23rd World Gas Conference, Amsterdam 2006

SAFETY COMPARISON OF LNG TANK DESIGNS WITH FAULT TREE ANALYSIS

Main author

S. R. Lee

Korea

ABSTRACT

The objective of paper is to carry out a comparative Quantitative Risk Assessment (QRA) of two KOGAS tank designs using a fault tree methodology, a standard “Full Containment” tank and a “Membrane” tank. For the membrane tank, both the initial KOGAS design and 4 modified KOGAS designs have been assessed, giving six separate cases.

In this paper, the frequencies of releases are quantified using a fault tree approach. For clarity in the analysis, and to ensure consistency, all cases have been quantified using the same fault tree. Logic within the fault tree is used to select each of the cases. Full quantification of risks is often difficult, owing to a lack of relevant failure data, but the aim of this study has been to be as quantitative as possible, with full transparency of failure information.

The most significant general cause of external LNG leaks is predicted to be a seismic event, which has only been quantified nominally since it depends on the particular tank circumstances. 4 KOGAS modifications have been assessed that are designed to prevent damage to the bottom membrane panels due to pump impact. According to result, the predicted frequencies of an external LNG leak for the full containment and modified membrane tanks are very similar, except failures due to dropped pumps are predicted to be significantly greater for the membrane tank with only a thickened bottom plate compared with the full containment tank.

Key words: Tank Design, Fault Tree Analysis, Failure Frequency, Quantitative Risk Assessment (QRA), Leak

TABLE OF CONTENTS

Paper

1. INTRODUCTION

In recent years, the majority of new LNG storage tanks have been designed on the basis of the Full Containment Tank concept, which provides an inner vessel to contain the LNG and an outer, gas tight, concrete vessel which can also contain the LNG in an emergency. A significant variation on this concept is the membrane type tank developed by KOGAS where the inner vessel is a thin stainless steel membrane which is supported by structural insulation and the concrete outer vessel.

The objective of the study is to carry out a comparative Quantitative Risk Assessment (QRA) of two KOGAS tank designs using a fault tree methodology, a standard "Full Containment" tank and a "Membrane" tank. For the membrane tank, both the initial KOGAS design and 4 modified KOGAS designs have been assessed, giving six separate cases. The modified membrane tanks are as follows:

1) Modification 1: An absorber structure to prevent dropped pumps penetrating the membrane.
2) Modification 2: In addition to the absorber structure a secondary barrier consisting of a 0.5mm aluminum sheet sandwiched within the insulation is included.
3) Modification 3: A pump catcher is added to the pump lifting connection.
4) Modification 4: In addition to the absorber structure and pump catcher a secondary barrier is included.

A frequency has been assessed for the three types of release: 1) external LNG liquid leak to the environment, 2) internal liquid leak (retained within the concrete vessel); and 3) vapour leak to the atmosphere. The external LNG leak is the critical safety concern. The internal and vapour leaks are largely operational issues.

In this paper, the frequencies of releases are quantified using a fault tree approach. For clarity in the analysis, and to ensure consistency, all cases have been quantified using the same fault tree. Logic within the fault tree is used to select each of the cases. Full quantification of risks is often difficult, owing to a lack of relevant failure data, but the aim of this study has been to be as quantitative as possible, with full transparency of failure information.

2. FALUT TREE ANALYSIS

Fault trees are a means of quantifying the frequency (or probability) of a TOP EVENT based on the combinations of failures which are needed for the TOP EVENT to occur. The BASE EVENTS, for which failure rates (or probabilities of failure) are provided, are combined together using LOGIC GATES that reflect the combinations of failures which are needed for the TOP EVENT to be realised. Using Boolean algebra, the combination of events can be reduced to produce combinations of events, known as CUTSETS, that can result in the TOP EVENT. By studying the CUTSETS and the failure results within the tree, the main contributors to the failure of a system can be determined.

In general, events which are common to all the tank types are quantified with a single number, while events which are quantified differently for each tank require a switch in the fault tree. The fault tree for external leakage consists of three main branches:

1) Failures starting with a failure of the outer concrete vessel walls or base,
2) Failures starting with the concrete roof, and
3) Failures starting with a failure of the inner vessel wall (whether nickel steel or membrane).

In each case, the causes of the initial failure are further divided below these events. For example, failures of the outer concrete wall or base can be caused by:

1) External fire.
2) Aircraft impact.
3) High winds/hurricane damage.
4) Flood.
5) Structural failures from
    i) Ground movement, due to ice heave of piling failures.
    ii) Latent defects in the concrete construction or failures of pre-stressing.

Safeguards (e.g. the hydrotest of the concrete vessel for the membrane tank) are included where appropriate. Many events are the same for both the full containment and membrane tanks. Where there is a difference, different events or branches of the tree are used for each case.

Initial failures of the roof are divided between:

1) Extraneous causes (snow loading and lightning strike).
2) Structural failures due to a defect in roof construction.
3) Operational failures due to overpressure, overfilling and vacuum.
4) Impact from a dropped pump during removal.
5) An explosion in the external plant.

Initial failures of the inner vessel are divided between as follows:

1) Operational failures from dropped pumps and internal missiles split between:
   i) Events that directly fail the outer vessel as well.
   ii) Events that fail the outer vessel indirectly
2) Operational failures, as above, but with an indirect cause of failure of the outer vessel.
3) Seismic failures (which are not fully quantified)
4) Structural defects (split between failures on initial filling and failures in normal operation).
5) Failures due to detachment of the membrane due to a differential pressure across the membrane.

3. RESULTS AND DISCUSSIONS

- **Top event frequencies**

The top event frequencies are summarised in the Table 1. Because the seismic events were assessed nominally only, the frequencies are presented with and without seismic events included.

The vapour leak frequencies are the same with and without seismic events.

The external (LNG) leak frequency is the main measure used to compare the safety of the tank designs. The internal and vapour leaks are considered more as operational issues. An internal leak has no external safety implications, but would require repairs to the tank. A vapour leak will release flammable vapour external to the tank, but the pressures and flow rate are expected to be low and have only very limited safety implications.

		FT	**MT**	**MT: Mod1**	**MT: Mod2**	**MT: Mod3**	**MT: Mod4**
Including seismic events	External Leak	1.63×10^{-6}	4.47×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.46×10^{-6}	1.45×10^{-6}
	Internal Leak	1.08×10^{-4}	1.33×10^{-4}	1.05×10^{-4}	1.05×10^{-4}	1.03×10^{-4}	1.03×10^{-4}
	Vapour Leak	1.80×10^{-4}	8.02×10^{-5}	8.02×10^{-5}	8.02×10^{-5}	8.02×10^{-5}	8.02×10^{-5}
Excluding seismic events	External Leak	6.32×10^{-7}	3.47×10^{-6}	7.29×10^{-7}	7.29×10^{-7}	4.55×10^{-7}	4.55×10^{-7}
	Internal Leak	8.05×10^{-6}	3.27×10^{-5}	5.33×10^{-6}	5.33×10^{-6}	2.64×10^{-6}	2.64×10^{-6}
	Vapour Leak	1.80×10^{-4}	8.02×10^{-5}	8.02×10^{-5}	8.02×10^{-5}	8.02×10^{-5}	8.02×10^{-5}

Table 1 : Top event frequencies

The external LNG leak frequency should not be taken as directly equivalent to measures of individual and societal risk. These measures include additional effects due to the vaporisation of the liquid, distance the vapour travels, how much the vapour cloud spreads, the probability of the cloud being ignited, the location of people, etc. The estimate of individual risk of fatality (often quoted in risk criteria) will always be lower than the estimate of external leak frequency made here and will depend on distance and direction from the tank. An assessment of individual (or societal) risk levels for comparison with criteria would require these additional factors to be taken into account by including consequence analysis for the identified leaks.

However, we would expect all the factors in the consequence analysis to be the same for each tank. This would only change if the modes of failure of the different tanks were very different, and would result in releases of different sizes, or if differences in design (e.g. including a dike for one tank) would alter the consequences between the tanks. This is not the case here, with the dominant failure modes being similar and expected to result in similar sizes of releases.

The external (LNG) leak frequency therefore provides a good comparison between the safety performance of the full containment and membrane tank, without introducing the additional complexities of the consequence of a release.

The spread of the results between the full containment tank and the membrane tank with modifications 1~4 is only 16%. This is small compared to the uncertainties in the analysis. These differences are considered minor and, if individual risk contours were plotted for these different release frequencies (based on additional consequence analysis), they would be expected to be almost indistinguishable. The results for the modified membrane tank span the results for the full containment tank.

For the membrane tank, without any modification, the external LNG leak frequency is predicted to be significantly higher than for the full containment tank (a factor of 2.7 higher or 170% increase). This difference is due to the different predictions for the failure probabilities of the membrane with only thicker plates for protection and the nickel steel tank base in the event of a dropped pump. Modifications 1 and 3, for the membrane tank, address this issue to provide an overall external LNG leak frequency that is comparable to the full containment tank.

- **Comparison between designs**

The relative magnitudes of the types of the causes of failure are shown in the following Figs.1~3.

Fig. 1 shows the difference in vapour release frequencies between the tanks. The vapour release frequency is predicted to be higher for the full containment tank, and is dominated by concrete defect failures. These are reduced for the membrane tank due to the hydrotest of the concrete wall. The internal release frequencies shown in Fig. 2 are predicted to be almost the same for all the tanks except for the unmodified membrane tank, where the failures are dominated by dropped pump.

Fig. 3 shows the predicted external release frequency for all the tank designs. The unmodified membrane tank shows a greater external leak frequency than the full containment tank. This is because, even with the 20mm reinforced plates above and below the membrane, the dropped pump could still penetrate. The addition of the absorber structure (MOD1) reduces the dropped pump frequency to a similar level to the full containment tank. The addition of a pump catcher (MOD3) reduces the dropped pump frequency further bringing the overall leak frequency of a membrane tank to a marginally lower level than predicted for the full containment tank.

It is possible that the absorber structure may perform better in avoiding penetration of the tank base than the thicker nickel steel plate, but the uncertainties involved are larger and a more conservative approach is appropriate for the membrane absorber design. However, modification 1 is predicted to remove the additional susceptibility of the unmodified membrane tank to this type of incident. Careful attention to lifting equipment and lifting operations remains important to avoid damage to the tank (which would require repair of the pump well at least) even when the potential for an external LNG release has been reduced. Whilst a “pump catcher” has been included in the membrane tank analysis, it is noted that this could also be included for the full containment tank and that there is no particular reason for including it in only one tank once the absorber structure has been included. The “pump catcher” would have the potential advantage (for both tanks) of avoiding significant damage in the event of a lifting equipment failure. However, the additional equipment could potentially cause operational issues if any of the pivots seize whilst in service. This could cause difficulties in removing a pump from the tank, which have not been assessed here.

Seismic failures dominate the external LNG leak frequency for the full containment tank and the modified membrane tanks. However, seismic failures have only been nominally quantified and rely on the tanks all being qualified to the same seismic standard. There is no reason why the membrane and full containment tanks cannot be designed to resist the same seismic loads, but this may include greater strength in the outer tank wall for the membrane tank due to the greater static loading. It should be remembered that the magnitude of the earthquake required to cause failure is also expected to be sufficiently large to cause widespread destruction of buildings and loss of life, independent of the failure of an LNG tank. However, it remains clear that the seismic design of the LNG tank is critical in ensuring that risk levels are kept as low as reasonably practicable.

Failures of the base slab heating system are predicted to be the next most significant cause of external LNG leaks, due to ice heave. Ice heave will take a long time to occur after failures of the base slab heating system and time should be available to correct the failure or empty the tank. A base event has been included to quantify the probability of the tank continuing to be operated long term without an adequate base slab heating system. This allows for the uncertainty in the level of the potential problem and the difficulty in correcting failures within the base slab. It should be noted that ice heave will not be critical if a tank is not operated for a long time (typical timescale of months) without effective base heating. If this can be guaranteed then an external LNG leak due to a base slab heating system failure cannot occur. This is a matter for good operational practice and effective regulation.

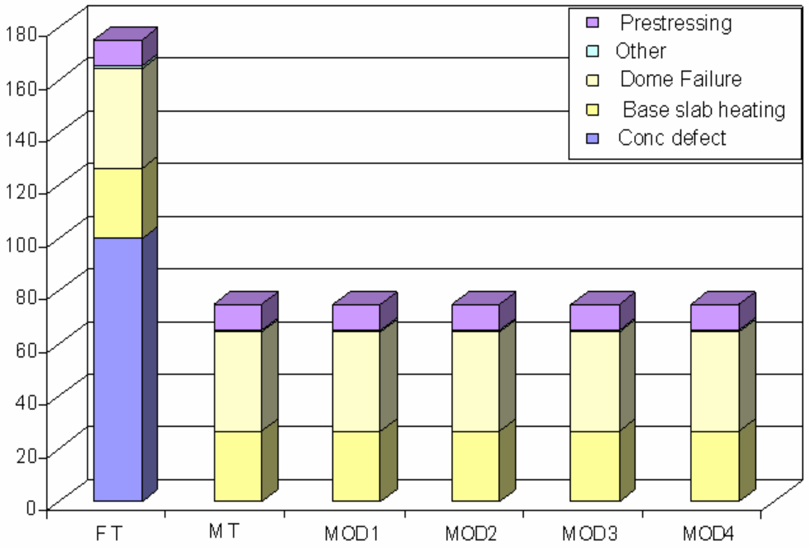

Fig. 1 Vapour leaks

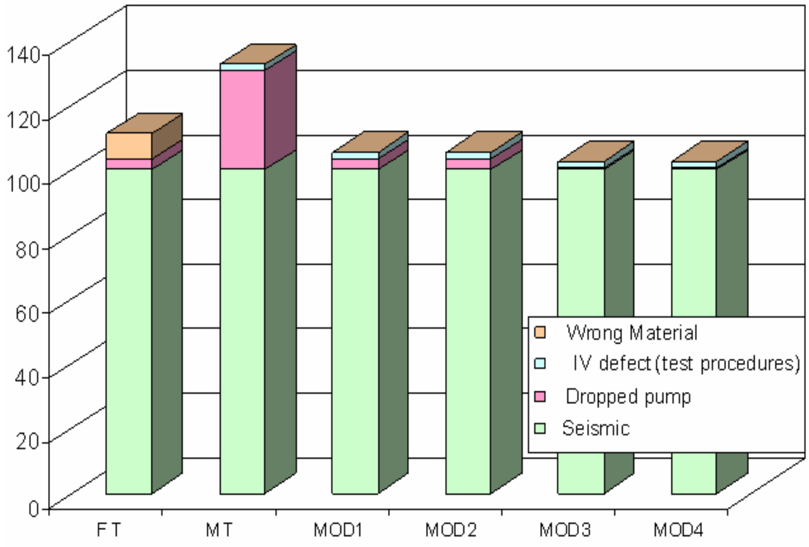

Fig. 2 Internal leaks

The second barrier included for modifications 2 and 4 is predicted to make a negligible difference to the external LNG leak frequency. The barrier has very little structural strength and will make essentially no difference to the dominant causes of seismic failure, dropped pumps and base slab failure. The construction of the barrier also requires extensive bolting between panels and there is no test of the integrity of these joints. For the limited cases where the barrier could be effective, the probability of there being a leak at the joints is predicted to be high. This second barrier also performs no additional useful function if the foam insulation is liquid tight. Overall, the inclusion of a second barrier, of this type, does not appear to make any useful contribution to the integrity of the membrane tank against external LNG leakage.

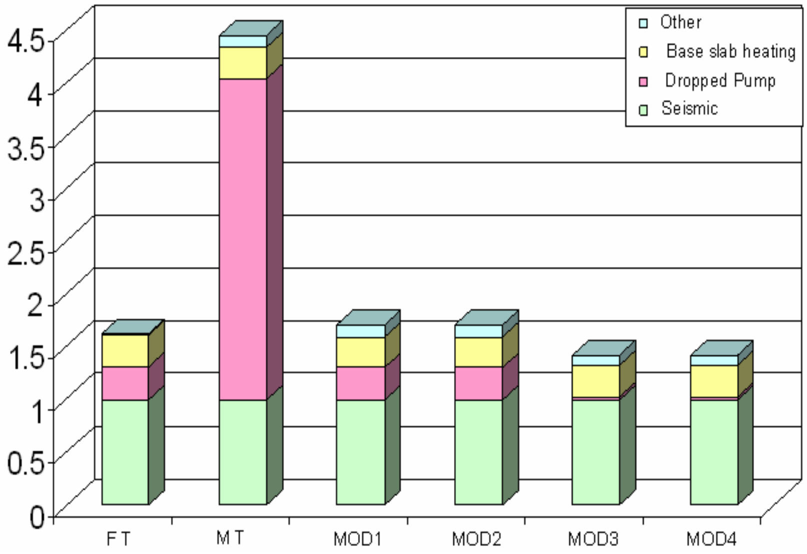

Fig. 3 External leaks

- **Uncertainty levels**

For each of the events in the fault tree an estimate has been made of the uncertainty level. This is included in the fault tree as an estimate of the standard deviation of the value and the confidence level is assessed based on a Monte Carlo technique.

Fig. 4 shows these estimates for the total LNG leak frequency for each of the six LNG tank designs. The upper 95% confidence bound is as calculated by *Fault Tree+* and the lower bound is simply set based on an equivalent number of standard deviations below the nominal value.

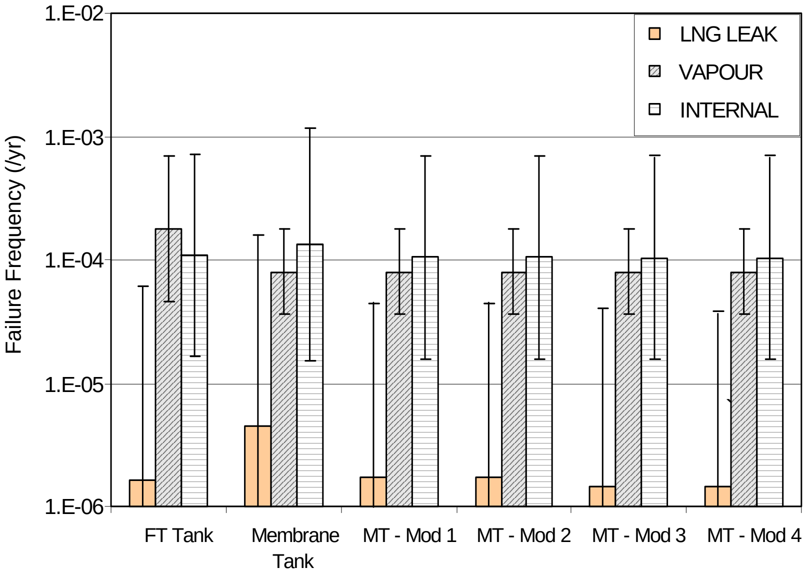

Fig. 4 Uncertainty Levels

5. CONCLUSIONS

The comparative risks of leakage from the KOGAS design of membrane LNG tank and a full containment LNG tank have been analysed using a fault tree approach. The following conclusions are apparent:

1) The predicted frequencies of an external LNG leak for the full containment and modified membrane tanks are very similar.
2) Failures due to dropped pumps are predicted to be significantly greater for the membrane tank with only a thickened bottom plate than for the full containment tank. The impact absorbing structure (modification 1) is expected to result in a similar level of risk to the full containment tank. The pump catcher (modification 3 - which is not assumed to be present in the full containment tank) reduces this risk further.
3) The addition of a secondary barrier to the modified membrane tank (modification 2 and 4) is predicted to make very little difference to the overall LNG leak frequency.
4) The frequency of vapour leaks is greater for the full containment tank. This is because the hydrostatic test on the membrane tank is assumed to detect defects on the pre-stressed concrete wall, while the pneumatic test on the full containment tank is only a leak test for the dome vapour barrier.
5) The most significant general cause of external LNG leaks is predicted to be a seismic event, which has been quantified nominally. An improvement on this would require a more detailed assessment (e.g. finite element). However, if the membrane tank is seismically qualified to the same level as the full containment tank (as assumed in this study) and designed to be equally protected against a dropped pump (as for modifications 1-4), there is little to differentiate the tanks in terms of the risk of an external LNG leak.
6) Failure of the base slab heating system and subsequent ice heave is potentially a serious problem for both tanks. The failure of both coils within the base slab is quite likely during the tank lifetime and could present a major problem as they are not replaceable. There will be little risk if it is ensured that a tank does not operate for an extended period without adequate base-mat heating.

REFERENCES

1. Meeting at KGS and KOGAS offices, 9th February 2004 - 12th February 2004.
2. Preliminary Design, Ammonia Leak Test Procedure.
3. Definition of Single Loadings, Commercial Membrane Type LNG Storage Tank Design Project, Doc. CM-C-Cal-002 rev 0, Korea Gas Engineering & Construction Co., Ltd., Whessoe International Limited.
4. Definition of Single Loadings, Commercial Membrane Type LNG Tank Design Project, Doc. No. CM-C-CAL-002 rev 0, KOGAS Main. & Eng. Co. Ltd.
5. Unified Partial Method Version 3, “A Practical Approach to Dependent Failure Assessment”, AEA Technology plc
6. Outer Tank Bottom Corner Liner Plate, Commercial 9% Ni Type LNG Storage Tank Design Project, Dwg. CN-M-155-005 Rev 0, Korea Gas Engineering & Construction Co., Ltd., Whessoe International Limited.
7. Seismic Calculation for LNG Storage Tank Design Project, CN-C-Cal-010, Korea Gas Engineering & Construction Co., Ltd., Whessoe International Limited.
8. Pump and Nozzle Orientation and Membrane Protection from Drop of the Pump, 140,000m3 Membrane Type LNG Storage Tank Project, CM-M-ME-0616, Korea Gas Corporation.
9. Details of Pumpwell Nozzle, Commercial 9% Ni Type LNG Storage Tank Design Project, CN-M-160-001 rev 0, Korea Gas Engineering & Construction Co., Ltd., Whessoe International Limited.
10. BS7777: Flat-bottomed, vertical, cylindrical storage tanks for low temperature service; Parts 1 – 4, British Standards Institution, 1993
11. BS6399: Loading for Buildings; Part 2 Code of practice for wind loads; Part 3 Code of practice for imposed roof loads Code of Practice CP3, Chapter V, Part 2 (Wind loads)
12. Theofanous, T. G., “On the Proper Formulation of Safety Goals and Assessment of Safety Margins for Rare and High-Consequence Hazards,” Reliability Engineering and System Safety, 54, 243 (1996).
13. Welker, J. R. and Schorr, H. P., “LNG Plant Experience Data Base,” American Gas Association 1979 Operation Section Proceedings, A.G.A., Arlington, VA, USA (1979).
14. Han, S. H., “KAERI Integrated Reliability Analysis Code Package (KIRAP),” Korea Atomic Energy Research Institute, Korea (1999).
15. Johnson, E.M. and Welker, J. R., “Development of an Improved LNG Plant Failure Rate Data Base,” GRI-80/0093, Gas Research Institute, Chicago, IL, USA (1980).
16. N. Ketchell, R. Robinson and P. Genoud, “Quantification and comparison of the risks of LNG storage concepts – membrane and full containment,” LNG12, Perth, Australia, 1998

List Tables

List of Figures