Rollover in LNG Storage Tanks

Summary Report by the GIIGNL Technical Study Group on the Behaviour of LNG in Storage

2nd Edition: 2012 - 2015 | Public Version

Summary

LNG “rollover” refers to the rapid release of LNG vapours from a storage tank caused by stratification. The potential for rollover arises when two separate layers of different densities (due to different LNG compositions) exist in a tank. In the top layer, liquid warms up due to heat leakage into the tank, rises up to the surface, where it evaporates. Thus light gases are preferentially evaporated and the liquid in the upper layer becomes denser. This phenomenon is called “weathering”. In the bottom layer, the warmed liquid rises to the interface by free convection but does not evaporate due to the hydrostatic head exerted by the top layer. Thus the lower layer becomes warmer and less dense. As the density of two layers approach each other, the two layers mix rapidly, and the lower layer which has been superheated gives off large amount of vapour as it rises to the surface of the tank.

The main hazard arising out of a rollover accident is the rapid release of large amounts of vapour leading to potential over-pressurization of the tank. It is also possible that the tank relief system may not be able to handle the rapid boil-off rates, and as a result the storage tank will fail leading to the rapid release of large amounts of LNG to the atmosphere. It is important to emphasise the difference between stratification and rollover. Stratification is the phenomenon of stored LNG forming distinctive cells which is driven by density differences and can be manipulated for boil-off gas optimisation; rollover is the rapid release of boil-off gas in an uncontrolled event which can have safety implications. LNG rollover received considerable attention following a major unexpected venting incident at an LNG receiving terminal at La Spezia, Italy in 1971.

Stratification is managed by use of measurement devices upon the LNG storage tanks, of which, the types of instrumentation required are stipulated within design codes. Advances of rollover prediction models have also enabled operators to prevent and make informed decisions for the management of stratification within LNG storage tanks.

Any queries relating to this document, please contact GIIGNL Head Office at:
E-mail: central-office@giignl.org
Website: www.giignl.org

Preference to First Edition

In presenting the second edition of Rollover in LNG Storage Tanks, it has been our intention to cover what we believe to be the important developments within the LNG industry for the management of stratification of stored LNG leading to rollover events. Significant advances have been made in areas covering, design, instrumentation, operating knowledge, training operators on LNG behaviour and the use of modelling software to prevent and in some cases instigate stratification to seek operating efficiencies. The reader will find that this edition is written with one eye on the future as the LNG industry at the time of writing is continuing to develop at a fast rate, with new processes being introduced. The principles of management stratification for these new processes are as yet not thoroughly developed.

Organisation of the Study

The composition of the Task Force which collected the information contained in this report and met regularly in the process of the evaluation of the information is as follows:

Simon Culkin (Chairman)	National Grid Grain LNG
Jason Shirley (Technical Co-ordinator)	National Grid Grain LNG
Abrar Bajwa (Technical Assistant)	National Grid Grain LNG
Hugues Malvos	GDF Suez
Yacine Zellouf	GDF Suez
Haakon Olav Huglen	Statoil
Jingshi Yang Ruan	Statoil
Angel Benito	Enagás
Jonathan Kershaw	BP
James Bradley	BP
Jeremy Shiflett	BG Group
Makoto Yamada	Tokyo Gas
Eisaku Sato	Tokyo Gas

The authors acknowledge with thanks the assistance given by companies and individuals in providing suggestions and for additions that they have felt to be important along with illustrations and data for this edition and giving their permission for reproduction. Everyone was most helpful and some firms went to considerable trouble to provide exactly what was required. We are extremely grateful to them all.

This report was based on the first edition and was developed in reference to numerous reports and other sources of information produced by the members of the Task Force. The report was written by Dr Jason Shirley, Technical Co-ordinator for the Task Force.

Contents

1. Introduction

At the 2012 Technical Study Group meeting of GIIGNL member companies in Osaka, it was decided to revise the "Rollover in LNG Storage Tanks" study document. The original document was published in 1983 and was a reactive response following the first significant rollover incident widely reported in the history of the LNG (Liquefied Natural Gas) industry that occurred in La Spezia, Italy, 1971. In the intervening 31 years from the publication of the original study, there have been considerable developments in the study of the behaviour of LNG in storage tanks and the whole subject has undergone a number of changes. A Task Force was formed with the aim of updating the original study to reflect the current industry position whilst retaining a similar structure and physicochemical study findings provided by the original authors. This report presents a summary of the Task Forces assessment of the current state of knowledge of rollover and incidents of excessive vapour evolution in LNG storage tanks.

The remainder of this section gives a brief introduction to rollover and a description of how the study was carried out. Following sections deal with the fluid dynamics and thermodynamics of LNG in storage tanks (Section 2), rollover incident case studies (Section 3), measurement and prevention of stratification (Sections 4 & 5) and prediction modelling which is developing areas of study within this subject area (Sections 6). The report concludes with a general bibliography.

1.1 The Occurrence of Rollover

It is possible in LNG storage tanks for two stable stratified layers or cells to be established, as a result of inadequate mixing of either fresh "light" LNG with a denser heel (a process typical of a Peak Shave storage plant), or by unloading LNG of different densities into a storage tank (a process that may occur within an import LNG Terminal). Importation terminals receive cargos from many parts of the world and are delivered with varying densities and temperatures.

Within the stratified cells, the liquid density is uniform but the bottom cell is composed of liquid that is denser than the liquid in the cell above. Subsequently, if a layering condition is allowed to persist over a period of time, the energy in the lower layer will build up due to heat leak into tank. The boil-off gas from the bottom layer is suppressed due to the hydrostatic pressure impressed on it from the upper layer. Heat leak into the tank will gradually increase the bottom layer temperature and therefore decrease its density. As the densities of the two layers approach equilibrium, the potential for a rollover event increases. As the two layers mix, the boil-off gas that was retained by the bottom layer will be released, which can result in a high rate of vapour generation. This rate can be significantly greater than the tank's normal boil-off rate and in a few instances the pressure rise in the tank has been sufficient to cause pressure relief valves to lift.

This phenomenon is known as 'rollover', meaning the layers roll over or reverse. Technically, this is not exactly what happens, but this terminology has become quite established across the industry. Depending on the severity of the event, the effects can range from simply a small pressure rise in the tank for a short period of time to a significant loss of product over an extended period of time through the tank's relief valves. Although, very unlikely, in the event of a serious rollover the potential also exists of physical damage to the tank due to over pressurisation.

LNG rollover phenomena received considerable attention following a major unexpected venting incident at an LNG receiving terminal at La Spezia, Italy in 1971. Therefore precautions must be taken to manage the potential for stratification to ensure that it doesn't lead to a rollover event. Detection and mitigation techniques are employed to identify when conditions exist for a possible rollover event and to impede the occurrence of such an event.

1.2 Advances in the Industry

The main advances in the LNG industry that have affected the management of stratification for the prevention of rollover occurrence have been in both the design and technology deployed on LNG terminals and ships as well as the trading patterns.

The growth of the LNG trade worldwide has led to an increase in differing LNG qualities being available in the world market. Thus, import terminals are now faced with the need to handle these differing LNG qualities according to the source.

LNG demand in the world has been increasing and expected from current 170 million tons per annum to 400 million tons per annum in mid 2020's. In conjunction with the growing demand, many new LNG receiving terminals will be constructed all over the world in a variety of circumstances. The global network of terminals is growing in the US, South America, Europe, China and India because of the growing demand for LNG as a cleaner energy source.

A change in LNG trading and shipping patterns can have a direct effect on the potential of rollover in storage tanks. As market demand increases and new supply sources emerge, importers are widening their range of LNG quality. The evolving spot market has increased the potential of commingling lean and rich cargo in the same storage tank.

The growth phase that the LNG industry is currently experiencing means that there is a wide variety of LNG in the supply chain and there are more operators on both supply and demand sides. There have been developments within the size of ships and new shipping patterns such as partial offload and reload.

A current area of interest is within the development of a prediction tool for preventing rollover within Floating LNG Production, Storage and Off-loading (FPSO) plants. These floating production plants present challenges for the use of current prediction tools due to the sloshing motion of the ships that is not needed for consideration of shore based LNG storage tanks. Also, the geometry of ships tanks differs from the more regular cylindrical shore based tanks particularly for the Moss style spherical tanks. Tank 1 membrane style tanks (located at the ship's bow end) tend to be a more irregular shape. Floating tanks are also being equipped with bottom fill only to reduce the boil-off gas generated during filling. This design limitation reduces the operational flexibility for management of stratification. There is a potential for rollover on FPSO ships as rollover events have occurred on convention LNG cargo ships. A case study of rollover on an LNG cargo ship is presented in Section 3.

The expanding market for LNG as a fuel will see LNG being utilised in more applications such as road tankers, satellite stations and bunkering stations (refer to the GIIGNL Retail Handbook for further reading). The management of the physicochemical properties of LNG will have to be considered within all of these developments to ensure that potentially hazardous events such as rollover are prevented.

1.3 Organisation of the Study

The study was carried out by leading expert representatives from eight Member Companies of GIIGNL.

Data was collated by questionnaires from Technical Study Group (TSG) members, other GIIGNL member companies and a number of companies with peak shaving operations that were known to have or thought to have an interest in rollover. Additional important data came from the published literature and directly from the GIIGNL database and other gas companies. Experts from the wider LNG industry contributed on specific subject areas.

1. Introduction

In order to spread the workload and to utilise specific expertise within individual companies in the best way, the subject was split into five topics. Eight Technical Study Group member companies took responsibility for devising questionnaires and for the analysis of data as follows:

SECTION 1	Introduction
SECTION 2	Rollover Phenomenon
SECTION 3	Rollover Incidents
SECTION 4	Measurement of Stratification
SECTION 5	LNG Stock Management
SECTION 6	Rollover Prediction Models

Disclaimer: The purpose of this document is to serve as a reference manual to assist readers to understand the procedures and equipment available to and used by the members of GIIGNL to manage stratification and prevent rollover in LNG terminals. It is neither a standard nor a specification and should be viewed as a summary of observations within the industry.

This document is not intended to provide the reader with the detailed occurrence of LNG stratification and rollover as such, but sets out the practical issues and requirements to guide and facilitate a skilled operator team to work out a suitable procedure for management of stratification and prevention of rollover.

This rollover study document has included commercially available software as part of the summary of the LNG prediction models that are being used by LNG operators. It was important to include reference to the different types of approaches for prediction models as this has been a significant area of development in the field of research for LNG stratification and rollover. GIIGNL have presented a balanced summary of the models that are in use by members of the Task Force. It is not GIIGNL's intention to promote commercial products and the group recognises that other products exist on the market. Readers should ensure that they are in possession of the latest information, standards and specifications for any procedures and equipment they intend to employ.

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Three preliminary teleconferences were conducted to initiate the Task Force and three full meetings were held with the members of the group in London, Paris and Gujarat, India in 2012. An update of the Task Force's progress was provided at the GIIGNL TSG meetings in Hammerfest and Dunkirk in 2013. The Task Force met for the final time in Paris 2013. The final document was presented at the 2014 TSG meeting in Boston.

In an attempt to understand the frequency of the occurrence of rollover incidents, a survey form was distributed amongst the member companies of GIIGNL. The results from the survey were intended to shape the discussion points within this document as to whether the rollover phenomenon is well understood and sufficiently managed within the industry. The questionnaire was sent out to 25 companies, of which there were 15 responses.

It is recognised that commercial and contractual issues have presented challenges with supply of information to the Task Force for rollover incidents. This resulted in a very limited capture of new data from the survey. Therefore, the data in this study has been supplemented with information from the GIIGNL incident database, commercial companies who work with LNG related products and literature in the public domain.

2. Rollover Phenomenon

LNG is a multi-component naturally occurring mixture of differing quantities of hydrocarbons (alkanes mostly methane CH_4 but also containing smaller concentrations of ethane C_2H_6, propane C_3H_8 and butane C_4H_{10}) and nitrogen (N_2). The LNG is stored in bulk in large storage tanks at a gauge pressure of some 0.10 to 0.24 bar and a temperature of approximately – 160°C. The tanks are insulated to reduce heat in-leak but heat is still transferred from the environment to the LNG in the tank. As a result of this heat in-leak, evaporation takes place of the more volatile components (N_2 and CH_4). This process is known as "weathering". Normally, weathering is a fairly slow process. Typically, an LNG tank will lose about 0.05% of its contents per day in boil-off gas to absorb the heat input and keep the remaining liquid cold. The weathering process therefore causes the composition of LNG to evolve over a period of time thus altering the density of the LNG. Generally, LNG of different densities can form separate layers within a storage tank. This layering is referred to as stratification and can also be formed during filling an LNG tank with LNG of different densities (commonly referred to within the industry as "light" and "heavy" LNG). The potential for rollover arises when two separate layers of different densities exist in a tank. This study will summarise the occurrence of stratification leading to rollover.

2.1 Equilibrium Conditions and the Surface Layer

The evaporation that occurs in an LNG tank is commonly referred to as "boil-off gas" (BOG). In this document the term "vapour evolution rate" is preferred to the term "boil-off rate" because the liquid does not normally boil in a commercial LNG tank. The term boil-off and boil-off rate are strictly applicable only when the liquid is boiling by the heat transfer process of nucleate boiling. In the majority of storage situations, there is only evaporation from the surface of the liquid and there is no boiling, then the term "evaporation rate" is then the correct terminology to use. However, boil-off is commonly used to describe all liquid evaporation and is frequently used in the industry. The gradual loss of methane by preferential evaporation causes the tank stock to increase in density as the concentration of C_2+ remaining in the tank increases. This weathering process is particularly important if the heat leak from the walls of the tank is large as in the case of some in-ground tanks or if the storage period is long as in the case of peak-shaving installations. Heat in-leak is also significant for LNG re-gasification terminals as the pipe work external from the tank has to be kept cold, particularly the LNG unloading lines from the jetty to the tanks. Large volumes of BOG are attributed to this form of heat in-leak which is evolved from the LNG upon returning to the tanks during LNG recirculation.

The heat input to the liquid from the floor and walls of the tank is absorbed and convected to the liquid surface where evaporation takes place. A free-convective circulation is set up with a (mainly turbulent) boundary-layer of slightly warm and less-dense liquid moving upwards close to the tank walls. Warmed liquid reaching the surface cools by evaporation, becomes more dense than the liquid surrounding it, and returns to the tank bottom as a central plug flow. Figure 2.1 shows the circulation, which has been observed in the laboratory (1, 2) and which accounts for the small (1 K or less) temperature differences usually found in LNG in commercial storage tanks (3). Estimates of the temperature difference across the wall boundary layer based on extrapolations of a turbulent flow correlation equation (4) give 0.05 K and 0.17 K for typical 50,000 m^3 tanks with losses or 0.03% and 0.06% of contents per day respectively.

2. Rollover Phenomenon

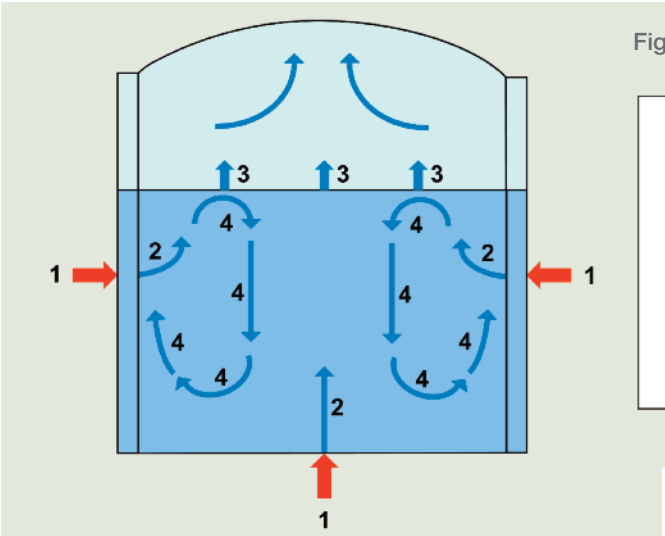


Figure 2.1 Free convective Circulation in LNG Tank

1. **Heat** passing into tank from atmosphere.
2. Warmed LNG becomes lighter and rises.
3. **Evaporation** takes place at the surface removing heat and lighter components.
4. Cooler and heavier LNG falls.

Several studies (5, 6, 7 and 8) have shown that a surface layer that is slightly cooler than the bulk liquid exists under these conditions. This surface layer is frequently called the Hashemi-Wesson layer. By adapting a well-known correlation equation for free convection from horizontal surfaces, Hashemi and Wesson arrived at an equation which can be used to show that the temperature difference in the layer depends on the mass flux (the rate of mass evaporation through unit surface area), i.e.

$$\dot{m} = 0.00127\,\Delta T_S^{\frac{4}{3}} \qquad (2.1)$$

Where $\dot{m}$ is the mass flux in kg/m²s and $\Delta T_S^{4/3}$ is the temperature difference across the layer in K. The liquid surface is effectively at the saturation temperature, T_S, corresponding to the pressure in the vapour space above (for its particular composition) and the bulk of the liquid is at an almost constant temperature warmer by an amount given by equation (2.1). For typical 50,000 m³ LNG tanks with total losses of 0.03% and 0.06% of contents per day, Equation (2.1) gives ΔT_S equal to 0.1 K and 0.15 K respectively. Small temperature differences must exist in the bulk liquid away from the boundary layer and the surface layer in order to maintain the free-convective circulation, but these can be ignored in a simple model.

Studies have shown (7) that there is a nearly linear variation of temperature in the surface layer. These studies were with liquid nitrogen but similar effects are likely with LNG. Figure 2.2 shows a typical (time-smoothed) vertical temperature profile in the liquid and vapour.

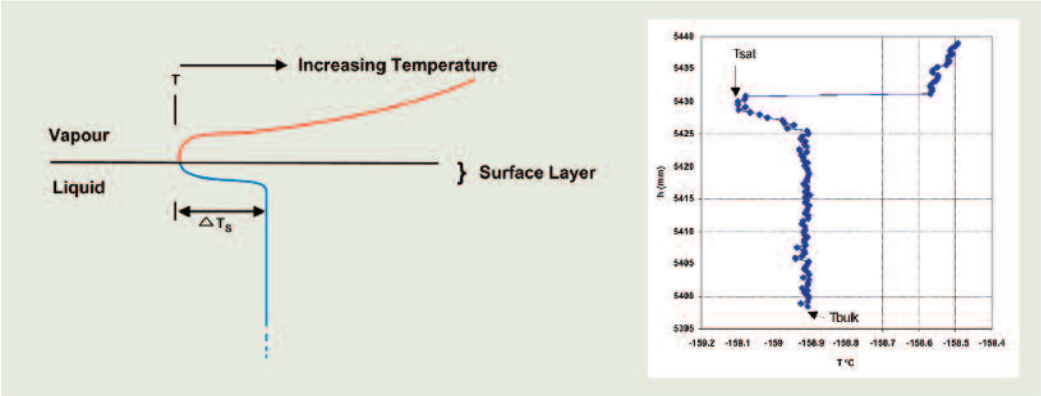


Figure 2.2 Typical temperature profile near liquid surface combined with experimental data from GDF Suez test in 500m³ pilot tank

Random temperature variations in the liquid which are not shown in this smoothed profile occur, probably due to turbulence in the flow. Above the liquid surface there is a region of approximately uniform temperature corresponding to a turbulent vapour layer, and above this the vapour temperature increases rapidly with the distance (8).

2.2 Effect of Disturbing the Equilibrium

Under normal storage conditions two types of disturbance occur to affect the vapour-evolution rate, pressure changes and physical disturbance of the surface layer.

2.2.1 Pressure Changes

Under certain operational conditions changes in barometric pressure are reflected as changes in the absolute pressure in the vapour space of a storage tank. At some installations this absolute pressure also depends on the number and capacity of vapour compressors in operation.

A fall in absolute pressure above the liquid surface causes the vapour-evolution rate to increase: a rise in absolute pressure causes the rate to decrease. Figures 2.3 (a) and 2.3 (b) show the results of a historic experiment that serves to demonstrate the effects on vapour-evolution rate of sudden changes in the pressure above liquid nitrogen contained in a 160 litre experimental vessel (9). Similar effects are observed in LNG storage tanks (3). After the initial change the vapour-evolution rate settles to the equilibrium rate exponentially. The surface layer plays an important role in the process, sustaining the difference between the temperature of the bulk liquid which changes only slowly and the temperature of the liquid-vapour interface which responds rapidly to changes in pressure. In the case of a large pressure rise it is possible for the interface temperature to equal or to rise above the bulk temperature in which cause the vapour evolution essentially stops until the heat input has raised the bulk temperature above the surface temperature once more.

In practice, the pressure changes take some considerable time, typically several hours in a commercial LNG tank. Also, a second change may occur before the effects of the first one are complete. However, the equations describing the boil-off rate are simple (9) and can be applied to these practical situations.

2.2.2 Physical Disturbances of the Surface

If the liquid surface is agitated, either during top-filling or in some other way, superheated liquid from beneath the surface layer is exposed and the vapour-evolution rate increases. The surface layer is expected to re-establish fairly quickly after the disturbance ceases but there is no known quantitative information on the time taken to reach equilibrium.

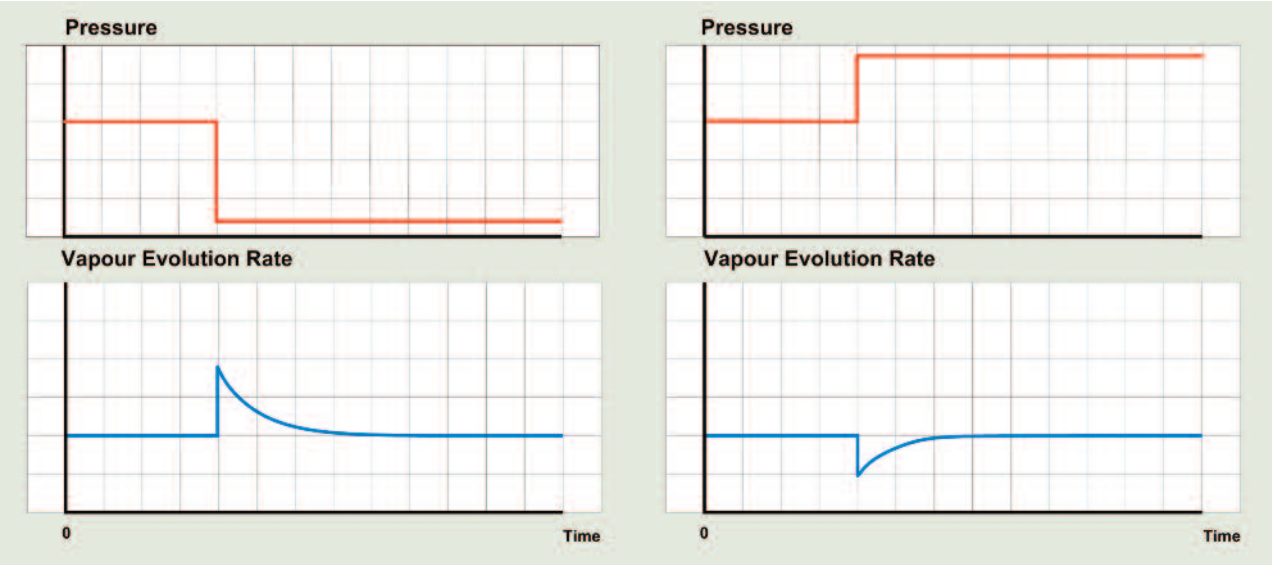


Figure 2.3 (a) Effect of sudden fall in pressure on vapour-evolution rate, (b) effect of sudden rise in pressure on vapour evolution rate.

Certain top-filling devices, particularly sprays and splash plates, cause high vapour-evolution rates, because they disturb the surface over an appreciable area. Some experiments in which non-condensable gas was bubbled through LNG (10, 11) resulting in a total vapour evolution to be considerably in excess of the amount calculated from the heat content of the bubbled gas, possibly also because of disturbances of the surface layer. Alternatively or additionally, the gas bubbles may have acted as nucleation centres, causing the superheated bulk liquid to boil and the vapour-evolution rate to increase.

2.3 Fill-induced Stratification

LNG is stored in bulk in large storage tanks with volumes from 40,000 m^3 to ~ 200,000 m^3 with LNG storage tank design advancing and volumes continually increasing. There are four main types of LNG storage tanks:

1. Single containment tanks
2. Double containment tanks
3. Full containment tanks
4. Below ground tanks

The four types are depicted in Figure 2.4. The design of the storage tank used depends upon the age of the process plant, the location for safety and operational consideration, engineering design standards, code requirements and layout constraints.

Single containment tank | Double containment tank | Full containment tank | Below ground tanks

Figure 2.4 Four types of commercial LNG storage tank

The single containment tank design was the common style worldwide pre 1980's and typically had volumes between ~ 40,000 m^3 and 95,000 m^3. Some larger single containment tanks are still being built depending on risk assessment, for example Peru LNG tanks are 130,000 m^3 which were completed in 2010. A single containment tank was selected by Peru LNG due to the site remoteness (hence reduced societal risk) and enough space being available to accommodate different secondary containment features that complied with regulations and represented a safe design installation. Single containment tanks typically feature a primary liquid containment open-top inner tank, a carbon steel primary vapour containing outer tank and an earthen dike for secondary liquid containment.

Double containment tanks are similar to single containment designs except that the outer tank is capable of containing liquid spills in the event of a breach in the inner tank wall. This tank design has a freestanding 9% nickel inner tank and an outer tank made of either prestressed reinforced concrete. However, the roof is still constructed of steel and will not contain vapour produced by failure of the inner tank.

Full containment tanks are the latest design development. National Grid Grain LNG has four 190,000 m^3 tanks which were completed over the period of 2008 to 2010. Full-containment tanks typically feature a primary liquid containment open-top inner tank and a concrete outer tank. The outer tank provides primary vapour containment and secondary liquid containment. In the unlikely event of a leak, the outer tank contains the liquid and provides controlled release of the vapour.

Below ground and underground LNG storage tanks are some of the world largest LNG tanks with capacities over 200,000 m^3. They have advantages in requiring less land area and reduced seismic loading but are expensive and are only common in the Far East Asia.

2. Rollover Phenomenon

As tank design and volumes have advanced, the heel height (an important parameter for consideration in the prevention of rollover) has reduced. This is because increases in storage volume are due to the increased diameter of the tanks, whereas the height has not significantly changed (45,000 m^3 double containment tanks have a height of ~ 50 m and 190,000 m^3 full containment tanks have a height of ~ 55 m). Therefore, for the same volume of heel, the heel height is reduced within the larger capacity tanks.

Due to the advancements in the scale of LNG storage, this has allowed for advancements in LNG trade. The LNG shipping market has witnessed a rapid development in recent years in-line with the rising world LNG trade. LNG buyers started to move upstream and participated in upstream activities such as shipping. Sellers also started to move along the chain, becoming minority owners in shipping and occasionally in regasification plants. The history of LNG vessels shows that since the 1970's the vessels have steadily become larger. From a typical size of 70,000 m^3 in the 1970's, to 125,000 m^3 in the 1980/90's and 145,000 m^3 in early 2000 with some ships over 200,000 m^3. Today, it seems that the ~ 160,000 m^3 has become a popular size, being the "standard" ship size for the large amounts of LNG vessels to be delivered in 2012-2015.

A new trend in the LNG business world is the increasing use of storage and reloading services which are provided by several terminals. This creates new opportunities for short-term trading and developing of geographical arbitrage. The potential risk of rollover when mixing LNG with different densities should always have a high focus.

The composition of these components depends on the source of origin of the LNG. The component characteristics of LNG for global gas fields are detailed in (12) which reports that the methane content of LNG can vary from ~ 89% to 97%. The regasification terminal at National Grid Grain LNG has received LNG from global sources and has contracts for the delivery of cargos from Trinidad (96.8% CH_4 content (12)) and Algerian (88.9% CH_4 content (12)) which are the two ends of the CH_4 component spectrum. Therefore, LNG from a Trinidad source is lighter (less dense) than weathered stock in the LNG tanks, which will have a reduced mixing affinity.

If a storage tank containing LNG is further filled with LNG of different density, then it is possible for the two liquids to remain unmixed, forming independent layers. The stratification is initially stable with the most dense liquid at the bottom.

Fill-induced stratification occurs readily if the added liquid (the cargo) is more dense than the liquid already in the tank (the heel) and filling is at the bottom or if the cargo is less dense than the heel and filling is at the top. Once formed, the layers are stable and can last for long periods of time. Two independent circulation cells are set up in the liquid as shown in Figure 2.4. Both heat and mass are transferred convectively across the interface between cells.

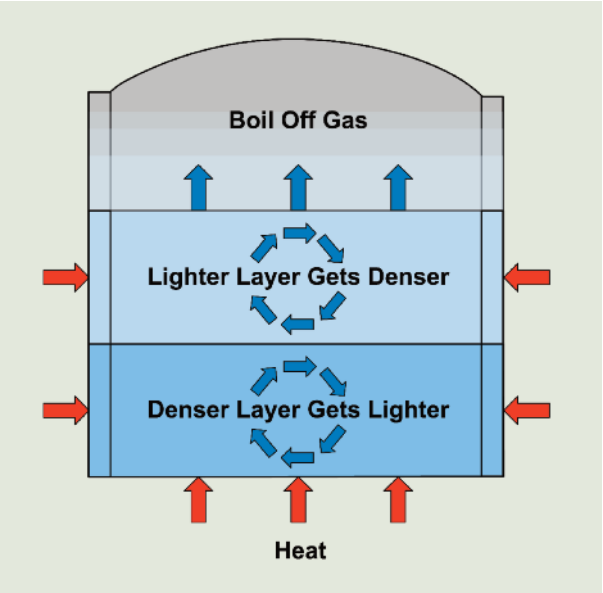


Figure 2.4 Liquid stability stratified in to cells

Heat entering the top cell is absorbed at its sides and bottom, transported to the surface in the free-convective circulation and lost as latent heat of evaporation at the surface layer. This is similar to the behaviour in the single cell of an unstratified tank. The bottom cell, however, gains heat from the bottom and sides of the tank but can only loose heat at the interface between the two cells by convective mechanisms. Generally, these mechanisms transfer less heat than is lost by evaporation at the surface layer, and so the bottom layer heats up. Sometimes, however, the heat addition to the bottom cell is less than the heat transfer across the interface and the bottom cell cools, tending to increase its density and stabilise stratification.

Figure 2.5 shows the variation of temperature and density of the top liquid with time in the two cells for the bottom cell heating up (case I) and Figure 2.6 shows the variation for the bottom cell cooling (case II). In both cases the liquid in the top cell shows an effect of weathering, heating up and increasing in density with time.

In Figure 2.5 (case I), the temperature of the bottom cell increases rapidly and its density falls. When the densities are equal (or approximately so) the interface disappears and the cells mix. This mixing of cells, which is usually fairly rapid, is called a rollover and is often accompanied by an increase in vapour evolution, see section 2.6.

In Figure 2.6 (case II), the temperature of the bottom cell decreases and the density rises. Rollover is delayed until the top layer weathers sufficiently for the densities of the two cells to equalise.

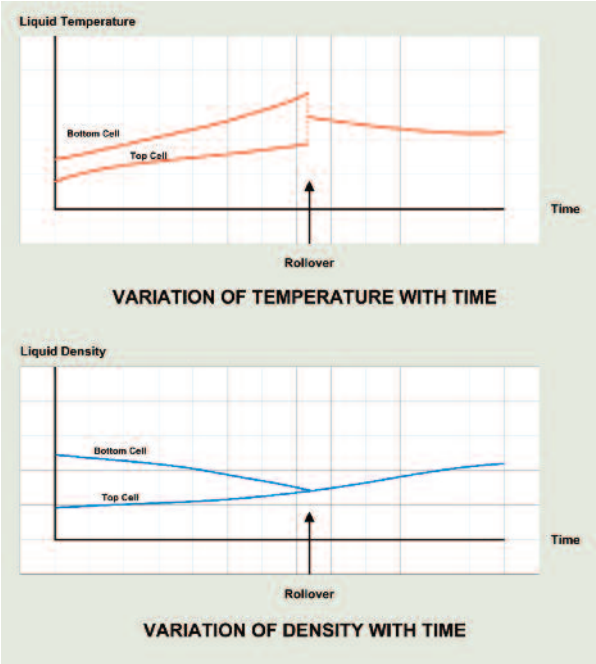


Figure 2.5 (a) Case I, variation of temperature with time
Figure 2.5 (b) Case I, variation of density with time

The likelihood of stratification occurring can be reduced considerably, although not eliminated in every circumstance, by encouraging mixing during filling as follows,

(i) The difference in density of the two liquids can be used to promote their mixing (i.e. by bottom-filling light liquid or top filling heavy liquid),

(ii) Jet nozzles can be used to deliver additional momentum to bottom-filled heavy liquid, increasing entrainment of heel liquid in the flow of cargo liquid and

(iii) Fill tubes pierced holes can be used to distribute cargo liquid within the heel.

2.4 Effects of Nitrogen

Nitrogen, if present in LNG, is the most volatile component, boiling off preferentially and causing the saturation temperature (bubble point) of the remaining liquid to increase. The molecular weight of nitrogen (equal to 28g/mol) is larger than that of methane (equal to 16g/mol) and consequently for most LNG the preferential loss of nitrogen causes the density of the remaining liquid to decrease. By contrast, in a nitrogen-free LNG, preferential loss of the most volatile component (methane) causes increases in both the saturation temperature and the density of the remaining liquid. This characteristic of nitrogen in LNG has two important consequences for rollover, the need for special filling procedures and the possibility of auto stratification.

2.4.1 Filling Procedures

Because weathering increases the density of nitrogen-free LNG, it is usually appropriate to bottom-fill fresh LNG from the same sources as the weathered heel in order to promote mixing. However, if the LNG contains nitrogen, weathering decreases the density initially. In this circumstance it is appropriate to top-fill fresh LNG from the same source as the weathered heel in order to promote mixing, or alternatively to use a mixing nozzle located at the bottom of the tank. Prevention methods are described further in Section 5.1. It is noted that recirculation of LNG from tank to tank within an LNG facility to maintain cryogenic temperatures of pipe work can contribute to the occurrence of stratification. Recirculation flows are of much lower flow rates than the flows associated with ship offloads, this lower flow rate combined with LNG of a high nitrogen content can generate stratification. The nitrogen will flash off when the pressure of the LNG is dropped upon return to the tank, thus generating a thin layer of lighter LNG at the top level of the tank.

2.4.2 Auto Stratification

There is evidence that the presence of nitrogen in LNG can cause a previously homogenous liquid to self stratify. This self stratification is also called auto stratification or nitrogen-induced stratification. Figure 2.1 shows the boundary layer rise associated with auto-stratification when LNG in a storage tank gains heat through the wall. On reaching the surface, the liquid flashes. If there is sufficient nitrogen present*, its preferential loss can cause the flashed liquid to be less dense than the remaining liquid. There is then no driving force for recirculation and the light, flashed liquid would be expected to accumulate near the surface. The accumulation of light liquid would continue until the layer of light liquid reached a height such that the kinetic energy of the liquid in the boundary layer would be insufficient to overcome the potential energy due to density difference and carry liquid to the surface. No further flashing could then occur and the height of the layer of liquid would stabilise.

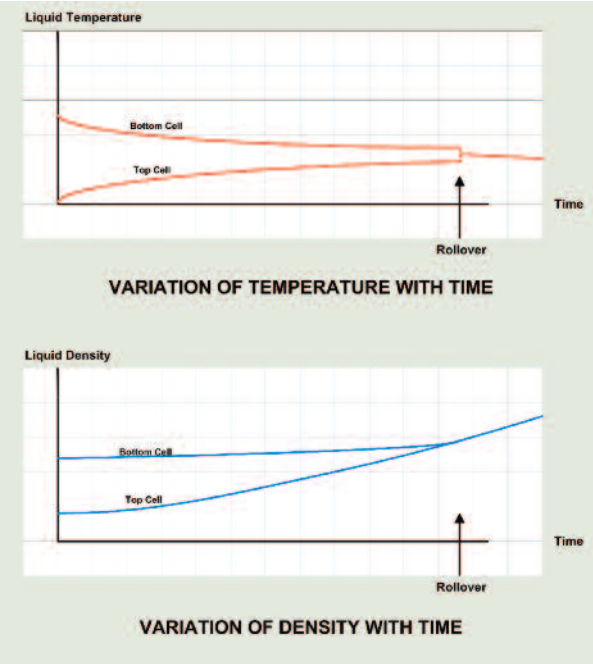


Figure 2.6 (a) Case II, variation of temperature with time
Figure 2.6 (b) Case II, variation of density with time

Chatterjee and Geist (13) give an expression for the stable height (h) of the top layer as follows.

$$h = \frac{u^2}{2g}\left(\frac{\rho_1}{\rho_1 - \rho_2}\right) \qquad (2.2)$$

Where u is the average velocity of liquid in the boundary layer, ρ_1 is the density of unflashed liquid ρ_2 is the density of flashed (light) liquid and g is the acceleration due to gravity.

Once a layer of height given by Equation (2.2) is formed the lower layer can no longer lose heat by flashing and the temperature of the layer (bottom cell) begins to rise. Thereafter, the behaviour is similar to that for fill-induced stratification, rollover occurring when the densities of the two layers equalise, see section 2.3. However, there is one significant difference that after the rollover event the mixed liquid may still contain an appreciable amount of nitrogen, which may continue to drive the process of auto stratification and rollover may be repeated one of more times.

** Chatterjee and Geist (13) do not precisely define critical nitrogen content but state that only mild effects are expected for nitrogen content between 1% and 3%. Even if stratification occurs, which is not certain, the subsequent vapour-evolution rates at rollover are estimated to be only two or three times normal. For 4% nitrogen or higher, auto stratification is an established cause of rollover.*

These findings arose from looking at some incidents at US peak shaving plants where nitrogen content in the LNG was as high as 6% and repeated events occurred which is a characteristic only predicted for auto-stratification. GDF Suez performed, in 1990 and 1991, two experiments on a 120,000 m³ tank at Montoir receiving terminal to study LNG ageing phenomenon. For each test, a homogeneous layer of LNG containing up to 0.8% of nitrogen had been stored inside a tank up to four months. No auto-stratification was reported at the end of these tests. Operational experience has also suggested that LNG is stored in Japanese LNG receiving terminals for long periods of time with no stratification due to convection inside the tanks.

2.5 Other Types of Stratification

Stratification has been observed to develop in cryogenic liquids following pressurisation and in laboratory tests with aqueous solutions in which there was an initial vertical density gradient. Neither type is thought to play an important role in rollover in LNG storage tanks, but they are mentioned here for completeness.

2.5.1 Stratification on Pressurisation

A number of tests (14, 15, 16, 17, 18 and 19) for single-component cryogenic liquids (mainly hydrogen) in tanks up to 170 m³ capacity has shown that raising the gas pressure above the liquid surface can cause stratification to develop within the liquid. Similar effects have been observed in 35,000 m³ LNG tanks (20). This stratification is time-dependent, taking the form shown in Figure 2.7. Initially, the liquid is at uniform temperature roughly equal to the saturation temperature, T_S, at the pressure of the vapour above it. If the pressure is then raised, a region near to the top increases in temperature. This region grows downwards with time. A correlation equation exists (14) that predicts the vertical extent of the region of non-uniform temperature. The Hashemi-Wesson layer at the liquid-vapour interface was not resolved in these tests.

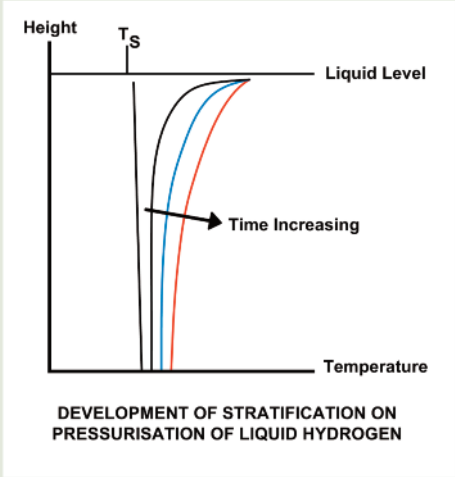


Figure 2.7 Development of stratification on pressurisation of liquid hydrogen

For large pressure rises producing the effects shown in Figure 2.7, the vapour evolution essentially stops, see section 2.2.1, and the heat absorbed through the base and sides of the vessel serves to heat up the liquid and produce stratification. Small pressure rises that reduce the vapour evolution but which are insufficient to stop it would not be expected to produce stratification.

This type of stratification does not produce separate cells and no instances of rollover associated with it are known. However, it does explain the occurrence of pressures in excess of the saturation pressure corresponding to the mixed mean liquid temperatures that have been observed in some closed LNG transports, in particular, a barge and a number of trailers (21).

2.5.2 Double-diffusive Convection

A number of experimental and theoretical studies (22, 23, 24, 25, 26, 27 and 28) have shown that multiple horizontal cells can develop in liquids with an initial density gradient as a result of side heating. The experimental studies are mainly on the laboratory scale and are with aqueous solutions in which the solute increases in concentration in a vertical, downward direction. Cells start to develop close to the side wall and progress towards the centre of the liquid container, ultimately forming complete horizontal cells.

It is possible for a density gradient of the right type to occur in an LNG tank if fresh liquid is poorly mixed with an existing heel and, if certain conditions are satisfied, it is conceivable that horizontal cells could develop also. Rollover might then follow after the cells had agglomerated to such an extent that only two cells remained. According to Griffis & Smith and Narusawa & Suzukawa (25, 26), an important condition for development of the multiple horizontal cells is that the value of the stability parameter, *e*, (which relates buoyancy effects due to concentration gradients to those due to thermal gradients) must lie within certain limits. Unfortunately, the value of *r* for a typical LNG tank is below the range of the experiments and so it is not possible to predict from these studies whether or not multiple horizontal cells can be formed in such a tank.

There are no known instances in which multiple horizontal cells have been detected in LNG storage tanks, whereas fill-induced stratification has been detected by in-tank instruments on a number of occasions. This fact, plus the absence of incidents requiring explanation other than as consequences of fill-induced or nitrogen-induced stratification, suggests that stratification arising from double-diffusive convection is not a problem in operational tanks.

2.6 Characteristics of Rollover

Rollover, the rapid mixing of two stratified cells, occurs when the densities of the cells approximately equalise. Density equalisation is a result of changes in the temperature and composition of the cells brought about by heat absorption from the surroundings and weathering, see Section 2.3. If the mixed liquid has temperature and composition such that it is appreciably superheated with respect to the vapour pressure in the tank, which is frequently the case, there is a sharp increase in the vapour-evolution rate.

2.6.1 Mixing of Stratified Cells

Information on the way mixing occurs is important because the mode and speed of mixing are likely to exert a strong influence on the vapour-evolution rate during an incident. Experiments with Freon (1) and water (2) show that as the densities of the two cells approach one another the boundary layer at the wall tends to penetrate the interface and that away from the wall, waves can develop at the interface. It is therefore probably not necessary for the densities to equalise exactly before mixing begins. The critical density difference for mixing is not known with any certainty but Miyakawa et al. (29) present evidence suggestion that it is small in LNG, about 1 kg/m^3. The Freon experiments (1) also show a dependence of the rate at which mixing occurs on the physical distribution of the heat input to the test tank. Side heating produces "slow mixing", the wall boundary layer penetrating the interface between cells and the interface moving gradually down to the bottom of the tank. Heating from below produces "rapid mixing", the contents of the bottom cell rising bodily upwards on the outside of a downward-moving plug formed by the contents of the upper cell and the interface losing its shape immediately. Combined side and bottom heating can produce either "slow mixing" or "rapid mixing".

A layer of density intermediate between the densities of the two cells has been observed between the cells on several occasions with LNG (29, 30 and 31). Such a layer is likely to affect the mixing process.

It has been suggested (10) that stratification may be terminated by the onset of boiling in the bottom cell rather than by convective mixing of cells. This is conceivable at the tank wall near to the interface between cells if the temperature of the liquid in the bottom cell exceeds the saturation value corresponding to the pressure at the interface (pressure in vapour space plus pressure due to hydrostatic head of liquid in top cell). Boiling at this point would occur first, requiring additional superheat of perhaps 0.5 K to 2 K for bubble nucleation (32). Progressively larger superheat would be required for boiling lower down the wall or at the tank base because of the increasing hydrostatic head of liquid above. Boiling throughout

the bulk liquid due to homogenous nucleation is inconceivable, requiring additional superheat of 50 K at least (33). This is how the Partington rollover incident that occurred in 1993 was justified by Baker and Creed (34) who described it. The researchers claimed that around the time of rollover the lower layer had reached its new bubble point under the hydrostatic head of the upper layer.

2.6.2 The Vapour Evolution Rate

Once stratified cells have been created and allowed to evolve over a period of days, the bottom cell cannot cool by evaporation which results in the vapour evolution from the tank being lower than the nominal rate. One of the initial indications that stratification has occurred is a drop off of the BOG evolution rate from the nominal rate and an increase of the temperature of the LNG in the bottom part of the tank, due to heat in leak into the bottom layer which cannot be released at the free surface by evaporation. Uznanski and Versluijs (35) stated that for an experimental trial the presence of stratification reduced the nominal BOG by a factor of five.

When rollover occurs, it is accompanied by a rapid increase in the rate of vapour evolution to a value which can be many times the normal rate. Uznanski and Versluijs (35) stated that the vapour evolution that can be 10 to 30 times greater than the tank's normal boil-off rate, thus giving rise to potential over pressurisation of the tank. Starting from the rollover event the vapour evolution rate declines steadily to the normal operational value.

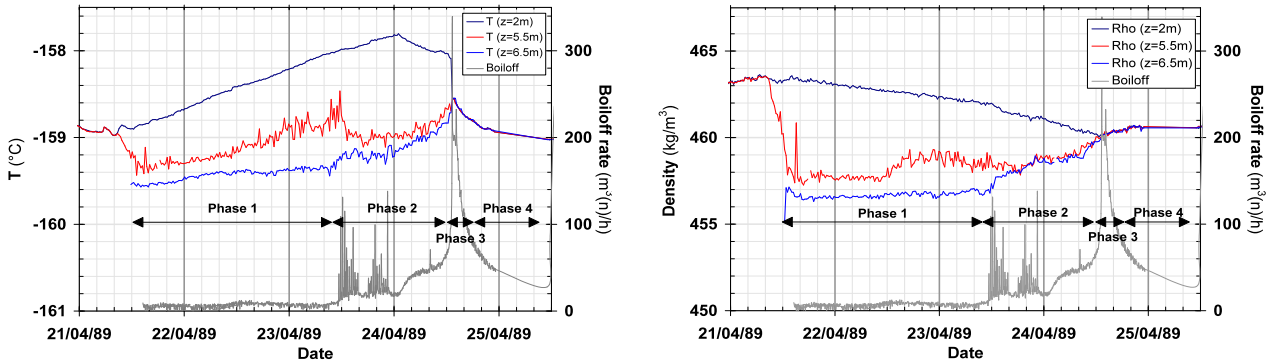


Figure 2.8 Experimental stratification evolution with respect to (a) temperature and BOG rate and (b) Density and BOG rate.

Figure 2.8 (a) and (b) show the evolution of an LNG stratification created in a 500 m³ LNG tank for experiments conducted by GDF Suez during the late 1980's, (35) and (36). This evolution can be broken down into four distinct phases with regard to BOG rate. During a first phase, the stratified layers can be considered as insulated from one another with respect to both heat and mass and only the lower layer heats up progressively, which decreases the density difference between the layers. During a second phase, interlayer penetration takes place between the two layers, further reducing the layer's density difference. During the third phase, density equalisation occurs, which results in a rapid mixing of the two layers, producing the rollover event. The rollover is characterised by a sudden release of superheat from the lower layer, which is released at the free surface through evaporation. The LNG then progressively loses this overheat and returns to an equilibrium state in a fourth phase.

Bates and Morrison (36) used this research to support their modelling approach for describing the evolution of stratified LNG. The behaviour of moving interfaces has also been reported by Scurlock (37), who arrived at the same conclusion after carrying out over 100 experiments with cryogenic liquids.

3. Incident Data

As part of the research for the revision of this document, the Task Force surveyed GIIGNL members and conducted a literature review for the occurrence of rollover events and additional events post 1983 that build upon the incidents that were reported in the first addition of this study. This study reports 24 incidents of rollover events which are presented in Appendix A.

In summary, the study returned a lesser count of incidents than the study completed as part of the first addition. What may be concluded from this result is that either the first study may have influenced the industry and lessons may have been learnt, thus resulting in fewer incidents recorded as part of the second survey conducted as part of this study; or the second survey had less penetration into the industry. In reality these events are far more common than the documented cases suggest, but LNG operators priorities are in preventing and understanding rollovers, rather than publishing data. The majority of the rollover incidents reported occurred within the 1970 – 1980's. Fewer incidents are reported in the 2000's but rollover events are still occurring with a predictable frequency, implying that the industry still has lessons to be learnt even if the events appear to be of a lesser impact than the events in the 1970's. Out of these 24 incidents, three case studies are provided to demonstrate the different types of rollover events that have occurred.

It is possible to classify incidents as per type of phenomena that occurred. The fill-induced stratification is the most common scenario and the two best documented cases of it occurred in La Spezia, Italy in 1971 (38) and in Partington, UK in 1993 (34). Other fill-induced stratification is more specific to particular sites and local technical limitations, and in recent years a number of rollover incidents were recorded on peak-shaving terminals, where despite the lighter product being fed from the bottom of the tank containing a denser heel, instead of mixing it would float to the surface forming a stratified layer. Investigation performed by Sheats and Tennant (39) attributed this initially unexpected behaviour to two main factors, firstly being the lack of an efficient mixing nozzle, and secondly a very low filling rate.

It may be possible to classify incidents as per situational root cause:

- Peak shave – Less flexible operationally and of a generally older design with less instrumentation
- Import Terminals – More flexible operationally and of a generally newer with instrumentation
- LNG carriers – Incidents are more hidden from the public domain and therefore less reported

The results from the study show that rollover incidents continue occurring over the LNG industry, implying that lessons still need to be learnt. The study reported incidents associated with new commercial shipping arrangements such as partial offload and reload, signifying that the industry should consider more attention within this area, particularly considering rollover in the design of ships tanks. The rate of rollover incidents might be an emerging theme with an increasing diversification of LNG supply sources caused by a growing number of liquefaction plants around the world along with an increase in short-term trade. This combined with the industries transition into a new growth phase with new technology, such as FPSO (Floating LNG Production, Storage and Off-loading), bulk breaking and small scale LNG, ship to ship reloading, LNG as a fuel and growth of road tanker sector may see rollover incidents continue in the future.

3. Incident Data

3.1 Case Studies

3.1.1 Case Study 1: LNG Rollover at La Spezia, Italy, 1971

The terminal had two vertical cylindrical single containment 9% Ni storage tanks each with a capacity of 50,000 m^3 and a maximum design pressure of 50 mbarg. Bottom filling was achieved by a side entry point and recirculation was achieved via a top connection. The tank that was filled had a heel of 5,170 tonnes with a density 541.7 kg/m^3 (40) to which a cargo of 18,200 tonnes of a density of 545.6 kg/m^3 was added. Prior to discharging its cargo, the "Esso Brega" LNG carrier had been berthed in La Spezia for more than one month, during which time the cargo had weathered and warmed. When this heavier warmer LNG was loaded through the bottom fill of the LNG storage tank it stayed on the bottom forming a layer, with the lighter cooler tank heel being displaced upwards with only minimal mixing.

About 30 hours after the loading had commenced rollover occurred. The tank relief valves lifted for approximately 1 hour and the process vent discharged at high rates for a further 2 hours after the tank relief valves were closed. The vapour release peak was estimated at 10 tonnes/hour. It is calculated that 185 tonnes of LNG vapour was released in total, 89 tonnes from the tank's roof vents and the remainder from the process vent on site (41). Some vapour drifted offsite to a public road and as a precaution the public road was closed and the LNG carrier was moved off the berth. No ignition took place and no injuries were sustained but some minor damage to the roof of the tank occurred. Sarsten (38) studied this incident in further detail.

The incident at La Spezia was the first significant rollover event that occurred on an LNG storage tank to be reported. The incident led to important changes in storage tank design, instrumentation and operations across the LNG industry.

3.1.2 Case Study 2: LNG Rollover at Partington, UK, 1993

Tank No. 2 at the Partington site had a heel of 17,266 tonnes of LNG and a total of 3,433 tonnes of liquefaction product was added over a period of 24 days (40). During the final 13 days of liquefaction production, two significant events occurred. Firstly a cryogenic distillation plant was commissioned that reduced the heavy hydrocarbon and carbon dioxide content of the feed gas to the liquefaction plant, and secondly the nitrogen content of the feed gas to the plant reduced due to the shutdown of a specific gas field that supplied the UK gas transmission system.

After 68 days following the end of liquefaction production, the tank pressure started to rise rapidly and both the process relief valves and the emergency relief valves lifted resulting in approximately 150 tonnes of vapour being vented to atmosphere from the tank over a 2 hour period. The pressure in the tank did not exceed the design pressure and the tank was not damaged.

Calculations undertaken as part of the investigation into the incident indicated that the tank heel prior to filling was approximately 446 kg/m^3, to which 1,533 tonnes of LNG at 449 kg/m^3 was initially added to the tank followed by 1,900 tonnes of the lighter LNG, resulting in a product density of 433 kg/m^3. The first phase of the run would have been expected to mix with the heel, but the lighter second phase would have stratified. In the first 58 days after filling approximately 160 tonnes of LNG had boiled off whereas calculations showed that 350 tonnes would have been expected to boil-off if no stratification was present.

As a result of the incident, the operator amended their operating procedure at the Partington plant and other peak shaving sites across the UK for filling tanks and identifying stratification. These included determination of heel density by analysing export gas, controlling LNG density from the liquefaction plant to ensure it does not differ from the heel by more than 5 kg/m^3, limiting nitrogen concentrations in the tank to less than 0.8% after filling and regular analysis of boil-off composition and rates. If stratification was detected then the contents of the tank were circulated from bottom to top of the tank to promote mixing and release superheat from the LNG. Baker and Creed (34) studied this incident in further detail.

3.1.3 Case Study 3: LNG Rollover on a Moss Rosenberg Type LNG Carrier

It was believed that rollover on a Moss Type LNG carrier was unlikely to occur because the spherical shape of the tank would enhanced the convection current and ensure thorough mixing of the tank inventory which would be further aided by the vessel's motion during transportation (40).

The first publication of this rollover Task Force (1983) stated that there had been a rollover aboard an LNG ship that occurred shortly after completion of loading operations, but there were no details available to publish as part of the study. The original rollover Task Force also noted that stratification had occurred onboard an LNG carrier on another occasion. This second event was confirmed by the recording of LNG densities during unloading and by an unusually high vapour-evolution rate, more than three times the normal value. The current Task Force have reported the occurrence of a rollover event on a Moss Rosenberg type LNG carrier, the events are summarised below.

In 2008, a Moss Rosenberg type 125,000 m^3 LNG carrier discharged a cargo in the Far East that had been loaded in the Atlantic Basin keeping over 8,500 m^3 of LNG as heel in two cargo tanks (No. 3 and No.4) for the return voyage to the Mediterranean to load (40). After 8 days at sea the vessel received orders to change course and load in a port in the Far East where it arrived 17 days after leaving the discharge port, arriving with a heel of over 5,000 m^3 of LNG. The port where the vessel loaded was a receiving terminal and the loading rate was less than half of what would normally be expected; also the vessel had to interrupt loading for several hours to ensure that the cargo tanks were cooled to acceptable limits and both of these factors may have contributed to the stratification of the tanks contents. The density of the cargo loaded in the Atlantic Basin was 427 kg/m^3, that of the 8,500 m^3 heel 434 kg/m^3 and that loaded in the Far East 454 kg/m^3, nitrogen content was negligible.

After 24 hours from leaving port the levels were seen to increase in tanks No. 3 and No. 4. After 5 days, whilst the vessel was waiting to berth at the discharge port, the tank pressures were seen to rise, accompanied by a drop in the tank levels in 3 and 4 tanks as rollover occurred. The crew closed the vapour valves from tanks 1, 2 and 5 to send as much vapour as possible to the boilers from No. 3 and No. 4 tanks, which peaked at 200 mbarg. Shortly after this event occurred, the vessel berthed at an importation terminal and was able to send vapour to the shore flare to manage boil-off and commence custody transfer.

This was not considered to be a serious rollover event when compared with the La Spezia incident, but demonstrated that LNG carriers can experience stratification and rollover if heavy LNG is loaded under a heel of lighter density. The changes in tank level were more apparent because a spherical tank will have a greater change for a given volume than a prismatic tank when the tank is fully loaded. At no time did the tank pressures exceed the design pressure nor did the cargo tanks pressure relief valves lift (40). Knowledge of how to manage different density cargos by the ship operations team could have attributed to the occurrence of the incident. The changing shipping pattern of the vessel was also an attributing factor. These factors are a concern as this result may highlight a future trend in the industry as LNG as a commodity is utilised in an ever increasing manner with different ways of operating, new technologies and new operators / users.

4. Measurement of Stratification

The first signal of the presence of stratification in a tank is a decrease of the boil-off rate of the tank and an increase of the temperature of the LNG in the bottom part of the tank. This temperature increase is due to the fact that the heat leaks in the bottom layer are not evacuated at the free surface by evaporation but contribute to that layer's temperature increase. Another sign that conditions exist for a rollover event is the stratification of the stored LNG. This results in the development of two distinct layers of liquid densities within the product in the tank. All of these effects are measurable and tank instrumentation can be included to detect these stratifications by measuring temperature and/or density at various levels within the stored LNG. Software is also available that uses data from instrumentation on the storage tank to predict when a rollover incident may occur which may be many days after a filling operation has been completed.

Since the publication of the first rollover study in 1983, the instrumentation available to the industry has advanced. In those days a technician would take a sample of the stored LNG from one of the LNG pumps while it was operating. The sample would be run through a chromatograph in a laboratory. The results would be returned to the plant via interoffice mail. These sampling routines would take place prior to the start of any operations to refill the LNG storage tank. It is obvious to foresee that this procedure could lead to errors where the analysis results were either delayed returning to the plant or lost resulting in incorrect filling, i.e. top fill when it should have been bottom fill or vice versa. Today LNG plants are equipped with sophisticated and unmanned systems to analyse the properties of the LNG in situ with real time results available to operators. Gas chromatograph-based techniques analyse vaporised LNG samples, which provide a routine means of providing LNG composition and other properties. This data is then sent to the SCADA system which informs the operators in the control room as to the quality and density of the LNG both incoming and existing. This information combined with a LTD travelling gauge provides a useful setup for the prevention and control of the stratification phenomenon. Moreover, the present requirements for the design and operation of LNG plants are governed by internationals codes, such as:

- "Tank Systems for Refrigerated Liquefied Gas Storage" (API 625),
- "Installation and Equipment for Liquefied Natural Gas – Design of Onshore Installations" (BS EN 1473), and
- "Design and Manufacture of Site Built, Vertical, Cylindrical, Flat-Bottomed Steel tanks for the Storage of Refrigerated, Liquefied Gases with Operating Temperatures Between 0°C and 165°C (BS EN 14620),

These codes require that LNG storage tanks be equipped with a density measurement system to monitor the density of the LNG over the full liquid height. The following is a summary of the different types of instrumentation used on LNG storage tanks.

4.1 Useful Measurements

LNG tanks are equipped with intelligent tank gauges with high accuracy liquid level, interface level, density and density profile measurements with the following three main purposes:

- Detection of stratification,
- Monitoring the effectiveness of methods of preventing or eliminating stratification and
- Obtaining data for investigation of any incidents that occur.

A list of useful measurements for these purposes is as follows:

- Vertical temperature profile in LNG
- Vertical density profile in LNG
- Vapour withdrawal rate
- LNG level
- LNG filling and withdrawal rate
- LNG recirculation rate
- Composition
- Tank pressure

It is generally not necessary to make all these measurements: for example, stratification can be detected from the temperature profile, from the density profile, from analysis of composition or from the vapour evolution. Also, not all parameters need to be monitored continually. The choice of which measurements are made and when they are made ultimately depends on individual site conditions and requirements.

4.1.1 Instruments in Use

The instrumentation on new LNG storage tanks has developed into a standard configuration. The setup normally includes two level gauges (either servo or radar) with associated temperature arrays for average LNG temperature, a dedicated high level gauge, a level temperature density (LTD) gauge for profiling, and some combination of skin temperature measurement for cool-down monitoring and leak detection (Figure 4.1). The LTD travelling gauge is an instrument that has been designed to collect the temperature and density over the entire depth of the liquid. This is accomplished by traversing a single, multifunctional probe through the height of the liquid and recording the temperature and density at present intervals. This operation requires less than an hour depending on the height of the liquid in the tank and can be done as often as desired. It is normally done after a significant change in tank conditions and once a day under static conditions (39). The association of a travelling liquid temperature density (LTD) gauge with rollover prediction software gives the operator an integrated predictive tool with real time validation, in order to optimise the management of LNG storage.

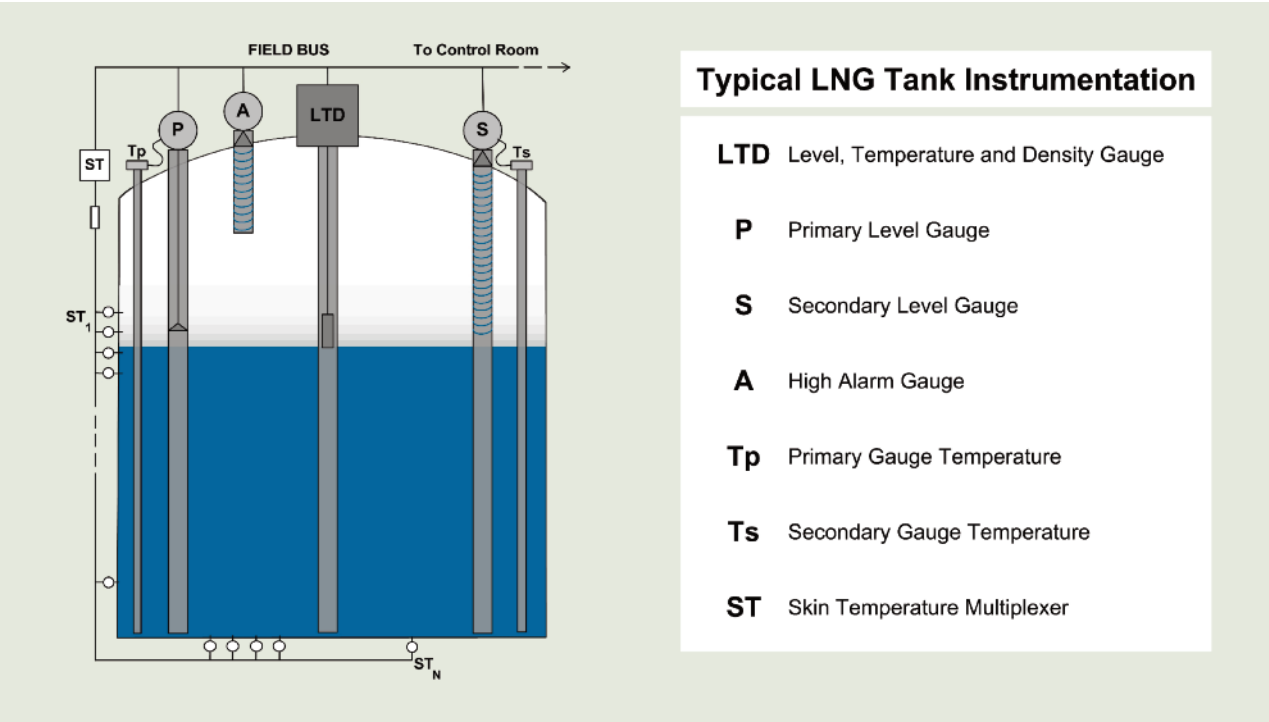


Figure 4.1 Typical LNG Tank Instrumentation

4.1.2 Vertical Temperature Profile in LNG

One of the features of the LTD device is to measure the temperature profile across the height of the LNG storage tank. Figure 4.2 shows real operational data for temperature variation across the height of a tank that contains stratified LNG. There is a clear transitional region for of both temperature and density around a level of 1500 mm as measured by a travelling gauge. The graph also depicts how both the measured parameters of temperature and density evolve with respect to time. Calibrated platinum RTD's are typically used for temperature measurement which have an accuracy of ± 0.1°C and a high level of resolution (typically 0.01°C) to be able to detect changes in the temperature of stratified layers. LNG storage tanks are also normally installed with temperature sensors on the tank walls for cool down monitoring purposes. These temperature probes are not suitable for detection of LNG stratification as they are not very accurate.

4.1.3 Vertical Density Profile in LNG

A key measurement for determining the presence of stratification is a vertical density profile across the height of the LNG storage tank. This measurement is typically performed by use of a LTD device. The accuracy range for this type of instrument for density measurement is typically 0.1% of range, 0.5 kg/m^3, however, the accuracy of the measurements is not as important as the resolution and repeatability. What is important of this type of device is that the resolution is high enough to detect changes in the density of potential layers within the storage tank. Figure 4.2 is an example to show a typical result for density measurement across a storage tank height for stratified LNG.

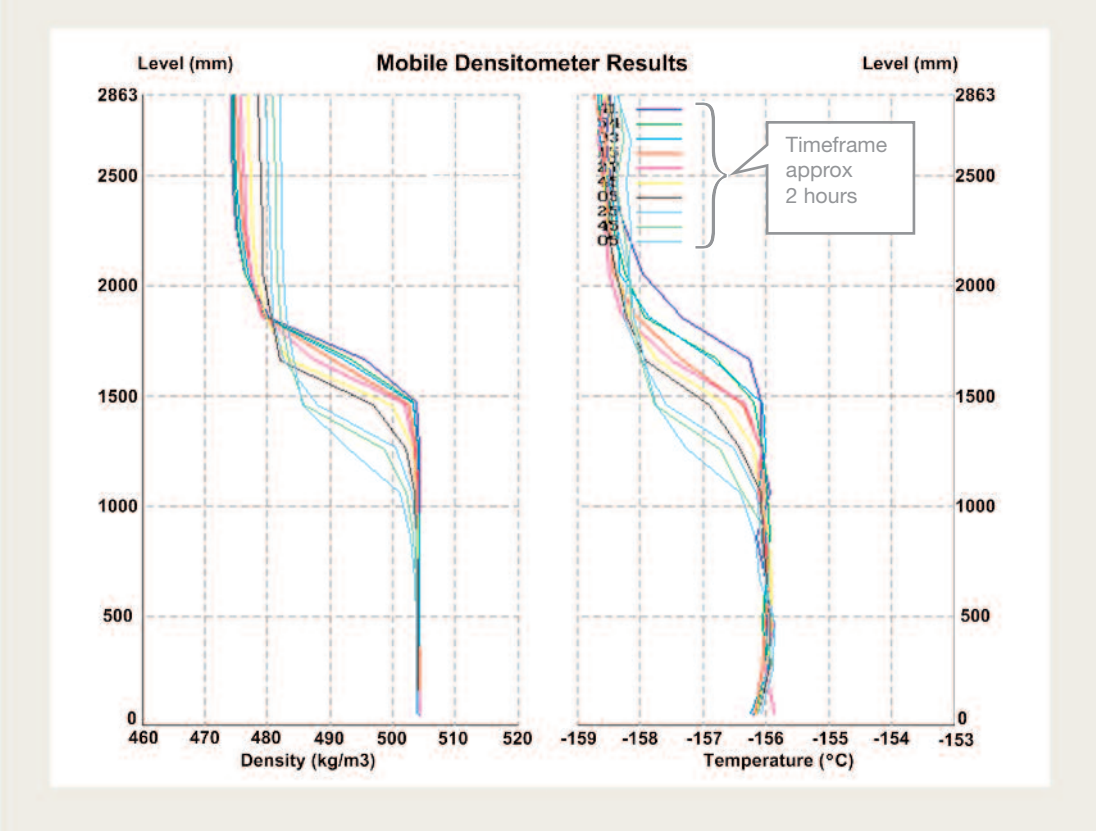


Figure 4.2 Temperature and density profiling across an LNG tank height for stratified stock

Capacitance gauges instruments were historically used for the purpose of measuring vertical density profiles. However, capacitance gauges are seldom installed in newly constructed LNG storage tanks as other types of instrumentation have been developed that are more accurate.

4.1.4 Vapour Withdrawal Rate

Turbine meters and orifice plates predominate as gas flow meter used for BOG flow measurement. Instruments need to be able to withstand and measure high vapour-evolution rates during an incident. The vapour withdrawal rate can also be deduced from the BOG compressor capacity and experienced operators will detect a deviation from the normal compressor demand, signifying that stratification may exist.

4.1.5 LNG Level

Float gauges, displacement gauges and radar gauges predominate. Recording systems are available these can be useful for monitoring liquid loss before and during an incident.

4.1.6 Other Measurements

LNG filling, withdrawal and recirculation rates are known from the pump characteristics.

Composition is universally determined by gas chromatography, accurate techniques for which have been extensively developed for custody transfer purposes.

Tank pressure is monitored during normal operation. During rollover the data are useful for three purposes;

- to ensure that operating limits are not exceeded,
- for estimating the vapour evolution if direct measurements are not made
- for correcting any measurements of vapour withdrawal that are made (the ullage space may retain a significant quantity of vapour if the pressure rises appreciably).

4.2 Peak Shave Plants

Peak shave plants are typically older facilities that have issues with rollover occurrences primarily due to the fact that their design and build predates significant advances in rollover identification and prediction techniques. Therefore, they typically only have top fill capabilities during liquefaction and limited instrumentation installed. The Chattanooga Gas Peak Shave Facility, USA operated safely for many years without any specialised instrumentation to detect and minimise the consequences of rollover (39). The main indication of an impending rollover was a decrease of the BOG rate and an increase in temperature the bottom of the tank. The LNG storage tank was retrofitted with LTD system together with an LNG management data acquisition software system. The combination of this equipment provided the ability to collect temperature and density profile information over the entire height if the LNG stored in the tank and analyse the data to assist the operator in making the correct decision for stock management. Of particular importance in this application is the fact the system may be installed in a tank in service and does not require a stilling well to protect the probe. Whilst the plant had operated safely for many years without this instrumentation, increased requirements from regulatory agencies were one of the primary drivers for the installation of this equipment to demonstrate that the plant was being operated safely at all times (39).

5. Prevention of Stratification Leading to Rollover

The incident at La Spezia is the first known rollover event that occurred on an LNG storage tank. This incident led to important changes in storage tank design, instrumentation and operations. Also, the Partington incident led to further changes in the LNG industry and in the UK this led to all LNG tanks being fitted with densitometers. The learnings from these incidents fed into international codes such as API 625, EN 1473 "The design of onshore LNG terminals", and NFPA 59A "Standard for the Production, Storage and Handling of LNG" now require that LNG tanks be equipped with the necessary systems to mitigate potential rollover conditions. Additionally, they require that a top and bottom fill be provided to allow the mixing of tank contents.

The possibility of a sudden release of large amounts of vapour and the potential over-pressurisation of the tank resulting in possible damage or failure is recognised by the major design codes. EN 1473 and NFPA 59A, both require this phenomenon to be taken into consideration when sizing relief devices. Whilst the relief valves may prevent damage to the tank, LNG vapour is not only flammable and heavier than air on release, but a valuable commodity and a potent greenhouse gas and therefore venting should be avoided whenever possible.

Potential stratification may be prevented during filling operations by loading the denser liquid above the heel of a lighter stored LNG or loading a lighter LNG into the bottom of the tank combined with proper filling rate and/or mixing nozzle so that the light grade does not float to the surface. This creates mixing of the unloaded product with the stored contents. If stratification is detected, product can be moved to prevent rollover from occurring. Product can be recirculated by moving it from the bottom of a particular tank to the top of that same tank. Alternatively, the product can be transferred from the bottom of one tank to the top or bottom of an adjacent tank. Top and bottom fill nozzles designed to promote mixing (in conjunction with the in-tank pumps) are used to move the product for loading, recirculation, and transfer operations. Not only does this move the product to areas with similar compositions, but it also serves to mix the product and release any trapped heat or vapour within the product being moved. Mixing may also be promoted with mechanical agitators such as jet mixing nozzles on the top-filling and mixing slots on the bottom-filling.

Informed LNG storage tank design combined with appropriate plant operational procedures can mitigate the risk of rollover. Mitigation measures that are used are:

- Stratification inside storage tanks is avoided by top or bottom filling according to heel and fill LNG densities, bottom/top recirculation, mixing the liquids by filling using jet nozzles and distributed fill systems
- Different compositions of LNG are stored in separate tanks
- Specify LNG with nitrogen content less than 1%
- Monitoring of LNG density and temperature over height of tank
- Monitoring of total boil-off and heat balance to detect superheating
- Use of software based on LNG tank thermodynamic modelling to predict potential for roll-over
- Ensure LNG residence period in tank is not too long
- Process relief systems and safety valves are designed to handle rollover effects

Out of all of these mitigation approaches, the direct measurement of density across the tanks' height is the primary means of detecting stratification. During stratified conditions the bottom layer often becomes superheated, but monitoring BOG rate is a better indication of potential stratification, rather than direct measurement of the temperature of superheated LNG.

5. Prevention of Stratification Leading to Rollover

5.1 Prevention Methods

5.1.1 Bottom Filling

If the incoming LNG is lighter than the heel in the tank, a bottom filling operation will generally ensure a complete mixing of the two LNG grades, with little or no chance of stratification. The boil-off gas production, generated due to the temperature rise of the LNG during transfer from the LNG carrier to the filled tank, is limited by the hydrostatic pressure at the bottom of the tank. The bottom filling device (Figure 5.1) consists of a tube attached to the support of the tanks and goes down vertically from the top to the bottom of the tank. At the bottom of the tube, there are some slots that direct the incoming LNG into several directions to promote mixing with the LNG in the heel. The bottom filling device is positioned at the edge of the tank near the tank wall. The location, diameter, number and width of slots and other characteristics depend on the specific design.

5.1.2 Top Filling

If the incoming LNG is heavier than the stored LNG a tank top filling operation will avoid stratification and the risk of subsequent rollover, but this usually results in excessive vapour generation due to the flashing of the injected LNG into the tank's vapour space and subsequent increase in tank pressure which must be managed. A simple solution to this is to reduce the loading rate, but this may not always be commercially acceptable and other means may need to be adopted. Furthermore, top filling is not generally provided on LNG carriers, unless they have been modified for use as a floating storage regasification unit (FSRU) when they are often provided with top fill connections.

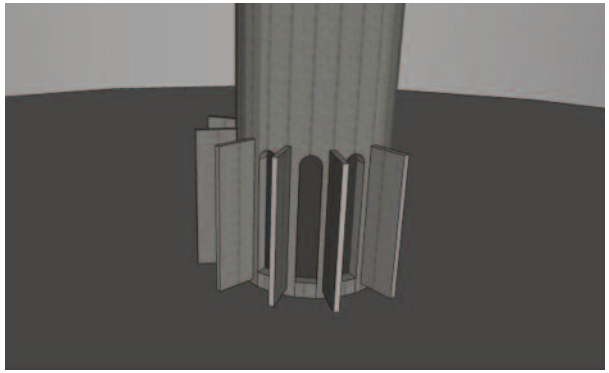


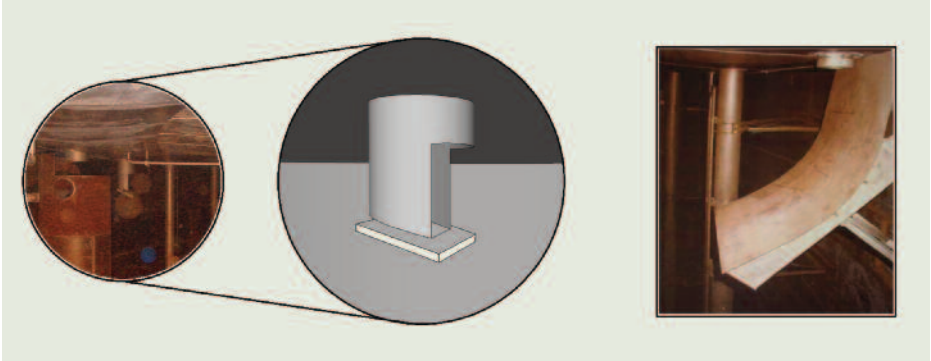
Figure 5.1 Model drawing of a typical bottom filling device

Top-filling devices such as sprays or splash plates are common and appear to be fairly effective insofar as they cause large vapour evolution rates. However, it is thought that this type of device creates droplets that can be carried over into the vapour line, masking the effectiveness of the device and sometimes making the vapour evolution rate excessive.

One method of reducing overall vapour generation when top filling is to lower the tank pressure prior to filling the tank; this will create more boil-off and drop the temperature of the heel. Immediately before filling commences the tank pressure is raised to above normal operating pressure to limit the amount of LNG that flashes off when discharging into the tanks vapour space. This raised pressure is maintained throughout the loading process and when filling is complete the tank pressure is slowly returned to its normal level.

A top filling device is a pipe that enters into the top of the tank though the dome chamber (Figure 5.2). Normally the device consists of a plate at 45° to the direction of flow. When incoming LNG comes into contact with the plate it produces droplets of LNG that fall down the tank into the heel.

Figure 5.2 Example of two types of top filling devices



5.1.3 Filling using Multi-orifice Tube

A mixing device that comprises of a vertical tube drilled with numerous holes over part of its height. The device has the advantage that the discharge rate for a given pump head is higher than for a single nozzle. It is necessary for the holes to be located so that they are submerged for most of the time to avoid excessive vapour evolution. Additionally, the holes are arranged so that the jets miss internal tank fitting, instruments etc.

5.1.4 Jet Nozzles and Other Mixing Devices

A jet nozzle fitted to a fill line located at the bottom of the tank can be very effective in preventing stratification, but there must be sufficient head in the filling line to ensure the jet can reach the surface of the liquid and sufficient time must be allowed to ensure the mixing process takes place in all of the tank contents. Diffusers at the bottom of the fill line can also aid mixing.

5.2 Filling Logistics

In order to prevent stratification, it is advised to adjust the mode of filling the tank (top or bottom) to the relation between density of the existent heel and cargo. If density of the heel is lower, filling heavier liquid from the top will promote natural mixing. Provided a proper mixing nozzle and a suitable filling rate are possible (in order to avoid the fill-induced stratification described earlier) filling lighter liquid from the bottom will also promote mixing. It is quite common to top or bottom fill liquid according to whether it is more or less dense than the heel in order to avoid stratification, but it needs to be used with caution: cases of stratification or rollover in operational tanks following the correct choice of filling point are known.

A common problem with top filling is that this mode of operation causes a large vapour evolution rate. Older sites tend to only have top filling to tank fill. A way of avoiding stratification is to put liquids of different density into separate tanks. This may reduce operational flexibility, and difficulties can arise matching storage tank and ship capacities and scheduling deliveries. It may also be necessary to send out liquid from more than one tank at once to produce a composite mixture for control of the heating value.

Tank stock management for optimisation of use of gas quality blending utilities often sees tanks filled with LNG of different ‘quality’. A ship acceptance model is typically used to carry out calculations and support the strategy for stock management during unloading. For LNG receiving terminals there is a need for a continuous flow of LNG from the in-tank pump discharge to keep the unloading lines cold. Due to continuous recirculation, stock transfer will take place from the tanks with in-tank pumps running to all other tanks. Thus consideration for generation of stratification should be taken for stock management due to LNG transfer during reduced export or holding conditions.

5.3 Management of Stratification and Rollover

Stratification can be destroyed by recirculation, by rotating stock between storage tanks and by sending out liquid before rollover can occur (this may require stock to be exported during less commercially viable periods). To use these methods with confidence, the time to rollover needs to be known, information that can be obtained by modelling, this covered further in Section 6.

Breaking up stratified cells can be achieved by external recirculation of LNG by running the in tank pumps and drawing in the bottom layer, circulating this LNG around the plant (i.e. to the jetty) and feeding it to the top of the tank. However, this process has a cost associated through increased power consumption from running additional pumps and compressors and depletion of stock by production of BOG which will need to be exported. This process may also cause rollover to occur sooner, but with less severity. The reason is that by recirculating the liquid we effectively speed up the process of densities equalisation, which is the criterion for rollover occurrence. If a sophisticated tank management system is provided, the operator will have real time information on how long he has to break up the stratification.

In recent years, following work pioneered by GDF Suez, there has been a growing trend to intentionally induce density stratification. This approach is used to reduce high LNG boil-off gas rates, particularly when top filling is required for heavier cargo. Thus BOG compression costs can be reduced both during and after unloading LNG carriers. These procedures require the sophisticated tank management systems and a means to break up the stratification as referred to earlier.

5.3.1 Detection of Stratification and Prevention of Rollover for LNG Carriers

Rollover risks for shore LNG plants are well documented and understood and the risk of a rollover occurring on an LNG ship has always been considered low (40). This is because LNG ships often maintain a dominant trading pattern for specific vessels, therefore the opportunity for rich cargo to be loaded beneath a lean heel is reduced. Also, due to the process of weathering the remaining heel in the ship is expected to be richer than the cargo that is being loaded.

However, as reported in Section 3.1.3, at least one rollover has occurred within a ship. The incident arose because there was an unusually large heel aboard and the heel was lighter then the incoming cargo. It is also possible to foresee a set of circumstances that could lead to rollover where a ship is being used as floating storage for an extended period of time, which is then topped up with LNG from a richer source (40). Because ships do not normally have either the instrumentation to detect stratification, or the means of mixing the tanks, the best way to manage stratification is to avoid the conditions required to instigate it. Steps such as keeping ships on dedicated trading routes (i.e. within a rich or lean region), reducing the heel for ships arriving at load ports and floating storage being replenished with LNG from the same source, these steps are all deemed as good practice to reduce the risk of stratification. However, if the circumstances for stratification present themselves, then (40) suggests the following actions to mitigate the potential risk. The advice given in (40) is to:

1. Consolidate the heel into one tank.
2. Partially load a second tank to a level such that there is room to transfer into the tank the entire heel.
3. Close the manifold liquid valves - leaving the vapour manifold open.
4. Transfer the heel into the partially filled tank. This should be done using the ship's cargo pumps as fast as safely possible, prudence and vapour generation permitting. The reason for speed is to promote as much turbulence as possible in the bottom of the receiving tank to aid mixing.
5. Do not load any further LNG into the tank containing the mixture.
6. Complete loading the other tanks as per normal procedures.

The procedure above is to be carefully discussed between ship and shore before commencement of loading. It should be noted that the transfer and mixing process may generate significant amounts of vapour.

5.4 Operating Methods

This section summarises how operators for different types of LNG sites put the above recommendations into practice.

5.4.1 Statoil Hammerfest LNG Export Terminal Method

The LNG storage and loading facility is controlled by a central control system which is operated from the Central Control Room. In order to prevent LNG tank roll over phenomenon, each tank is equipped with a level-density-temperature device, which measures and indicates liquid density and temperature at various levels through the LNG tank inventory. Whenever a density difference of more than 1.0 kg/m^3 or if the difference of product temperature between any two layers is more than 0.5°C, or a change in level of ~ 2 m is observed, it is considered that stratification of the LNG inventory into distinct layers may be about to occur. The density measurement system will raise an alarm if the density difference is more than 1.0 kg/m^3. If this happens the operator takes immediate action to eliminate the stratified layers to prevent a potential rollover condition. Generally

the stratification will be eliminated by mixing of the tank's inventory or through inter-tank transfer. Tank recirculation will be undertaken by operating one of in-tank pumps on spillback to the tank. LNG is taken from the bottom of the tank and is filled into the top of the tank via the top filling device and the layer is gradually reduced.

5.4.2 National Grid Grain LNG Import Terminal Method

The LNG storage tanks are routinely monitored using densitometers to look for stratification within the stored liquid. This is conducted at least once per week and after ship unloading.

If the densitometer indicates that stratification exists, the tank is mixed by running the in-tank pumps on spill back. LNG is circulated until the density measurement indicates a top to bottom variation less than 2 kg/m^3 and the temperature measurement indicates a top to bottom variation less than 2°C. Additional boil-off compression capacity is required during the circulation process.

If a rollover condition would occur then the increased BOG would trigger high pressure alarms, release gas to the vent and lift tank relief valves. High pressure would also stop the unloading of cargo if it is in progress and would trip the recirculation of LNG through transfer pipelines from the jetty.

A typical emergency response would include the following steps:

- Maximise BOG disposal via site compressors and relief system.
- Identification of the likely direction of release based on wind data.
- Determination of a safe evacuation route for staff.
- Remote shutdown of sources of ignition potentially in the path of the dispersing gas cloud.

5.4.3 National Grid LNG Tewksbury, MA

The Tewksbury facility is a storage site that is filled by road tankers. The site deploys a strict policy when receiving liquid via road transport; lighter-colder liquid is bottom filled; heavier, warmer liquid is top filled. This method maintains a stable well blended liquid in the tanks. Storage sites of this nature may only empty half the contents of a tank during the vaporisation season. An average operating condition for a winter is to empty the tanks by 50% to create ullage for the summer refilling period. Also, the density of the LNG is monitored and if it corresponds to a Gross Heating Value approaching 41 MJ/m^3 then an export is run to vaporise to lower the tank level and create space for lighter LNG refill. Export also decreases the depth of the lower layer if the tank becomes stratified.

5.5 Safeguards against Rollover

In the event of a rollover, there may be a sudden release of vapour that results in an increase in the tank's internal pressure. This increase in pressure must be accommodated to avoid damaging the tank. The most common way to manage this increase is by providing pressure relief valves that vent the over pressure to a flare or to atmosphere. Other methods for lesser occurrences create the need to run boil-off compressors to recover the gas and send it to lower pressure distribution networks and minimise loss of product and environmental impacts. As previously stated in Section 4, Sheats and Tennant (39) reported that for the Chattanooga Gas peak shave plant, the normal BOG rate would be approximately between 14,158 and 19,822 m^3/day. Prior to rollover, the rollover rate would drop considerably (8,495 m^3/day). During the actual rollover event at the facility, the rate would rise to a range of 67,960 to 76,455 m^3/day. There are two BOG compressors at this site. During normal operations one compressor is required. During a rollover event, two compressors would be required to handle the load. Anything that would make one of the compressors unavailable (such as planned maintenance or a breakdown) would increase the likelihood of venting gas to the atmosphere to protect against tank over pressure.

5. Prevention of Stratification Leading to Rollover

International codes such as EN 1473 and NFPA 59A require that pressure relief be provided to each tank as a last layer of defence to protect against tank over pressurisation during a rollover event. These codes also establish relief sizing criteria that are expected to handle a "typical" rollover scenario. EN 1473 requires that the venting requirements for a rollover scenario be determined by a validated model. If a validated model does not exist, the venting requirement may be conservatively taken as 100 times the calculated boil-off. Alternatively, NFPA 59A requires that the relief system be capable of venting 3% of the full tank contents in a 24 hour period.

For information the design for relief valve sizing for an LNG tank used the guidance in appendix B of EN 1473. Extract given below;

The boil-off due to a roll-over (V_B) shall be calculated using appropriate validated models. In case where no model is used, the flow rate during rollover shall be conservatively taken equal to:

$V_B = 100 \times V_T$

This flow rate corresponds approximately to the maximum flow rate observed in the past during a real roll-over. Where V_T is the maximum flow rate of a tank boil-off due to heat input in normal operation is to be determined by assuming ambient air at the maximum temperature observed in the course of a hot summer day.

The approach NFPA 59A takes is to consider the minimum reliving capacity and states:

The required relieving rate is dependent on a number of factors, but sizing will be based on the NFPA 59A Section 7.8.5.3 (2006 edition) requirement that: "The minimum pressure relieving capacity in pounds per hour (kilograms per hour) shall not be less than 3% of full tank contents in 24 hours."

In Asia, the Japan Gas Association (JGA) is an association consisting of city gas utilities that develops technical standards and recommended practices that are used in Asian countries. Their suite of Recommended Practices include:

- Recommended Practice for In-ground type LNG Storage tanks (RPIS),
- Recommended Practice for Above ground type LNG Storage tanks (RPAS),
- Recommended Practice for LNG terminals facilities.

Rollover features within the Japanese design codes but a detailed procedure is not described within the code. Therefore, Japanese utility companies allow for rollover within the design by considering the specific features of the LNG terminal. As the result, API codes may also be used in addition to these standards depending on judgment of each company. For Japanese design codes, the relief valves of LNG storage tanks are sized for a fire case.

Calculating the boil-off quantity that is expected is very difficult, if not impossible to estimate as it would depend on so many different factors. Therefore, designers may put emphasis onto the code requirements or back on the client as only they know how they will operate the tank and the type of cargos or liquefied product that could be produced and the time it will remain in the tank. Vent headers or flare stacks (to reduce environmental impacts) can be used to relocate the release away from the localised relief valves if the vapour evolution period (rollover event) is extended for a significant period of time, Sheats and Tennant (39) have stated that depending on the severity of the rollover, this could take several weeks. Flare systems are often preferred as they displace methane emissions with CO_2 emissions, which have a significantly lower global warming potential. Methane (the principal component of natural gas) is reported to be 20 times more harmful to the environment than carbon dioxide.

6. Rollover Prediction Models

The original rollover study reported the development of seven LNG rollover simulation models in 1983. Today, the LNG rollover simulation market is dominated by a few commercial proprietary software's that are based on the principles of the earlier models. This section provides an overview of the four main models on the market and their principal use.

Some LNG terminals around the world use rollover simulation models to predict the behaviour of LNG in storage tanks. Enagás use an LNG rollover simulation model to provide their operators with unloading strategies to manage cargos of different densities and simulate the stratification process once the LNG is stored.

A second motivating factor for utilising rollover prediction models is for operator training. Personnel with considerable experience feel comfortable in operating the plant with the indication of normal operating pressure and LNG stock temperature. However, newer operators do not have that experience to draw upon, and modelling and rollover simulation becomes an important tool to give confidence that the plant is being operated in a safe and efficient manner.

A growing trend for the use of model prediction software has been to manage the purposeful instigation of stratification as a stock management strategy. The advantage is to gain efficiencies during unloading operations by suppression of BOG evolution. This will be discussed further later in this section.

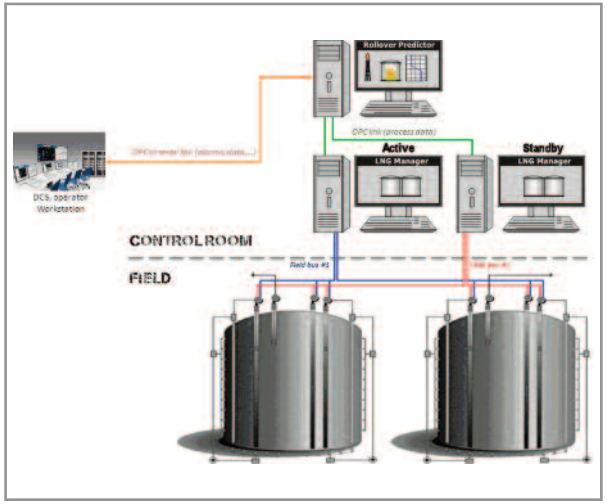


Figure 6.1 Typical Whessoe Tank gauging architecture

6.1 Whessoe Rollover Predictor

The LTD gauge monitors and detects a potential stratification of a stored LNG. But it doesn't provide the LNG terminal's operators with the evolution of the said stratification. Wärtsilä has developed, in collaboration with GDF Suez, the Whessoe Rollover Predictor software. The heart of the software, the calculation module, has been developed and validated in the Nantes, France 500 m^3 LNG storage tank during a Gaz de France experimental campaign on its cryogenic testing station.

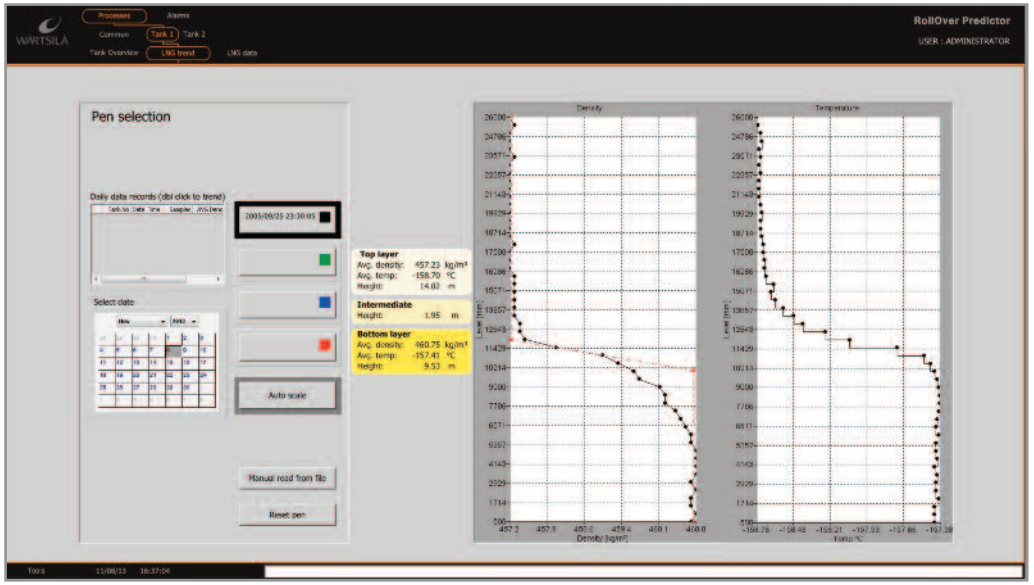


Figure 6.2
Density profiling overview

6. Rollover Prediction Models

The Whessoe Rollover Predictor software is directly connected to the Tank Data Acquisition platforms for an immediate processing of the LTD profiling data.

In case of layered LNG, the software analyses the density and temperature measurements from the LTD gauge (layer height, densities and temperatures). Other information is required such as the availability of safety equipment (flare, compressors, vents, valves, rupture disks) used in the operation of the LNG terminal. The connection of tanks vapour phases is also taken into account.

Based on the chemical compositions of the layers, densities, temperatures and safety equipment availability, the software determines an operational scenario that includes the evolution of each layer. This leads to predict also the evolution of the chemical composition for each LNG layer. These data feeds are recorded in order to be used at the next calculation step and thus increases the accuracy and the reliability of the predicted scenario.

The Whessoe Rollover Predictor predicts the occurrence of a rollover within the next 30 days, and provides the operator with:

- The tank where rollover is expected
- The remaining time to rollover
- The predicted boil-off gas level during rollover
- The predicted pressure rise during rollover

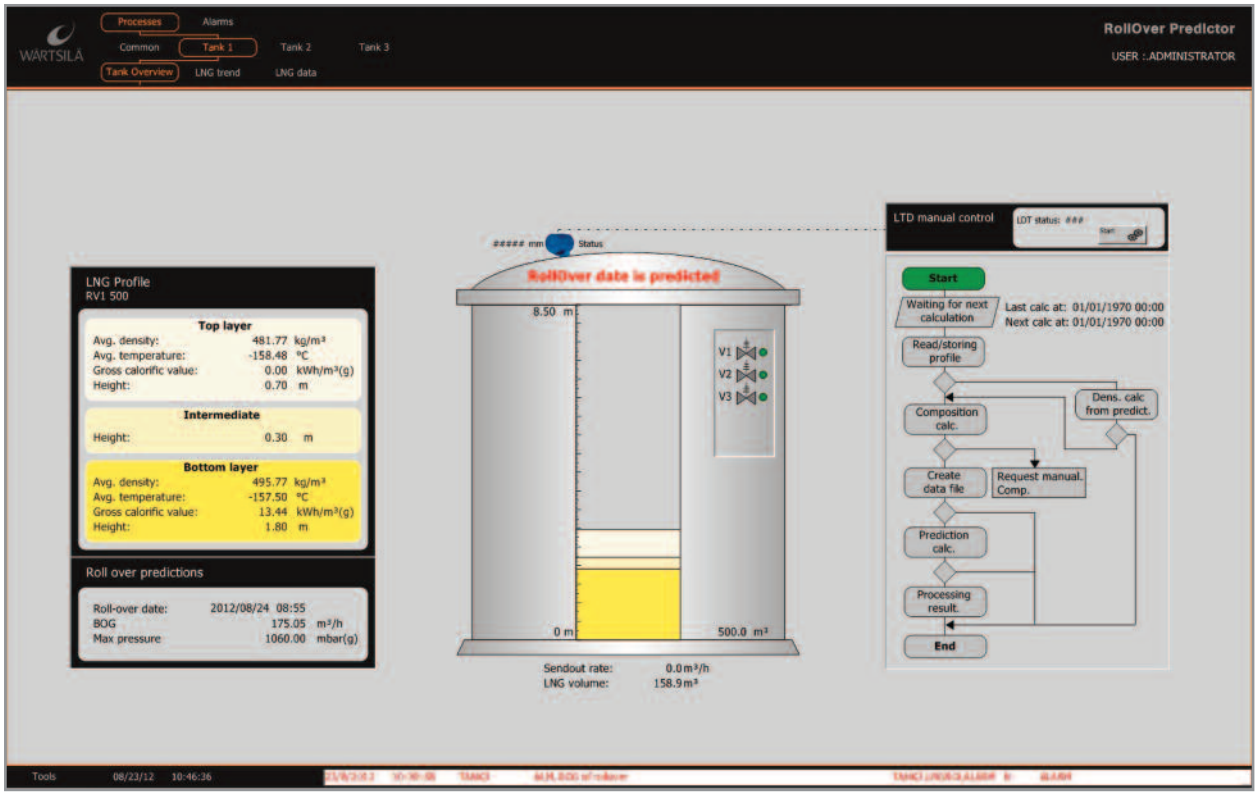


Figure 6.3 Tank overview screen in Rollover Predictor

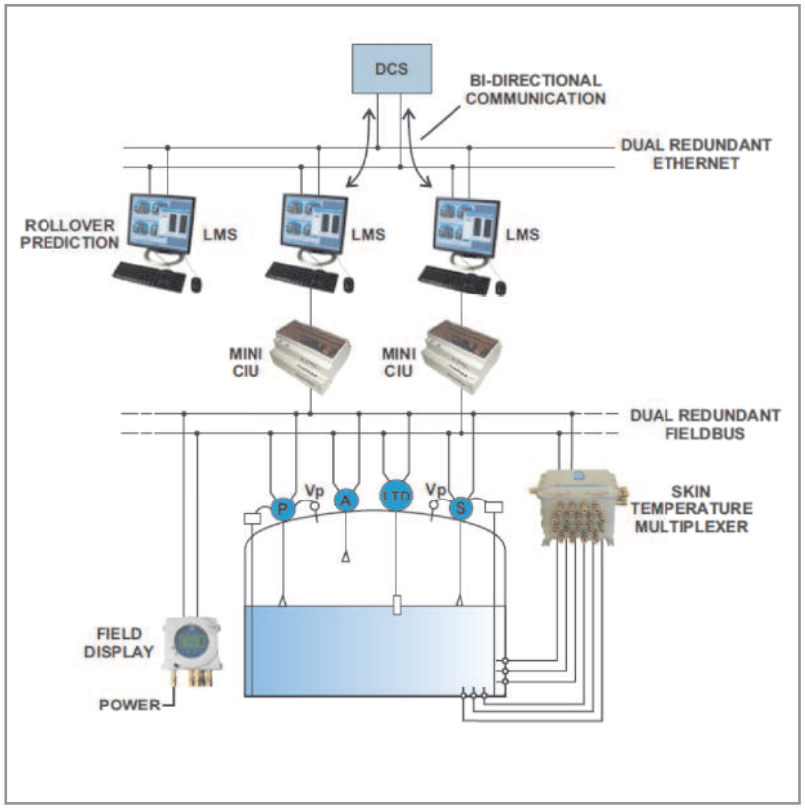


Figure 6.4 Instrumentation array as used by MHT rollover prediction Model

6.2 MHT Technology Ltd. Rollover Prediction Model

The Rollover Module developed by MHT Technology for predicting the behaviour of stratified LNG in storage tanks is based on the concept of lumped parameter model. It simplifies the spatial dependence of the system, compared with Computational Fluid Dynamics models. The module forms a part of an integrated LNG stock management system such as the one shown on Figure 6.4

Based on the given initial conditions, the model allows the user to visualise a number of process parameters and properties using screen such as the one shown on Figure 6.5, as well as number of graphs and tables.

The user can display the evolution of temperature, density, thickness of the stratified layers within a tank, as well as other parameters characterising the conditions inside the tank and inventory properties during rollover incubation. The novelty of the model comes from its ability to estimate heat and mass transfer coefficients from the real time level-temperature-density (LTD) profiles using the inverse method. These parameters have significant influence on heat and mass transfer between the liquid layers and consequently the onset of rollover and so their accurate prediction is of crucial importance.

The inverse method uses LTD profiles taken at two known instances in time. The lumped parameter model is solved iteratively varying the heat and mass transfer coefficients after each loop, until the predicted change in density will match the actual one between the two profiles within the defined accuracy. This way, starting with an initial estimate of the heat and mass transfer coefficients it is possible to obtain the adjusted values that best describe the given LNG tank at the time.

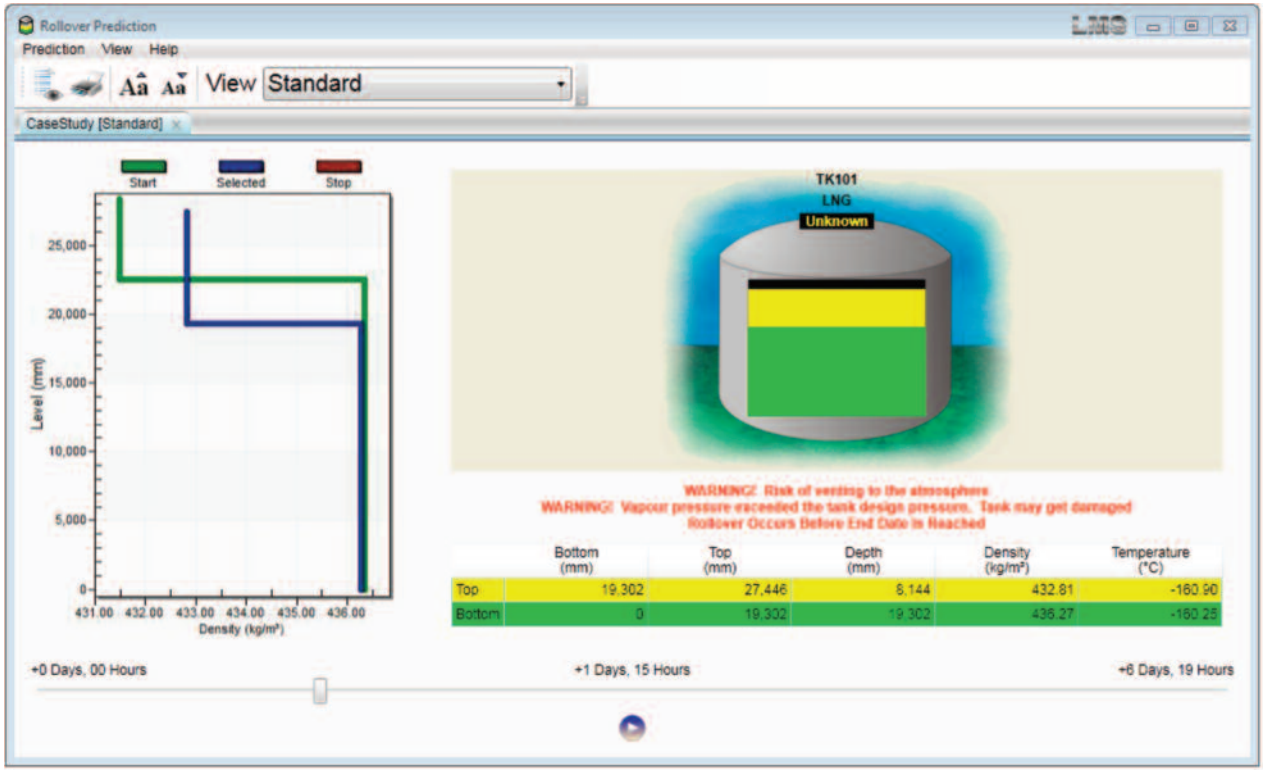


Figure 6.5 MHT Technology Rollover Module Standard View

The model accounts for all major tank operations such as external recirculation, emptying or filling, as well as processes such as flashing in the ullage vapour space. The output from the model calculations can be visualised (or displayed in tabulated form) and easily compared with different results for various operating conditions. This allows the operators of the plant to safely manage a tank in a stratified state if desired until it becomes necessary to take immediate actions to avoid rollover incident. The Rollover Module can annunciate the following alarms depending on the results of the performed simulation:

- The time to rollover event
- Warning: Risk of venting to atmosphere (in case the predicted peak vapour pressure exceeds the specified vent pressure)
- Warning: Risk of tank damage (in case the predicted peak vapour pressure exceeds the specified tank design pressure)

The module also recommends top or bottom filling depending on the density of the new LNG and the density of the LNG already in the tanks. It was validated against the two case studies described in detail in the open literature (La Spezia in Italy and Partington in UK) as well as the rollover incident which occurred at the Chattanooga peak-shaving terminal in US. Some of the principals of model operation were described by Deshpande (42).

6.3 LNG MASTER® GDF Suez

GDF Suez has developed a commercially decision-support software called LNG MASTER®, which predicts the behaviour of LNG in storage tanks. From the design to the operating phases of LNG facilities, the LNG MASTER® software predicts the behaviour of LNG during the operations that occur in LNG terminal storage tanks:

1. Unloading of LNG carriers into LNG storage tanks with assessment of tank filling consequences (boil-off gas generation, gas return flowrate from the terminal to the ship and LNG mixing).
2. Stratification evolution up to the rollover event with assessment of occurrence date and boil-off gas peak.
3. Ageing of homogeneous LNG with prediction of LNG composition changes, as well as Gross Calorific Value (GCV) and Wobbe Index changes.
4 Tank to tank transfer and LNG recycling within a tank.
5. Prediction of operating pressure changes on LNG behaviour.
6. LNG send-out operation to regasification unit (GCV and Wobbe index).

LNG MASTER® is intended both as a safety and optimisation tool for tank management operations in LNG storage sites (receiving terminals, liquefaction plants and peak shaving sites).

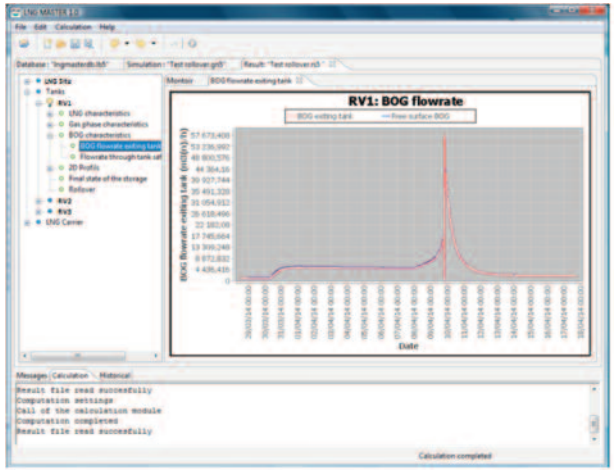


Figure 6.6 LNG MASTER® software

The LNG MASTER® software has been validated through a wide database developed from laboratory tests, a 500 m^3 pilot tank LNG tests conducted in the past by GDF Suez on their LNG cryogenic testing station in Nantes (France) and on-field tests and operations follow-up at various LNG receiving terminals (Montoir-de-Bretagne Fos-sur-Mer and Fos-Cavaou and La Spezia). It mainly included tests on:

- LNG ageing and dynamic evaporation of stored LNG.
- Tank filling with complete LNG mixing or stratification formation.
- Stratification follow-up including rollover occurrence.

The LNG MASTER® software is based on published as well as in-house physical models which have been adapted to LNG product through these experimental and operational data. These models cover all the phenomena that could occur into LNG storages, among them:

- Hashemi & Wesson model for modelling LNG evaporation process at the LNG free surface that was originally developed for water but which has been adapted to LNG (5).
- Heat and mass transfer models across a thick interface in a stratified LNG storage comprising both double diffusive model based on J.S. Turner model (43) and interfacial entrainment model for modeling dynamics and progressive erosion of the thick interface based on Y. Zellouf model (44).
- Advanced dynamic tank filling model that is capable of simulating mixing of various LNG qualities during filling operations carried out in large industrial tanks with commonly used industrial filling devices. This model is also capable of predicting stratification formation when mixing is unachieved (45).

All the implemented models help the LNG operators in predicting the evolution of the mean density, temperature and concentration profiles as a function of time, as well as the instantaneous boil-off gas flow rate allowing them to optimise the handling of different LNG in the same tank during filling operations.

LNG MASTER® can be applied to optimise the LNG unloading operation to storage tanks. It is well understood that a significant amount of gas is flashed off during the filling operation. One way of reducing the amount of gas produced during the unloading operation is to reduce the rate of filling, thus reducing flow of displaced vapour as the tank fills. Another solution is to optimise the tank's operating pressure in order to minimise gas production during tank filling. This is achieved by initially pre-cooling the tank heel before unloading by lowering the operating pressure. Changing the pressure draws off more BOG, thus lowering the temperature of the LNG. Prior to unloading, the operating pressure is increased above the normal operating pressure in order to suppress the amount of flashing for the unloaded LNG. Once tank filling has completed, the tank pressure is then progressively lowered to the normal operating level for storing LNG.

An alternative solution is to use a software prediction model such as LNG MASTER® to purposefully create a stratified condition as part of the unloading operation. By deliberately creating a stratification, in particular in the case of loading heavy cargo under light heel by bottom filling, the operator reduces BOG production rates during the filling operation, and reduces the BOG rate after tank filling during LNG holding condition. Uznanski and Versluijs (35) reported that the stratification method reduces the normal BOG rate by a factor of five. Other advantages for using this stratification method are to decrease electrical power consumption for BOG gas compression during LNG ageing, which reduces terminal operating costs. However, once such a stratification is formed, it needs to be managed safely particularly for the evolution of the stratification up to rollover.

Among the rollover mitigation methods available to the operator, tank emptying represents one of the most effective methods to safely manage stratifications. This method best suits LNG terminals with continuous or frequent exports of LNG. The emptying flow rate necessary to avoid rollover occurrence must be sufficient to completely empty the lower layer before its density equalises with that of the upper layer. LNG MASTER® can be used to calculate the critical emptying rate as shown in Figure 6.7.

Figure 6.7 shows the emptying rate curve giving the time necessary to empty the lower layer of a stratification at the prescribed emptying rate. The rollover time curve represents the rollover onset time at the given emptying rate. As the emptying rate increases, the rollover onset time decreases. At sufficiently high emptying rates, the two curves intersect. This intersection, defined by the critical onset time and the critical emptying flow rate, defines the critical point of stratification. The critical emptying flow rate of stratification is the flow rate at which the lower layer is entirely emptied just as

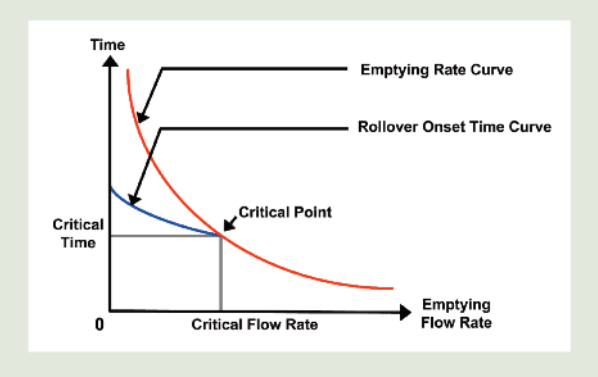


Figure 6.7 Stratification critical point

rollover occurs. Operating at an emptying flow rate above this critical flow rate ensures the withdrawal of the lower layer before rollover occurrence. In this way, the region in Figure 6.7 to the right of the emptying rate curve represents the safe operating zone of stratification. LNG MASTER® calculates the critical emptying flow rate with the site's operational constraints such as the number of pumps in tank to provide a strategy for operators to safely manage the stratification.

6.4 Computational Fluid Dynamics Model, Tokyo Gas

Tokyo Gas utilise a CFD 3D model, with the assistance of CFX, a general purpose CFD software for heat transfer and fluid flow analysis by ANSYS Inc., in order to improve safety, efficiency and reduce LNG storage costs. The CFD model is used for the simulation of LNG stratification and rollover for Tokyo Gas LNG importation terminals.

Koyama (46) evaluated the model's performance against measured values for an LNG importation terminal. Koyama's (46) results showed that the density contour (Figure 6.8) for lighter LNG received from bottom fill reaches the free surface driven by buoyancy, then spreads along the surface, forming a slow convective flow in the tank. These simulation results were then compared with the measured values recorded during a real unloading operation (Figure 6.8). Overall, a good correlation between simulation results and measured values was reported. Koyama (46) concluded that the initial density difference, the initial LNG depth, and the filling rate were directly related to any stratification that may have occurred post unload.

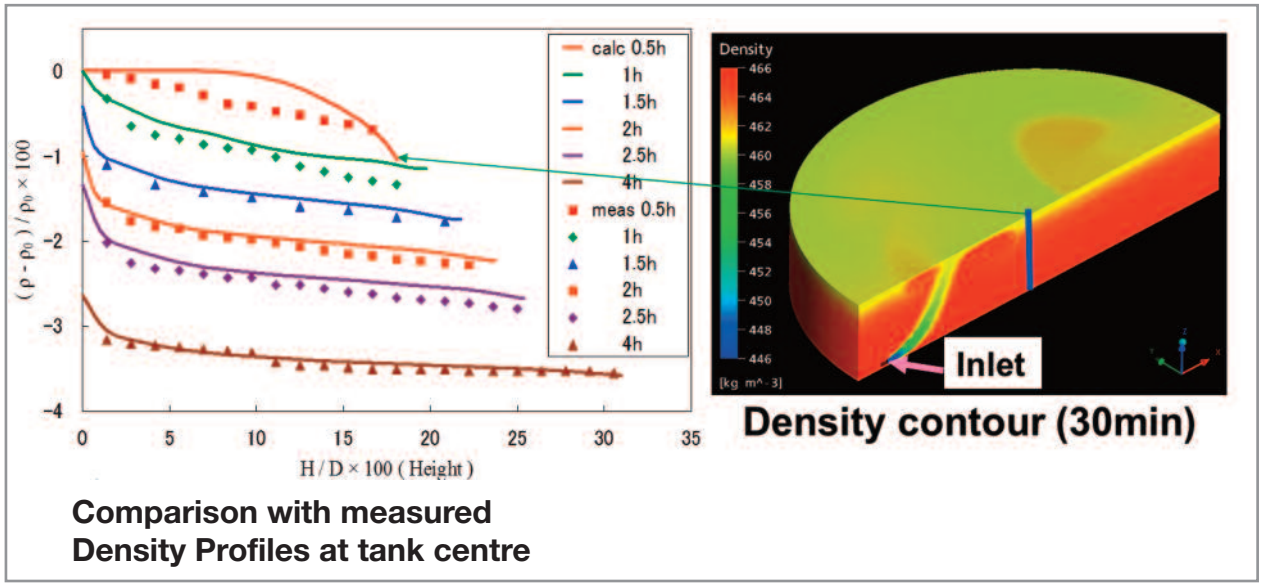


Figure 6.8 Comparison of density profiles simulation and measured

7. Conclusion

The GIIGNL Task Force have reviewed the phenomenon of LNG rollover within storage tanks. This document has presented the theory of the occurrence of stratification leading to rollover and the practical means of managing stratification, either to prevent rollover or to optimise BOG generation with the use of the right tools.

This document has summarised the occurrence of LNG rollover as the rapid release of LNG vapours from a storage tank that has become stratified. Stratification arises when two separate layers of LNG with different densities exist in a tank. The weathering effect enables the LNG densities to become approximately equal at which point the two cells rapidly mix. This rapid mixing causes large amounts of vapour to be released as part of an uncontrolled event that can have safety implications.

The Task Force conducted a worldwide survey and literature review for the collection of incident data. From the 24 rollover incidents reported, a conclusion was proposed that fewer incidents have been reported in recent years but rollover events are still occurring. This implies that the industry still has lessons to be learnt even if the events appear to be of a lesser impact than the events in the 1970's. This finding is of importance as the LNG industry is going through a growth phase with new operators and LNG being used in new processes. The principles of management stratification for these new processes are as yet not thoroughly developed.

Since the publication of the first GIIGNL rollover study in 1983 an increasing awareness of LNG stratification has resulted in a greater emphasis on the installation of advanced instrumentation. As a result, today LNG tanks are equipped with intelligent tank gauges that measure the key parameters such as level, temperature and density, with high accuracy and provide real time data to operators. The requirements for the design and operation of LNG plants are governed by international design codes which can specify the equipment that is necessary to manage LNG stratification.

An area of development within the study of LNG stratification is the growing trend for the use of model prediction software for stock management. These models are used for operator training and design purposes, and in some instances to manage the purposeful instigation of stratification as a means to optimise BOG generation.

This document also summarised the operating practices for different LNG terminals for how they manage LNG storage whilst preventing rollover.

8. Bibliography

1. Nakano, R. Sugawara, Y. et al. An experimental study on the mixing of stratified layers using liquefied Freon. 9th International LNG / LPG Conference (Gastech 82), Session 6, Paper 7. Paris, October 1982.

2. Morioka, M. Shioji, S. Natural convection of stratificational fluid in vessel (Report 1 phenomenon observation). Report D211, Ishikawajima Harima Heavy Industries Co., Japan, circa 1983.

3. Maher, J.B. Van Gelder, L.R. LNG tank dynamics. Third International Conference on Liquefied Natural Gas (LNG 3), Session II, Paper 6, Washington, D.C., September 1972.

4. Churchill, S.W. Chu, H.S.S. Correlating equations for laminar and turbulent free convection from a vertical plate. Int. J. Heat Mass Trans., Vol. 18. pp. 1323-1329, 1975.

5. Hashemi, H.T. Wesson, H.R. Cut LNG storage costs. Hydrocarbon Processing. Vol. 50, pp. 117-120, 1971.

6. Findlater, A.E. Drew, L.R. Operational experience with LNG ships. Fifth International Conference on Liquid Natural Gas (LNG 5), Session IV, Paper 5, Dusseldorf, September 1977.

7. Scurlock, R.G. Convection and heat exchange in low temperature storage tanks. Paper presented at One Day Conference on Static Measurement of Refrigerated Liquids (OYEZ Ltd.), London, June 1982.

8. Watson, P.B. Level measurement at low temperatures. Paper presented at One day Conference on Static Measurement of Refrigerated Liquids (OYEZ Ltd.), London, June 1983.

9. Reid, R.C. Smith, K.A. Virk, P.S. LNG Storage: safety analysis, annual report, January – December 1980. Gas Research Institute Report GRI-80/0032,1981.

10. Salvadori, A. Bellus, P. et al. Anti rollover techniques. Sixth International Conference on Liquefied Natural Gas (LNG 6), Appendix Paper 2, Kyoto, April 1980 (in French). Also available in English translation as T5306/DG/HQ/80, British Gas Corporation, UK, 1980.

11. Bonnaure, C. Test preformed by Gaz de France on filling LNG storage tanks and mixing their contents. Paper presented at the AGA Operating Section Transmission Conference, Atlanta, Georgia, USA, May 1981.

12. "The LNG Industry", Groupe International des Importateurs de Gaz Naturel Liquéfié (GIIGNL), 2012.

13. Chatterjee, N. Geist, J.M. Spontaneous stratification in LNG tanks containing nitrogen. ASME paper 76-WA/PID-6, American Society of Mechanical Engineers, New York, 1976.

14. Clark, J.A. A review of pressurisation, stratification and interfacial phenomena. International Advances in Cryogenic Engineering, Vol. 10, pp. 259-283, 1965.

15. Liebenberg, D.H. Edeskuty, F.J. Pressurisation analysis of a large-scale liquid-hydrogen dewar. International Advances in Cryogenic Engineering, Vol 10, pp. 284-289, 1965.

16. Epstein, M. Georgius, H.K. Anderson, R.E. A generalised propellant tank-pressurisation analysis. International Advances in Cryogenic Engineering, Vol. 10, pp. 290-301, 1965.

17. Segel, M.P. Experimental study of the phenomena of stratification and pressurisation of liquid hydrogen. International Advances in Cryogenic Engineering, Vol. 10, pp. 300-313, 1965.

8. Bibliography

18. Barnett, D.O. Winstead, T.W. McReynolds, L.S. An investigation of liquid-hydrogen stratification in a cylindrical tank of the Saturn configuration. International Advances in Cryogenic Engineering, Vol. 10, pp. 314-324, 1965.

19. Arnett, R.W. Voth, R.O. A computer program for the calculation of thermal stratification and self-pressurisation in a liquid hydrogen tank. NASA Report CR-2026, National Aeronautics and Space Administration, Washington, D.C., 1972.

20. Bellus, F. Reveillard, Y. et al. Test at the Fos Terminal on the behaviour of LNG in large tanks. Fifth International Conference on Liquefied Natural Gas (LNG 5), Session II, Paper 9, Dusseldorf, September 1977 (in French). Also available in English translation as T4324/BGC/1978, British Gas Corporation, UK, 1978.

21. Frangesh, N.E. Randall, Jr., G.A. Distrigas LNG barge operating experience. Cryogenic Engineering Conference, Paper H-1, Kingston, Ontario, July 1975.

22. Chen, C.F. Briggs, D.G. Wirtz, R.A. Stability of thermal convection in a salinity gradient due to lateral heating. Int. J. Heat Mass Trans., Vol. 14, pp. 57-65, 1971.

23. Chen, C.F. Onset of cellular convection in a salinity gradient due to a lateral temperature gradient. J. Fluid Mech., Vol. 63, pp. 563-576, 1974.

24. Griffis, K.A. Smith, K.A. Convection patterns in stratified LNG tanks-cells due to lateral heating. 3rd Conference on Natural Gas Research and Technology, AGA/IGT, Session VI, Paper 4, Dallas, Texas, March 1974.

25. Griffis, K.A. Smith, K.A. Numerical and physical experiments in double-diffusive convection: lateral heat flux imposed on a vertical concentration gradient. Gas Research Institute Report GRI-77/0011, 1979.

26. Narusawa, U. Suzukawa, Y. Experimental study of double-diffusive cellular convection due to uniform lateral heat flux. J. Fluid Mech., Vol. 113, pp. 387-405, 1981.

27. Takao, S. Suzuki, O. Prediction of LNG tank rollover. 9th international LNG/LPG conference (Gastech 82), Session 6, Paper 8, Paris, October 1982.

28. Suzukawa, Y. Narusawa, U. Structure of growing double-diffusive convection cells. J. Heat Transfer, Vol. 104, pp. 248-254, 1982.

29. Miyakawa, T. Matsumoto, T. Kshiji, K. The stratification and mixing of LNG in storage tanks. Sixth International Conference on Liquefied Natural Gas (LNG 6), Appendix Paper 1, Kyoto, April 1980.

30. Akiyama, M. Yanagi, H. Takayama, S. Observations of rollover in an LNG experimental vessel. Proc. 8th International Cryogenic Engineering Conference, pp. 686-690, Genova, Italy, June 1980.

31. Sugawara, Y. Kubota, A. Tashita, M. Shorter communication on La Spezian Rollover. Tokyo Gas Report, circa 1983.

32. Cole, R. Boiling nucleation. Advances in Heat Transfer, Vol. 10, pp. 85-166, 1974.

33. Porteous, W. Blander, M. Limits of superheat and explosive boiling of light hydrocarbons, halocarbons and hydrocarbon mixtures. AIChE Journal, Vol. 21, pp. 560-566, 1975.

34. Baker, N. Creed, M. Stratification and rollover in liquefied natural gas storage tanks. Trans. IChemE 74 (Part B), pp. 25–30, 1996.

35. Uznanski, D.; Versluijs, P. Advanced liquefied natural gas storage tank management, LNG Review, pp. 1-7, 2005.

8. Bibliography

36. Bates, S., Morrison, D.S. Modelling the behaviour of stratified liquid natural gas in storage tanks: a study of the rollover phenomenon. International Journal of Heat and Mass Transfer Volume 40, Issue 8, pp 1875–1884. May 1997.

37. Scurlock, R.G. Low-Loss Storage and Handling of Cryogenic Liquids: The Application of Cryogenic Fluid Dynamics. Kryos monograph. 2006.

38. Sarsten, J.A. LNG stratification and rollover. Paper presented at the AGA Operating Section Distribution Conference, Atlanta, Georgia, May 1972.

39. Sheats, D.C. and Tennant, T. Making Predictions. LNG Industry, Winter 2008.

40. Guidance for the Prevention of Rollover in LNG Ships, Society of International Gas Tanker and Terminal Operators (SIGTTO), 2012.

41. A guide for Decision-Makers on Safety Record and Safety Standards of LNG Import Terminals, Groupe International des Importateurs de Gaz Naturel Liquéfié (GIIGNL), Bureau Veritas, 2009.

42. Deshpande, K.B., Zimmerman, W.B., Tennant, M.T., Webster, M.B., Lukaszewski, M.W. Optimisation methods for the real-time inverse problem posed by modelling of liquefied natural gas storage, Chemical Engineering Journal, 170 (1), pp. 44-52. 2011.

43. Turner, J.S. The coupled turbulent transport of salt and heat across a sharp density interface, International Journal of Heat and Mass Transfer 8 (1965), 759-767.

44. Zellouf, Y., Dupont, P., Peerhossaini, H. Heat and mass fluxes across density interfaces in a grid-generated turbulence, International Journal of Heat and Mass Transfer 48 (2005), 3722-3735.

45. Uznanski, D., Malvos, H., Gorieu, O., Aoyagi, Y., Benito, A. Recent advances in the optimised management of LNG storage tank filling operations. 13th International Conference & Exhibition on Liquefied Natural Gas (LNG 13)

46. Koyama, K. CFD Simulation on LNG Storage Tank to Improve Safety and Reduce Cost. Systems Modelling and Simulation, pp 39-43. 2007.

GIIGNL
International Group of Liquefied Natural Gas Importers
8 rue de l'Hôtel de Ville
92200 Neuilly-sur-Seine (France)
Email: central-office@giignl.org
Website: www.giignl.org