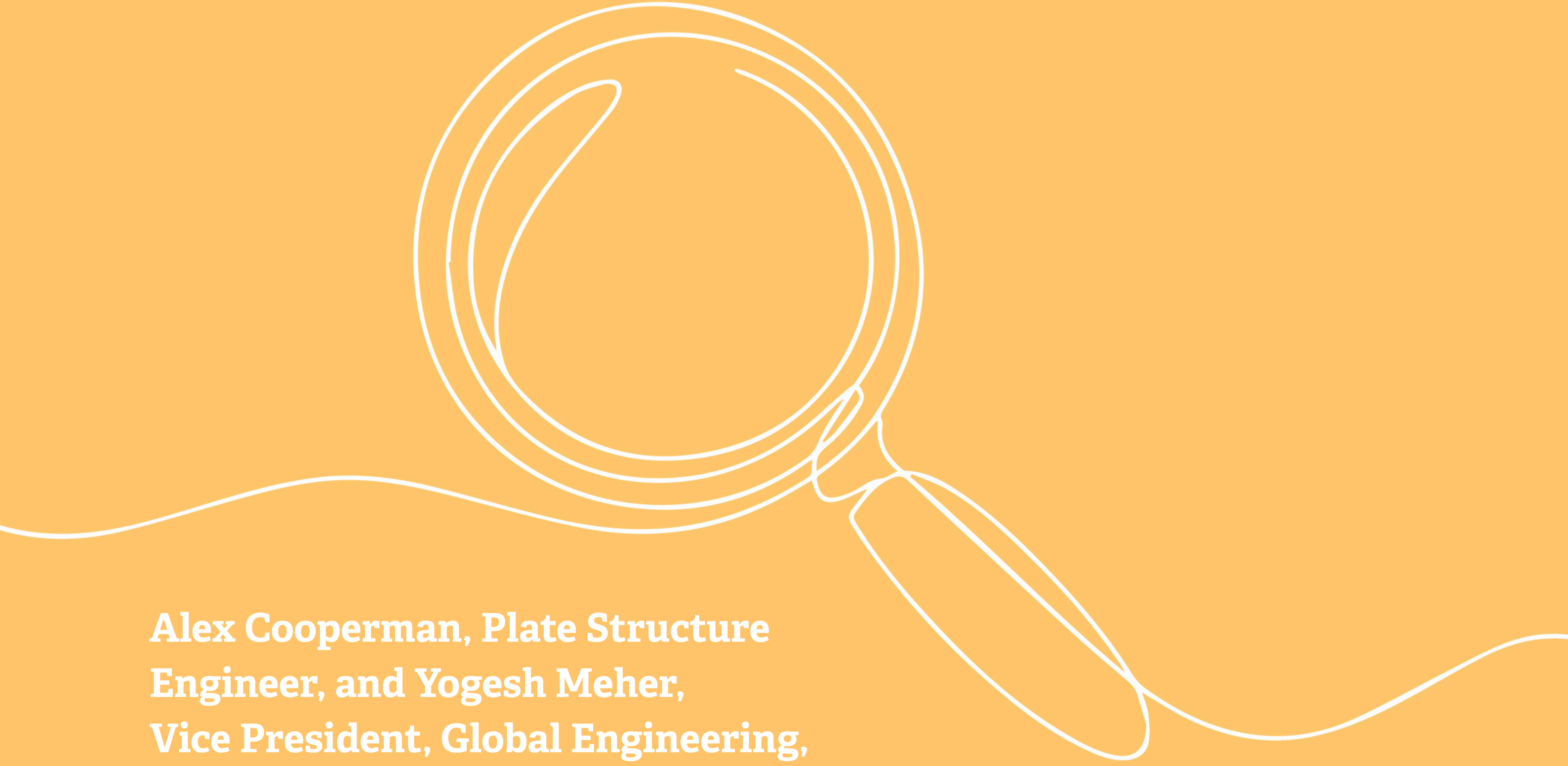
the hidden protection in LNG tanks



Alex Cooperman, Plate Structure Engineer, and Yogesh Meher, Vice President, Global Engineering, CB&I, examine the different liner configurations available for the LNG market, and outline the issues and benefits for each one.

There is more than one means to contain liquid and vapour in an LNG tank. In fact, the industry has standardised several configurations, such as single containment and full containment. Secondary containment is always provided and serves as an additional layer of protection against potential leaks or spills, providing a safeguard in the event of primary liquid containment failure. The secondary containment is engineered to prevent the spread of LNG beyond the primary area, by installing either a barrier (such as a dike or berm) in a single containment system or, in a full containment system, an outer tank surrounding the inner tank, which can be designed to contain both product vapour in service and liquid in case of a primary container failure. Secondary containers in full containment LNG storage systems are typically made from pre-stressed concrete.

Because concrete is a gas-permeable material, the outer concrete wall liner becomes an important component of the secondary concrete container for a full containment LNG tank. To ensure the concrete secondary container stays vapour-tight during operation, a welded metallic leak-tight liner is typically installed on the inside surface of the concrete wall. The liner serves the following purposes:

- Prevents product vapours from escaping the full containment system in service.

- Prevents atmospheric gases from entering the tank system.

- Prevents moisture ingress into the tank's insulation system.

There are two types of metallic liners currently in use by the industry:

1. Paste-on liner (POL) system, which are lap-welded to steel embedments installed on the inside surface of the concrete wall.

2. Butt-welded liner system, which are directly anchored in the concrete wall. This can be either a thin, non-self-supporting liner requiring external stiffening during installation, or a self-supporting free-standing liner (FSL) that serves as the interior formwork for the concrete wall construction.

The liner is normally constructed from carbon steel suitable for the temperature to which it may be exposed. Industry standards provide minimum guidelines for the liner material, configuration, and non-destructive examination (NDE), as summarised in Table 1. No guidelines on the liner design are provided in the standards.

Lap-welded POL

Industry standards do not prescribe a specific POL configuration. Consequently, designs vary across contractors based on individual project specifications or, in the absence of such requirements, the contractor's proprietary engineering standards. The most widely used POL design utilises liner plates lap-welded to continuous vertical embedment strips, spaced uniformly around the inside surface of the concrete wall. In this configuration, both vertical edges of each plate are welded to the embedments. Alternative configurations are less common but include welding only one edge of the liner plate to the embedment while overlapping the adjacent plate. Some contractors also use discrete rectangular embeds instead of continuous vertical strips, with overlapping liner plates lap-welded to the anchors to maintain leak tightness.

The described POL configurations are conceptually shown in Figure 1.

POL installation can be performed following the completion of the concrete wall, or concurrently with its construction. However, simultaneous construction requires heightened co-ordination between civil and mechanical trades to mitigate schedule interference and ensure site safety.

To optimise the construction sequence, a POL is often installed before the concrete wall post-tensioning. The behaviour of a POL at various stages of wall construction and in service is illustrated in Figure 2.

Post-tensioning the wall prior to liner installation avoids initial compressive buckling. However, the liner may still buckle over time as concrete creep induces inward wall deformations. Depending on the concrete mix, environmental conditions, and timing of post-tensioning, the magnitude of wall inward deformations associated with concrete creep may exceed the elastic deformations due to concrete wall initial post-tensioning. Once the concrete wall moves inward due to post-tensioning and creep, the circumference of the wall inside surface reduces. However, the liner circumference remains unchanged, forcing the liner to buckle. Once the buckled liner is pushed by internal pressure towards the concrete wall, it deforms (Figure 3).

Non-symmetrical deformation is the most probable scenario, as it accounts for inherent variables such as liner plate waviness, concrete wall tolerances,

Table 1. Industry-standard requirements for concrete wall liner

	API620 Annexes R & Q	EN14620-3:2006	prEN14620-2 & prEN14620-3 proposed revisions
Material	Selected following rules in API620 Annexes R & Q	Selected following rules in EN14620-2:2006	Selected following rules in prEN14620-2
Configuration	Both butt-welded and lap-welded are allowed	Not defined	Not defined
Minimum thickness	3/16 in. (4.76 mm)	3 mm	5 mm
Welding	Partial or full penetration butt- welded or lap-welded to embedment plates. If lap-welded, two pass minimum	Single lap-welded	If lap-welded, two pass minimum
NDE	Vacuum box for leak tightness		

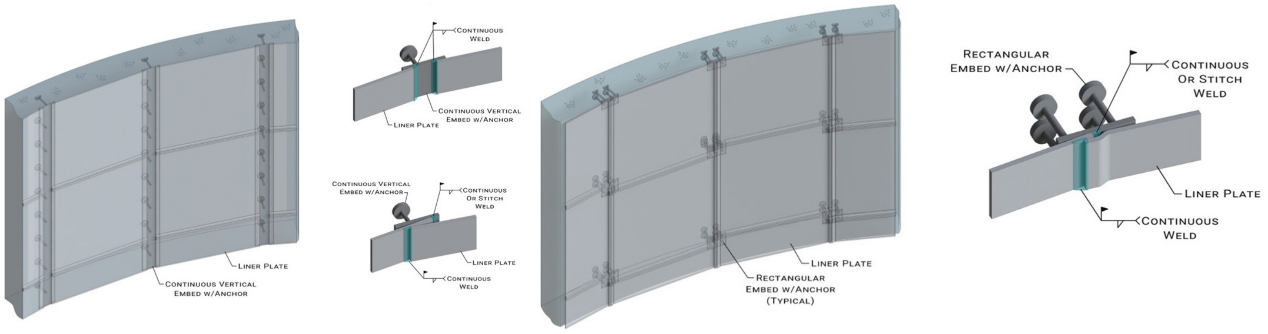


Figure 1. Paste-on liner (POL) configurations: POL attached to continuous vertical embedment strips (left), POL attached to discrete rectangular embedments (right).

and minor inconsistencies in the weld profiles across embedment strips. These combined factors lead to an asymmetrical deformation pattern, which enhances the rotation at the liner attachment to the embedment.

Liner buckling and subsequent deformations due to internal pressure generate significant strains in the fillet weld attaching the liner plate to the embedment. The analysis indicates that the strains at the weld toe may approach 10% (Figure 4).

Fillet welds may have imperfections like incomplete fusion. Small 1 – 2 mm recess of embedment plates, common during construction and within construction tolerances of the concrete wall design standards, is also possible. These imperfections further increase strains at the fillet weld toe. Under the worst conditions, the strains in the weld may significantly exceed strains shown in Figure 4. High strains in the weld toes, coupled with cyclic loading conditions due to tank internal pressure fluctuation in service, may result in fillet weld cracking and subsequent product vapour leaks. High pressure tanks with greater amplitude of pressure fluctuation have higher potential for vapour leakage compared to low pressure tanks.

High strains in the fillet welds may shed light on why gas leaks in service were reported for some tanks with POLs.

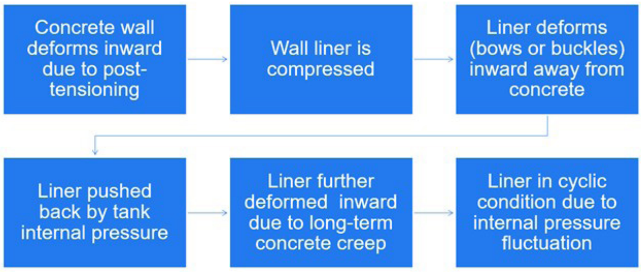


Figure 2. POL behaviour.

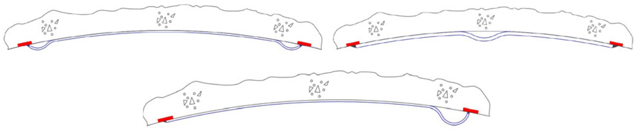


Figure 3. Buckled liner pushed by internal pressure towards concrete wall: symmetrical – idealised condition with perfectly symmetrical liner, concrete wall, and welds (top), and non-symmetrical – realistic conditions (bottom).

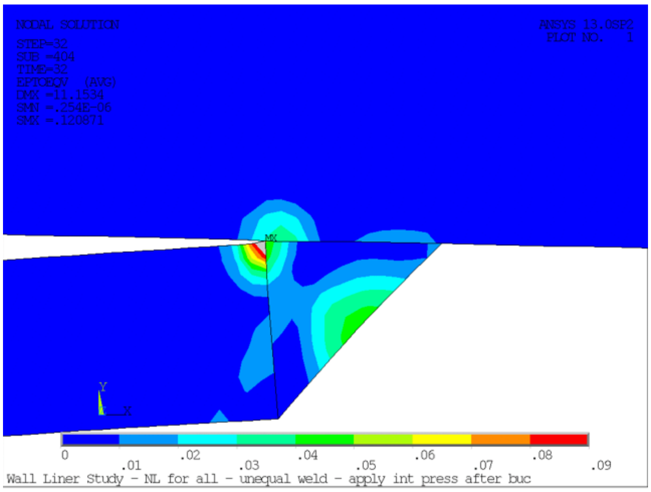


Figure 4. Strains in POL fillet weld.

This discussion is based on the liner plate welded to the vertical embedment strips at both vertical edges. The alternative detail featuring overlapping plates induces higher strain levels, as the rotational angle at the overlap is greater than that of a plate welded directly to the embedment. Consequently, this configuration is more susceptible to structural cracking.

Any liner crack for a POL welded to discrete rectangular embedments, as shown in the right of Figure 1, results in product vapour circulating in the entire space between the liner plates and the concrete wall. Consequently, should a product vapour leak occur, repairing this liner type is largely impractical. Attempting to purge vapour from the space between the liner and the concrete wall carries a significant risk of causing the liner to completely disengage from its multiple embedments.

Furthermore, the inherent flexibility of the liner, which leads to buckling and subsequent deformation, makes the structural analysis highly non-linear. The results are extremely sensitive to geometric imperfections in the liner plates, embedments, concrete wall inside surface, and fillet welds. As a result, considering all geometrical variables, it does not appear practical to accurately predict the liner behaviour by analysis.

The requirements in the tank standards specifying 5 mm minimum wall liner thickness and two-pass welding are as good as practically achievable. However, they do not guarantee with absolute certainty that the POL will never leak in service.

Butt-welded liner directly anchored in concrete wall

A butt-welded liner anchored directly to the concrete wall can be either a thin not self-supporting type, with thickness typically ranging between 6 – 8 mm, or a self-supporting FSL, with thickness in the range of 14 – 24 mm, depending on the tank diameter and height and the weight of the roof liner, suspended deck, and deck insulation.

Thin butt-welded liner

A thin butt-welded liner requires internal stiffening to resist concrete pressure during wall construction. Furthermore, the thin liner lacks the capacity to support the weight of the rings above, the weight of the roof liner, and weight of the suspended deck with insulation.

Therefore, erection of a thin butt-welded liner should be performed concurrently with building the concrete wall, which significantly complicates the overall construction process and keeps concrete wall construction on the critical path. Also, civil and mechanical trades must work concurrently, often overlapping, which reduces efficiency and significantly complicates construction management and safety.

If liner anchors are spaced too widely, thin butt-welded liners are susceptible to buckling between the anchors following post-tensioning and subsequent concrete creep. While butt-welded liners are less sensitive to overstraining from buckling and pressure fluctuations, these deformations must still be accounted in the liner's analysis and design. Liner buckling may be avoided, and direct transfer of internal pressure to concrete wall provided, if closely spaced anchors are installed on the liner plates' outside surfaces prior to wall concreting. However, excessively tight anchor spacing may create congestion for installation of wall inside face reinforcement and further complicate wall construction.

Self-supporting FSL

A butt-welded FSL is constructed using plate thickness that allows the liner to support concreting pressure during wall construction without additional stiffening. The FSL acts as an inside face formwork for concrete construction.

Also, the FSL is designed to handle the weight of the roof liner, suspended deck, and deck insulation, as well as to resist any other loads which may apply to the tank liner during construction, including live load on the roof liner and suspended deck and wind loads.

The liner anchors are spaced on the outside face of the FSL to prevent liner buckling due to wall post-tensioning and subsequent creep in both circumferential and vertical directions. The required anchor spacing to prevent buckling typically varies between 600 – 1200 mm, depending on the liner thickness and amount of post-tensioning, and can be easily determined. By preventing liner buckling and disengagement from the concrete after post-tensioning, the liner plates remain in a state of biaxial compression throughout the tank's operation. Tank internal pressure does not affect the liner and is directly transferred to the concrete wall structure.

The analysis and design of an FSL is straightforward due to the clearly defined load transfer path. Depending on construction requirements, an FSL can be designed with either double-sided or single-sided, full or partial-penetration butt welds. However, in any case, the possibility of product vapour leaking through the FSL in service is eliminated.

A qualified tank builder with experience in flat-bottom tank construction can construct an FSL quickly and efficiently. Upon completion of the FSL, the roof liner with a suspended deck constructed concurrently inside the FSL by the same mechanical construction team can be lifted in place by air-raising. This process creates an enclosed space, allowing construction of the inner tank to start quickly without being affected by weather and environmental conditions. The concrete wall construction can be performed by a separate civil construction team without impacting the overall project schedule (Figure 5).

In summary, while the initial material cost for an FSL is higher than that of a thin, non-self-supporting butt-welded liner or a POL, the FSL system offers the following strategic benefits:

- Eliminates the potential for product vapour leaks during tank operation.
- Removes concrete wall construction from the project's critical path.
- Facilitates an earlier start for inner tank assembly and insulation installation.
- Serves as the interior formwork, simplifying the concrete wall construction process.
- Decouples concrete work from the primary schedule, allowing for superior planning, preparation, and execution.
- Minimises interference between civil and mechanical teams, significantly improving construction efficiency and safety.
- Provides a simplified engineering and analysis process.

Figure 5. Construction of a full containment tank with free-standing liner.

Advancing of the inner tank construction, removing concrete work from the critical path, and improving efficiency by eliminating trade interferences due to using FSL allows a reduction of several months in the tank system construction schedule and, as a result, reduces overall project cost. FSL benefits are most obvious in high construction labour cost regions (for example, Europe, the US, Australia, Canada, and Japan), where material cost is a much smaller portion of the overall tank system cost compared to the cost of labour. Furthermore, the FSL system provides long-term assurance for tank owners by eliminating the risk of operational vapour leaks through the wall liner, which could otherwise trigger regulatory action or result in significant environmental impact.

Conclusions

POL systems, commonly used in LNG tanks, carry a significant risk of operational vapour leaks. While welding each plate to continuous vertical embedments at both edges offers the lowest risk within this category, the least desirable configuration utilises discrete rectangular anchors. This latter design makes leak repairs virtually impossible, as product vapours can circulate freely through the entire interstitial space between the liner and the concrete wall.

Industry standards establish 'best practice' guidelines for POL systems, typically stipulating a minimum plate thickness of 5 mm and the use of two-pass welding. Despite these measures, no POL configuration can fully guarantee a gas leak-free service life.

Thin, not self-supporting butt-welded liners anchored directly in concrete offer superior leak-tightness compared to POL systems. However, this method necessitates concurrent liner installation and concrete wall construction, which increases operational complexity. The resulting interference between civil and mechanical trades often leads to higher construction costs, extended project schedules, reduced efficiency, and more demanding safety management.

A self-supporting butt-welded FSL system appears to be the most attractive option, guaranteeing wall leak tightness in service while providing both schedule and overall cost advantages, especially in high labour cost parts of the world such as the aforementioned countries.

For the reasons outlined, the FSL is CB&I's preferred method for concrete wall liner construction in full containment LNG tanks. **LNG**