REDUCTION OF BOIL-OFF GENERATION IN CARGO TANKS OF LIQUID NATURAL GAS CARRIERS - RECENT DEVELOPMENTS OF GAZTRANSPORT & TECHNIGAZ (GTT) CARGO CONTAINMENT SYSTEMS" - Paper Nº 452.00 selected for Oral Presentation in CS9.1: PGCD Enhance LNG Facilities Compatibility

By David COLSON, Nicolas HAQUIN and Matthieu MALOCHET, GazTransport & Technigaz

1. BACKGROUND

In order to MEET the current needs of Ship-Owners and Offshore Operators, GTT has successfully completed an innovation program on its Mark III membrane containment system. GTT has also launched a development of its other principle membrane system, the NO 96, the first two phases of which will be completed during the second half of 2012.

These development activities demonstrate the adaptability of the GTT membrane technology to the evolving requirements of the Liquid Natural Gas (LNG) Industry.

During the transit of a Liquid Natural Gas Carriers (LNGC) from the loading terminal to the discharge terminal and vice-versa, the boil-off (BO) of LNG, which naturally evaporates within the tanks, is traditionally used as fuel and is burnt in the propulsion system of the vessel.

The traditional guaranteed boil-off rate (BOR) for an LNGC equipped with membrane tanks of capacity greater than 138.000 m^3 is 0.15% of cargo volume per day. Until recently, this amount of natural BO generated has been insufficient for the full propulsion requirements of the vessel and other fuel sources have been required. Vessels are generally resorting to forcing BO or using fuel oils.

Recent developments in propulsion systems have led to an increase in their thermal efficiencies (see figure 1 below). The industry has moved away from the use of steam turbines to the use of medium speed diesel engines, the so-called Duel-Fuel Diesel Electric (DFDE) engine.

At the same time, trading patterns of vessels have changed with the increase in the spot trade and vessels are now more likely to operate at lower speeds than the traditional cruising speed of 19 knots. As a consequence, the natural BO generated could exceed the quantity required to fuel the vessel. In this case, the vessel would be either forced to re-liquefy or burn the extra boil-off gas.

This results in extra cost (OPEX) or unnecessary wastage of gas and is not environmentally friendly.

For these reasons, GTT has launched the development for the reduction of the natural BO generated in membrane LNG carriers.

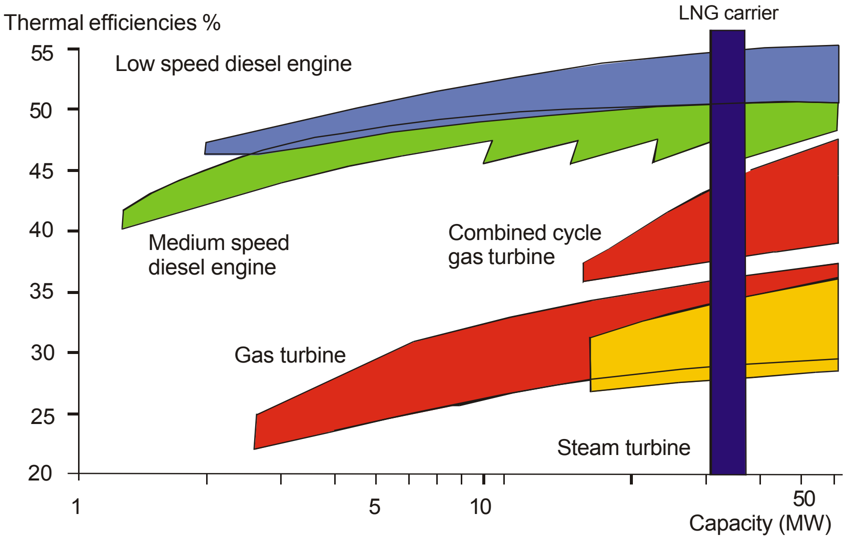


Figure 1: Requirement for lower BOR from use of more efficient propulsion system

2. AIMS

As previously stated, for membrane type LNGC (capacities greater than 138.000 m^3) equipped with GTT designed tanks, the current guaranteed natural BOR is 0.15% of cargo volume per day.

In order to satisfy, not only the market requirement for the use of more efficient propulsion systems, but also to add flexibility in LNGC operations such as change of route, spot trade, or temporary storage of LNG, a target of the completed, current and future developments by GTT is to reduce this value to 0.1% of cargo volume per day. Some applications for an even lower BOR are also currently being considered by GTT.

This paper will describe the development work completed and in progress, carried out to meet this target.

3. METHODS

A. The new MARK III system or "MARK III FLEX"

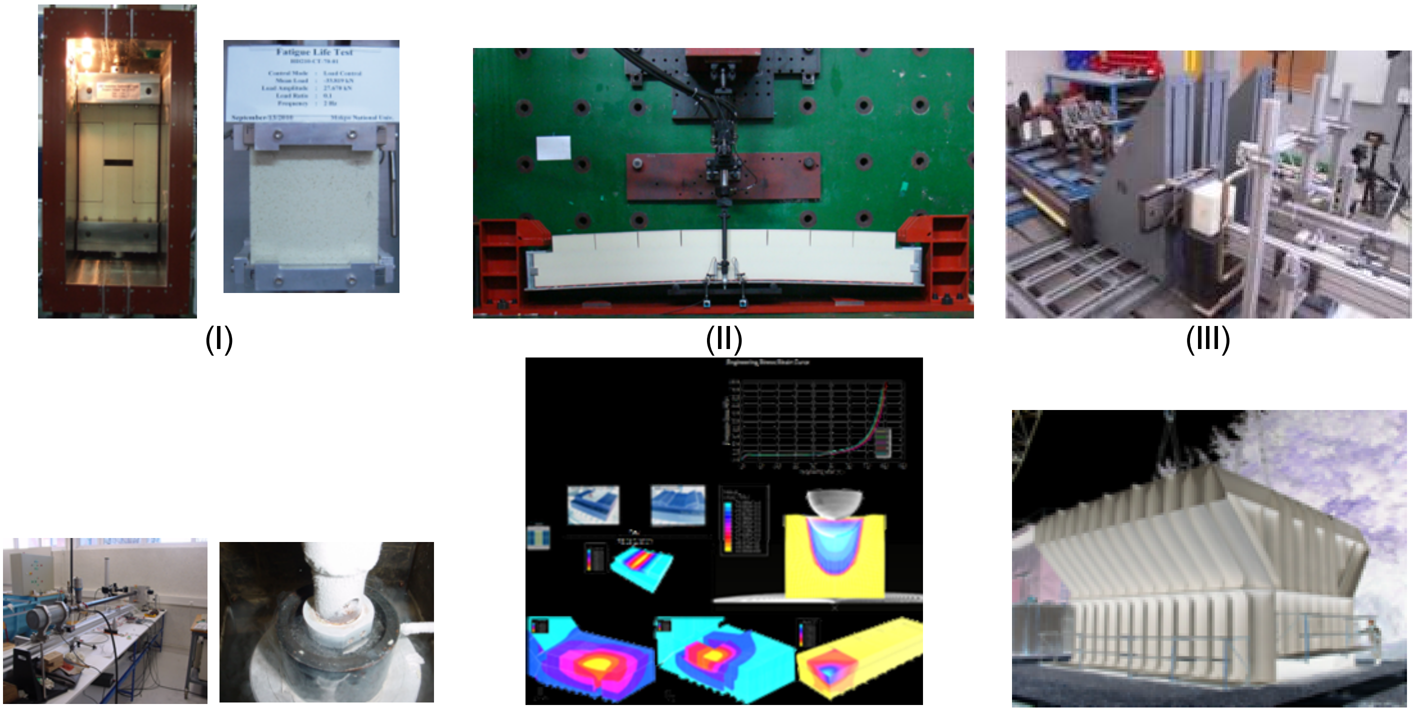
The present MARK III membrane system liner is composed of a primary stainless steel 304L membrane positioned on top of a pre-fabricated insulation panel which incorporates the composite secondary barrier or membrane. The containment system is directly supported by the ship's inner hull. The insulation consists of a load-bearing system made of prefabricated panels in reinforced polyurethane foam including both primary and secondary insulation layers and the secondary membrane.

In order to reduce the daily BOR, the thickness of the insulation panel can be increased from the standard 270 mm up to 400 mm, thereby reducing the Boil-Off Rate down to 0.1% per day. This replies to the market evolution of propulsion systems which require less feed gas.

The original design of the MARK III system had already envisaged the use of a thicker insulation. Indeed, Class had already given their Approval In Principal (AIP) for such a design. However, this idea had never been employed on an LNGC and it was decided to employ the current state of the art techniques to validate this system.

To ensure that the MARK III Flex system will behave effectively when submitted to its future environment (thermal loads, ship bending moments, ballast/cargo pressures, static/fatigue/dynamic loads as well as sloshing pressures, even if exceptionally high), an extensive qualification program (see figure 2 below) has been completed including :

(I) Static and fatigue tests under repetitive compression or elongation
(II) Bending tests at panel scale
(III) Dynamic tests on sub-systems
(IV) Material tests on foam coupons
(V) Finite Element Analysis (FEA) of Mark III Flex panels
(VI) Mock-up tests



(I) (II) (III)

(IV) (V) (VI)

Figure 2: Illustration of the extensive qualification program

The results of the qualification program confirm the fully satisfactory behavior of Mark III Flex CCS when submitted to bending and ballast tests as well as the ability of Mark III Flex CCS to withstand full thermal cycles, hull elongation cycles as well as repetitive sloshing events or cyclic cargo pressures.

a) Static strength assessment under worst conventional loading conditions

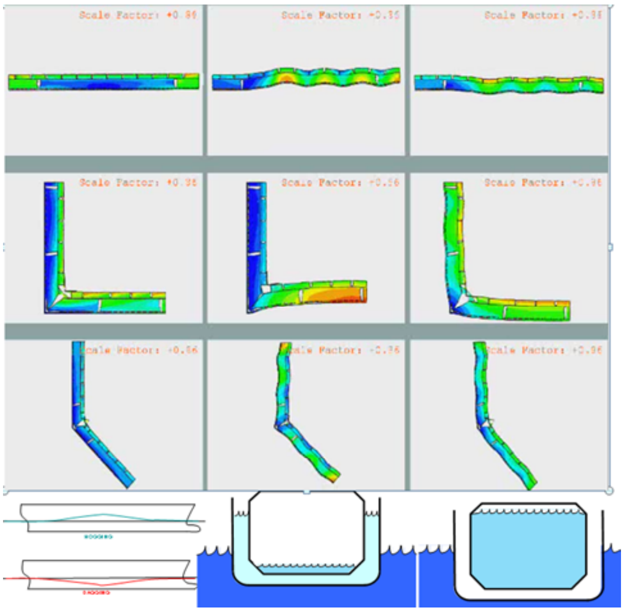
The ultimate strength of the MARK III Flex Cargo Containment System (CCS) including flat areas and typical corner sections has been assessed when the structure has been submitted to the conventional loads occurring during a ship life cycle and as required by the International Code for the construction and equipment of ships carrying liquid gases in bulk (IGC Code):

- Thermal load in normal conditions (-163°C on primary membrane)
- Thermal load in flooded conditions (-163°C on secondary membrane)
- Ship hull bending due to wave motions
- Cargo and ballast pressure loads

A set of tests and calculations (II, V and VI above) has been performed to assess the adequate behavior of MARK III Flex CCS under the above mentioned load conditions.

b) Static strength assessment by Finite Element Analysis (FEA)

The typical sections of MARK III Flex CCS have been modeled using the finite element calculation method (see figure 3 below). The simulation showed that the stresses induced in the MARK III Flex materials were less than twice as much as the individual strength of each component. Consequently, a safety factor of at least 2 is obtained for all the materials: this provides enough margins to anticipate that the fatigue behavior of those components will be acceptable when submitted to cyclical loads.



Hull bending Ballast Pressure Cargo Pressure

+ Thermal load (thermal gradient applied through the insulation)

Figure 3: Typical calculations of MARK III Flex CCS submitted to conventional and IGC load conditions

c) Static strength assessment by large scale tests

Based on the promising results from the FEA calculations, some large scale tests (II and VI) have been performed under the most severe in-service conditions, such as extreme ballast loadin d and repetitive sloshing loads:

- preliminary bending tests at panel scale
- full test program on specific mock-up of the system (see figure 4 below)

The purpose of the bending test was to investigate the effect of increased thickness and/or density on the panel anchoring (hull/mastic/plywood). The principle of the test consisted in applying a four-point bending load to the insulation panels. Various kinds of samples have been designed to represent the specific parts of flat areas (panel and transition areas).

The purpose of the mock-up test was to check that key functions of the new MARK III Flex CCS are fulfilled when submitted to heavy ballast conditions and thermal loads. The anchoring of the panel to the inner hull and the tightness of secondary barrier had to remain in fully satisfactory safety conditions in spite of the severe tests conditions.

Eight insulation panels (four by two) of higher thickness and density were fitted on the inner bottom of the mock-up. The scale of the mock-up to full-scale was about 1:7.

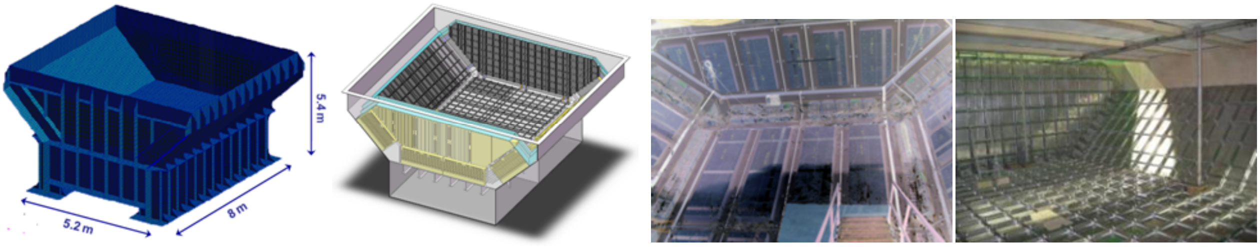


Figure 4 : Mock-up size and arrangement

Specific instrumentation was fitted to record in real time the temperature through the insulation panels (from the inner hull to the primary barrier) and the hull deflection.

Two thermal cycles were performed, one representing the normal conditions with liquid nitrogen (LN_2 at -196°C) in contact with primary membrane, the other one representing accidental conditions with primary space fully flooded and liquid nitrogen (LN_2) in contact with secondary membrane. Liquid nitrogen was used in lieu of liquid natural gas for safety reasons, offering more conservative conditions: the liquid temperature of LN_2 being -196°C instead of -163°C for LNG. To be in line with the IGC code, the LN_2 was kept in contact with the secondary membrane for fifteen days. For each thermal cycle, a 3 bar ballast pressure was applied to the inner bottom via a hydraulic pressurization unit.

A thermal cycle can be considered as follows:
Step 1; complete system

- cool down from room temperature to -196°C
- temperature stabilization of the secondary membrane
- ballast pressurization up to 3 bar
- release of ballast pressure
- warm-up to room temperature

Step 2; removal of primary membrane

- flooding of primary space
- ballast pressurization up to 3 bar
- release of ballast pressure
- inner hull scanning to check for cold spots
- warming-up
- mastic ropes scanning to verify if there is any damage
- verification of tightness of the secondary barrier

In addition to the instrumentation set-up in the mock-up, specific non-destructive inspections were performed to check the anchoring to the hull and potential leak points. The adhesion of mastic ropes was checked by ultrasound method commonly used in the industry to detect defects in bonds, welds or materials. The potential leakage was controlled by thermal mapping of the inner hull thanks to an infrared camera to check if some cold spots occurred during the flooding cycle (see figure 5 below).

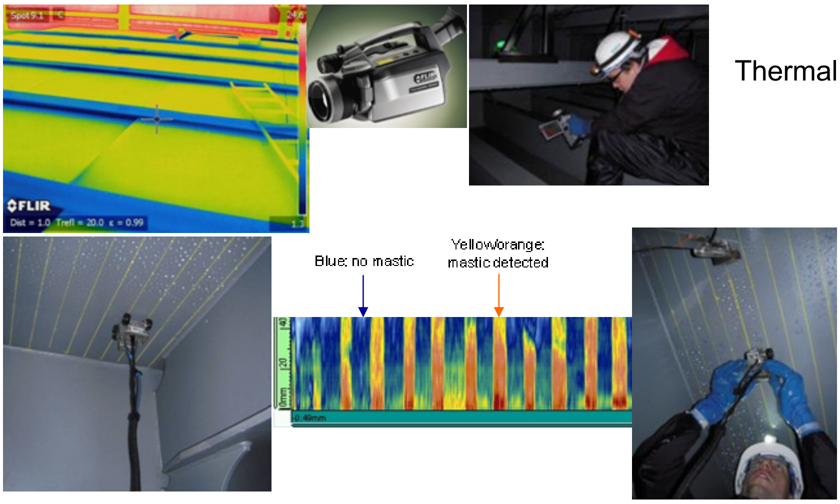


Figure 5: Non-destructive methods to check mastic adhesion and hull temperature

The anchoring of the MARK III Flex CCS to the hull remained fully satisfactory during the various bending tests at panel scale in one hand and during the two thermal cycles of the mock-up where heavy ballast pressure was applied on the other hand. The new CCS is therefore able to withstand typical hull deflection occurring during ship operation.

The thermal mapping of inner hull and the conventional secondary barrier tightness test (SBTT) which consists in depressurizing the secondary insulation and measuring the decay rate of pressure evolution as a function of time, did not reveal any leak despite the severe and conservative test conditions applied. The inner hull temperature remained greater than -5°C and the decay rate was in the same order of magnitude after each cycle.

The MARK III Flex CCS is therefore proved to be fully in accordance with IGC code requiring that the CCS must be able to withstand the worst standard conditions during a 15 days period.

d) Dynamic strength assessment by FEA calibrated by tests for exceptional sloshing loads

After having demonstrated that the MARK III Flex CCS is able to withstand the most severe conventional loads occurring in a ship life, the GTT team investigated its ability to withstand sloshing loads. The methodology, called “direct approach”, is used to determine the CCS capacities and is based on structural calculations simulating the dynamic response of CCS submitted to direct pressure pulses. In order to validate to this direct approach, it was necessary to characterize by tests the dynamic response of the Reinforced Polyurethane Foam (RPUF), taking into account cryogenic and dynamic conditions, and to correlate the Finite Element Model (FEM) with the tests results.

In this respect, dynamic material tests (III and IV) were performed at a suitable range of scales to ascertain the behavior of RPUF as a function of density and to build the final FEM of MARK III Flex CCS. Material tests on foam coupons, dynamic impacts on MARK III Flex subsystems and static compression on MARK III Flex panels have been performed.

The dynamic test campaign on foam coupons and subsystems showed an increase of compressive strength of more than 100% for the 210 kg/m3 high density (HD) foam when compared to the 130 kg/m3 standard density foam. It was also observed that the impact energy to obtain the same level of crushing between HD and standard density foam had to be increased by a factor of more than 2.

Those tests results allowed GTT to reach a high level of correlation between tests and calculations, thus validating the FEM.

Based on the correlation work, the FEM of MARK III Flex CCS was built and direct pressure pulses were simulated. The analysis indicated to an impressive increase in capacity for MARK III Flex CCS made with high density foam compared to the standard MARK III.

Another conclusion resulted of the analysis is that the effect of panel thickness on the capacity is almost negligible. Consequently, the 0.1 % BOR product of MARK III Flex will have the same capacity as the standard MARK III.

e) Fatigue strength assessment by FEA calibrated by tests for exceptional sloshing loads

The ultimate strength behavior of MARK III Flex CCS has been checked regarding conventional and sloshing loads. The fatigue strength has been also specifically assessed. Static calculations already showed significant margins between the individual component strength and the stresses induced in them. Specific tests (I) have been performed to check the fatigue behavior of the secondary barrier assembly and cyclic compression of the new HD foam.

On the one hand, specific sandwich samples were designed to faithfully represent the behaviour close to the secondary barrier. These samples are assembled in such a way as to fully simulate the cross-section of the MARK III Flex CCS assembly.

The sandwich samples were submitted to various tensile load levels. The tests have been performed at the in-service temperature of secondary barrier (-110°C) to establish a Wöhler curve and to calculate a fatigue damage linked to ship hull bending and to thermal cycles.

Considering a typical distribution of maximum ship hull bending and 2 000 full thermal cycles, the fatigue damage of the secondary barrier assembly is still less than 0.5 for 40 years life time.

On the other hand, high density foam blocks were tested under cyclical compression tests. These tests were performed at both room and cryogenic temperatures to establish Wöhler curves and to calculate fatigue damage linked to cyclical cargo pressure or to potential repeated sloshing events.

Considering typical sloshing events or cargo pressure distributions, the fatigue damage of the high density foam is still less than 0.5 for 40 years life time. It was also demonstrated that total fatigue damage linked to sloshing is obtained for less than 10 cycles, showing that sloshing is not a matter of fatigue.

B. The new NO96 system or “NO 96 EVOLUTION”

The current in-service NO 96 membrane system consists of 2 identical barriers or membranes in 36% Ni steel (very low coefficient of expansion) positioned on top of pre-fabricated primary and secondary insulation plywood boxes. The insulation material used in the boxes is “perlite” (granules of crushed volcanic rock). The containment system is directly supported by the ship’s inner hull.

The reduction in the daily BOR down to 0.15% for NO 96 is accomplished in two steps:

An initial gain with a BO reduction to around 0.125% of volume per day can be obtained by replacing the perlite by a material having improved thermal properties. The material chosen is glass wool. Glass wool is already used in the construction of the NO 96 system to fill in the space between adjacent boxes. It is therefore approved and compatible with LNG. This solution is known as NO 96 GW.

As this modification does not involve major structural changes such as an increase in thickness (see the MARK III Flex development above), the validation process is relatively rapid and does not include significant amounts of testing. In fact, the main issue is the industrialization, and, in particular, the correct positioning of the glass wool in the plywood boxes.

In order to optimize the thermal properties of the assembly, it is important to avoid gaps between the glass wool and the inner sides of the boxes and also a correct height of glass wool in the box. Gaps induce an increase in thermal flow and must therefore be limited in width and length. On the other hand, a gap will ease the filling of the boxes and remove the possible complication of bending of the box bulkhead.

In order to avoid any conductivity inside the boxes through the glass wool, several layers are required with the inclusion of Kraft paper between them. The first layer of glass wool will require some gap (1mm) so that the assembler can be certain that the glass wool reaches the bottom of the box. The other layers will have a nominal gap width of 0 mm. In the Primary boxes there are 5 layers of glass wool and in the secondary boxes 6 layers.

Currently (end of January 2012), GTT licensed shipyards are optimizing the assembly process in order to enter into full production by June of this year.

The final step to bring the NO 96 system BOR down to 0.1% of volume per day is to combine the use of glass wool with a new secondary layer. The primary boxes are identical to those of the NO 96 GW solution, but the secondary insulation layer (300 mm thick) is split into 2 parts; a plywood box filled with glass wool 100 mm thick and a pre-fabricated polyurethane foam panel, 200 mm thick (see figure 6 below). This solution is known as NO 96-L-03.

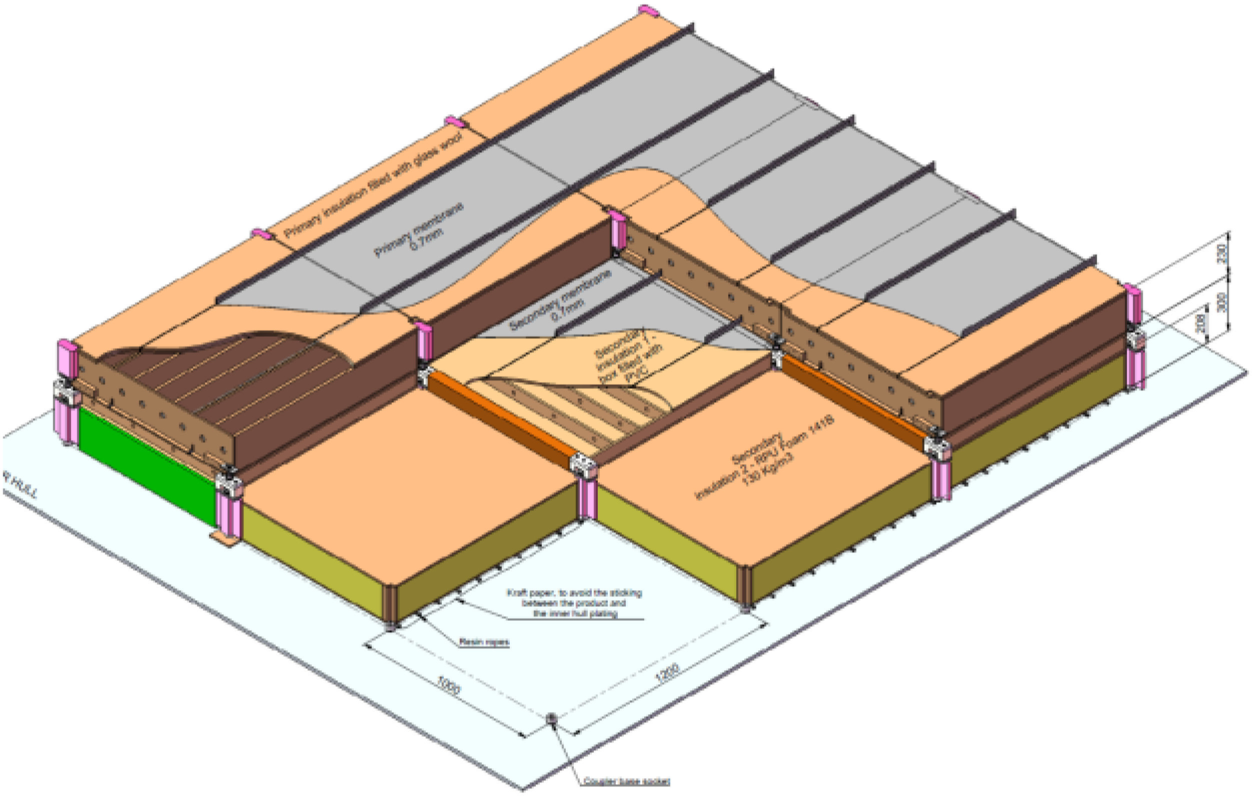


Figure 6: Schematic diagram of NO 96-3-L

In order to verify that the new system fulfils all the requirements of the traditional NO96 in terms of security, a qualification plan approved by the major classification societies has been launched. This qualification plan includes static strength test on the full system (primary plus secondary boxes), dynamic tests, as well as thermal and mechanical calculations under full load and ballasts conditions.

The qualification plan agreed by major Classification societies is simplified because the new system consists only in the introduction of a new secondary box.

Primary box, couplers, primary and secondary heights, corners both longitudinal and transversal, boxes arrangement around PTBS, gas dome and liquid dome are exactly the same as the NO96 GW system.

The decision to choose this solution was made in order to reach the thermal performance and strength of the system while shortening the time of development.

a) Thermo-mechanical calculations

The calculations were launched to check that the safety factor remains above 2 in normal conditions and 1 in flooded conditions, the primary space being deemed to be full of LNG (See figure 7 below).

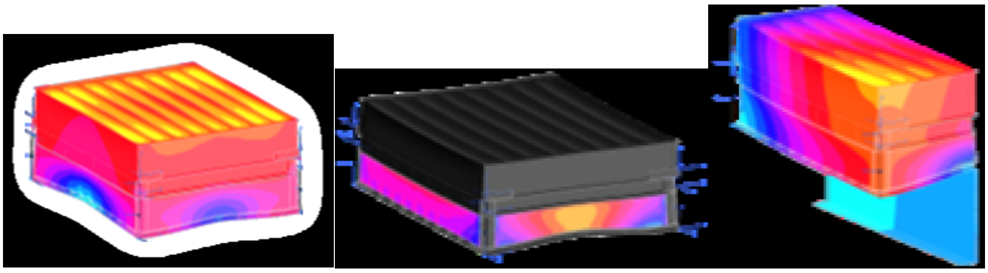


Figure 7: Thermo-mechanical calculations

b) Static tests

The static strength tests provide the reference strength of the new system (NO96 original primary box plus the new secondary boxes). They have been carried out through compression tests for which the system is placed under a press of 1000 metric Tons.

Loading is applied on several different area patches in order to get the full strength versus surface area curve. Examples of different patches are represented in the Figure 8 below:

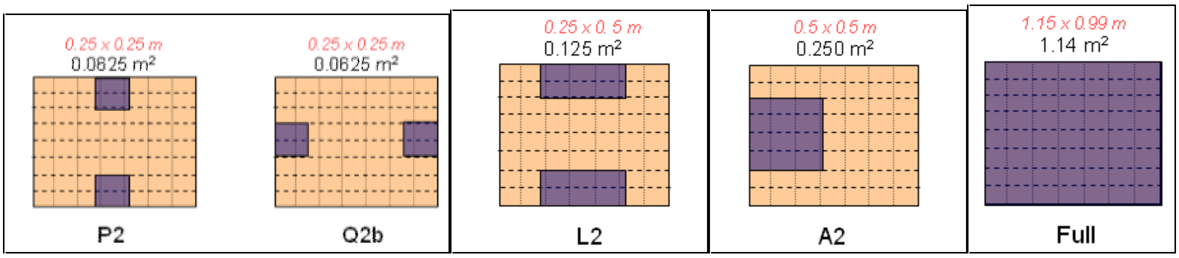


Figure 8: Examples of different loading areas

Figure 8a) Load Applied to full surface area of the box (1.2 m²)

Figure 8b) Load applied on small 0,0625 m² surface

Figure 8c) Load applied on two 0,125 m² surfaces

The strength of the new system can be compared to the reference type of box which consists in the 3 other types of reinforced boxes offered by GTT and applied in the tank in locations depending on the expected sloshing loads (see Figure 9 below). In figure 9, curves for S (standard boxes), R (reinforced boxes), UR (ultra reinforced boxes) and the new 3-layer system (L03-R) are shown. The new system is close to the performance of the ultra reinforced boxes, which are only generally used in areas of the tank where sloshing loads are at their highest. The new system strength is therefore fully acceptable.

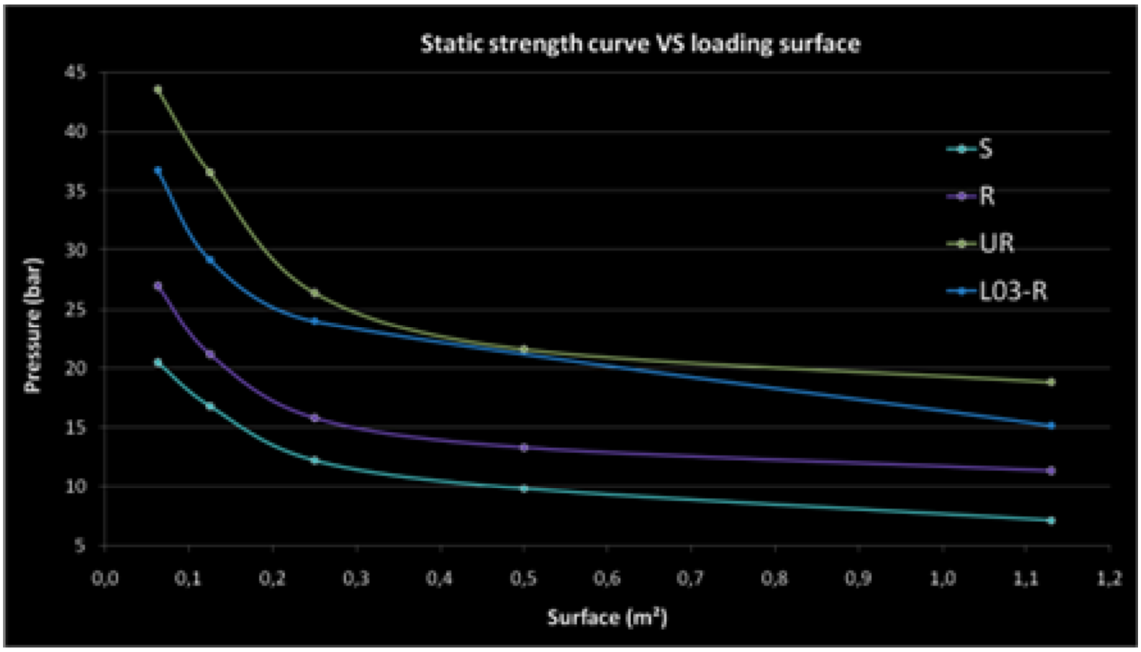


Figure 9: Comparison of strength for NO 96 boxes

Static strength versus loaded surface. Comparison of new L03 box to standard (S), Reinforced (R) and ultra reinforced (UR) of classical NO 96.

c) Dynamic tests

Dynamic have been performed on the system. The test setting consists in an impactor characterized by its mass and velocity which is accelerated along a rail so as to impact the sample under test (see Figure 10 below).

Figure 10: Small dynamic setting for simplified boxes (13 kg impactor at approximately 8 m/s)

The load is applied first on a simplified section of secondary box consisting of (see Figure 11 below):

- a box with only one bulkhead (representing the intermediate box)
- a small panel of 200 mm thick foam (representing the foam panel)

Figure 11: Simplified section of new secondary box

This test enables the validation of the satisfactory dynamic behaviour of the panel when subjected to a spherical impactor simulating the local concentrated loading due to sloshing. The results are compared to similar results on small standard box systems in order to check that no abnormalities occur due to high dynamic loads not detected during static tests.

The whole system is then tested under dynamic conditions. This test enables the identification of the ultimate energy that the new system can sustain. It has been verified that this sustainable energy is higher than the one of standard NO96 system.

This test enables the identification of the energy the new system can sustain. It is verified that this sustainable energy is higher that the equivalent standard NO96 system. A full box set-up is tested on an automotive crash-test bench (see Figure 12 below).

Figure 12: Crash-test for full box system (2T impactor at 4 m/s)

4. RESULTS

The results of the MK III qualification program illustrate:

- The fully satisfactory behavior of Mark III Flex CCS when submitted to bending and ballast tests,
- The ability of Mark III Flex CCS to withstand full thermal cycles, hull elongation cycles as well as repetitive sloshing events or cyclic cargo pressures,
- Satisfactory static strength under worst conventional loading conditions

All this research work was reviewed by DNV who delivered an Approval in Principle on June 24th 2011. GTT is now working on the next stage of Approval (Ship Application) and has begun the approval phases with the other world known Classification Societies.

GTT licenses shipyards are currently optimizing their industrial processes in order to construct the NO96 GW system. Class are currently in the process of announcing AIP and ship application approval.

AIP for the NO96-3-L is expected at the end of March 2012 and ship application approval is expected in August 2012. Testing has so far proved positive.

5. CONCLUSION

GTT has developed a new MARK III Flex membrane technology offering more flexibility in terms in the reduction of the generation of natural BO. The testing and analyses showed that a thickness increase up to 400 mm of standard Mark III panel made with standard density foam allows a reduction of BO down to 0.1% of tank volume per day.

To qualify these solutions which cope with new market requirements, an extensive qualification program was carried out. All the studies provided fully satisfactory results.

GTT are currently in the process of approval for an evolution of the NO 96 system. The NO96 GW solution gives a BOR down to 0.125% of volume per day, and the NO96-3-L permits a BOR down to 0.1% of tank volume per day.

All current testing has been reviewed by Class and Approvals in Principal have either been received or are in progress.

These successful improvements fully correspond to the market demand; 19 LNG Carriers have already been ordered for the low BO application for MARK III and NO 96 technologies.