developed by one of the major Korean shipbuilders (Samsung Heavy Industries) for 228,000 m<sup>3</sup> capacity dubbed the "Superflex" design. This design is a five-tank ship utilizing conventionally-proportioned LNG cargo tanks.

The ships described have two notable constraints. First, the draft is limited to 12m to accommodate both the loading and the discharge port channel depths. Second, they are both sized to accommodate one of the shipbuilder's two assembly docks that restricts the maximum beam to 51m. A secondary constraint is that the ships will transit the Suez Canal, so Suez tonnage measurement must be considered as well as maximum air draft.

The perceived advantages of the Prism ship are reduced LNG sloshing and higher LNG cargo volume to membrane surface area. This is proved using analytical techniques and physical model tests, as will be described later in this paper.

Two ship arrangements were investigated, a 5-tank and a 4-tank arrangement. In comparison with a ship design based on conventional tanks, if cargo volume is held constant the Prism ship has shorter tanks (given the 5-tank arrangement) as the cross sectional area is higher than the conventional tank design. Assuming better sloshing behavior, the tanks can be lengthened and the number of tanks reduced by removing one bulkhead. Preliminary sloshing tests described in this paper show that the Prism ship can utilize the four-tank arrangement. This arrangement results in advantages in lower membrane area to cargo volume, favorable for reduced boil-off and lightweight.

Because of the draft restriction, the ships would be twin screw to achieve adequate propulsive efficiency. Studies by SSPA have shown that hull forms with twin skag sterns exhibit favorable powering characteristics even for relatively high block coefficients (up to and in excess of 0.800). This has the effect of allowing the LBP to be reduced, as the length is not needed for the cargo block or engine room. For the 228,000 m<sup>3</sup> ship, the length can be reduced approximately 6 to 8m.

**Principal Particulars and General Arrangement**

Table 1 presents a comparison of the principal particulars for the Conventional ship and the Prism ship. Note that beam, depth, draft, capacity, and displacement are similar between the two ship designs. Only the lengths and air drafts are different.

Figure 4 shows the arrangement of the Conventional Ship and Figure 5 presents the arrangement of the Prism Ship. Comparison of these figures shows the shorter length of the Prism ship that results from the shorter

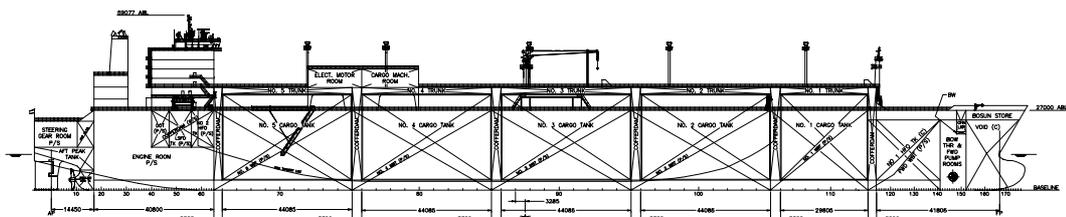
cargo block and higher block coefficient. Both ships have engine room and accommodations aft.

**Table 1 - Principal Particulars**

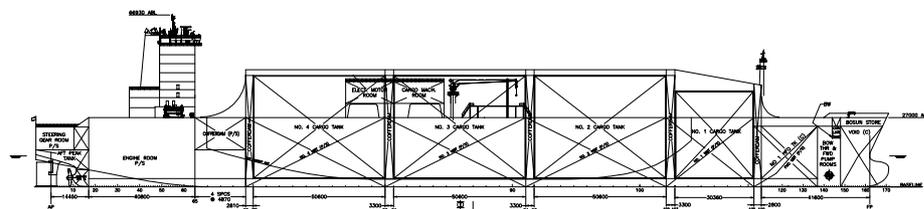
	Conventional	Prism
LOA	335.0 m	327.0 m
LBP	322.0 m	314.0 m
Beam	51.0 m	51.0 m
Depth	27.0 m	27.0 m
Design Draft	12.0 m	12.0 m
Displ at Design Draft	158,109.0 MT	158,105.0 MT
Air Draft (at Ballast Draft)	Approx. 49.5 m	Approx. 57.3 m
Cargo Cap 100% full	228,000 m <sup>3</sup>	228,000 m <sup>3</sup>
Cargo Cap 98.5% full	225,000 m <sup>3</sup>	225,000 m <sup>3</sup>
Number of Tanks	Five	Four
Service Speed	19.5 Knots	19.5 Knots

The Prism ship cargo block is approximately 20m shorter than for the conventional tank ship. This allows the LCG and therefore the LCB to be located close to amidships for maximum hull efficiency. This arrangement also opens up main deck space potentially for locating cargo handling or other specialized equipment.

Aft of the cargo block area is a portion of the hull given over to the aft fuel tanks. Both HFO and Low Sulfur Fuel Oil and Diesel Oil storage are provided in these tanks. The deck in this area is well protected by the trunk deck and could be used for cargo handling and reliquefaction equipment.



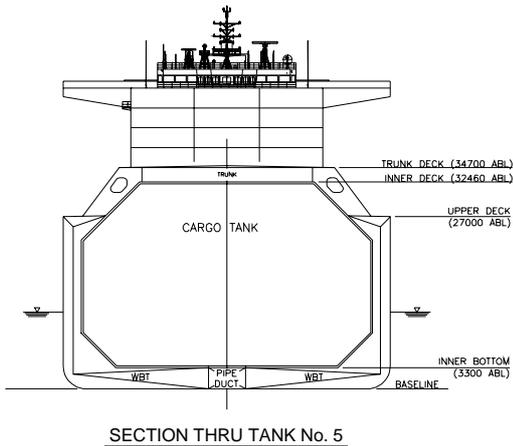
**Figure 4 - Conventional Ship - 228k m<sup>3</sup>**



**Figure 5 - Prism Ship - 228k m<sup>3</sup>**

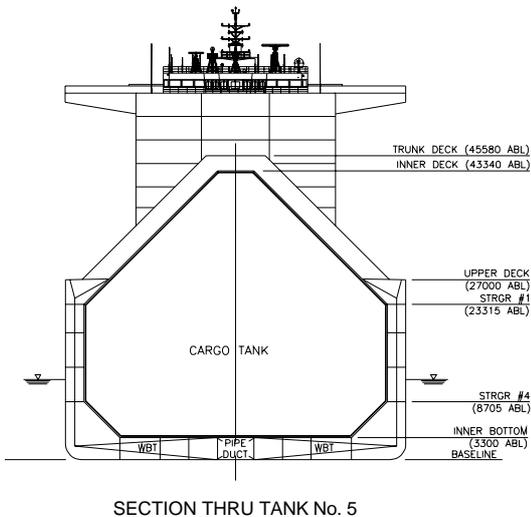
Figure 6 and Figure 7 present the tank cross sections within the hull for both ships. The conventional tank proportions are typical of membrane tanks with an upper hopper approximately 30 percent of the tank total height. The larger tanks, No. 2 through 5, are

approximately 44m long and contain approximately 51,000 m<sup>3</sup> LNG each. The forward No. 1 tank, approximately 30m long by 34m wide, contains 24,000 m<sup>3</sup> LNG.



**Figure 6 - Section through Conventional Ship**

The Prism tank features the higher upper hopper that is approximately 50 percent of the tank total height. For the 4-tank variant, the larger tanks, No. 2 through 4, are 50m long and contain approximately 65,000 m<sup>3</sup> LNG each. The forward No. 1 tank, approximately 30m long by 34m wide, also has hoppers with increased height, although not as extreme as the larger tanks. This tank contains 34,000 m<sup>3</sup> LNG.



**Figure 7 - Section through Prism Ship**

Visibility was identified as a concern early in the study because of the height of the center of the Prism tank trunk deck. IMO bridge visibility requirements were evaluated for the Base ship. Sufficient visibility is provided if the navigation bridge is six levels above the main deck for full load (12m) and ballast drafts (9.6m) with up to 2m trim aft. To provide the crew of the Prism Ship with sufficient visibility, the navigation bridge needed to be raised two decks, or located eight decks above the main deck.

**Prism Tank Sizing**

A parametric study was performed to investigate and understand the effect of varying different dimensions on the surface area of the tank, as the weight and cost of insulation and membrane are directly proportional to surface area of the inside of the tank.

The optimization scheme investigated the optimum dimensions of the upper and lower hoppers, the tank length, and the tank depth for a given width and constant volume. Generally, the closer the tank approaches a cylinder or an equal sided octagon, the lower the surface area of the tank for the given height and enclosed volume.

Figure 8 presents tank sections for the final tank height. The figure shows the lower and upper hopper combinations studied. The Prism and conventional tank sections are overlain (dashed bold line) on the figure. The resulting optimum section is also plotted (solid bold line) on these figures.

Figure 9 presents curves that show the effect on the ratio of volume to surface area (or volumetric efficiency) of varying the lower and the upper hopper heights for three tank depths. The width of the tank is kept constant (at 45m) as is the contained volume (50,500 m<sup>3</sup>) but the tank length is varied to obtain the target capacity. The curves plotted are the Volume/Surface Area (V/SA) against the upper hopper dimension for a series of lower hopper dimensions. The maximum V/SA typically results when the lower and the upper hopper and the vertical side are close to equal lengths. The V/SA for the Base ship (square labeled “Superflex”) and for the Prism ship (triangle labeled “5-tank Prism” and diamond labeled “4-tank Prism”) concept designs is also plotted. Note that neither the conventional tank section nor the Prism tank section used in the concept designs is particularly close to the optimum section.

For various reasons, including minimizing Suez Canal tonnage, the more conventional lower hopper and longer upper hopper arrangement shown in Figure 8 was selected. For the concept ship design study, the Prism tank was given primary transverse dimensions and depth to the upper hopper similar to the conventional ship. The width of the tanks and the dimensions of the lower hopper were also kept the same as the conventional ship. However, the tank top was allowed to be approximately six longitudinal stiffener spaces wide, and the upper hopper determined by a 45-degree sloping face between the uppermost stringer in the side shell and the tank inner deck. This configuration gives a V/SA ratio about 0.5% higher than that of the conventional tanks for the 5-tank Prism ship.

For the 4-tank Prism ship, V/SA shows an 8% improvement over the conventional ship; this means a savings of 8% of the insulation and membrane.

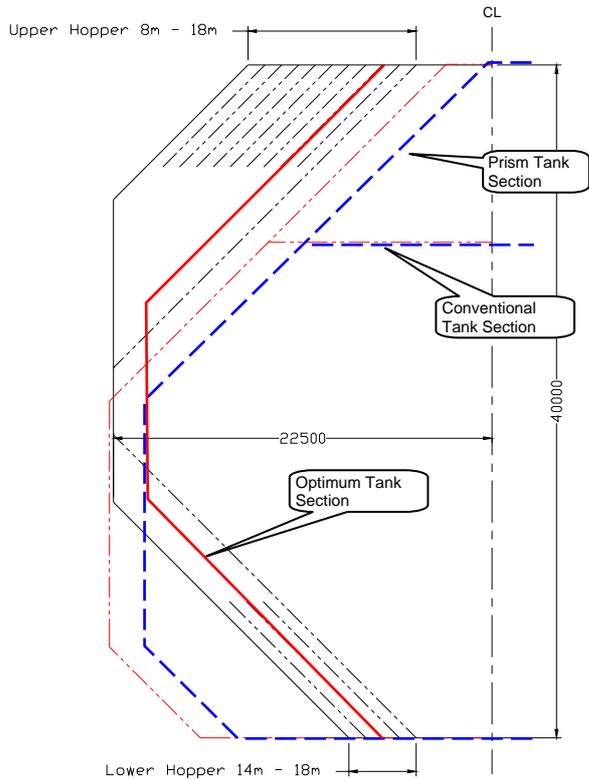


Figure 8 - Tank Variations - H = 40m

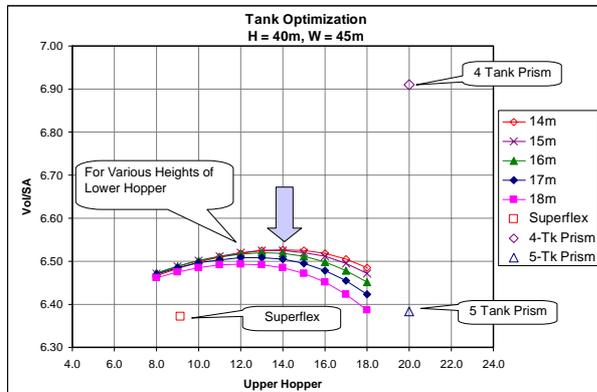


Figure 9 - Tank Efficiency - Height = 40m

**Structure**

The midship structure for the Prism ship was determined from a SafeHull Phase A analysis of the longitudinal structure. This analysis determines the required bending moments, the required section modulus and moment of inertia, and assesses input plate and stiffener scantlings for both global hull girder bending and local pressure loads. The minimum required bending moments all exceed the calculated still water bending moments.

Figure 10 and Figure 11 present the midship sections developed. For the Prism ship, the section scantlings for the inner skin are slightly higher than for similar locations in the conventional ship because of the increased static head of LNG. Steel area (and therefore weight) per meter is higher over the cargo block for the Prism tank as might be expected. However, the cargo block is shorter and features one less bulkhead. Lightship steel is therefore comparable between the two designs.

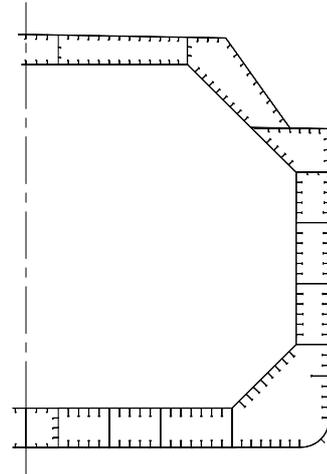


Figure 10 - Conventional Ship Midship Section

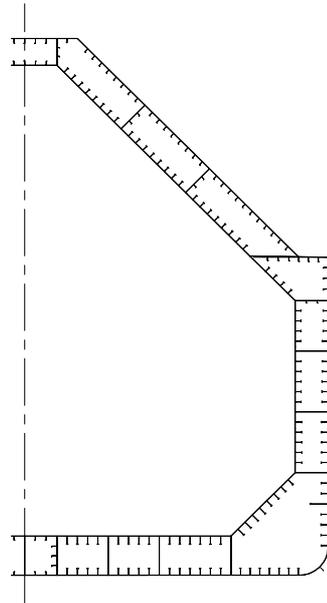


Figure 11 - Prism Ship Midship Section

**Constructability**

Fabrication of the high trunk deck was identified as a concern with the concept early on. Samsung Heavy Industries performed a review of the design including assessing constructability. No significant fabrication issues were found, although two minor ones will be discussed.

The high trunk deck presents no problem from a conventional shipbuilding point of view. The trunk deck itself would probably be fabricated in full transverse sections, of one cargo hold (50m) in length installed on the upper deck of the hull during block assembly.

The primary challenge involves installing the membrane and insulation inside the tank. The shipyard’s scaffolding would either need to be supplemented or modified for installation of these tanks. Therefore production of a series of these ships would provide the most efficient use of shipyard equipment and facilities.

**APPROVAL IN PRINCIPLE (AIP) PROCESS**

To prove the feasibility of the concept, American Bureau of Shipping was approached and requested to review the design. ABS was also asked to give Approval in Principle if the design was found to satisfy their concerns. For the Prism ship concept, ABS was primarily concerned with sloshing behavior of fluid in the tanks. Therefore, sloshing analysis and model testing was conducted. This analysis and testing program was devised to prove that the tank design did reduce the sloshing impact pressure by introducing a very high upper chamfer.

The objective in this AIP process was to evaluate the safety of the proposed tank design under sloshing load. First sloshing simulations were performed to select model test conditions, and secondly, model tests are conducted for both the Prism Tank ship and the 138K ship. Finally, the test results were analyzed to approve the design in principle. The 4-tank arrangement was considered for the Prism Tank ship. Figure 12 presents the sloshing analysis and testing process graphically.

As to filling levels, three cases were considered for sloshing analysis: 98.5%, 96.0%, and 93.5% of the tank volume. 98.5% of the tank volume (hereafter 98.5%V) corresponds to the full load departure condition and 96.0% volume is the calculated filling level considering the boil-off of LNG during the loaded voyage. The 93.5% volume is an extra filling level for unexpected or extreme situations. Therefore, a total of 6 loading cases were analyzed in sloshing simulations. Each will be identified as shown in Table 2.

**Table 2 - Identification for loading conditions**

Loading	% Volume	Prism 228K	138K
A	98.5	<b>PR225LCA</b>	<b>138LCA</b>
B	96.0	<b>PR225LCB</b>	<b>138LCB</b>
C	93.5	<b>PR225LCC</b>	<b>138LCC</b>

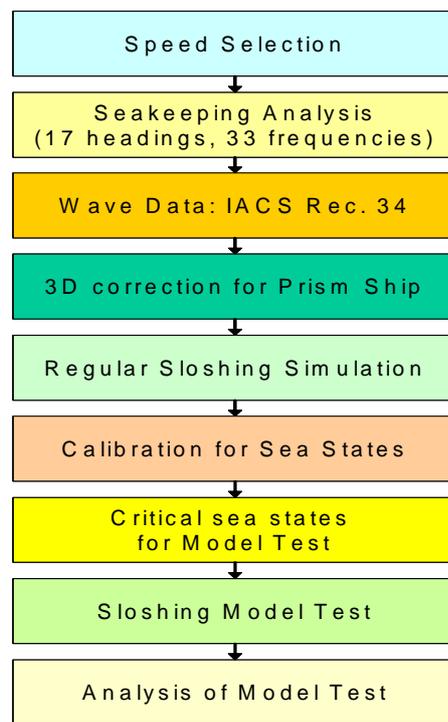
**SLOSHING ANALYSIS**

The seakeeping calculation was carried out using PRECAL version 5. The sloshing analysis was carried out using SLOFE2D version 2.1. The details of the numerical method can be found in [Ref. 3]. The density of 474 kg/m<sup>3</sup> was used for LNG.

**Environmental Conditions**

The wave scatter diagram from IACS Recommendation 34 was employed for the unrestricted service condition. The numbers in the diagram represent the probability of sea states described as occurrence per 100,000 observations.

A series of 40-year waves were selected for the sloshing analysis as shown in Table 3, where Tz is the average zero up-crossing wave period and Hs is the significant wave height. The analysis recognizes that vessel speed will be reduced in extreme seastates. Therefore, a vessel speed of 5 knots is assumed for the waves of 12 m and higher wave height, while 14.625 knots is applied to those of lower than 12 m wave height.



**Figure 12 - Analysis procedure in sloshing analysis**

**Table 3 - 40-year waves from IACS Recommendation 34**

Tz	Hs	Tz	Hs	Tz	Hs	Tz	Hs
4.0	1.9	7.5	11.1	11.0	15.5	14.5	14.9
4.5	3.1	8.0	12.1	11.5	15.7	15.0	14.5
5.0	4.4	8.5	13.0	12.0	15.8	15.5	13.9
5.5	5.9	9.0	13.8	12.5	15.8	16.0	13.2
6.0	7.3	9.5	14.4	13.0	15.7	16.5	12.3
6.5	8.7	10.0	14.9	13.5	15.5	17.0	11.0
7.0	10.0	10.5	15.2	14.0	15.3	17.5	8.7

**Seakeeping Analysis**

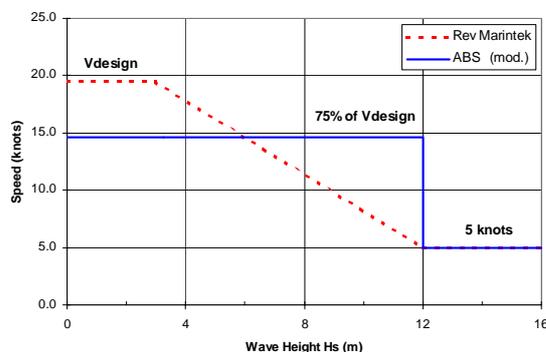
The three-dimensional linear seakeeping code, PRECAL version 5.0 was used for seakeeping analysis. Panels are generated on the ship surface and linearized boundary conditions are applied on the free surface. The details of the software can be found in [Ref. 1].

Hydrostatic characteristics are shown in Table 4 for the Prism Tank ship and for the 138K design, respectively. The LCG of Prism ship is closer to the mid-ship than the conventional 138K ship even considering the length difference. Also, the Prism ship has larger KG than the conventional ship, which is due to the increased upper chamfer.

**Table 4 - Hydrostatic characteristics of Prism Tank ship 228K and 138K**

Load Case		Prism Ship Full Load	138K Full Load
Filling(%H)		93.41	97.61
LCG	m-AP	156.870	132.97
LCG	m-Amid	-0.130	-0.03
KG	m-BL	18.657	16.897
KG	m-WL	6.634	5.551
Draft	m-BL	12.023	11.346
Trim	m: Tf-Ta	-0.002	-0.064
DISP	MT	158436	95740
GML	m	617.155	423.946
GMT	m	5.543	2.469
DGMT	m	0.128	0
kxx	m	15.94	15.981
kyy	m	75.348	58.612
kzz	m	76.314	59.073

The ship speed is determined from the speed reduction curve. Figure 13, shows the relationship of ship speeds and sea states.



**Figure 13 - Ship speed versus sea states**

Originally a speed reduction curve (dotted line) was proposed. However, using this reduction curve involves executing seakeeping analysis for a large number of ship speeds and sea state combinations, which is not

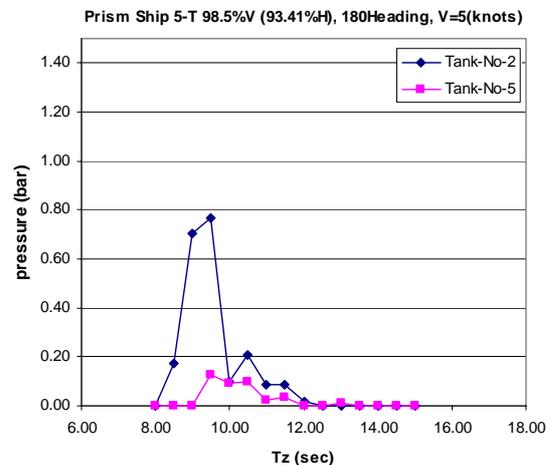
practical. Therefore, a compromised speed reduction curve (solid line) was employed for the analysis. As shown in the figure, 14.625 knots (75% of the design speed) was used for the wave height less than 12m and 5 knots is used for the wave heights greater than 12m.

One of the important input parameters for seakeeping analysis is the roll-damping ratio. In this study, a damping ratio of 0.1 was used with an implementation of a bilge keel. However, it is observed that the bilge keel shows negligible influence on the output RAO.

**Analysis of Tank Sloshing with 2-D CFD**

Two-dimensional sloshing simulations have been performed using SLOFE2D version 2.1. The details on SLOFE2D can be found in [Ref. 3]. The simulations modeled the response of the tank to regular excitation, i.e. a sinusoidal wave is applied to the ship and corresponding ship motion is generated.

Tank No.2 was selected for testing based on comparison of motion of Tank No.5 as well as Tank No.1. In long-term extreme value simulations, Tank No.1 shows relatively smaller impact pressure than Tank No.2 and Tank No.5. In short-term simulation, the impact pressure in Tank No.5 is considerably smaller than Tank No.2 as shown in Figure 14 for 98.5% V and 180(deg) heading. It is believed that vertical acceleration related to the phase of the ship motion (heave and pitch) accounts for this large impact pressure in Tank No.2.



**Figure 14 - Comparison of impact pressure between Tank No.2 and Tank No.5: 98.5%V filling, 180(deg) heading**

**Natural Period and Three-dimensional Correction for Prism Tank**

The natural period of tank motion is critical for sloshing analysis. In conventional tanks, the two-dimensional natural period based on the finite-depth water wave theory has been used for sloshing analysis. As shown in [Ref. 2], the following equations are used for the

calculation of longitudinal natural period,  $T_x$ , and the transverse natural period,  $T_y$ .

$$T_x = L^{1/2} / k_x, \quad T_y = b_f^{1/2} / k_y \quad (1)$$

where:

$$k_x = \left( \frac{\tanh[\pi d / L]}{4\pi / g} \right)^{1/2},$$

$$k_y = \left( \frac{\tanh[\pi d / b_f]}{4\pi / g} \right)^{1/2} \quad (2)$$

$b_f$  : breadth of the still liquid surface in the tank,

$L$  : length of the tank

$d$  : depth of liquid

$g$  : gravitational acceleration

Table 5 shows the natural periods for the longitudinal tank motion. As shown, the natural period decreases as the filling level increases. In particular, considerably shorter natural period can be observed in the Prism Tank ship in transverse motion. Also, the period in longitudinal motion is shorter in the Prism Tank ship than other ships.

**Table 5 - 2D Natural period in longitudinal tank motion**

%Volume	PR228		SH138	
	%H	Tn (sec)	%H	Tn (sec)
98.50	93.41	8.10	97.61	7.62
96.00	86.82	8.10	93.90	7.64
93.50	81.94	8.10	90.47	7.67

In conventional tanks, the 2D and 3D natural periods have small differences. However, in Prism Tank ship, the difference is expected to be relatively large due to its particular shape. Therefore, it may not be appropriate to use 2D natural period for sloshing analysis for Prism Tank.

To account for the 3D natural period, one should employ 3D sloshing simulation. However, 3D simulation requires considerably longer computation time. Roughly, 3D simulations take an order of magnitude longer time than 2D simulations.

For these reasons, a new method was proposed to compute the 3D natural period. The approach is based

on the dispersion relation ( $\omega^2 \propto g$ ), where the period of liquid surface wave is inversely proportional to the square root of the gravitational acceleration, therefore

$$T \propto \frac{1}{\sqrt{g}} \quad (3)$$

From this relation, an effective gravity can be calculated, that is

$$g_{eff} = g \left( \frac{T_{2D}}{T_{3D}} \right)^2 \quad (4)$$

The 3D natural period is then obtained by solving the Laplace equation in the three-dimensional domain using the boundary element method.

The calculated effective gravities for the Prism Tank ship are shown in Table 6. These effective gravities are used for sloshing simulation of the Prism Tank ship. It should be noted that the resulting pressure would be affected by the gravity change. However, this can be ignored because our interest is to determine critical wave conditions, where a relative maximum occurs for each filling level, rather than determining actual impact pressure magnitudes.

**Table 6 - Comparison of 2D and 3D natural periods for the Prism Tank ship**

FLVL	PR228(4-Tank-Model)		
	93.41%H	86.82%H	81.94%H
Tn (3D) (sec)	5.9	6.5	6.8
Tn (2D) (sec)	8.1	8.1	8.1
eff. Gravity (m/s <sup>2</sup> )	18.5	15.4	14.1

**Simulation Result and Model Test Case**

The simulation result presented herein is the maximum impact pressure on the tank ceiling (tank top). The pressure on the tank ceiling is most critical issue in high filling cases. To consider three-dimensional effects on the tank ceiling, a correction factor of 1.5 is multiplied to the impact pressure. In general, maximum pressure occurs near the upper corner of the tank ceiling.

Since the effective gravities are applied to Prism Tank ship, it is not appropriate to directly compare the pressure between the Prism Ship and the 138K ship. In fact, the focus is on the selection of the period at which the sloshing pressure is the maximum. In general, however, the 4-Tank Prism Tank shows larger impact pressures than the 5-Tank model.

**Comparison of Pressure for Various Headings**

Since two headings are to be selected, it is necessary to determine two critical headings from the result. It is not obvious but in general 180 deg heading (head sea) and 150 deg heading seem to be more critical than 165 deg heading. Therefore, 180 deg and 150 deg are selected for critical headings for model tests.

The maximum pressures are observed near the tank natural period as expected. One interesting result is that there is another peak in pressure close to the period equal to one and half times the tank natural period. This second peak is even larger than the first peak in some cases for the Prism Tank ship. This may be related to the introduction of effective gravity for Prism Tank. More studies are required to identify the cause of the second peak phenomenon.

**Comparison of 5-Tank model and 4-Tank model**

The maximum sloshing pressures on the tank ceiling for the 5-Tank model and the 4-Tank model are compared in this section. In the comparison, it should be noted that different effective gravities are applied for the 5-Tank and the 4-Tank models just as different gravities are applied for different filling levels.

Table 7 shows the comparison of the impact pressure between the 5-Tank model and the 4-Tank model. As expected, the 4-Tank model shows larger pressure than the 5-Tank model. It appears that the ratio increases as the filling level decreases. The largest factor is 6.0 at 180 deg heading with 93.5% volume filling.

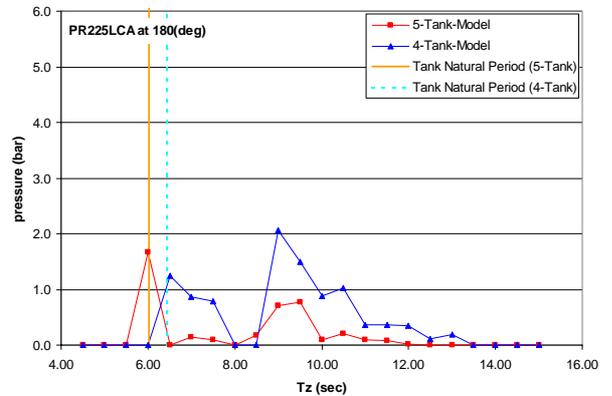
**Table 7 - Comparison of maximum sloshing pressure (bar) between 5-Tank model and 4-Tank model**

heading	98.5% V		96.0% V		93.5% V	
	150	180	150	180	150	180
5-Tank	2.07	1.67	1.93	1.86	3.35	0.83
4-Tank	2.33	2.06	4.08	2.89	4.58	5.00
Ratio(4-T/5-T)	1.1	1.2	2.1	1.6	1.4	6.0

If the maximums are compared, the factor of increase becomes more reasonable values as shown in Table 8. The maximum factor is close to 2.0 in this case. As shown in Figure 15, both 5-Tank and 4-Tank cases show resonance at the natural periods.

**Table 8 - Ratio of pressure increase from 5-Tank model to 4-Tank model - maximum to maximum**

	98.5% V	96.0% V	93.5% V
ratio(5T/4T)	1.2	1.9	1.5



**Figure 15 - Comparison of Prism Tank ship 5-Tank model versus 4-Tank model: 98.5% V, 180 deg heading**

**Development of Test Matrix**

Based on the simulation result, a test matrix for the model test was developed. Three sea states were selected for two headings (head sea, bow-quartering sea) and for three filling levels. Therefore a total of 18 test cases were selected for each ship. Based on comparison to previous model test results, a calibration has been performed for the sea state selection.

The following is the general procedure of the selection:

- Select three sea states in which the sloshing pressure is the largest.
- If the selected sea state is near the tank resonance, shift the period by 2 seconds.
- Spread the sea states so that the interval of period is at least 1.0 second.

**Calibration for Test Conditions**

Comparison of the simulation result with previous model test results [Ref. 4] shows that there is about 2 sec difference between tank natural period and Tz of the seastate where maximum sloshing pressure occurs. Test results for the 92.5% H and 70% H filling levels were compared for this calibration. It is believed that the difference is due to the differences in regular and irregular tests. To include this effect, the test conditions are calibrated accordingly.

In this study, the test conditions near the tank resonance period were shifted by 2 sec, while the other test conditions remained as they were. This is based on the fact that the response in the regular test is more sensitive to the natural period while the response in the irregular test was considered less sensitive to the natural period. The calibration process is graphically presented in Figure 16.

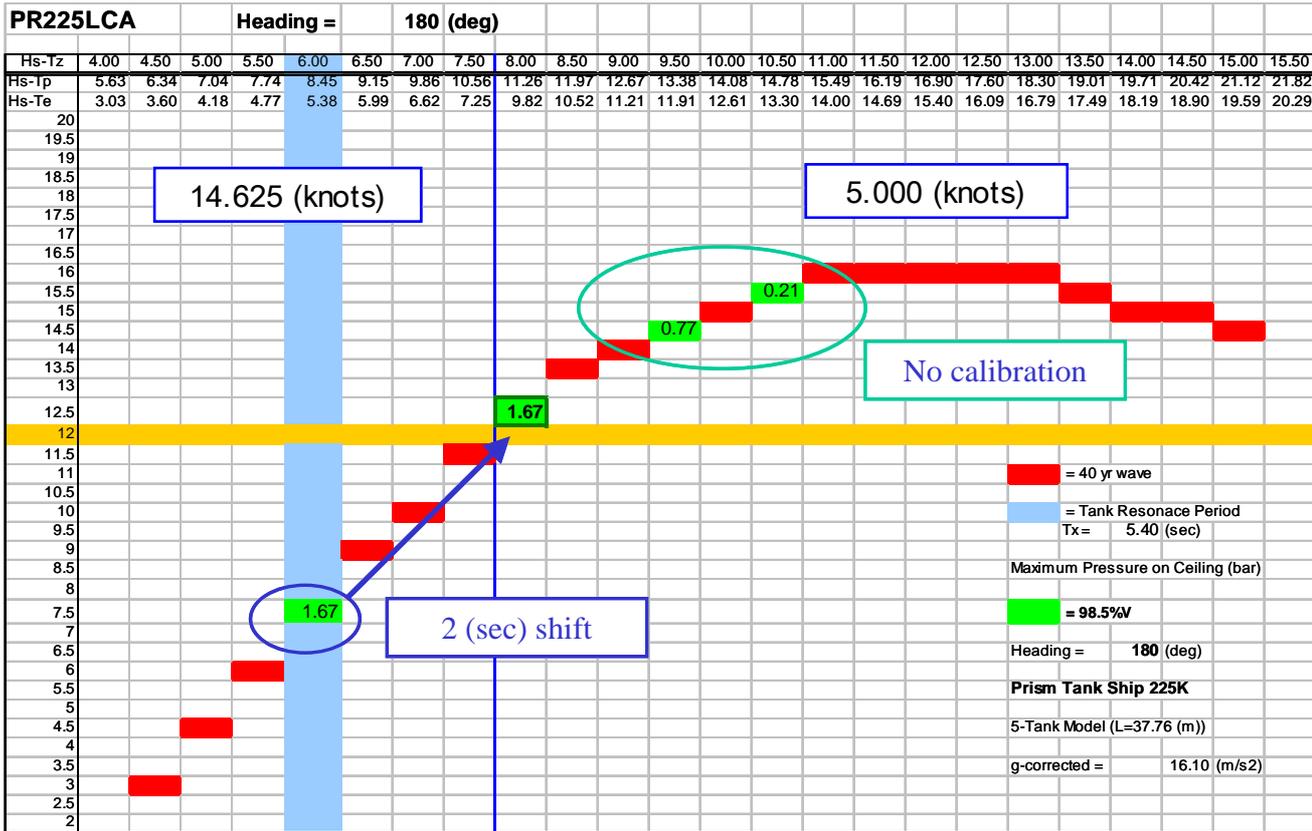


Figure 16 - Calibration procedure for Tz near tank natural period

**Recommended Test Conditions**

Recommended test conditions are summarized in Table 9 and Table 10. As shown, the test conditions are located between 8 and 12 sec of Tz, and between 10 and 16 m of Hs.

**Table 9 - Recommended model test conditions for Prism Tank ship 228K (4-Tank model: L=50.0 m): Heading(deg), Tz(sec), Hs(m)**

PR228-4T FL(%V)	Heading	Wave#1		Wave#2		Wave#3	
		Tz	Hs	Tz	Hs	Tz	Hs
98.50	180	8.0	12.1	9.0	13.8	10.0	14.9
	150	8.0	12.1	9.0	13.8	10.0	14.9
96.00	180	9.0	13.8	10.5	15.2	11.5	15.7
	150	8.5	13.0	10.0	14.9	11.0	15.5
93.50	180	9.0	13.8	10.0	14.9	11.0	15.5
	150	9.0	13.8	10.5	15.2	11.5	15.7

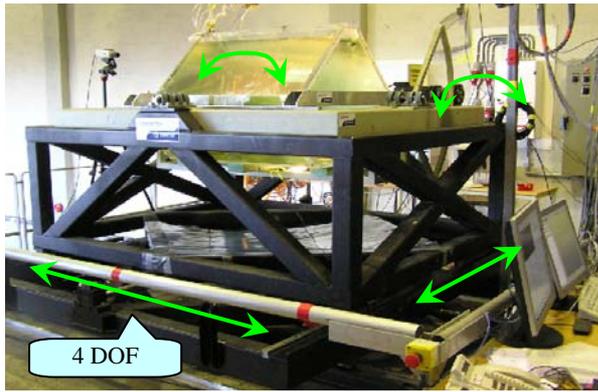
**Table 10 - Recommended model test conditions for SHI 138K: Heading(deg), Tz(sec), Hs(m)**

SH138 FL(%V)	Heading	Wave#1		Wave#2		Wave#3	
		Tz	Hs	Tz	Hs	Tz	Hs
98.50	180	9.0	13.8	10.0	14.9	11.0	15.5
	150	9.0	13.8	10.0	14.9	11.0	15.5
96.00	180	8.5	13.0	9.5	14.4	10.5	15.2
	150	8.5	13.0	10.0	14.9	11.0	15.5
93.50	180	9.0	13.8	10.0	14.9	11.0	15.5
	150	8.5	13.0	9.5	14.4	10.5	15.2

**MODEL TESTS**

Sloshing model tests for the Prism Tank ship and the 138K ship were performed at MARINTEK employing the recommended test conditions. For the 228k ship, only the 4-tank version of the tank was tested.

The model tank was built to 1/50<sup>th</sup> scale of the full-size tank, to which four degrees of freedom motion were applied: surge, sway, roll and pitch.



**Figure 17 - Sloshing Test Set-up**

Figure 17 presents a photograph of the MARINTEK testing facility. In addition to applying the four degrees of ship motions, the testing facility includes motion control for the test rig and data acquisition equipment. For the tests conducted as part of this program, test data were collected from a total of 32 sensors at the rate of 19.2kHz. The sensors included 30 pressure sensors and two accelerometers.

All cases were tested in irregular waves with 40-year return period at the speed of 5 knots. The total number of cases is 38 for Prism ship, and 16 for 138K. Comparison in detail is presented in the following sections starting with Prism Tank versus 138K.

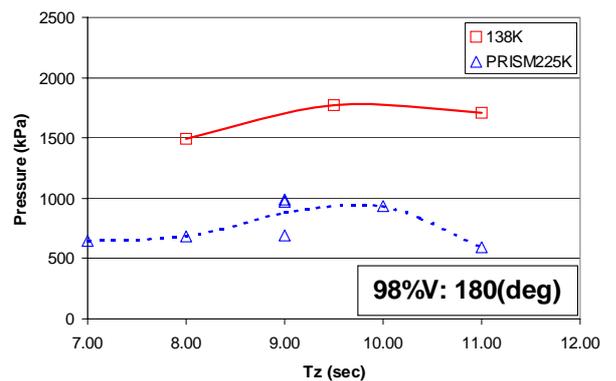
## TEST RESULTS AND DISCUSSION

### Comparison of Prism 228K with 138K

The test result for the Prism Tank ship was assessed in a comparative study with the model test results for a 138K ship. As mentioned in the earlier section, the 5-Tank version of the Prism Tank ship is shorter with narrower free surface than the 138K No. 2 tank, which is the reason why low sloshing pressure was expected. However, the 4-Tank model is longer than 138K in length, which might result in larger sloshing pressure.

In fact, it is found that the Prism Tank showed comparable or lower pressures than the 138K ship. The pressures are compared for two headings; 180 deg and 210 deg, and also for fill volumes of about 98%V and about 96%V (where V = 100% tank volume). The model tests for 138K were done for 95% of the tank height and 92.5% of the tank height, which correspond to 96.8%V and 95%V. Therefore, the comparisons are performed for Prism 98.5%V vs. 138K 96.8%V and Prism 96%V vs. 138K 95%V. All comparisons for the impact pressure are applied to the most probable 3-hour values otherwise specified.

Figure 18 shows the comparison for 98%V filling at 180 deg heading condition, (head sea). While the maximum pressure occurs at similar period of about 9.5 sec Tz, the magnitudes show significant difference. The pressure for the 138K is about 17 bars and that for the Prism Tank is only about 10 bars. Considering the filling level in the tank height is not much different (93%H for Prism, 95%H for 138K), this large decrease in impact pressure is probably due to the geometry of the Prism Tank. In other words, the smaller free surface and the larger upper chamfer contribute to the reduction of impact pressure in spite of the longer length and larger volume of the Prism tank.



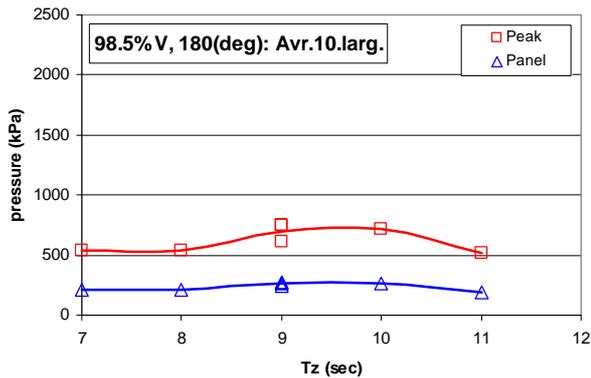
**Figure 18 - Most probable 3hr pressures for 98% Volume filling at 180 deg heading (head sea): Prism 228K vs. 138K**

### Comparison of Peak Pressure and Panel Pressure

In the model test two arrays of clustered sensors were employed to measure panel pressure. Each cluster consists of 16 sensors arranged in a 4x4-array.

In this section, two types of measurement will be compared: one is 'peak pressure', which is the highest pressure measured from any single sensor, and the other is 'panel pressure', which is the averaged pressure over the sensor array. The panel pressure is known to be more appropriate for structural analysis than the peak pressure because the load is distributed over a panel due to gas bubble cushioning, hydroelasticity, and other effects.

Figure 19 shows the comparison of peak pressure and panel pressure for Prism Tank ship at 98.5%V filling. The averaged 10 largest values are compared for the filling levels and headings of interest. As shown, the panel pressure shows considerably smaller values than the peak pressure. In average, the reduction in pressure is more than 50% of the peak pressure. In addition, the scatterings of pressure visibly decrease in the panel pressure.



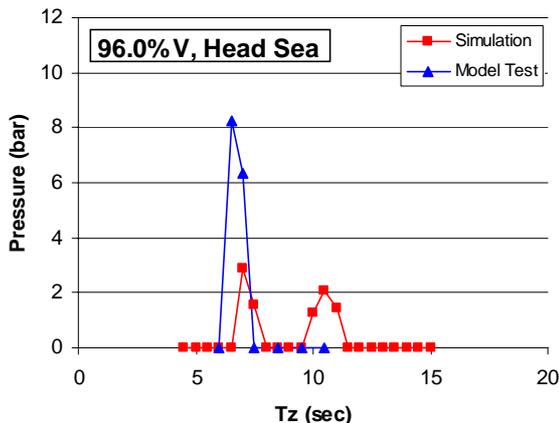
**Figure 19 - Average of 10 largest pressures for 98.5% Volume filling at 180 deg heading (head sea): Prism 228K-4T**

**Regular Test Comparison**

The simulation results presented earlier are based on regular waves corresponding to the 40-year waves in the IACS wave scatter diagram. The corresponding wave amplitudes were calculated by statistical analysis for most probable 3-hour values.

MARINTEK also conducted several regular tests to identify the natural period of the tank motion. The model test results are converted into full scale by using the scale factor of 50. It should be noted that the conditions are not the same between the simulation and the model test. In other words, the focus in this comparison is on the periods of maximum pressure not on magnitudes of pressure.

Figure 20 shows the comparison of the simulation and the regular model test for 96%V filling. As shown, the period for the maximum pressure is slightly shorter in the simulation than in the model test. Also the second peak observed in the simulation is not seen in the model test.



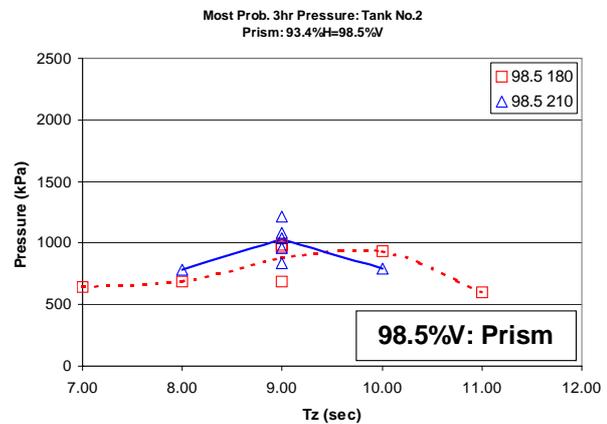
**Figure 20 - Comparison of regular test result 96%V, Head Sea: note that the wave amplitudes are not the same in simulation and model test**

**Heading Dependency**

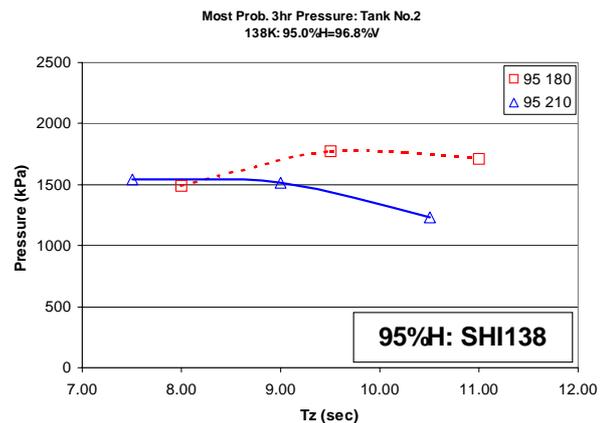
Model test results for Prism Tank indicate that the pressure levels are about the same for 180 deg and 210 deg

deg headings for the Prism Tank ship. For the 138K ship, on the other hand, the pressure at 180 deg is slightly larger than that at 210 deg. Figure 21 shows sloshing pressure for the Prism Tank ship at 98.5%V filling ratio, where both 180 deg and 210 deg cases have similar impact pressure. As mentioned in the previous section, the encountering period change is thought to be the reason for the difference in the maximum period, or the period at which maximum pressure occurs.

Similar results for 138K ship are shown in Figure 22. Compared to the Prism Tank ship, the difference in pressure between the headings is slightly larger. The corresponding period of the maximum pressure also follows the same trend as for the Prism ship. In other words, at 180 deg heading, the longer encountering period in 210 deg may result in the shorter maximum period. But, as for the Prism ship, this is not the case for the 92.5%H filling level.



**Figure 21 - Most probable 3hr pressures for 98.5% Volume filling of Prism Tank ship**



**Figure 22 - Most probable 3hr pressures for 95%H filling of 138K ship**

**Filling Level Dependency**

Figure 23 shows the maximum impact pressure versus filling level at 180 deg and 210 deg headings for both the Prism and the 138K ships. The symbols are the most probable 3- hour values of pressure for each model test,

and the lines are the maximum averaged values at the corresponding filling levels.

For the Prism ship, it is clear that the pressure at 96% V, which is 86.82% H, is the largest among the filling levels considered. The pressure at 180 deg is generally larger than 210 deg except 98.5% V. For the 138K ship, it appears that 92.5% H shows higher pressure than 95% H for both headings. As for the Prism ship, the 180 deg heading shows larger pressure than 210 deg.

Figure 24 and Figure 25 show pressure plotted against wave period, Tz for the comparison of filling levels at each heading angle. In Figure 24 for Prism ship at 180 deg, as seen before, 96% V shows larger pressure than 98.5% V. Interestingly, it seems the maximum period appears longer in 98.5% V than 96.0% V. Since the natural period becomes shorter as the filling level increases, it is expected that the maximum pressure occurs at shorter period at 98.5% V than 96.0% V. In simulations the result matches with this expectation, but it is not observed in the model test result.

Similarly, as shown in Figure 25, 138K result also shows the maximum period is longer in 95% H than 92.5% H, which is opposite to the expectation. However, it is difficult to tell from the natural period because the difference in the natural period between 95% H and 92.5% H is very small (less than 0.2 sec).

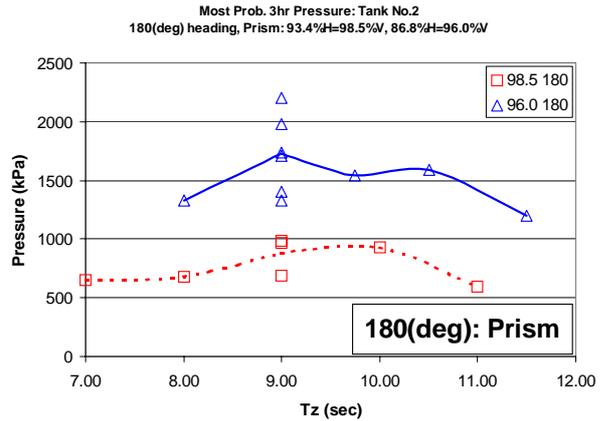


Figure 24 - Most probable 3hr pressures at 180(deg) heading for Prism Tank ship 228K

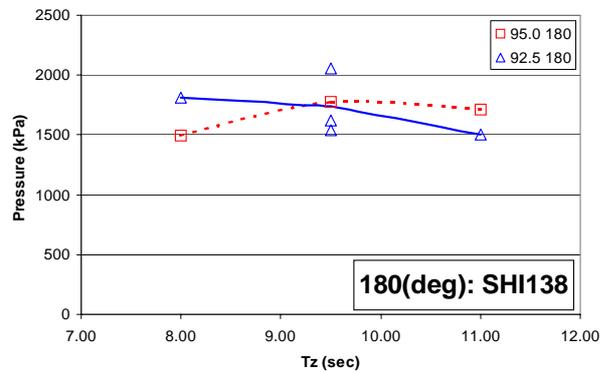


Figure 25 - Most probable 3hr pressures at 180(deg) heading for SHI 138K

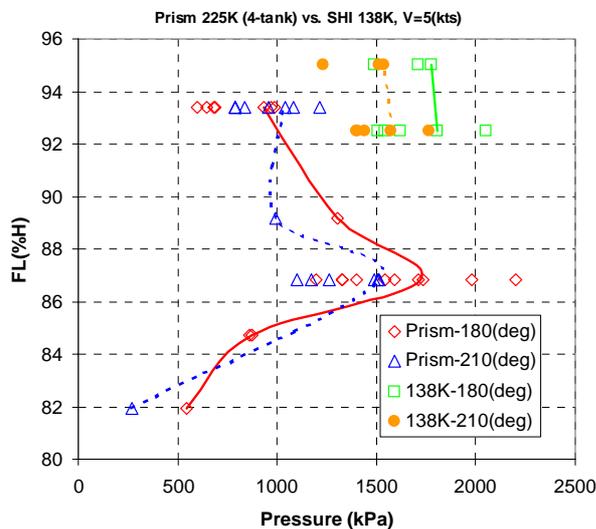


Figure 23 - Filling level vs. sloshing pressure for Prism 228K and SHI 138K

### CONCLUSIONS

Sloshing analysis for ConocoPhillips' Prism Tank LNG carrier has been performed by simulation and model testing for the purpose of obtaining 'Approval In Principle' for the Prism Tank concept. Model test conditions were selected based on sloshing simulations and model tests were conducted for Prism Tank ship and a conventional 138,000m<sup>3</sup> LNG carrier.

The sloshing simulations were carried out for Tank No.2 at the ship speed of 14.625 knots (75% of design speed as per ABS practice) and 5 knots for low seas and high seas, respectively, along 40-year waves in IACS Recommendation 34 wave scatter diagram. Two headings (180 and 150 deg) were selected for the model test based on simulation. Selected test conditions are varied between 8-12 sec of zero-crossing period and 10-16 m of significant wave height.

Sloshing model test results were analyzed for the Prism Tank ship (4-tank model) and a conventional 138,000m<sup>3</sup> carrier. The tests were in irregular waves at the ship speed of 5 knots. Three filling levels (98.5% V, 96.0% V, and 93.5% V) were applied to the Prism Tank ship and two filling levels (95% H, and 92.5% H) to the conventional ship. Due to high filling levels, only head

sea (180 deg.) and bow-quartering sea (210 deg.) were considered for the model test. The measured pressure is converted to the full scale using the Froude scaling law.

Comparison of the model test results is summarized as follows:

- The Prism Tank ship generally shows smaller pressure than the 138K ship. In average values, the Prism ship experiences 42% lower pressure than the 138K ship at near 98%V filling level, while the Prism ship pressures are about 4% lower near the 96%V filling level.
- As shown in the following table, the maximum average pressure for the Prism ship is found in the head sea condition with 96.0%V filling level, and is approximately 17 bars in full scale. The maximum pressure occurs at  $T_z = 9$  sec. For the 138K ship, the average highest pressure is about 18 bars at  $T_z = 8$  sec, also in head seas with 95%V filling level.

**Table 11 - Maximum averaged impact pressure for 228K Prism Tank ship and 138K ships**

Maximum Averaged Impact Pressure					
Prism 228K			138K		
FL(%V)	P(bar)	Head(deg)	FL(%V)	P(bar)	Head(deg)
98.5	10.3	210	96.8	17.7	180
96.0	17.3	180	95.0	18.1	180
93.5	5.5	180			

- Larger pressure was found in head sea condition (180 deg.) than bow-quartering sea (210 deg.) for both ships. The pressure difference between headings is smaller in Prism ship than in 138K. This lower dependency on heading angles may be attributed to the larger aspect ratio of free surface in Prism ship.
- Among filling levels, 96%V shows largest pressure in Prism ship. Combined effect from ullage spacing and free surface area could be one possible reason for this phenomenon. The 98.5%V and 93.5%V fill levels are nearly 50% lower in impact pressure compared to 96%V. For the 138K ship, the pressure at 92.5%H is slightly higher than the corresponding pressure at 95.0%H.

Based on the results, Prism Tank ship seems to show no significant increase in sloshing impact pressure compared to the conventional 138K ship. In fact, the pressure in the Prism tank is found to be similar in magnitude or even lower than the corresponding pressure in the conventional 138K ship in spite of its larger tank dimensions. The relative decrease of pressure in Prism ship is believed to be due to the unique shape of the Prism Tank, specifically, the larger upper chamfer and small free surface area. Consequent change in liquid motion including natural period change is a key factor for making the design beneficial.

Besides improved sloshing behavior, the Prism ship offers further advantages. Among these are the following:

- Hull form may be optimized with regards to LCB location because arrangement is not constrained by tank or cargo block length
- Initial cost estimates appear to show a small benefit to the Prism ship over the conventional ship. Further work is underway which may indicate a larger cost benefit for the Prism ship
- The membrane area to enclosed cargo volume is lower, possibly resulting in slight reduction in boil-off. Further work is planned in this area, since reduced boil-off is very advantageous for ships that may use onboard reliquefaction.

## REFERENCES

- [1] MARIN, "PRECAL V 5.0: User's Guide", Maritime Research Institute Netherlands, P.O. Box 28, 6700 AA Wageningen, The Netherlands
- [2] American Bureau of Shipping, 2002, "Guide for Building and Classing Membrane Tank LNG Vessels," October 2002
- [3] Kim, J. W., Shin, Y. S. and Bai, K. J., 2002, "A Finite-Element Computation for the Sloshing Motion in LNG Tank," ISOPE 2002, Fukuoka, Japan.
- [4] "Sloshing test of 138k/4 tanks LNG ship with partial filling," MARINTEK Report No. 820033.00.02, March 25, 2004