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Comparative Risk Assessment for Different LNG-Storage Tank Concepts

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LNG can be stored either in flat bottom storage tanks or pressurized storage tanks such as bullets or spheres. Safety levels of atmospheric storage tanks are classified by codes as "single containment", "double containment" and "full containment". For spherical and bullet tanks an analogical definition by codes is missing and containment philosophies for atmospheric storage cannot be applied to pressurized storage. Therefore a new definition is proposed to describe the safety levels of pressurized tank types and flat-bottom tank types consistently.

It is supposed to use the definitions single, double and full integrity instead of single, double and full containment in order not to mix up definitions. The integrity level a storage tank has been assigned to gives a direct link to the consequences that would have to be taken into account in case the primary container fails totally. The advantage of these new containment definitions is having available a normalized basis for the comparison of different tanks fulfilling similar requirements on safety design.

It is expected, that the integrity level of the LNG storage vessel has influence on the risk to external population. To evaluate this influence, the risk to external population caused by the different LNG storage alternatives has been calculated by means of a quantitative risk assessment. These calculations show, that in general the risk to external population is the higher the lower the integrity level of the LNG storage. Therefore it can be concluded that high integrity solutions should be chosen where exposure of third party population is high. This should be considered when selecting the tank type (i.e. integrity level) with regard to the distance to populated areas as well as the population density.

1. LNG Storage Containment Philosophies

For LNG storage different concepts are applied depending on individual process or local requirements. While flat-bottom tanks are operated at pressures below 0.5 barg, in spherical and bullet tanks the product is stored at 2.0-3.0 barg to which the LNG supply chain systems (LNG trucks, ships, etc.) are compatible.
Atmospheric storage is well established and comprehensively regulated by codes. E.g. the safety levels are classified by codes as "single containment", "double containment" and "full containment". For spherical and bullet tanks an equal definition by codes is missing and containment philosophies for atmospheric storage of LNG cannot be strictly copied to pressurized storage due to significant differences in tank design.
Therefore the basic safety requirements from flat-bottom tanks shall be transferred to pressurized tanks by definition in order to be able to assign a bullet tank type to a flat-bottom tank type for the purpose of comparison and equalization in safety considerations. In order not to mix-up definitions used by codes, the terms for bullet and spherical tanks shall be single, double and full **integrity** instead of single, double and full **containment**.

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1.1 Flat Bottom Storage Tanks

Single Containment

A single containment LNG tank design is defined as a tank comprising an inner tank and an outer container designed and constructed so that only the inner tank is required to meet the low temperature ductility requirements for the storage of the product.

The outer container of a single containment storage tank is primarily for the retention and the protection of the insulation and to constrain the vapour purge gas pressure, but is not designed to contain the refrigerated liquid in the event of a leakage from the inner tank, i.e. it will collapse due to brittle fracture when getting in contact with large quantities of cryogenic liquid leaking from the inner tank.

Therefore a single containment LNG tank needs to be surrounded by a bund wall or dike in order to prevent uncontrolled liquid spillage. A single containment tank may be referred to as a double integrity LNG container since the bund wall is considered a second barrier.

For the single containment design philosophy pipe penetrations below the liquid level are permitted according to US regulations (NFPA 59A, 5.3.2.7) while in European regulations they are prohibited (EN 1473, 6.3.3).

Double Containment

A double containment LNG tank (Figure 1) is designed and constructed so that both the inner self-supporting primary container and the secondary container are capable of independently containing the refrigerated liquid stored. To minimize the pool surface of escaping liquid (and herewith the evaporation rate), the secondary container should be located at a distance not exceeding 6 m from the primary container.

The primary container contains the refrigerated liquid under normal operating conditions. The secondary container is intended to contain any leakage of the refrigerated liquid, but is not intended to contain any vapour resulting from this leakage. A double containment tank may be referred to as a double integrity LNG container.

For the double containment design philosophy pipe penetrations below the liquid level are prohibited (NFPA 59A, 5.3.2.7; EN 1473, 6.3.3).

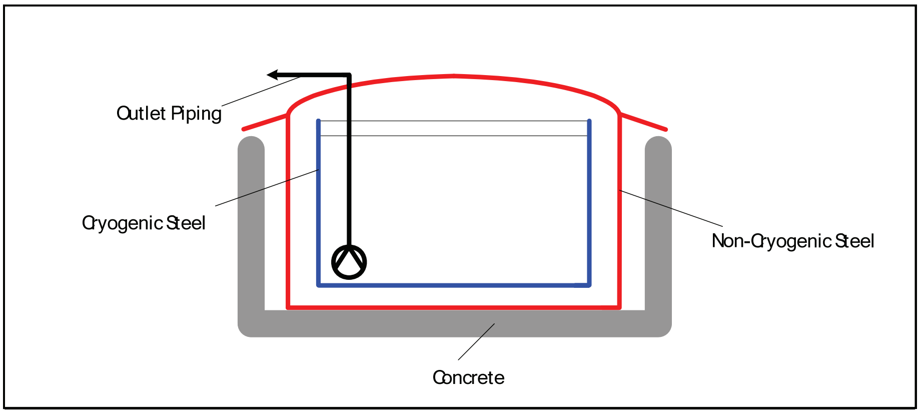

Figure 1: Double Containment LNG Tank Design (outer Shell of Concrete) (double integrity)

Full Containment

A full containment tank design is defined as a double tank designed and constructed so that both the inner tank and the outer tank are capable of independently containing the refrigerated liquid stored.

The inner tank contains the refrigerated liquid under normal operating conditions. The outer roof is supported by the outer tank. The outer tank is intended to be capable of both containing the refrigerated liquid and controlled venting of the vapour resulting from a product leakage after a credible event.

A full containment tank may be referred to as a full integrity LNG container.

For the full containment design philosophy pipe penetrations below the liquid level are prohibited (NFPA 59A, 5.3.2.7; EN 1473, 6.3.3).

1.2 Pressurised Storage Tanks

Single Integrity

A vessel arrangement with an inner tank holding the cryogenic liquid and an outer insulation casing not able to withstand the LNG in case of inner tank leakage shall be defined as a single integrity. An example for a single integrity LNG sphere is given in Figure 2. In terms of containment philosophy, such a tank design should no longer be accepted anywhere in the world for larger LNG storage volumes. Therefore a code like EN13645 is describing this design only for capacities up to 200 t LNG.

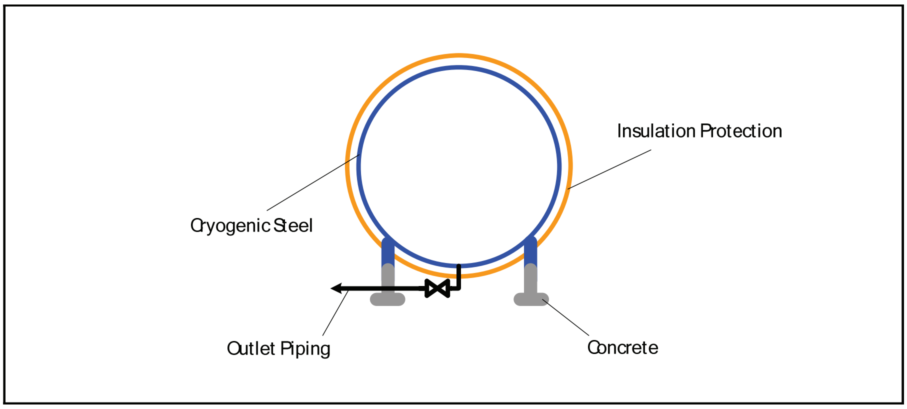

Figure 2: Single Integrity LNG Sphere Design

Double Integrity

For the storage of hydrocarbons a single integrity bullet design for larger LNG storage volumes should be upgraded from a hazard point of view by a bund wall or dike, preventing uncontrolled release of liquid into the environment similar to the secondary barrier around single containment flat-bottom tanks. Such a double integrity bullet or spherical tank design shall be defined as single integrity bullet/sphere installed along with a leakage collection system preventing uncontrolled spillage of LNG to the environment (refer to Figure 3). This secondary barrier may be realised as a containment pool or a collection basin directing any spillages away from the equipment and into a separate pit located in a safe location.

Since bullet tanks are typically installed in groups elevated above the ground on two supports, a containment pool is deemed counter-productive since a potential pool fire resulting from one single tank failure will also be affecting all the other intact tanks installed inside the pool (risk of BLEVE). This hazard should be avoided by installation of a spillage collection system directing any leakages to a safe location away from where a bullet farm is located.

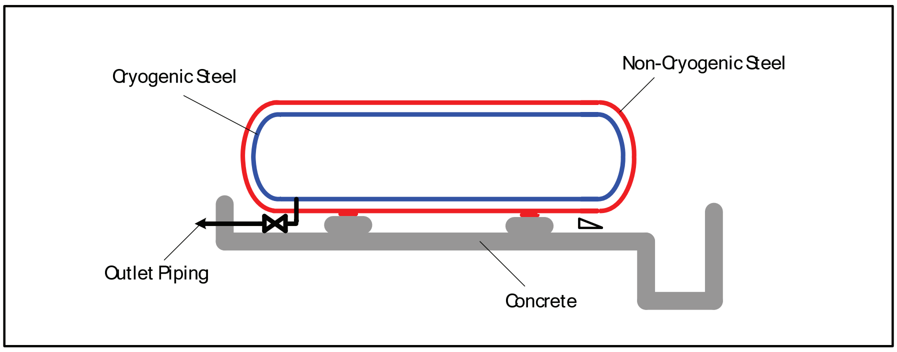

Figure3: Double Integrity LNG Bullet Design

Full Integrity

A LNG bullet or spherical tank is defined as full integrity when the inner and the outer container of the vessel are constructed from cryogenic steel being able to hold the LNG. In case of inner tank leakage the

cryogenic liquid is contained in the outer tank and the structural integrity of the complete bullet is maintained. An example for a full integrity LNG sphere is given in Figure 4.
A proposed safeguard against leakages in the export piping is an internal emergency shut-off valve installed inside the vessel (refer to API 625, Section 7.3.1.4.2b). This ESD valve can be closed from a remote location and thereby stop LNG leakage in case of export piping rupture.

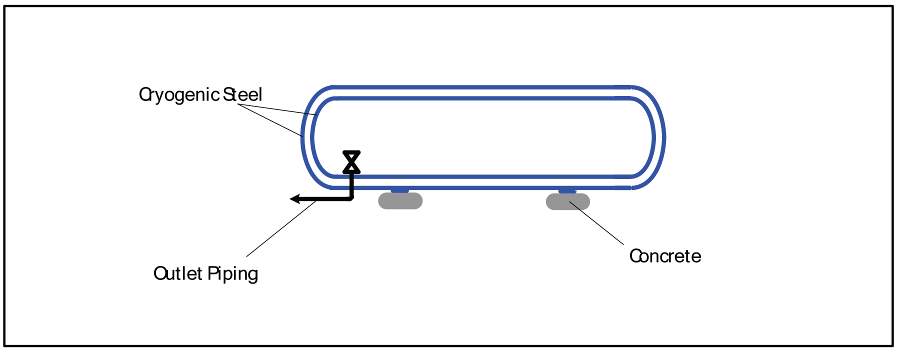

Figure 4: Full Integrity LNG Bullet Design

1.3 Normalised Safety Classification of Tank Designs

The different tank designs as shown above for flat bottom tanks and pressurized storage respectively have been brought to one common definition of integrity levels. The advantage of these new containment definitions is having available a normalized basis for the economic comparison of different tank types (flat-bottom, bullet or spherical tank) fulfilling an equal requirement on safety design.
The integrity level a storage tank has been assigned to gives a direct link to the consequences that would have to be taken into account in case the primary container fails totally which may be roughly summarized as shown in Figure 5.

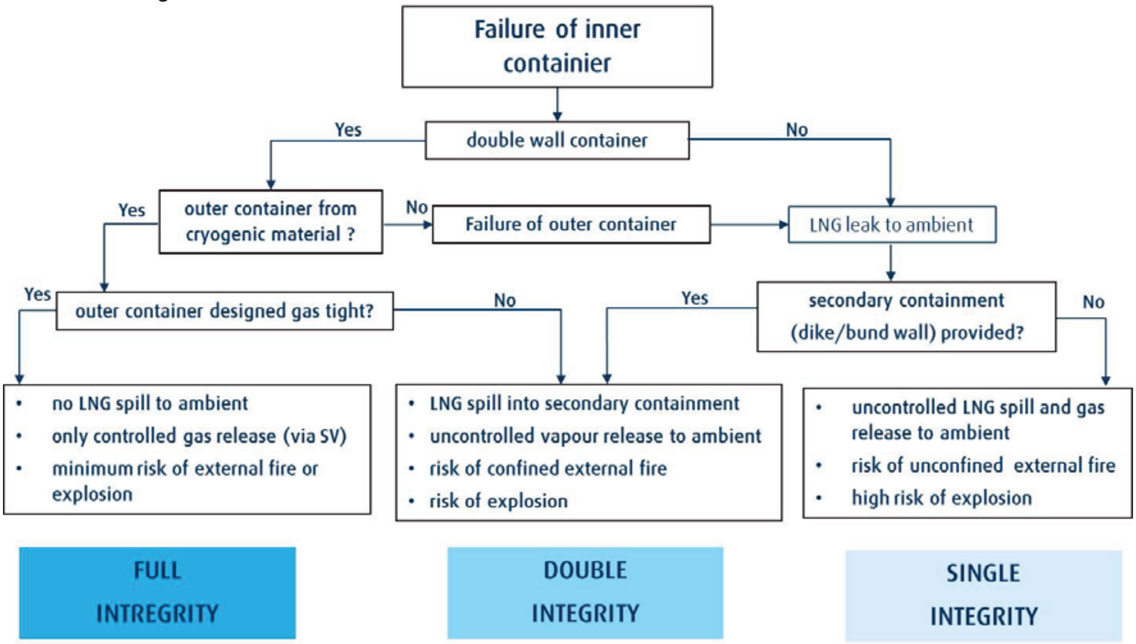

Figure 5: Normalised Safety Classification of LNG Tank Designs

2. Risk Assessment

It is expected, that the integrity level of the LNG storage vessel has influence on the risk to external population. Therefore the risk to external population caused by the different LNG storage alternatives has been calculated by means of a quantitative risk assessment.

2.1 Main QRA Assumptions

Nine different tank designs have been analyzed: flat bottom tank (4,000 m^3), bullets (5 times 800 m^3) and sphere (4,000 m^3); each type designed as either single, double or full integrity. The pressure in the flat bottom tank is atmospheric, in the pressurized tanks 3.5 bara.

The frequencies for catastrophic rupture have been taken from OGP data for flat bottom tanks and for failure of primary containment of single and double integrity pressurized storage vessels. According data for failure of primary container of full integrity pressurized storage vessels and failure of secondary container of pressurized storage vessels have been estimated accordingly based on the OGP data analogy. The leak frequencies for connected piping and equipment were simplified assumed to be the same for all storage alternatives. The catastrophic failures of bullets and the sphere have been modeled as release of the whole inventory with impingement on the ground within 1 s.

For 3rd party risk calculations a population was defined in an area between 100 m and 3,000 m outside plant boundary. The population density was set to 500 / km^2 for a plant distance between 100 m and 500 m and 1,000 / km^2 for a distance between 500 m and 3,000 m.

2.2 Risk Results

The 3rd party risk is shown by FN-Curves indicating the max. tolerable risk according to Dutch acceptable limit. Figures 6 and 7 show FN-diagrams for flat bottom LNG tanks. The FN-diagrams for bullets and spheres are provided in Figure 8 (single integrity), Figure 9 (double integrity) and Figure 10 (full integrity). The y-axis shows the frequency per year in a range from 10^{-9} / y through 10^{-3} / y. The x-axis represents the number of fatalities in a range from 1 through 1,000.

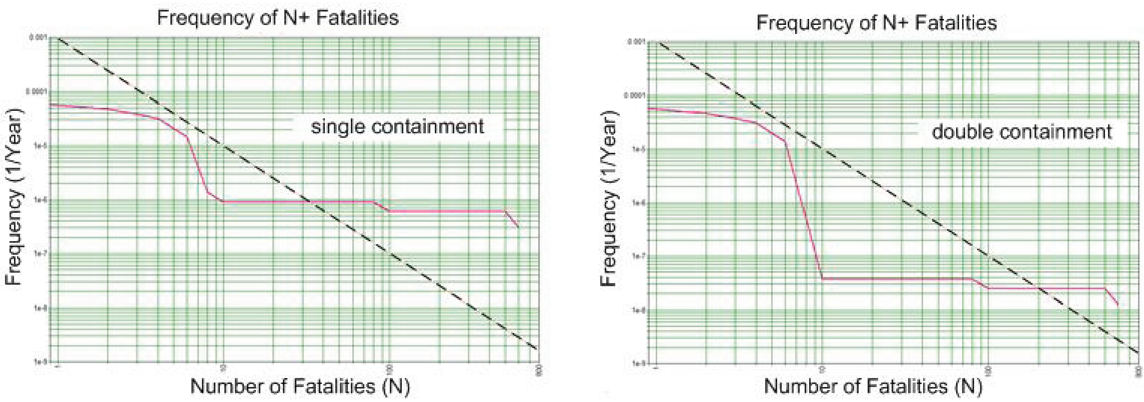

Figure 6: FN-Diagram for Flat Bottom Tank: double integrity

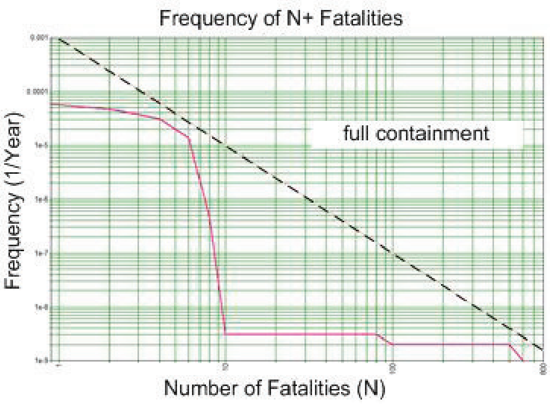

Figure 7: FN-Diagram for Flat Bottom Tank: full integrity

Different tank types, but with the same integrity level, show similar risk pictures. The risk calculations show, that in general the risk to external population is the higher the lower the integrity level of the LNG storage. Therefore it can be concluded that high integrity solutions should be applied where exposure of third party population is high.

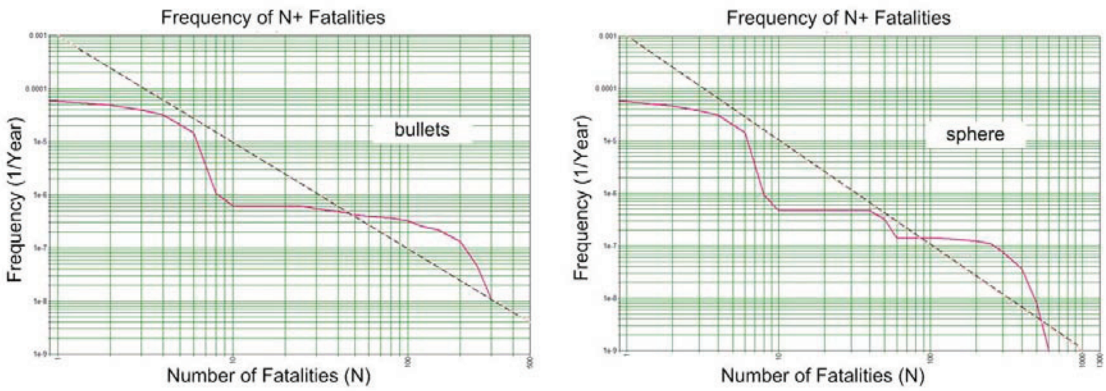

Figure 8: FN-Diagram for Pressurized Storage: single integrity

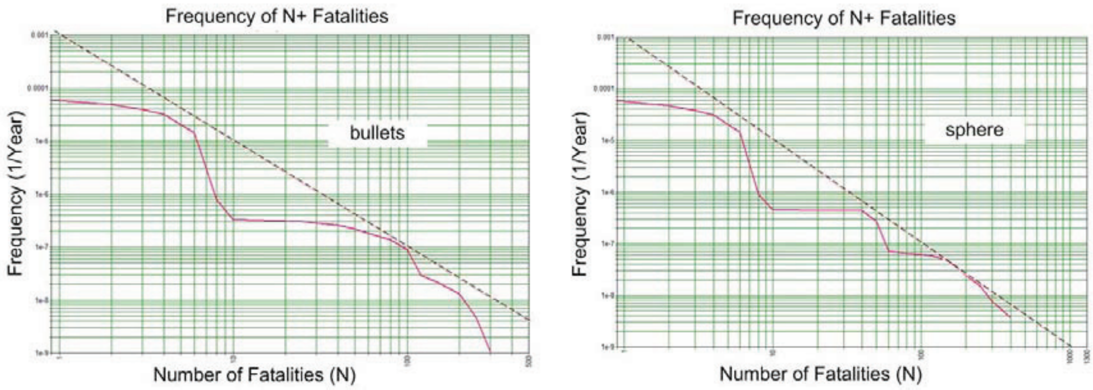

Figure 9: FN-Diagram for Pressurized Storage: double integrity

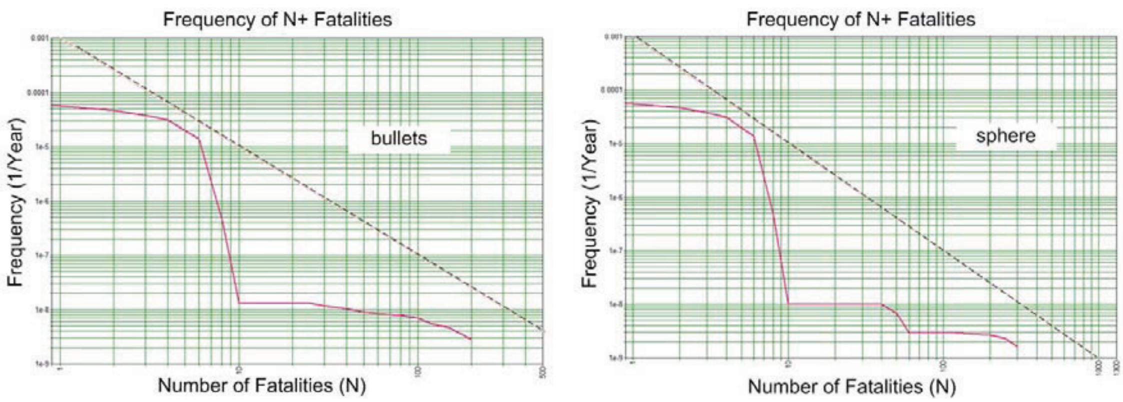

Figure 10: FN-Diagram for Pressurized Storage: full integrity

Codes and standards should be established to cover large scale storage of LNG in pressurized tanks. The proposed definitions for single, double and full integrity might be applied to categorize the safety levels. This allows assigning a pressurized tank type to a flat-bottom tank type for the purpose of comparison and equalization in safety considerations.

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