

GAS CONCENTRATIONS IN THE INSULATION SPACES OF MEMBRANE LNG CARRIERS

March 2007

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CHAPTER 1

Introduction

1.1 Background to the issue

The first three decades of the LNG industry, i.e. until the end of the 1990s, were dominated by base load projects with long-term sale and purchase and associated shipping contracts, typically of 20 years duration. With such arrangements the project partners had an equity share or knowledge in all facets of the project, from gas gathering to gas distribution, including shipping. Furthermore, their technical staff had a detailed knowledge and familiarity with all the individual sections of the contractual chain.

By the end of the 20th century, however, a short-term or “spot” market was starting to develop within the industry. In this market LNG vessels are hired on “spot” and “short-term” charters, with the charterer often having little or no knowledge of the history of such vessels. This has led to charterers and buyers and sellers of the cargoes drawing upon their oil industry experience and insisting on vetting these vessels prior to accepting them. This has occasionally raised questions about aspects of the vessels’ operation and maintenance that partners in the original long-term projects had previously understood and accepted.

One area, unique to the LNG trade, in which this has occurred is the maximum, operationally acceptable, gas concentration to be found in the insulation spaces of the cargo containment system of the membrane-type liquefied natural gas carriers, particularly those of older design.

The International Maritime Organization’s International Gas Carrier (IGC) Code, Section 13.6.11 (ref bibliography B3) states:

*“Interbarrier spaces should be provided with a permanently installed gas detection system capable of measuring gas concentrations of 0 to 100% by volume (v/v). Alarms should be activated when the vapour concentration reaches the equivalent of 30% of the lower flammability limit (LFL) in air or other such limit as **may be approved by the Administration in light of particular cargo containment arrangements.**”*

Under this clause of the Code (as emboldened above), different “alarm” levels are applied for the various designs of membrane containment system. Furthermore, two different terms, i.e. percentage of lower flammability limit (LFL) and percentage by volume, are both used as units of gas concentration in these spaces. This variety in alarm levels and terminology has the potential to cause confusion among those with limited operational experience of membrane-type LNG vessels.

Note:- 30% LFL of methane in air is equivalent to 1.5% by volume and care should be taken not to confuse this LFL value with the value 30% by volume used for the primary insulation space alarm setting in the GTT NO systems

For the purposes of this study, there are two primary types of membrane LNG containment system in use today. These are the systems that were originally known as the “Gaz Transport” and “Technigaz” membrane designs respectively. Today, both systems are marketed by the company “Gaztransport & Technigaz” (GTT) and the latest versions of each are known as the GTT NO 96 and GTT Mark III systems, respectively. Both systems have evolved over the last 35 years and there have been several versions of each over that period.

GTT has recently introduced its new CS1 membrane containment system, which is an amalgamation of the two existing membrane systems. However, as this document is based on experience to date and the issue covered is of most relevant to older ships, the new CS1 system is not specifically considered here.

1.2 Purpose of the guidance document

In 2003, following approaches to the SIGTTO Secretariat, the SIGTTO General Purposes Committee (GPC) sanctioned the formation of a working group comprising representatives of ship-owners and operators, charterers and classification societies; all with extensive experience of this type of vessel. The group has also been supported by Gaztransport & Technigaz (GTT), the designer and licensor of the membrane containment systems.

The terms of reference of this working group were to:-

“Examine the gas concentrations likely to be found in the insulation spaces of membrane LNG ships and determine, by good engineering practice, an acceptable upper limit. The group was also to examine the operational procedures for the cargo containment systems of these ships; in particular, the monitoring and testing of insulation spaces for gas concentrations”.

The first working group meeting was held in Paris in November 2003 and the group subsequently met another four times through May 2005. The resultant findings and recommendations of this SIGTTO Working Group on Gas Concentrations in the Insulation Spaces of Membrane LNG Ships, as the group was titled, are detailed in this document, which is intended to give guidance only and not aspire to provide a technical specification.

1.3 Risk assessment

In order to fully understand the nature of any hazards that may be associated with gas concentrations in the insulation spaces of membrane LNG ships and in order to be able to make recommendations on how any such risks can be mitigated to acceptable levels, the working group carried out a detailed risk assessment. The analysis was a major exercise and represents the most extensive investigation yet undertaken by the gas shipping industry on this gas concentration issue. The risk assessment is covered in Chapter 5 and the associated Appendices 1-4. The analysis by the working group experts has resulted in a clearer understanding of the operation of membrane LNG carriers and the results are made available to the industry at large through this document.

CHAPTER 2

Background and Design Parameters

2.1 History and applicability of the IMO Gas Codes

Prior to 1976 LNG ships were built to class rules only. Until that time there was no single set of universally accepted regulations governing gas carrier design and construction. Then, the Inter-governmental Maritime Consultative Organization (IMCO), the forerunner of today's International Maritime Organization (IMO), introduced the Gas Code (GC Code). This set of rules combined elements from the existing class rules and industry best practice prevailing at the time and was to be applied to new building gas ships worldwide commencing from 1976.

To cater for the gas ships already in service, the Existing Ships Code was introduced at the same time. This Existing Ships Code was, by necessity, made less restrictive in some respects than the GC Code in order to accommodate the diversity in design which had existed until that time.

As a number of gas ships were already on order in 1976 which had not been contracted to the GC Code, these ships ended up with Certificates of Fitness to the Existing Ships Code. This was despite the entry into service date of the vessels, which in some cases was late as 1979 or 1980.

The GC Code was extensively amended and reissued in 1986 as the International Gas Code (IGC Code). Some amendments have been applied since then, but the IGC Code remains the applicable IMO document for gas ships built since 1986.

2.2 IGC Code requirements and practices

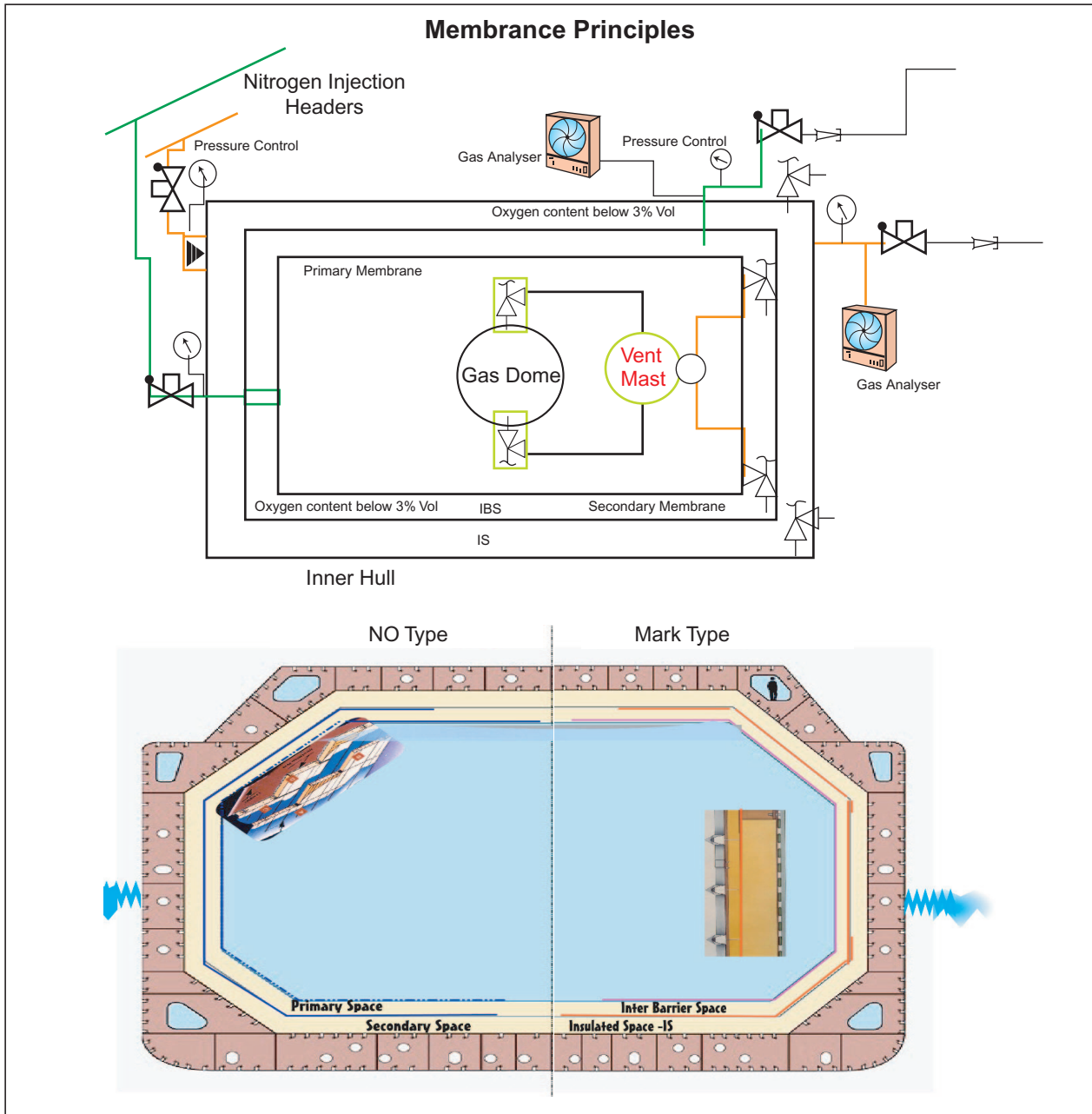
"The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk" (IGC Code) requires that gas carrier designers and operators provide adequate segregation between all elements which, if put together, may form a potential hazard in all gas dangerous spaces and zones.

The overall safety of the system is achieved by a combination satisfying the Code requirements and operational practices, such as:

- Using only materials with proven cryogenic capabilities.
- Using efficient insulation materials.
- Reducing the oxygen content to, or below, 5% by volume by circulating inert gas.
- Maintaining a slight overpressure in order to prevent any air ingress.
- Using only approved electrical equipment and wiring.
- Disconnecting power to submerged pumps during gas-freeing operations.
- Employing reliable and redundant instrumentation to monitor all safety-related elements.

2.3 Conceptual principles of membrane containment systems

From the delivery in 1969 of the first gas ship with a membrane-type containment system, the Gaztransport NO 82 system, containment systems constructed to the membrane design concept have incorporated all the mandatory design features listed above.



The design concept of all membrane containment systems is based on the utilisation of materials with proven cryogenic and insulation capabilities and on the ability to create and maintain inert atmospheres all around the spaces between the inner hulls and the cargo (see diagrams above).

The insulation spaces around tanks built to membrane cargo containment system designs are permanently monitored for possible defects using detection methods based on a gas concentration assessment and continuous temperature monitoring at the secondary membranes and at the double-hull levels.

Nitrogen breathing and, if necessary, sweeping of the insulation spaces are key features on ships with membrane containment systems. The mixture that has circulated in these spaces is analysed for possible hydrocarbon content before being discharged to a vent mast at a height equal to the

CHAPTER 3

Statutory and Flag State Requirements

The Safety of Life At Sea (SOLAS) Convention (bibliography ref B4) requires each gas carrier trading internationally to have onboard a Certificate of Fitness for the Carriage of Liquefied Gases in Bulk issued by the vessel's flag state or the classification society delegated by the flag state.

3.1 Delegation by the national authorities of the right to issue IMO Gas Code Certificates of Fitness

Flag state administrations may check directly that gas ships flying their flag comply with the requirements of the IMO Gas Codes, or may choose to delegate part or all of the process to their recognised classification societies. This is generally recorded by written agreement between each flag state and its appointed classification society. The agreement either defines the extent of the delegation of responsibility or specifies that it is to be decided on a case-by-case basis. The class societies maintain databases of such authorisations, keeping them updated to reflect any changes to individual agreements which may occur from time to time.

It is noteworthy that when the class societies are authorised by the flag state, they must abide strictly by the requirements of the Gas Codes and are not permitted to make their own interpretations. Only the Unified Gas Code Interpretations issued by the International Association of Classification Societies (IACS) and recorded in the IACS "Blue Book" and which have been accepted by IMO and are applied by the flag states and authorised class societies alike, are permitted. Such Unified Gas Code Interpretations may also be found on the IACS web site - www.iacs.org.

The Gas Codes themselves allow for what may be described as alternative arrangements being provided in some respects. Paragraph 13.6.11 of the IGC Code concerning gas concentration alarm settings is an example of this. It states that "Alarms should be activated when the vapour concentration reaches the equivalent of 30% of the lower flammable limit in air or other such limit as may be approved by the Administration in the light of particular cargo containment arrangements."

The Gas Codes also permit equivalents to be fitted, provided they can be shown to be at least as effective as those required by the applicable requirements of the Code - see paragraphs 1.4.1 and 1.4.2 of the IGC Code or similar paragraphs in the other Gas Codes. It is to be noted that when such an equivalent is proposed, it is the duty of the authorised class society to seek acceptance from the flag state, who must in turn pass details to IMO.

The extent to which such interpretations, alternatives and equivalents should be stated on the Certificate of Fitness (CoF) is described in section (d) of this Chapter.

3.2 Special requirements set by the United States Coast Guard (USCG)

National maritime administrations may decide to go beyond the requirements of the Gas Codes and impose additional regulations on gas ships visiting ports under their jurisdiction and/or on gas ships flying their flag. An example of this is the US Coast Guard, which acts as both the US flag state and port state. The USCG requires foreign flag gas ships trading to the United States to comply with the applicable paragraphs in Title 46 of the US Code of Federal Regulations Part 154 (46 CFR 154) "Safety Standards for Self-Propelled Vessels Carrying Bulk Liquefied Gases". (ref bibliography B5). The great majority of gas ships have been built to meet these requirements anticipating they may at some time visit the US, even if this is not their expected trade route.

These USCG regulations parallel the Gas Codes in many respects, but there are some important differences. The most notable differences are those concerning the grades of steel to be incorporated in parts of the hull structure, although there are other aspects of 46 CFR 154 which differ from the Gas Codes.

When a shipyard completes a new gas ship, a statement and accompanying letter are issued by the recognised class society confirming compliance with the various specified paragraphs of 46 CFR 154 which must be complied with in addition to the applicable Gas Code. This statement is a document drawn up to a standard format agreed by the USCG. Then, when the ship first visits a US port, USCG inspectors attend onboard, view the class society's statement, and carry out their own inspection. When satisfied, the USCG issues the ship with a Certificate of Compliance (CoC) to be kept onboard for future reference.

N.B. This is a separate document additional to the CoF required under the IMO Gas Codes.

With regard to the specific issue of gas concentration alarm settings in the US regulations, the applicable part of 46 CFR paragraph 154.1350 states that "Each flammable gas detection system must have audible and visual alarms that are actuated at a cargo concentration that is 30% or less of the lower flammable limit (LFL) in air of the cargo carried". Although this is not identical to paragraph 13.6.11 of the IGC Code stated above, 46 CFR paragraphs 154.1350 is not among those recognised as requiring inclusion in the statement from the class society. Furthermore, the USCG has accepted values of 30% by volume in the interbarrier space of NO type systems, and up to 36% by volume for the first two NO 82 vessels built.

3.3 Relationship to class requirements

Class societies have their own rules for the classification of the various types of ships commonly in service. For gas ships, many of the class societies have not only incorporated the text of the IGC Code into their rules, but also added their own requirements for classification aspects not included in the IGC Code. Some class societies have also included the recognised IACS Blue Book interpretations in their rules.

However, classification is a separate matter not to be confused with satisfying the SOLAS requirement for compliance with the applicable Gas Code and issuance of the CoF.

3.4 Gas Code Certificates of Fitness

All gas ships engaged in international voyages require a current Certificate of Fitness (CoF). The CoF is issued under the Existing Ships Code (EGC Code), the Gas Code (GC Code) or the International Gas Code (IGC Code), depending on the ship's date of construction. Each of these Codes includes an outline CoF in an appendix.

The EGC Code states in paragraph 1.2.3(b) that its CoFs are to be endorsed to indicate "specifically the aspects of the vessel which do not comply with the Code" - a requirement which originated from the fact that this Code was for retrospective application to gas ships already in service.

The GC and IGC Codes give no instruction within the body of their texts on how the CoFs are to be endorsed, with one exception. This concerns damage stability calculations on small ships (paragraph 2.5.2(a) of the GC Code/paragraph 2.8.2 of the IGC Code). However, the outline CoFs in all three Codes have a heading for describing the ways in which the provisions have been modified with respect to equivalents and small ship considerations. Currently there is no requirement for recognised IACS Blue Book interpretations or alternatives, e.g. gas concentration alarm settings per paragraph 13.6.11 of the IGC Code, being stated on the CoF.

Accordingly, normal practice has been to omit reference to any alternative gas concentration alarm setting on the CoF. To date there is no known precedent for any flag state requesting alarm settings or other alternatives being stated on the CoF.

CHAPTER 4

Systems and Equipment

Chapter 4 describes, in general terms, the main systems and equipment relevant to the measurement of gas concentrations in the insulation spaces of membrane LNG ships, i.e. nitrogen distribution systems, gas detection systems and temperature monitoring systems. For information on specific ships, that ship's documentation must be referred to.

4.1 Use of nitrogen in membrane containment systems

High-purity, dry nitrogen gas, i.e. more than 95% nitrogen v/v, as specified in Section 9.5.1 of the IGC Code, is used onboard membrane-type LNG carriers, mainly as inert gas in the insulation spaces. It is also necessary for purging cargo equipment and piping; flushing the gas fuel line systems; and as seal gas between motor and compressor rooms and instrumentation located in gas dangerous zones.

The nitrogen system is designed to maintain a positive pressure in the insulation spaces during the initial cooling down of the containment system, i.e. from ambient to LNG temperature, and to provide the daily consumption of nitrogen during normal operating conditions.

4.2 Nitrogen distribution system designs

The following paragraphs describe how nitrogen is supplied and distributed into the insulation spaces of membrane-type LNG carriers in operation today. Irrespective of the nitrogen source onboard, its distribution into the insulation spaces must follow the guidelines of the containment system designer. It is advisable to monitor the temperature, pressure and dew point at which nitrogen is supplied into the insulation spaces.

Nitrogen can be provided onboard either through receiving liquid nitrogen (LN2) from shore and storing it in this form prior to it being vaporised for use, or producing it onboard using the ship's nitrogen-generating plant. Nitrogen generating plants produce nitrogen with a purity of over 97%.

Nitrogen pressurisation of the insulation spaces of typical 145 000 m³ LNG carrier designs

	NO 96	Mark III	CS1
Nitrogen generators (Nm ³ /h)	2 X 90	2 X 90	2 X 55
Vacuum pump (Nm ³ /h)*	2 X 1250	300	250
Primary space vol. (m ³)	3938	444	132
Secondary space vol. (m ³)	5829	640	610
Total volume (m³)	9767	1084	742

* Vacuum pumps are standard fixed equipment on NO type systems and portable units are provided on the Mark and CS1 systems

4.2.1 Liquid nitrogen systems

The first generation of LNGCs used liquid nitrogen (LN₂) supplied from shore and stored in cryogenic tanks which were normally located on the open trunk deck. To supply the insulated spaces, LN₂ is circulated through either an atmospheric or steam vaporiser. The resulting nitrogen gas is routed to the distribution header at the required temperature and pressure.

4.2.2 Nitrogen generator systems

Onboard nitrogen generators are generally configured as two independent units. The nitrogen generator capacity depends on the type of GTT membrane cargo containment system, i.e. either Mark III, NO 96 or CS-1. Nitrogen generated onboard normally has a purity of not less than 97% nitrogen. The nitrogen is stored in a buffer tank, and the system is designed to operate automatically and maintain the pressure in the buffer tank, from where distribution is effected. An oxygen (O₂) and dew point analyser continuously monitor the oxygen content and a dryness level of the gas produced at the outlet from the generators. The analyser also provides alarms for high oxygen content and unsuitable dew points.

4.2.3 Nitrogen distribution and consumption

Irrespective of the source of the ship's nitrogen, gaseous nitrogen is distributed to the insulation spaces, as required. Additionally, nitrogen is supplied to relevant instrumentation and gas seals. If necessary, nitrogen can also be used to purge gas lines to the boilers and as a fire extinguishing medium for fires at the main vent mast.

A typical process and instrumentation (P & I) diagram for a nitrogen distribution system to the insulation spaces is shown in appendix 7 and a simple schematic in 2.3.

Initial filling of the insulation spaces is accomplished by drawing a vacuum and then slowly introducing nitrogen gas to the spaces. This process of drawing a vacuum and then filling with nitrogen is repeated until the oxygen concentration is in the order of 1-2%.

All nitrogen distribution system designs incorporate a pressure control system featuring regulating valves and independent primary and secondary nitrogen headers. The pressure control system is used to maintain the desired pressure in the insulation spaces.

Each cargo tank insulation space is protected from over-pressurisation by sets of safety relief valves. In general, primary spaces are vented via a dedicated vent mast sized as per the IGC Code and secondary vents near the trunk deck level.

4.3 Gas detection systems

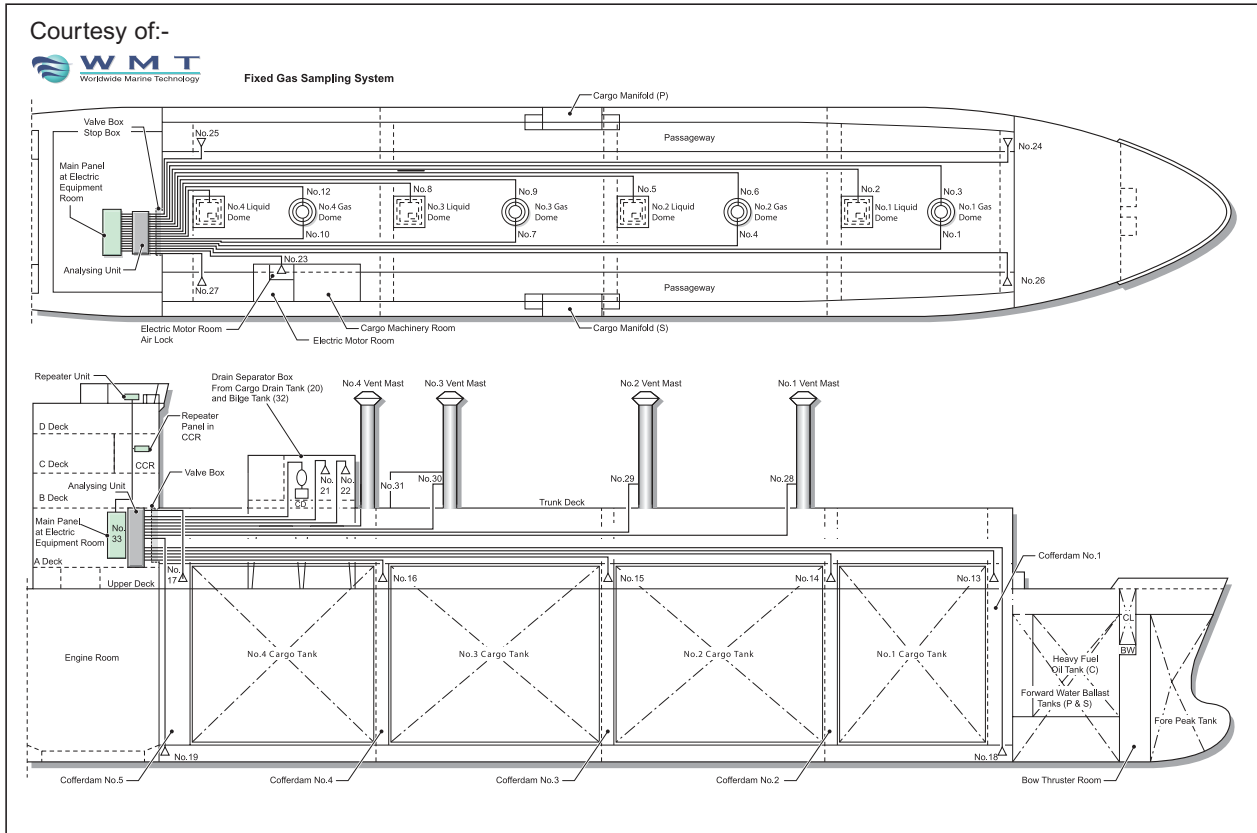
The provision and operation of gas detection systems onboard gas carriers are required by the IGC Code, Chapter 13.6.

The IGC Code requires audible and visual alarms from the gas detection equipment. In addition and irrespective of where the main gas detection panel is situated, there are usually repeater panels displaying the same information and these are located in the following areas:

- the cargo control room
- the wheelhouse
- the engine control room

Gas detection systems on new vessels are generally interfaced with the centralised control system in the form of mimics which show the location of individual detector heads and sampling points.

Typical gas detection system layout



Sampling points are provided as per IGC Code requirements, as a minimum. In addition, connections for portable gas measuring equipment are provided for each insulation space.

Each sampling point is monitored by an automatic switching circuit or by manual selection. As required by the IGC Code, the gas detection equipment should be capable of sampling and analysing from each sampling head location sequentially at intervals not exceeding 30 minutes, except that in the case of gas detection for the ventilation hoods and gas ducts referred to in Chapter 13.6.7.6, sampling should be continuous. Common sampling lines to the detection equipment should not be fitted.

Gas analyser units should be regularly checked, calibrated and maintained for proper and reliable operation, as per the manufacturer's recommendations. Span gases, of a known composition, with their laboratory certificates of analysis, are to be available onboard for calibration purpose, as per instructions contained in the specific instrument manuals.

4.4 Temperature monitoring systems

In addition to gas detection equipment, ships are also provided with sensor devices for continuously monitoring the temperatures of cargo tank membranes, insulation spaces and the inner hull. In conjunction with the gas detection system, temperature monitoring systems may also provide a warning in the case of failure of insulation or a gas passage through the membranes into the insulation spaces.

Temperature sensors are installed in the insulation spaces and in way of the inner hull associated with each cargo tank. Each sensor generally has a back-up capability. Sensors must be manufactured to a design of proven longevity and reliability.

CHAPTER 5

Risk Assessment

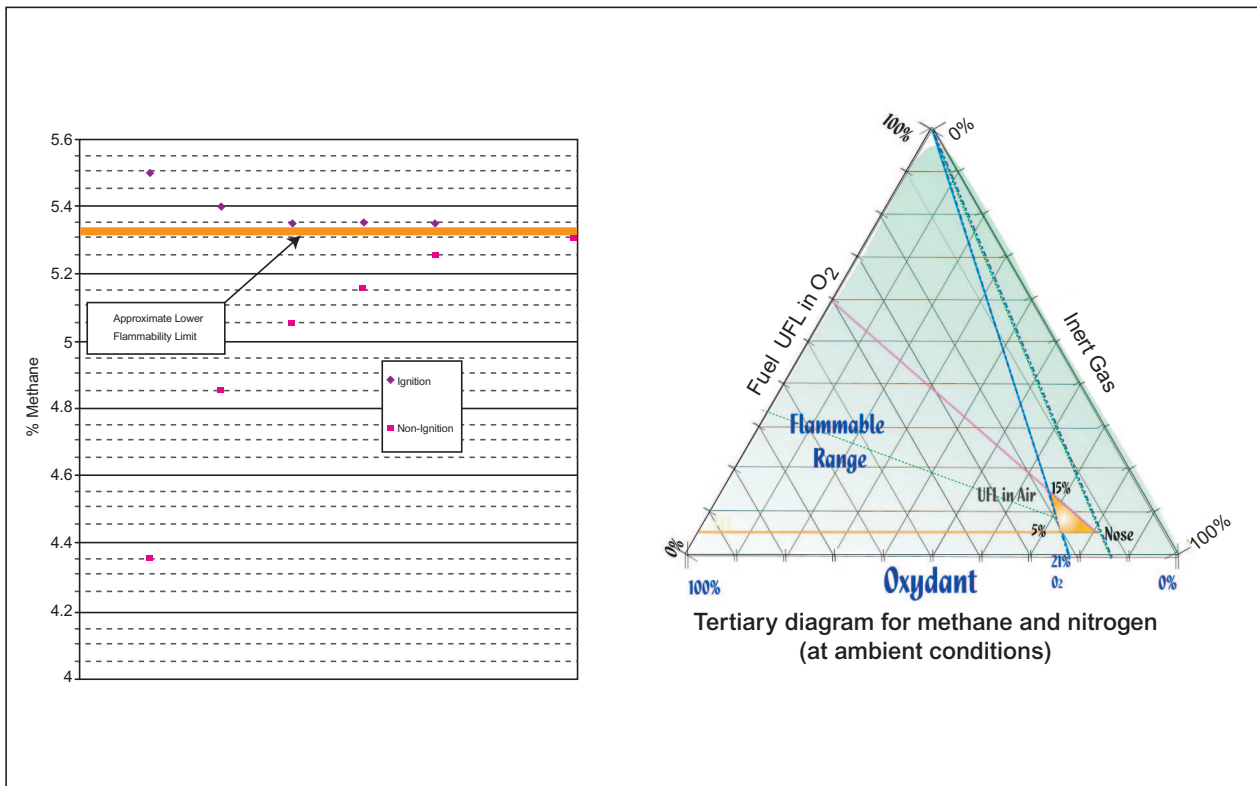
The cryogenic and flammability properties possessed by all grades of liquefied natural gas comprise the principal hazards to be considered during the design, maintenance and operation of LNG carriers. Fire and the brittle fracture of normal marine steels when in contact with cryogenic liquids are the two phenomena that pose the greatest danger and could, in extreme cases, lead to a loss of integrity of the LNG cargo containment system.

5.1 Flammability limits of natural gases

Natural gas is a mixture of several hydrocarbons, each of them with its own set of hazardous characteristics. Although methane is the principal constituent of all natural gas, the precise composition of a particular natural gas varies, depending on where it is produced.

Ignition of a combustible fuel can take place only if a flammable vapour of that fuel, when mixed with air, falls between the lower flammable limit (LFL) and upper flammable limit (UFL) of that fuel. These volumetric proportion limits are unique to each flammable substance. If the mixture of fuel vapour and air falls outside these flammability limits, it is either too lean or too rich to ignite.

Recent research work carried out by Steven Summer, (ref bibliography B6), attributes a LFL value of 5.35% for methane, as shown on the graph he has published. The accompanying tertiary diagram (methane-nitrogen) shows the effect of oxygen on the UFL of the fuel involved and the relatively small area of the triangle representing the flammability zone of methane in air.



The minimum oxygen concentration (MOC) required in a fire/chemical reaction involving natural gas is 12% at ambient conditions. The lowering of ambient temperature effectively increases the MOC and LFL levels for all fuels as well as the minimum energy level required for ignition.

For the purpose of this assessment, conservative LFL and UFL values of 5 and 15%, respectively, have been selected for natural gas, which provides a safety margin. As a result, it can be stated that no natural gas, irrespective of its source, will represent a fire or explosion hazard when exposed to an ignition source, as long as:

- the content of oxygen is below 12% by volume
- the fraction of fuel in a mixture is less than 5% by volume
- the fraction of fuel in a mixture is above 15% by volume

5.2 Risk of cryogenic brittle fracture

Accidental spillages of cryogenic liquids such as LNG and liquid nitrogen (LN₂) on unprotected ship hulls made of normal marine steels will cause brittle fractures in that steel. Such spills, if large enough in magnitude, have the potential to result in major damage to the ship and a potential release of LNG from the vessel.

Since the first commercial LNG cargo was carried in 1964, there has been no known incident involving a brittle fracture of the steelwork of the inner hull of an LNG carrier as a result of LNG leaking through the primary and secondary barriers of a membrane containment system. However, there have been several cases involving spillage of small volumes of LNG onboard ships resulting from accidental tank overfilling, faulty valve glands or leaking flanges on deck piping.

The accompanying photograph shows the fractures caused in a 16 mm thick deck stiffener as a consequence of an LNG spillage.

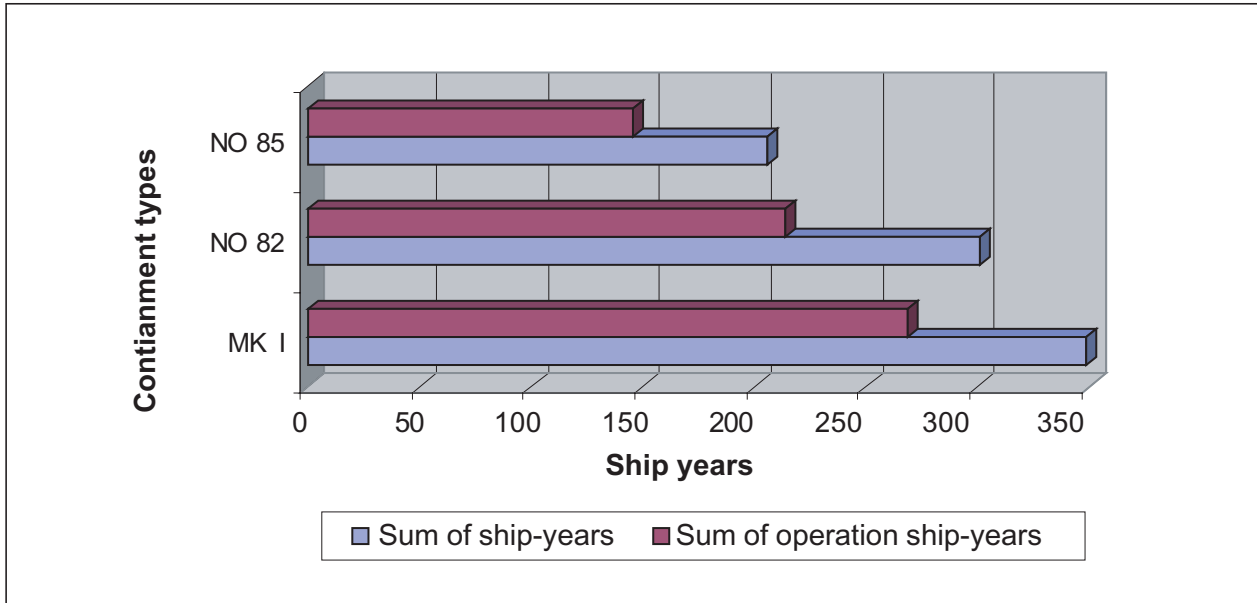


The measures needed to prevent tanks being overfilled during cargo transfers and causing spillages of LNG onto the decks of an LNG carrier need to be addressed at the ship design stage. These measures now assume even greater importance as the industry stands poised at the beginning of a new era in LNG transport, with the emergence of a new generation of large LNG carriers in excess of 200,000 m³ in capacity and with onboard reliquefaction plants for processing all the cargo boil-off gas back into a liquid and returning it to the tanks. On such ships LNG will be permanently circulated in the piping situated on main or trunk decks.

5.3 Operational experience and failures

For the purpose of this study the first 30 LNG carriers built with membrane containment systems, each of which now has well over 25 years of operating and trading experience, have been considered. All entries made in the relevant classification society's records relating to the cargo containment systems on each of these ships have been reviewed and checked against the records of GazTransport and Technigaz (GTT), the designer of the two membrane containment systems used on these ships. The two membrane systems in question are the Technigaz system, with its waffled stainless steel primary barrier, and the Gaz Transport system which utilises the high nickel content Invar alloy as both a primary and secondary barrier. The Technigaz system employed on the early membrane ships is the Mark I version while the so-called NO 82 and NO 85 versions of the Gaz Transport membrane are utilised on these older vessels.

The cumulative total operating life of the 30 ships in this fleet amounted to a total of 629 ship-years as at end-2004, once the lay-up periods experienced by some of the vessels have been deducted.



5.3.1 Defects history

In view of all the known incidents, defects or near misses reported on these early membrane tank ships, the following observations and statements can be made:

1. No fire or explosion has ever occurred in the insulation spaces of an operational LNG carrier.
2. There is no record of any containment system incident that required a cargo to be urgently and immediately discharged. Even the most famous LNG carrier incident, the high speed grounding of the laden, 125,000 m³ LNG carrier “El Paso Paul Kayser” while underway near Gibraltar in June 1979 - involved a few days of preparation before the cargo could be transferred to another ship. No cargo was lost as a result of this incident.
3. The only known gas explosion onboard an LNG ship occurred in the inert gas plant room following an operational mistake in which the inert gas to the cargo tanks was not blanked off before gassing up the cargo tanks.
4. Several fires are known to have occurred in the insulation spaces of membrane LNG carriers while the ships were under construction or repair at the shipyard. These fires involved insulation materials ignited by hot work, and LNG or its vapours were not involved.

Explanations of the main defects encountered with these early membrane tank designs, while the ships were still in their infancy, are given in the following paragraphs, along with details of how they were subsequently corrected.

5.3.2 Types of membrane defects

Events which could conceivably contribute to the loss of integrity of either the Gaz Transport or the Technigaz membranes have been reviewed. They are categorised in the following matrix and described below:

	Mechanical damage	Corrosion pitting	Fatigue cracks	Design faults
Leak thru primary membrane	known	known	known	known
Gas in primary space	known	known	known	known
Leak thru secondary membrane	No record	No record	See text	See text
Gas in secondary space	No record	No record	No record	No record

1. Mechanical damage

Mechanical damage is the most frequently encountered type of defect. It can result from broken pump inducers or sharp objects dropped during tank entry. Sloshing is not known to have been the direct cause of membrane failure, but there is one incident on record whereby sloshing caused a cable tray to become loose and damage the membrane.

2. Corrosion pitting

Corrosion pitting has occurred on the primary membranes of certain vessels after they have been in service for more than 20 years. Such pitting can arise as a result of poor lay-up conditions, improper tank protection during scheduled drydockings or, more probably, the aggressive nature of inert flue gas produced onboard. On one occasion severe corrosion occurred after a vessel handled a cargo of “off-spec” LPG very early in its operating life.

3. Fatigue cracks

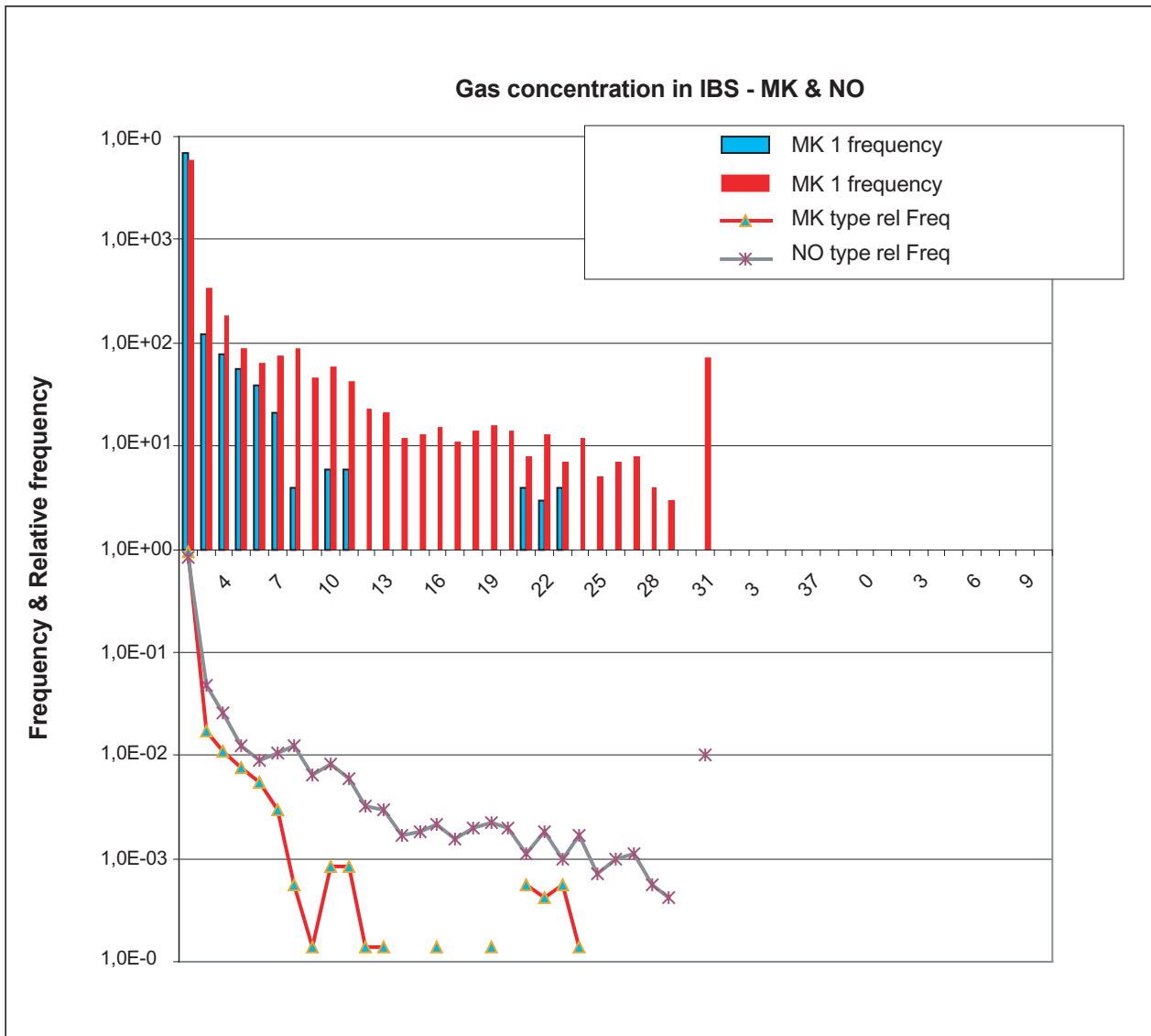
Using acoustic detection methods, fatigue cracks have been found in welds on secondary membranes. Such welds, carried out to ensure tightness of the barrier, were located around the protruding tubes that support the membrane system’s primary chairs. Design faults and fatigue defects, such as micro-cracks and pinholes, were effectively “teething problems” for these early membrane ships with their pioneering containment systems. By carrying out repairs and implementing design modifications in subsequent ships, such problems have not recurred.

5.3.3 Gas concentrations in primary spaces of older ships - normal operation

Gas concentrations in the primary spaces of membrane ships have sometimes been a source of concern to the various parties involved, including shipboard personnel, ship operators and managers, classification societies and gas terminal representatives; particularly whenever the content of methane in primary spaces rose sharply and quickly.

To provide an idea of the level of gas concentrations experienced, daily readings of gas concentrations in the primary spaces of two membrane ships - one Gaz Transport and one Technigaz - have been recorded over the last five years. Both ships have five cargo tanks and both are serving on the same trading routes.

The graph below shows the frequency of occurrence of each level of gas concentration in the primary spaces and the relative frequency of occurrence for each level of gas pollution experienced in the primary spaces of these two vessels. Neither of the vessels required repairs to their membranes during the period the measurements were recorded.



As expected, the distributions of gas concentration experienced in the two types of containment systems show many similarities. However, the sweeping function is most likely activated earlier in the Technigaz systems where the alarm level is set at 1.5% by volume.

The likely occurrence rating for each level of gas concentration - shown on the x axis in the chart - can be defined as per the table below, provided the model considered is accepted as being representative of the behaviour of gas concentration in the primary spaces irrespective of the type of containment systems considered in this study.

Relative frequency	Likelihood
$f > 10^{-2}$	Frequent
$10^{-3} \leq f \leq 10^{-2}$	Probable
$10^{-4} \leq f \leq 10^{-3}$	Remote
$f < 10^{-4}$	Improbable

The data reviewed shows that in a number of occasions the gas concentration suddenly rose to relatively high levels, for no apparent reason, before dropping down again to a more usual concentration in the primary space of the tank concerned. The gas concentration data made available did not include all the external parameters which influence the level of gas readings. Nevertheless, experience shows that:

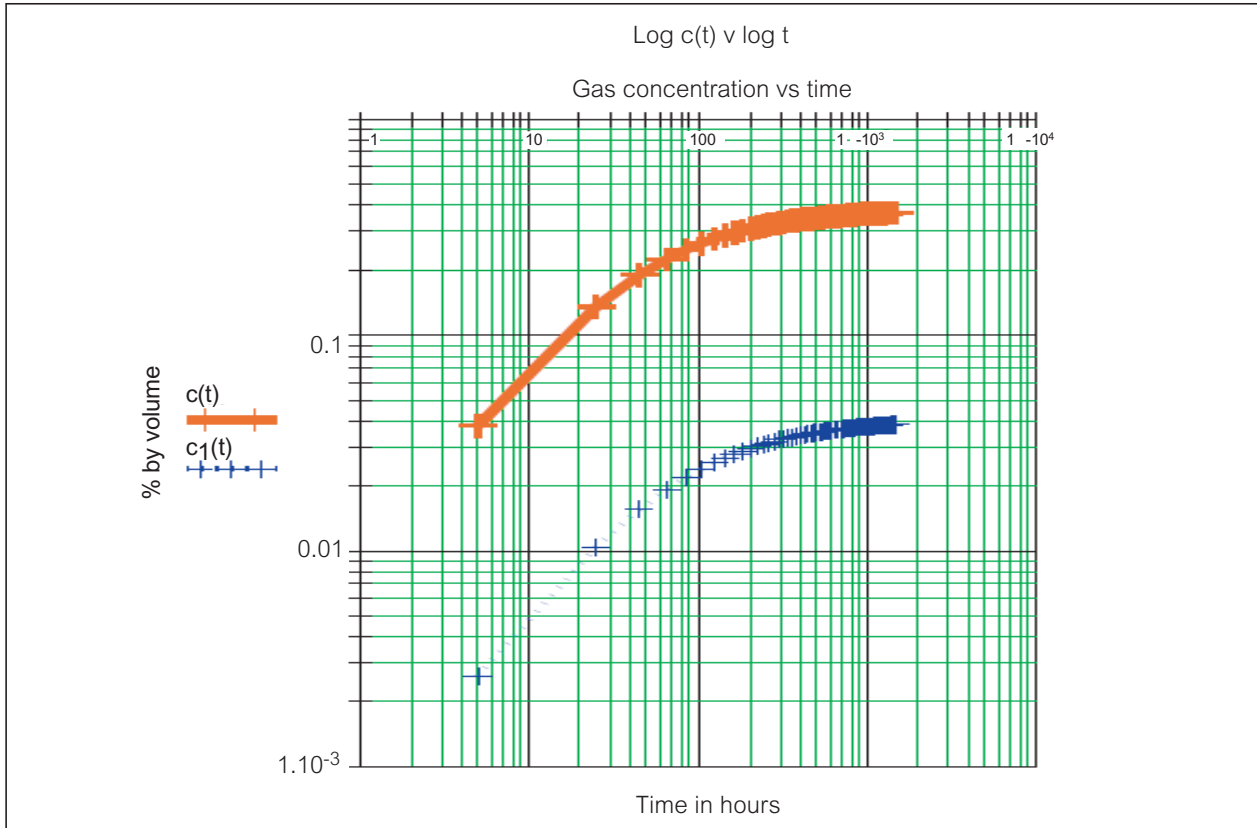
- Rough sea state conditions affect the level of gas concentration in primary spaces, most probably by increasing temporarily the overall porosity and by improving the gas circulation in the primary spaces towards the sampling points.
- Warming up of primary spaces during ballast legs influences the gas concentration level.
- Discontinuities in nitrogen flow affect the gas concentration.
- Shipboard management of the primary spaces pressurisation system has a considerable impact on the concentration.
- The calibration of the gas detection equipment is also a factor.

5.3.4 Gas concentration against time (seepage through pinholes)

In order to illustrate the level of gas concentration which would result from the passage of gas or liquid through pinholes in a membrane tank offering a primary barrier area of, say, 5,000 m², theoretical calculations assuming two different levels of porosity have been carried out.

In the first case a single leak through a pinhole of 0.65 mm in diameter (the red curve in the graph overleaf) is considered and in the second calculation the fluid is passing through 500 capillaries, each of 28 microns in diameter. An idea of the size of such a capillary is given by the fact that the thickness of a human hair is between 8 and 18 microns. In both cases the same level of porosity is achieved.

The results of these calculations have been plotted in the graph shown overleaf, in which gas concentration is plotted against time:



The worst case is represented by the passage of fluid through a single defect causing the gas concentration in the primary spaces to peak at around 38% by volume after 1,000 hours of operation with normal nitrogen breathing and sweeping. For an equivalent porosity area and under similar conditions, seepage through the 500 capillaries would induce gas concentration levels not exceeding 4% v/v.

5.3.5 The passage of liquid through the primary membrane

Experience from the few known liquid leaks through primary membranes into the primary space shows that it is easy to diagnose and recognise this type of event. Liquid leaks are characterised by the following symptoms:

1. The gas concentration in the primary space rises very rapidly above the alarm level settings
2. Temperature sensors located in way of the secondary membrane show readings dropping rapidly and activating the low temperature alarm.
3. The pressure increases rapidly in the primary space and may be high enough to activate the pressure relief valves soon after an incident takes place.

Events that have caused sudden liquid leaks include the following:

1. Items falling from the top of the tank to puncture the membrane
2. A major failure of a cargo pump, leading to pump parts penetrating the membrane
3. The accidental operation of a punching device on the primary barrier. Such devices were installed on some early Gaz Transport NO type LNG carriers. Mitigation measures have been implemented to eliminate this particular risk.

The vast majority of liquid leaks have taken place shortly after the tanks have been cooled down and loaded, following tank entries for work or inspection.

5.3.6 The extent of defects

5.3.6.1 Gaz Transport NO type containment systems

All ships constructed to the Gaz Transport NO type membrane designs have gas detection alarms generally set at 30% methane (CH₄) by volume for the primary space.

A partial loss of secondary membrane integrity experienced in some ships built to NO 82 and NO 85 systems was detected during routine “global vacuum tests”. Fatigue cracks in welds attaching the primary chair supports to the secondary membrane barrier appeared during the very early years of operation of the first 125,000 m³ vessels in the late 1970s.

Similar deficiencies occurred much later in the operating lives of some of the smaller NO type vessels. Defects in the secondary membrane barriers were eliminated in the early 1980s by modifying the weaker zones of ships built to the NO 82 and NO 85 type systems and prior to deliveries of all NO 88 type vessels.

5.3.6.2 Technigaz Mark type containment systems

Some minor defects of very low severity, occurring in way of the gas domes on deck, were discovered during the first years of operation of some ships with Technigaz Mark I type containment systems. Because of their position in the tanks, this type of defect could only permit the passage of gas, not liquid.

The secondary membrane of the Technigaz Mark type containment system is designed to be liquid tight only, as per the IGC Code. Its tightness or porosity is evaluated at regular intervals by means of a non-destructive testing (NDT) method that employs a vacuum decay test. The evaluation for Mk I is made against an acceptable normalised porosity area (NPA) established by laboratory testing and validated by tests onboard the LNGC “Descartes”, a vessel built in 1970s to the Mark I containment system. The evaluation for the Mk III system is more stringent on the assumption that it should be possible to achieve a greater degree of secondary barrier integrity for this later version of the design.

Note: At the time of drafting this document the acceptance criteria for tightness testing of secondary barriers of MK III systems is being re-evaluated.

5.3.6.3 Nitrogen pressurisation of insulation spaces on NO and Mark type ships

The nitrogen piping system on LNG carriers is an extension of the insulation spaces. Such systems have suffered some minor defects in the past, including small leaks in the nitrogen piping network and malfunctions of pressure control valves.

The dimensioning of the nitrogen piping system incorporates a very high safety factor, and operating pressures do not exceed 0.5 barg.

5.3.7 Conclusions - operational experience

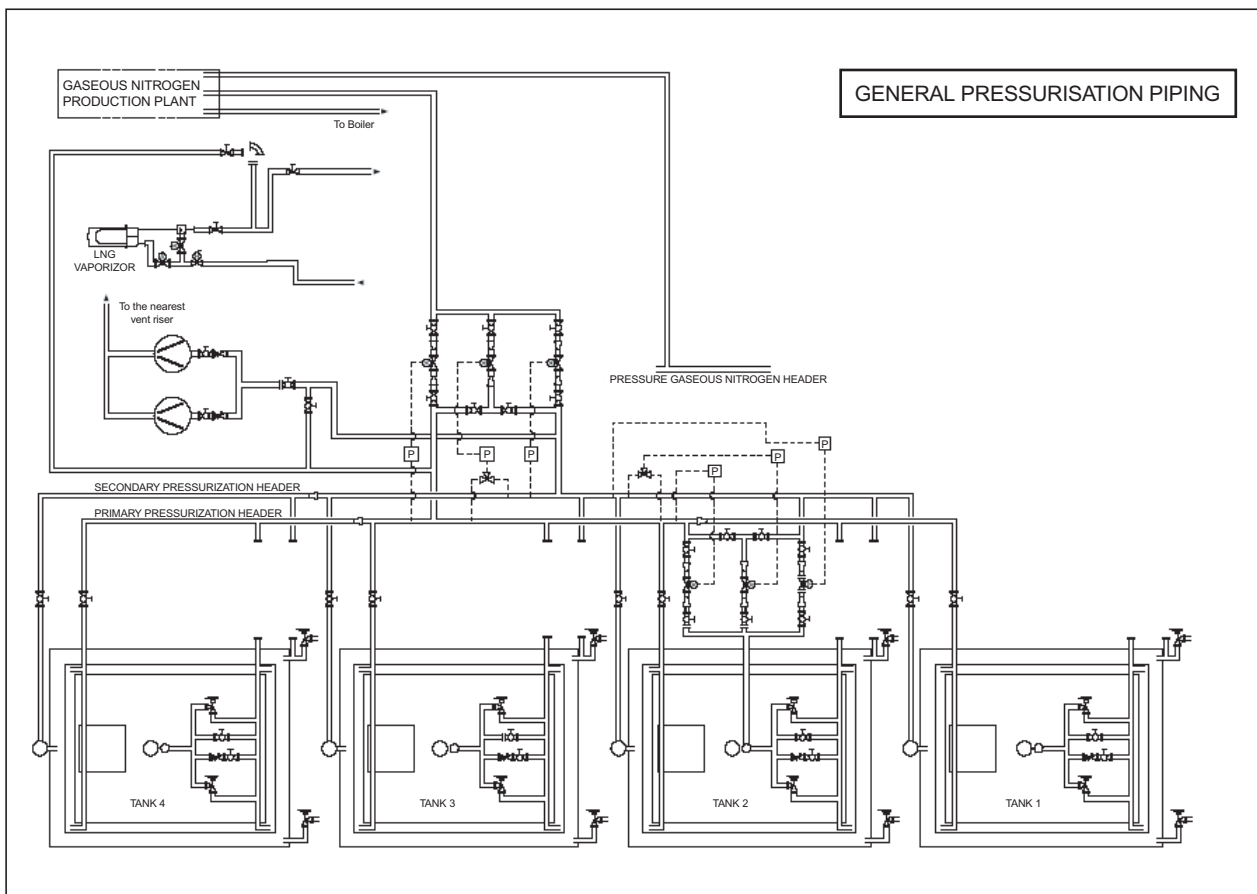
In-service LNG carrier experience shows that membranes may present micro-porosities through which gas or liquid may penetrate, depending mainly on the size of each of the openings. This situation is immediately detected by a noticeable increase in the gas concentration readings in the primary space. However, such a development does not constitute an imminent hazard as long as oxygen is absent from this space.

Small seepages of LNG through the primary membrane will vaporise instantly due to the heat ingress supplied by both the cargo tank surroundings and the circulation of relatively warm nitrogen.

The records we have reviewed show that there have never been any serious consequences of these seepages, even at the highest level of gas concentration ever observed. A total deficiency of the

nitrogen distribution network and/or of the insulation spaces has never occurred. In addition, there have never been any fire or explosion events involving LNG or its gas vapours in the insulation spaces.

5.4 Assessment of the fire risk in the insulation spaces



5.4.1 Safety analysis of the nitrogen supply

In terms of the supply of nitrogen (N_2) to the insulation spaces the two undesirable events are:

- the loss of the nitrogen production
- the nitrogen supplied by the system has an unusually high oxygen (O_2) concentration

Either of the two above conditions may occur if:

- there is an undetected failure of the nitrogen production plant which leads to abnormal oxygen concentration at the nitrogen outlet; this is an unlikely event since each nitrogen generator plant is used separately while the other one is on standby;
- a malfunction of the O_2 sensor and a defective alarm system make it possible for a potentially unsafe gas mixture to be sent downstream to the insulation spaces;
- an engine room “blackout” of a duration exceeding that which the buffer tank can supply; and
- fire in a location which would prevent N_2 production/delivery.

Other scenarios are not critical, as long as the oxygen content in the primary spaces does not rise to or above 12% by volume and that the gauge pressure in the primary spaces remains positive. In recognition of the fact that the fundamental safety of the cargo system is dependent upon the supply of high-quality nitrogen, it is recommended that, unless it can be demonstrated using risk analysis techniques such as fault tree analysis (IEC 61025:1990) that nitrogen, with an oxygen content in excess of 3%, cannot be supplied to the system as a result of equipment failure or operator error, an oxygen detector and alarm is installed in the common supply line from the nitrogen source to the system.

5.4.2 A “what if” analysis of the GTT NO type containment systems

A “what if” fault tree diagram for GTT NO containment systems is represented in the sketch and table shown below. A tentative approach to the resulting frequencies and risks is developed in Appendix 4.

EVENT	ASSOCIATED OUTCOME	SAFEGUARDS	COMMENTS
Failure of N ₂ production (flow rate)	Loss of N ₂ Pressurization	Two nitrogen plants + buffer tank	Very unlikely
Failure in N ₂ quality	Risk of O ₂ ingress in insulation spaces	O ₂ monitoring (< 3%)	O ₂ monitoring must be highly reliable
Small leak in N ₂ piping network	N ₂ leakage	Warm N ₂ with no consequence other than loss of nitrogen	Repairs can easily be done by the crew.
N ₂ piping network rupture	Loss of N ₂ pressurization	Adequate check and maintenance	Very unlikely (low pressure) Repairs can easily be done by the crew.
Failure of pressurization control valve system (valve jammed or not working properly) (primary space)	No (or low) N ₂ flow rate	* One spare control valve * Sweeping valve	Adequate redundancy
Ditto secondary space	Ditto	* One spare control valve	
No opening of sweepingvalve in case of gasdetection in primary space	Risk of increase of gas concentration	By pass valve	
Undesirable opening of sweeping valve	Increase of N ₂ flow rate	no consequence other than loss of nitrogen	

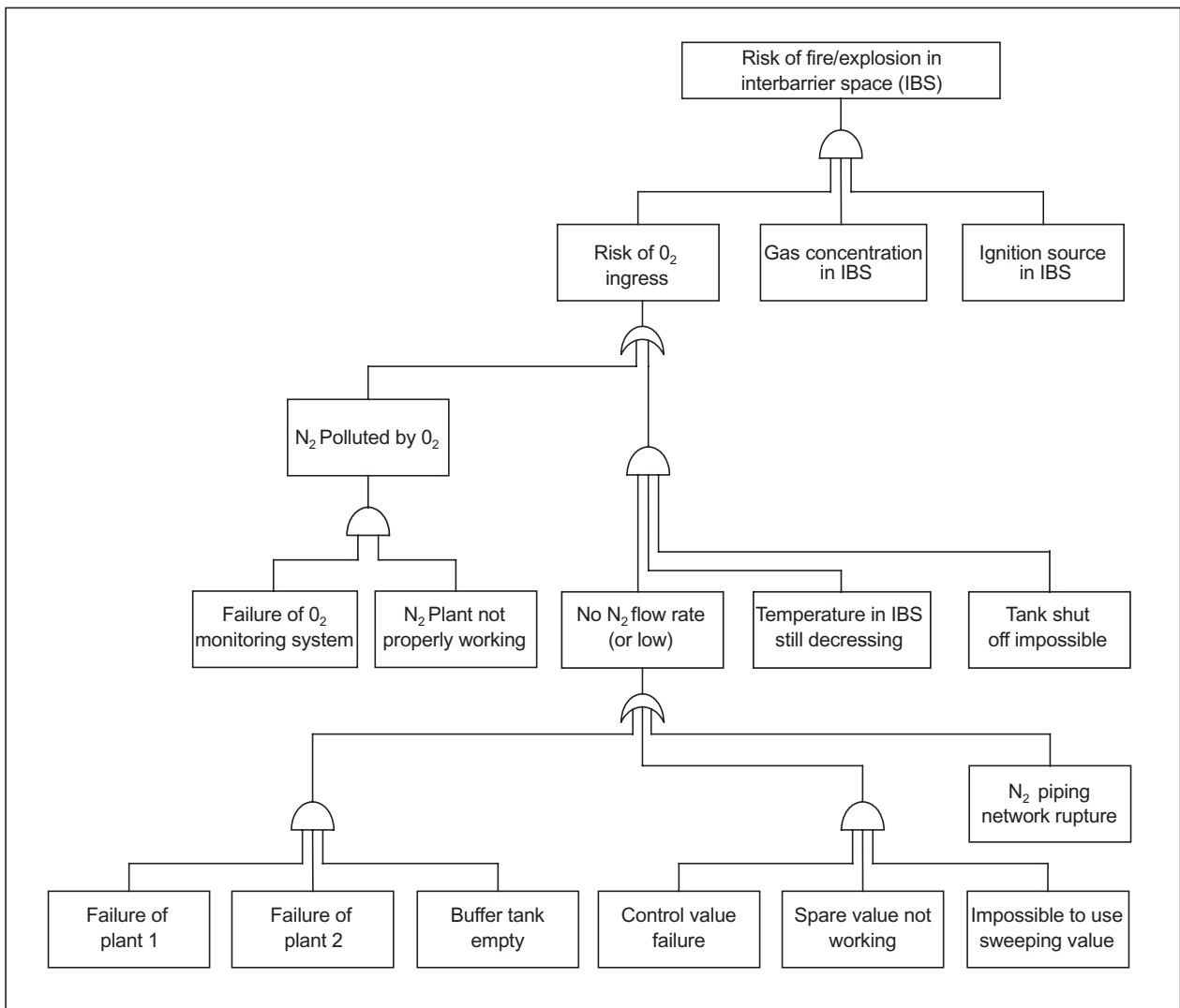
EVENT	ASSOCIATED OUTCOME	SAFEGUARDS	COMMENTS
Failure of primary barrier	Gas leak or liquid leak. Gas concentration could increase up to 100%	<ul style="list-style-type: none"> * Sweeping valve * By pass valve * Pressure relief concentration 	<ul style="list-style-type: none"> * Risk of 100% gas to the venting mast * Risk of fire at the venting mast outlet if external ignition source * Can be mastered (not critical)
Breach in inner hull	<p>Risk of O₂ ingress in secondary space</p> <p>Risk of ballast water ingress into secondary space</p>	<ul style="list-style-type: none"> * Alarm if gas concentration > 1.5% by volume * Observe by manual sampling * Alarm water detection * Warming up of secondary temperature sensors 	<ul style="list-style-type: none"> * No consequence if N₂ pressurization is working * The main risk is water ingress (out of scope of this analysis)
Gas concentration in secondary space	Risk only if O ₂ content >12% and ignition source	<ul style="list-style-type: none"> * Alarm if gas concentration > 1.5% by volume * Pressure relief system 	

5.4.3. A “what if” analysis of the GTT Mark type containment systems

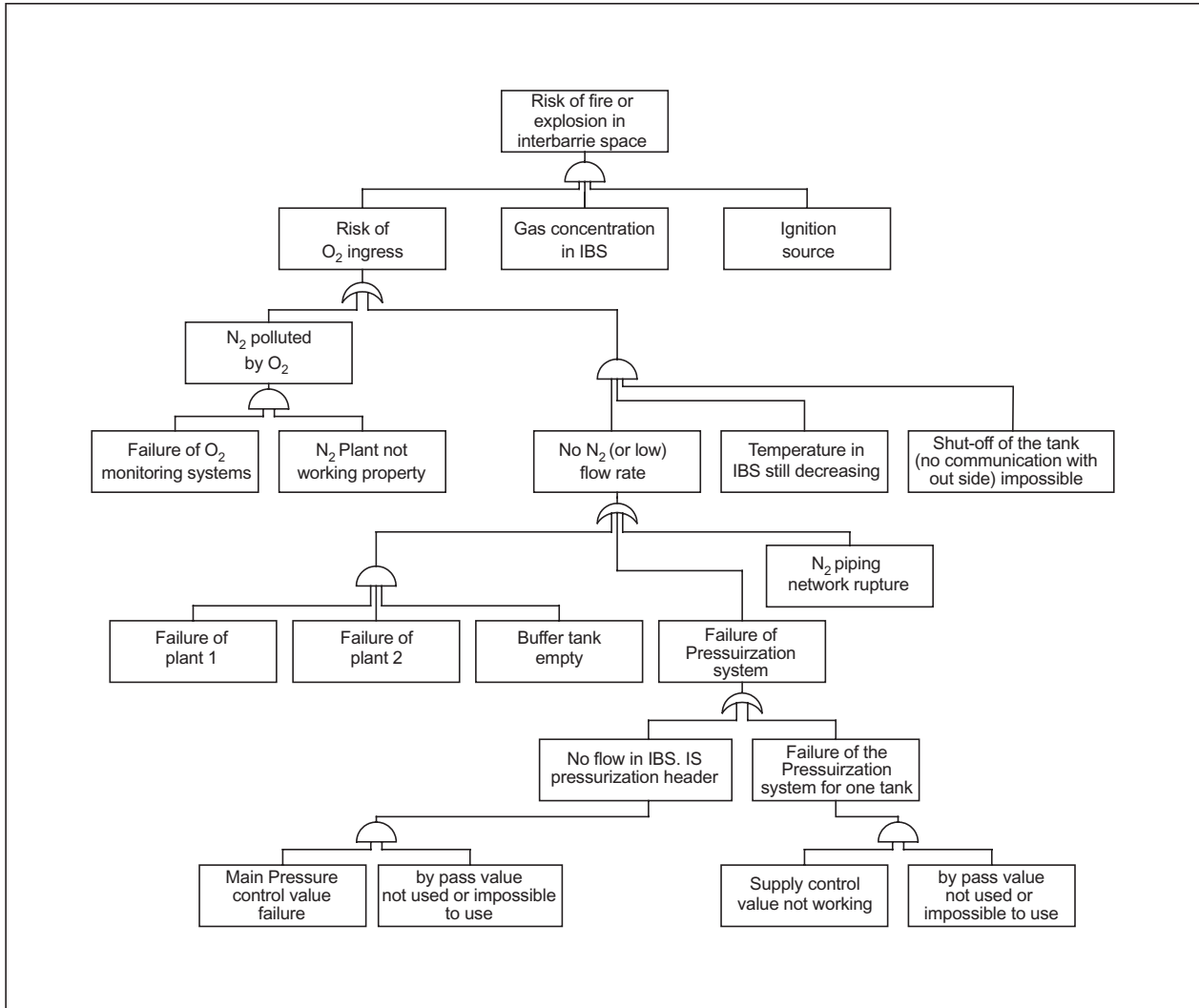
In the original GTT Mark I containment system, the insulation spaces were filled with nitrogen and maintained automatically at a pressure slightly below the atmospheric pressure. Nitrogen was injected into the secondary space of each cargo tank and migrated to the primary space, through the gas porous secondary membrane. Two nitrogen vacuum pumps, one of which was a standby, were used to reduce pressure in the primary space.

To alleviate the potential risk of air or moisture ingress to the insulation spaces, in the late 1970s, the nitrogen system was modified in order to maintain a positive pressure in the insulation spaces and purging header. To the best knowledge of GTT, all vessels built to the Mark I system had their nitrogen pressurisation systems modified in the early 1980s.

Although the pressure control system installed for the insulation spaces on GTT Mark type vessels is different from the system used on GTT NO type ships, the risk analysis is very similar.



EVENT	ASSOCIATED OUTCOME	SAFEGUARDS	COMMENTS
Failure of N ₂ production (flow rate)	Loss of N ₂ pressurization	Two nitrogen plants + buffer tank.	Very unlikely.
Failure in N ₂ quality.	Risk of O ₂ ingress in insulation spaces.	O ₂ monitoring (< 3%).	O ₂ monitoring must be highly reliable.
Small leak in N ₂ piping	Spillage of N ₂ .		
N ₂ piping rupture.	Loss of N ₂ pressure.	Effective maintenance.	Very unlikely.
Failure of main pressure control valve.	N ₂ supply not working properly for all tanks.	By pass valve.	
Primary space of each tank: N ₂ control valve not working properly.	Abnormal N ₂ flow rate in the primary space of one tank.	By pass valve.	
Secondary space of each tank : N ₂ control valves not working properly.	Abnormal N ₂ flow rate in the secondary space of one tank.	By pass valve	
Failure of primary barrier.	Gas leak or liquid leak gas concentration could increase up to 100%.	* Safety vent and pressure relief system. Drainage of liquid in primary spaces possible	* Risk of 100% gas to the vent mast. * Fire at the mast outlet if xternal ignition source (not critical).
Breach in the inner hull.	Risk of O ₂ ingress in secondary space.	Alarm if gas concentration > 1.5% by volume.	* No onsequence if N ₂ system is working. * The main risk is water ingress
Gas concentration in secondary space.	Risk only if O ₂ ingress and ignition source.	* Alarm if gas concentration > 1.5% v/v * Pressure relief system. in the secondary barrier.	Very unlikely if N ₂ pressurization of the secondary space working and no damage



5.5 Ignition sources

Determining the probability of an ignition source with sufficient energy being present in the atmosphere of the primary spaces is a key step in the assessment of a risk of fire. This is applicable for most installations where combustible materials are stored or handled.

5.5.1 Static electricity in insulation spaces

Static electricity generated by the contact between and/or the separation of materials has been ascertained as the cause of numerous serious explosion incidents in conventional oil tankers. As a result, it is necessary for this phenomenon to be examined in this study, even though there has been no recorded static electricity-related incident onboard a gas carrier nor is there any evidence to support the possibility of such an event occurring.

In GTT NO-type membrane containment systems, the current is grounded through chairs, Invar tubes or trihedrons and there is no difference in potential between the primary membrane, the secondary membrane and the inner hull. In GTT Mark-type systems the membrane is also grounded through the liquid and gas domes. There is no difference of potential between the primary membrane and the inner hull, and the nitrogen flowing into the spaces is dry.

The special case of carbon dioxide-blown polyurethane foams used as insulation, which are not present in the older membrane systems considered in this study, is addressed in Appendix 3.

In addition to the above, an experienced consultant has also made an assessment of the risks associated with secondary barriers made of “Triplex” material, as is used in the current GTT Mark III membrane containment system. Two risk scenarios were considered:

1. discharges from the charged flexible secondary barrier membrane during the construction phase in the presence of solvent vapour;
2. discharges from the charged flexible secondary membrane to LNG should the primary membrane become perforated.

The resultant hazard ratings for these risks were found to be either low or negligible.

Therefore, it can be deduced from these internal and external studies that the risk of static discharge in the insulation spaces is very unlikely.

5.5.2 Electrical source of ignition

Approved intrinsically safe temperature sensors are the only electrical equipment installed in the insulation spaces. A careful review of the membrane systems has shown that there is no ignition source of electrical nature in the insulation spaces of LNG carriers.

5.5.3 Ignition by lightning

The only situation where a gas mixture present in the insulation spaces may be exposed to sufficient oxygen and to a possible ignition source would be when this mixture is flowing out at the top of the primary spaces exhaust masts during a thunderstorm.

The Gaz de France (GdF) Research Department, with a team under Dr V. Sauter, was contracted to carry out a study in order to assess the risks which may be encountered by an LNGC with respect to the ignition by lightning of a gas mixture flowing out of the primary spaces vent mast. The study is based on the lightning impact density defined in the French standard NF C 17-100 “Protection des structures contre la foudre” published in December 1997, (ref bibliography B7). The GdF researchers concluded that there is a possibility of an LNGC being struck by a lightning impact and, hence, that it was important to ensure that the gas mixture rejected from the insulation spaces will not support combustion.

The Gaz de France study showed that such a combustion reaction depends only on the gas concentration and on the exhaust flow-rate. The various combinations of these two parameters were then studied. It was subsequently demonstrated that in normal operating conditions and with maximum sweeping flow-rate, the possible flame lengths are negligible at all levels of gas concentration.

The results obtained by Dr Sauter’s team demonstrate that, with maximum sweeping flow rate, the likelihood of such an incident can be said to be very remote at all levels of gas concentration.

Examples of the models studied are shown overleaf:

Scenario 06.1 – 3D % CH₄, 2 % O₂ In N₂ – 17.3 Nm³/h

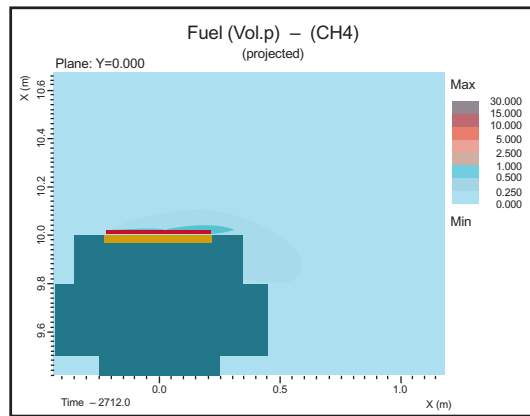


FIGURE 17: projected CH₄ % V/V concentration
Flammable plume: 5% concentration

Scenario 06.1 – 70 % CH₄ – 17.3 Nm³/h

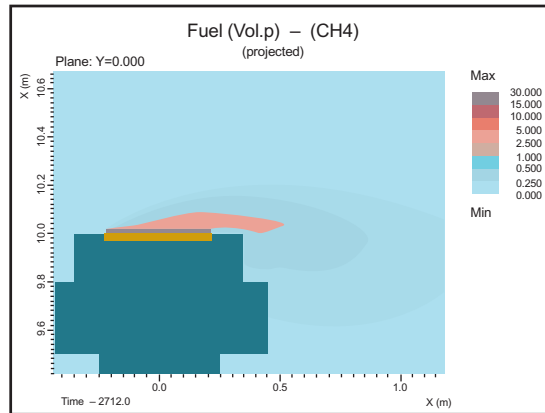


FIGURE 29: projected CH₄ %v/v concentration
Flammable plume: 5% concentration contour

Scenario 10.1 – 90 % CH₄ – 17.3 Nm³/h

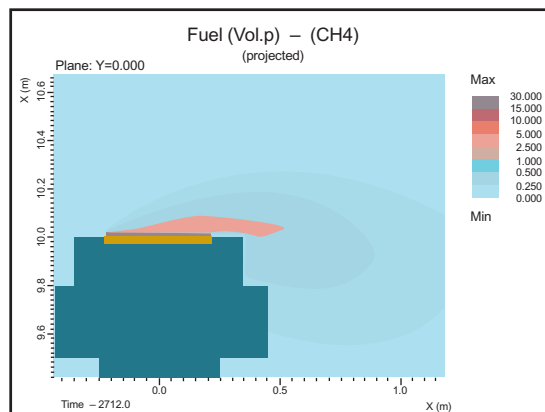


FIGURE 29: projected CH₄ %v/v concentration
Flammable plume: 5% concentration contour

5.5.4 Risks associated with routine maintenance operations

Risks associated with repairs in way of the insulation spaces, and the inspections attendant on such repairs, must also be considered. Such inspections and repairs often involve both hot and cold work and the use of tools, portable equipment, ladders, scaffoldings, etc. In these situations the atmosphere in the insulation spaces must be checked for flammability levels before any tank entry or work inside the tanks is undertaken (see also Section 5.6 below) and at regular intervals thereafter.

No hot work should be permitted on the inner hull as long as the insulation spaces are under vacuum, however small the vacuum in these spaces may be. Subsequent to any repairs or dry-docking, multiple operations of vacuum and charging with inert gas of the insulation spaces shall be conducted while monitoring very closely the oxygen content. Readers are referred to SIGTTO's, "*Fire Prevention in the Cargo Containment Systems of Liquefied Gas Carriers in Shipyards*" published, in 2001 (ref bibliography B8)

5.6 Heavier hydrocarbons - a special case

Natural gas contains small quantities of heavier hydrocarbons (C_2+), i.e. ethane, propane and butane. Due to the porosity of the primary membrane, it is possible for a small amount of these heavier hydrocarbons to accumulate in the primary space, eventually condensing to liquid form. These liquids will evaporate as soon as the temperature in the primary space exceeds their boiling point. Such a point may be reached during ballast legs and, for the heavier fractions, during the warming up of the tank preceding any tank openings.

Gas sensors are more sensitive to C_2+ hydrocarbons. Therefore, the readings of the global gas concentration will be slightly overestimated. The presence of C_2+ fractions in the primary spaces of LNGCs should not be a critical situation for ships in service, provided that the O_2 concentration does not reach or exceed 12% by volume.

Whenever cargo tanks are to be decommissioned for maintenance or inspection, it is essential to "gas free" the insulation spaces by repeatedly pulling a vacuum in the spaces, and refilling them with nitrogen until the residual content of the products to be eliminated is below the safe threshold.

GTT Mark and CS1 membrane systems allow the stripping of residual liquids at the bottom of primary space. With GTT NO membrane systems special procedures are needed before repairs in the bottom of a tank.

Another consideration, which concerns all hydrocarbons, is the gas absorption by the insulation materials of the cargo containment system, e.g. balsa, plywood, polyurethane foam (PUF). An effective way to speed up decontamination is to sweep the insulation spaces with warm nitrogen, keeping a regular check on the insulation space and cargo tank atmosphere.

5.7 Fire hazards - conclusions

All the issues addressed in this risk assessment demonstrate that the probability of a fire occurring in the primary spaces is very low, provided that the oxygen content is below 12% by volume and thus unable to support combustion. High gas concentrations will not create a hazard as the mixture in primary spaces will be too rich to ignite. However, a very high gas concentration may indicate a liquid leak, which is associated with the cryogenic hazard.

The study shows that during the course of normal operation there is no ignition source available in the spaces considered, including the venting system. However, it is necessary to closely monitor the oxygen content in these spaces.

5.7.1 Possible improvements

On older ships fitted with liquid nitrogen storage tanks, rigorous checks of the oxygen content in the insulation spaces are not usually carried out because the presence of oxygen in the nitrogen storage tanks is very unlikely. However, it is good practice to make manual checks for oxygen content in the spaces.

5.7.2 Prevention of oxygen entering the insulation spaces

The only possible ways for oxygen to enter the insulation spaces after it has been initially reduced below are through the circulation of nitrogen polluted with oxygen, or through a physical defect in the system such that the pressure falls below atmospheric pressure. Otherwise, there is no reason to find oxygen in the system if the network has been correctly inerted and pressurised.

For oxygen to enter the insulation spaces through the exhaust system there must be a combination of several unlikely events. This may occur if the following conditions are met simultaneously:

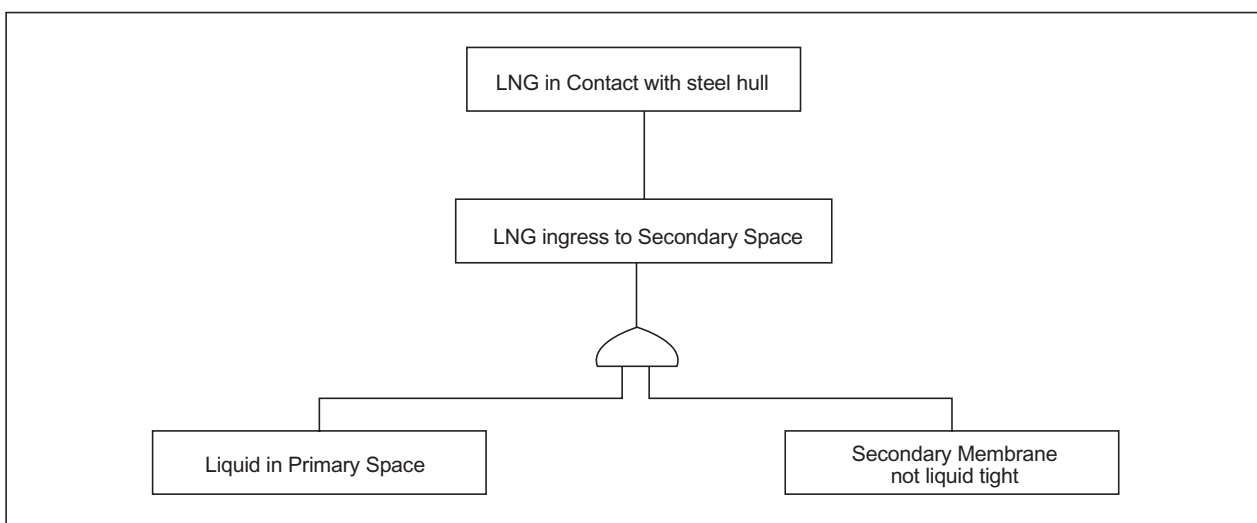
1. there is failure in the pressurisation system;
- and
2. the nitrogen exhaust network remains linked to the atmosphere for any reason, e.g. the bypass valve in the GTT NO membrane system has been previously opened and inadvertently left open.

Under the above conditions, and provided that the tanks are in a cooling down phase during which the pressure and temperature of the gas in the spaces is decreasing, a contra-flow of air from the atmosphere into the insulation spaces may be made possible.

5.8 Risk assessment for hull integrity

5.8.1 Liquid in primary space

The failure event tree covering the integrity of the LNGC hull is very simple. A liquid leak is assumed in the primary membrane, and if the secondary barrier is not liquid-tight, there is a risk of liquid contacting the inner hull. If a liquid leak is possible, the only safeguard for preventing LNG contacting the inner hull is the integrity of the secondary barrier, particularly at the bottom and on the sides of the tank.



5.8.2 Secondary membrane not liquid-tight

5.8.2.1 Ships in commercial operation

(a) GTT NO membrane systems

The pressure in the secondary spaces of GTT NO membrane systems is maintained slightly below (or equal to) the pressure in the primary space. Presence of gas inside secondary space at a significant concentration level would most probably mean that there is porosity through the secondary membrane. However, this would be true only if a high gas concentration is detected in the primary space. The fact that the nitrogen pressurisation network is common to all tanks must also be taken into account. If there are problems on a tank, experience has shown that gas can migrate into the insulation spaces of the other tanks, even if these are perfectly tight. Some operators have found by experience that keeping a pressure in the secondary spaces slightly above that of the primary spaces enables more accurate monitoring of the conditions and reduces the number of spurious alarms.

(b) GTT Mark membrane systems

The secondary barrier of GTT Mark membrane system is intended to be only liquid tight and it has some porosity to gas. To avoid gas diffusion from contaminated interbarrier spaces a slight over-pressure is maintained in the insulated spaces. This characteristic can be used in normal operation as a symptom of potential joint de-bonding if difficulties in maintaining the correct operation of the nitrogen pressurisation system are experienced. Should this occur then careful investigation into the cause should be implemented..

Conclusions

The absence of gas in the secondary space is not necessarily indicative of the condition of the secondary barrier. Therefore, in general, the only conclusive assessment of the membrane condition can be ascertained through tests when the ship is out of service.

5.8.2.2 Tightness testing

Periodic tests of the secondary membrane are the only way to check the condition of the secondary membrane on an ongoing basis. In Appendix 2 it is shown that the associated criteria are very conservative when unsafe events, such as hazardous temperatures on the inner hull, are considered. Tests must be performed at approximately five-year intervals and should be conducted in accordance with the GTT recommendations given in Ext Doc 182, 1093 and 1136 for mark systems.

CHAPTER 6

Insulation Space Pressurisation - Normal Conditions

Chapter 6 covers the general principles behind the normal operational procedures associated with the pressurisation of a typical GTT NO type membrane containment system. The principles are similar for the GTT Mark type membrane containment systems.

6.1 Controlling nitrogen pressures

During the course of normal operations on a GTT NO membrane vessel the primary and secondary spaces are kept full of nitrogen gas at a pressure of between 3 mbarg and 5 mbarg. All primary spaces are common, as are all secondary spaces, but the two sets of spaces are kept separate. Each set of spaces has a make-up control valve, which supplies nitrogen to the spaces if the pressure drops to 3 mbarg, and also an exhaust control valve, which will vent any pressure in excess of 5 mbarg. The set points can be adjusted from the ship's cargo control room.

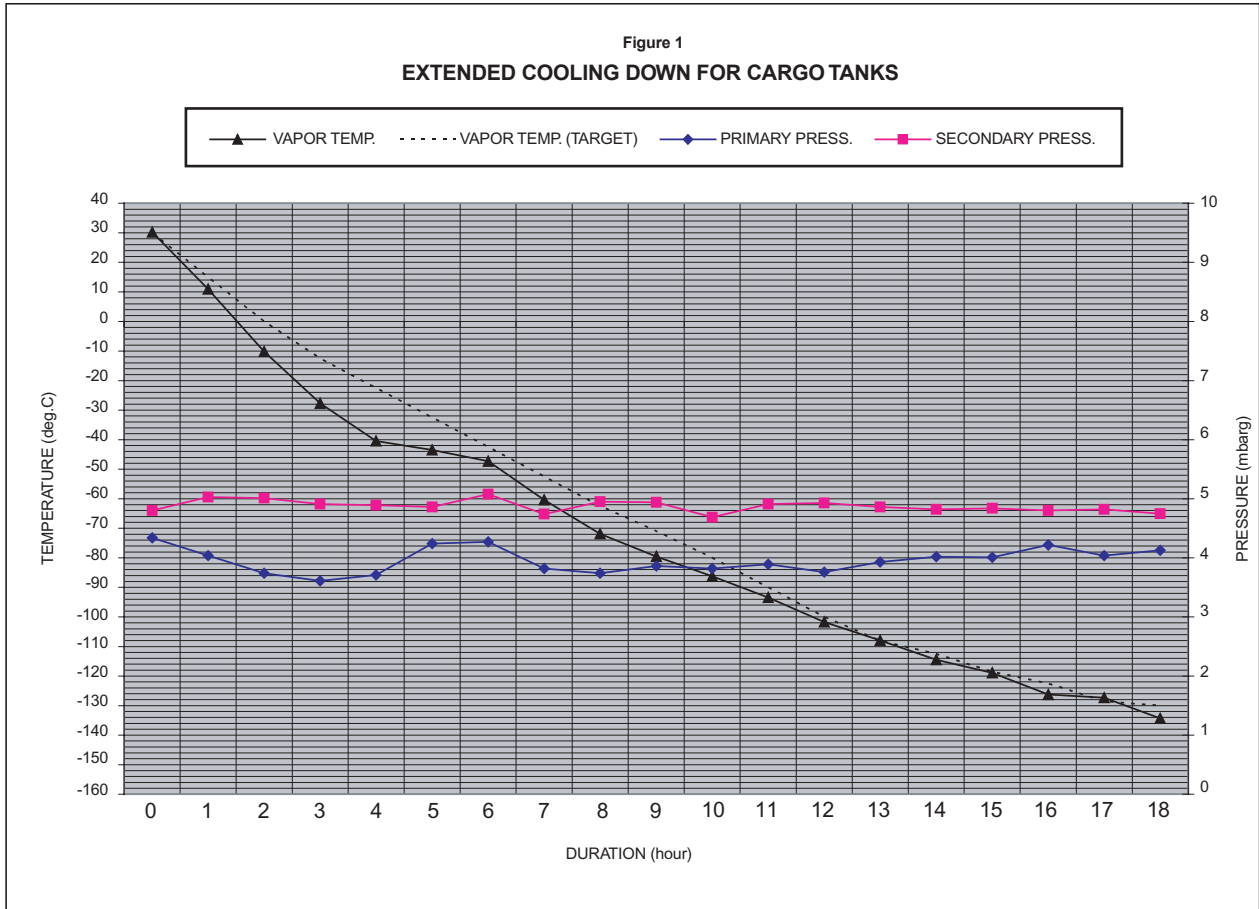
With the ship in service, and when steady temperatures have been achieved in the cargo tanks, the only time the make-up control valves should be activated are in response to variations in atmospheric pressure and environmental temperature changes. On short voyages stable temperatures may not be achieved.

When the cargo tanks warm slightly in the ballast condition, the secondary spaces in particular will warm up, causing the pressure to rise and the exhaust control valve to vent excess pressure.

When the cargo tanks are cooled down prior to loading and also in the initial stages of loading, the insulation spaces, in particular the primary spaces, will experience a cool-down. This will cause the pressure to drop in the insulation spaces and the headers, and the make-up control valves will open. The attached graph in Figure 1 shows the variation of the pressures in the insulation spaces during extended cool-down of the cargo tanks. Occasionally, when cooling down cargo tanks, it may be found necessary to provide additional nitrogen make-up to the primary spaces.

In addition to the exhaust control valves, each insulation space has two pressure relief valves set to lift at 10 mbarg and to close again at 8 mbarg.

Each primary space is provided with the ability to sweep the spaces by having bypass valves either at the supply line or at the exhaust line.



6.2 Pressure variations

As mentioned, the main pressures in the primary and secondary spaces are automatically controlled between 3 mbarg and 5 mbarg by the normal make-up control valves and exhaust control valves. In practice, the secondary insulation spaces are maintained at 0.5 to 1.0 mbar above the primary insulation spaces. This is to ensure the secondary spaces are not contaminated by the primary spaces in the event of leakages through the space. Typically, three make-up controllers and three exhaust controllers control the supply of nitrogen to the insulation spaces and the relief of excess pressure from the insulation spaces.

CHAPTER 7

Insulation spaces pressurisation - abnormal conditions

Chapter 7 covers the issue of insulation space pressurisation for membrane LNGCs in the context of abnormal conditions and the ability of ship operators to discern fluctuations in parameters which could lead to an adverse impact on the cargo containment system and associated equipment. In the text all content figures, e.g. for gas, nitrogen, oxygen, etc, are given as % by volume. Natural gas is taken to be the same substance as pure methane.

7.1 Recognition of abnormal conditions

An intimate knowledge of the way in which the cargo containment system behaves and “breathes” during the course of normal operations is essential in order for the crew to recognise abnormal conditions.

Membrane LNG ships are unique in that the main “health parameters” of the cargo containment system, i.e. the nitrogen consumption, oxygen content, local temperatures in the insulation and gas content in the insulation spaces, are monitored and evaluated on a continuous basis. It is possible to record all these parameters over the ship’s life and gain an understanding of the reasons behind any particular deviation. See Appendix 6.

The knowledge of the cargo containment system and its performance is gained with time. Therefore it is important that the so-called “health parameters” of the system are clearly understood and recorded in logbooks for each ship. Historical records of nitrogen consumption, oxygen content, gas content and temperatures in insulation spaces are of critical importance and must be available at any time for the ship management as well as for new ship’s staff.

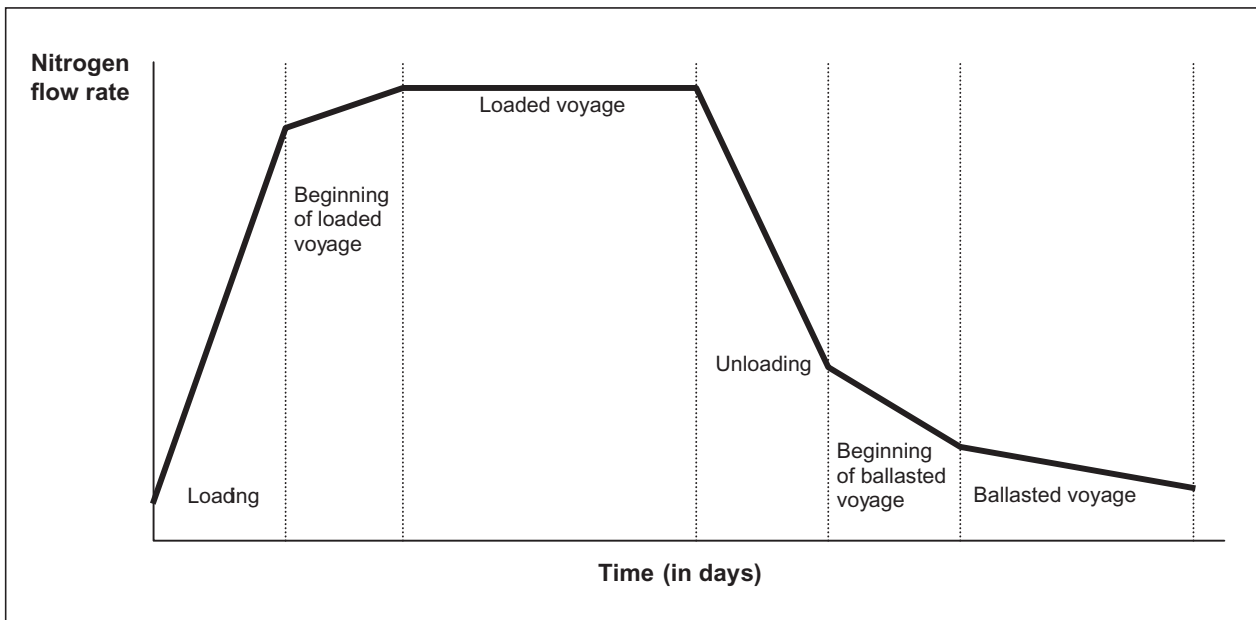
It is accepted that some of these parameters may fluctuate over a long-term timescale without jeopardising safety. The performance logbook will aid detection of conditions deemed to be abnormal. It needs to be noted that the performance of membrane containment systems tend to be sensitive to events such as incidents involving the membrane and associated equipment. Experience also shows that the signature of each of the above parameters may change after repair or maintenance work has been undertaken in the cargo containment system.

7.2 Reference values of the operating parameters

The parameters of a cargo containment system are ship-specific and depend on such factors as the capacity of the ship, the age of the ship, the trip distances, and the initial parameters of the cargo containment system at delivery. These parameters may even vary between sister ships. The individualistic nature of a cargo containment system’s parameters explains why each ship needs to be appreciated independently. It is dangerous to assume that the performance parameters of the containment system of a given LNG ship of a new building series will mirror those of all the others of the same series.. Therefore it is imperative that operators establish reference values for each vessel in their fleet.

7.3 Nitrogen flow rates in insulation spaces

The following diagram shows a simplified schematic profile of nitrogen flow rate versus time in the primary space of a typical LNGC.



In order to establish reference nitrogen flow rate curve to highlight “abnormalities”, it is prudent that such profiles are drawn up for each typical trip, i.e. long, medium or short distances and to estimate the daily nitrogen consumption.

7.4 Oxygen content in nitrogen

In normal service, oxygen in the insulation spaces is measured soon after a high nitrogen demand, e.g. just after loading or following a nitrogen system upset. The design is such that it is unlikely that oxygen can enter the insulation spaces. However, it is considered prudent that this value be checked at approximately weekly intervals.

7.5 Gas content in insulation spaces

The content of gas in the insulation spaces is measured continuously using gas analysers. With regard to the several parameters utilised in monitoring cargo containment system performance, the use of a gas detection system in the insulation spaces is certainly the easiest method by which operators can determine the transition from normal to abnormal conditions. Gas detection systems have demonstrated their efficiency and reliability in many years of service. In cases of malfunction the, gas detection equipment needs to be repaired or recalibrated prior to the next cargo operation. Manual procedures to check gas concentrations should be implemented in the interim period.

7.5.1 Alarm levels in secondary space

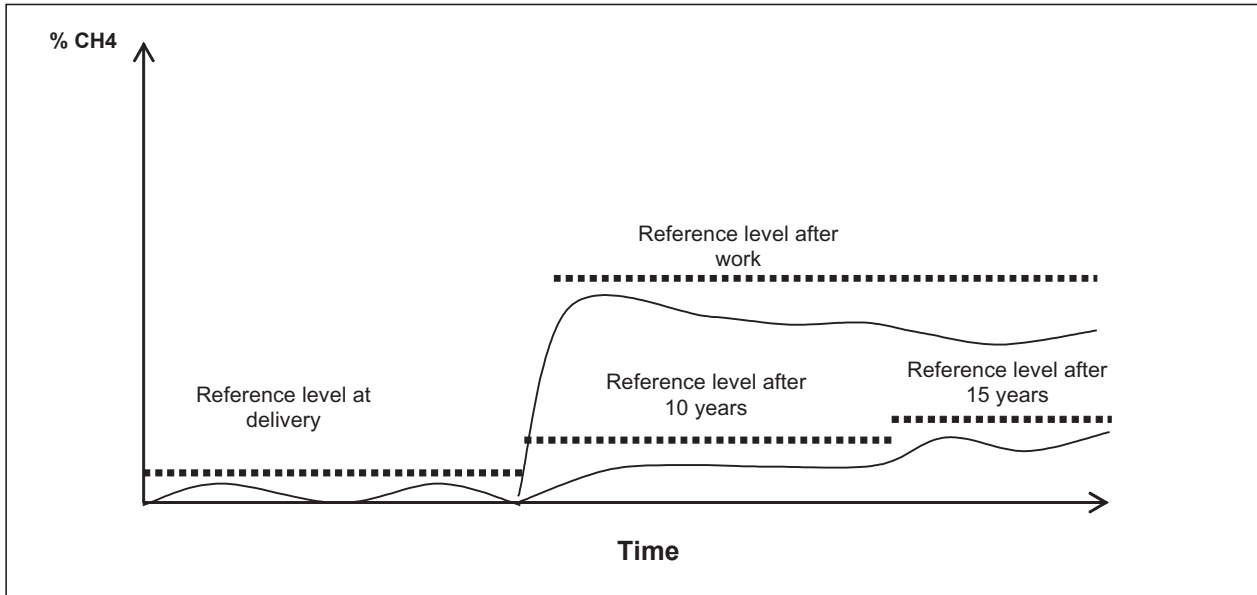
For the reference mean nitrogen flow-rate previously stated, the level alarm is set to 1.5% for all current membrane systems.

7.5.2 Alarm and reference levels in primary space

An alarm is set to a maximum of 30% by volume for the GTT NO systems, with the exception of the first two NO82 vessels,(where the alarms were set at 35% by volume in the primary space and 4% by volume in the secondary space). Certain GTT Mark membrane systems have an alarm set at 30% by volume, while all other GTT Mark vessels have the alarms for both primary and secondary

spaces set at 1.5% by volume. Both of these alarm set points for the primary insulation spaces are accepted values by the classification societies and have been accepted by the port states

It is suggested that a system be in place to draw operators' attention to deviations from normal gas concentrations. This may be achieved by establishing a reference level from historic data for an individual cargo tank. Gas reference conditions may change with time, at the reference nitrogen flow-rate, due to micro-porosities on the primary membrane (see following diagram).



Two ways have been identified for dealing with the normal gas content variations in primary spaces:

1. modifying the gas reference conditions within normal operating limits; this method is preferred because the "true" gas content in the primary space at nominal nitrogen flow-rate is known.

or

2. increasing the reference nitrogen flow-rate in order to maintain the gas content in the mixture at the same level; this method may entail continuous or regular sweeping;

It is almost impossible to be prescriptive about what action to take for a given gas concentration at the nitrogen reference flow. All data should be thoroughly analysed, including the rate of change of concentration level and historical data, by the ship's management.

As a general guide only, the following conclusions apply:-

- experience has shown that defects leading to relatively stable gas concentrations below 10% by volume are undetectable,
- a significant change in gas concentration, e.g. leading to a doubling of gas levels, should be investigated not later than the next refit if the concentration exceeds 10% by volume and
- if the gas concentration frequently exceeds 30% by volume the ship-operator should establish a plan of action and inform the classification society. Some port states may also require to be informed.

7.6 Temperatures in insulation spaces

The prime purpose of the temperature sensors located inside the insulation is to detect LNG leakage, however they will also indicate the presence of water should there be a defect in the inner hull. In normal conditions, depending on the condition of the ship, e.g. loaded or ballasted, the temperature measurements can change. The most important parameter here is the signature of each temperature sensor inside the insulation, rather than the temperature value which is function of the exact location of the probe in the insulation. For a given ship condition, the temperature measurement of each sensor shall remain stable and comparable to the historical data.

7.7 Abnormal condition procedures

7.7.1 Pressure decrease in insulation spaces/increase in nitrogen flow rate

A demand for nitrogen by the cargo containment system which is higher than the reference nitrogen flow rate discussed above is easily detected by regular checking of the nitrogen flow-meter on the generators or from the daily readings of the liquid nitrogen in the storage tanks. Cooling down the tanks too rapidly can cause the pressure in the insulation spaces to temporarily become sub-atmospheric, which increases the likelihood of air ingress into the system. Such an event is detected by the low pressure alarms in the insulation spaces.

7.7.2 Oxygen in insulation spaces

As previously stated, the presence of oxygen in the insulated spaces could only be due to a combination of unlikely events. Some kind of failure in the pressurisation system (see below) would be necessary while, at the same time, the nitrogen exhaust network remained open to the atmosphere, for whatever reason.

To reduce the risk of oxygen in insulation spaces, the following mitigation methods should be considered:

- carry out adequate maintenance work on all relevant pipe work;
- keep bypass valves closed and secured in this position during normal operating conditions;
- and
- install non-return valves after the sweeping valves in order to prevent any contra flow air ingress.

7.7.3 Loss of nitrogen production

The unlikely event of losing the ability to produce nitrogen might occur as the result of a major incident, such as a long engine blackout or fire, incapacitating the nitrogen generators. Such scenarios are managed by utilising the emergency procedures of the ship which define the remedial actions to be taken and the correct order of priority for such measures to be implemented.

7.7.4 Defective oxygen content measuring devices

In the case of a defective oxygen content measurement system, manual readings can be taken to check the information. The availability of redundant equipment helps to minimise the impact of such a problem. It is recommended that two oxygen sensors be arranged in series on the common part of the nitrogen network.

7.7.5 Production of off-spec gas by the nitrogen generation plant

The production of “off-spec” gas by the nitrogen generation plant is detected through the oxygen alarm which activates when the O₂ level exceeds 3%. When this happens, the oxygen measurement system should first be checked to confirm the oxygen content in the nitrogen network.

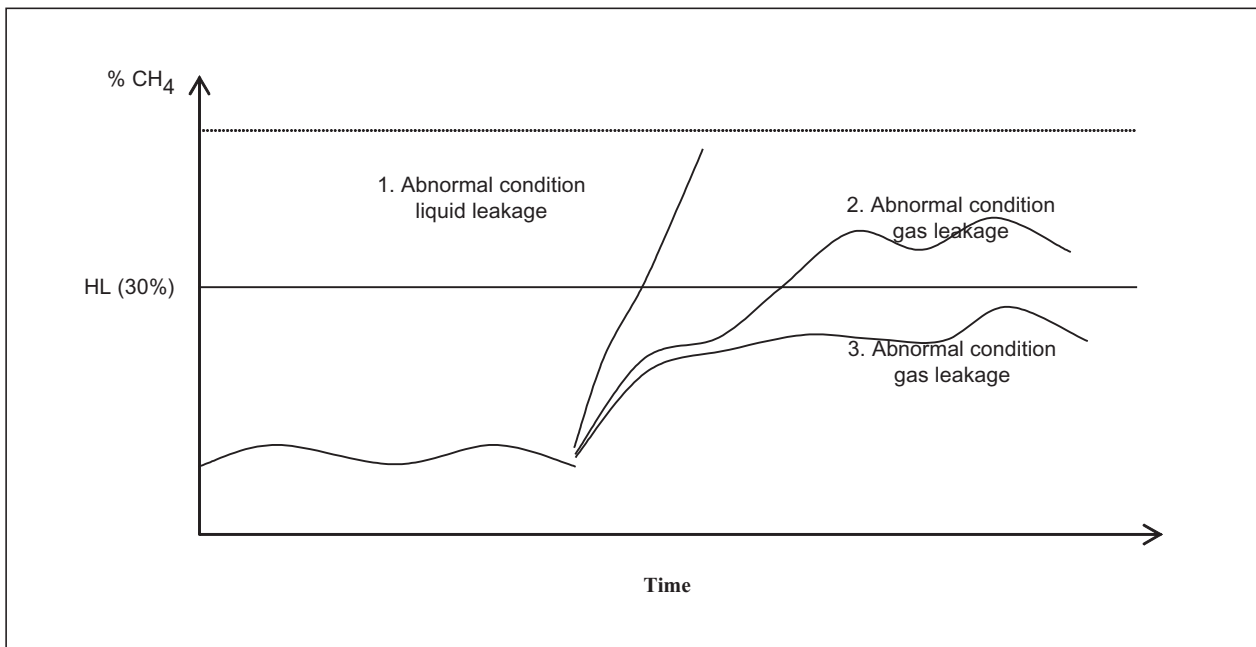
If nitrogen is supplied via dedicated liquid nitrogen tanks, it is important to prevent any possible contamination of the nitrogen during the liquid nitrogen loading operation. Ship operators should consider having the supplier provide a liquid nitrogen quality certificate, to take regular samples of nitrogen during loading, and to analyse them and reject the nitrogen if the O₂ content exceeds 3%. If “off-spec” nitrogen is detected, the tanks must be purged and clean liquid nitrogen loaded at the next port call. The insulation spaces gas detection systems should be accurately calibrated prior to loading clean nitrogen.

When nitrogen is supplied by means of nitrogen generators, the capacity of each shipboard plant, with its twin generators, should be such that the system can provide all the nitrogen that would normally be required using only one generator. In cases where one of the generators begins to malfunction, e.g. producing gas with an O₂ content in excess of 3%, a three-way valve is automatically opened to the atmosphere and the plant switches to the back-up nitrogen generator. When such a breakdown does occur, ship operators should consider repairing the defective generator as soon as possible, and certainly no later than the next port of call. Spare parts for electric power, compressors, membranes, etc must be available onboard in order to ensure that the repair of a deficient generator can be rapidly undertaken.

7.7.6 Deficient primary membrane

7.7.6.1 High gas content in interbarrier space

The following diagram presents the different abnormal conditions which can be observed in case of a deficient primary membrane.



If there is a defect in the primary membrane, it can be considered to be one of three general types. The type of deficiency, and the scenarios to which they give rise, are described in the cases below.

Case 1

A sudden increase of the gas content inside the primary insulation space approaching 100%, with possible lifting of the relief valves. This characterises a large liquid leak through the primary membrane. Immediate emergency procedures must be applied as per the ship's operating manual.

Case 2

An increase of the gas content in the primary space which requires a gradual increase of the nitrogen flow-rate to keep the gas concentration below 30% by volume. Such a scenario characterises a defect in the membrane. This situation may be managed by the ship operators until the next scheduled refit if the gas content in the secondary insulation space remains below 1.5% by volume and the insulation temperature measurements do not change with regard to the established reference temperatures. Ship operators will need to pay special attention to all other relevant parameters. The sweeping valve may be opened, in order to lower the gas concentration, provided that the nitrogen flow-rate remains within half the total nitrogen production/supply capacity. If the gas concentration cannot be controlled, immediate repairs shall be initiated.

Case 3

An increase of the gas concentration in the primary space of a tank to below 30% by volume and then stability of the value at the reference nitrogen flowrate. This type of evolution characterises a small defect of the primary membrane. The same procedure as prescribed for Case 2 shall apply, except that sweeping is not necessary.

7.7.6.2 High gas content in secondary space

The gas content in the secondary space of membrane systems should not exceed 1.5% by volume. A gas concentration above this value would necessitate an immediate investigation and repairs, as agreed with the classification society.

7.7.7 Deviation of the insulation space temperatures

In case of a liquid leak in the primary space, temperature sensors located inside the insulation will deviate rapidly due to the changing of the temperature gradient across the insulation. and gas concentrations will also increase rapidly. This situation should be treated as an emergency as in Case 1

If the gas detection system shows no variation, there are two possible reasons why the insulation spaces could be showing a deviation in temperatures:

1. There is a malfunction of a temperature sensor; such a situation can easily be remedied by using the back-up temperature sensor in place.
2. There is water or ice present in the secondary insulation space due to a deficiency of the double hull. Such an abnormality would need special investigation and is outside the scope of this discussion.

CHAPTER 8

Monitoring and Recordkeeping

The purpose of keeping records of gas concentrations in the insulation spaces is to enable monitoring of the condition of the primary barrier over long periods such that trends and “health parameters” can be established and appropriate intervention planned and implemented. For this monitoring to be effective, it is essential that an efficient recording system is in place and used. Chapter 8 reviews the type of records needed and gives an insight into monitoring.

8.1 Gas concentration records

For the gas concentration records to be useful, certain primary information is required, i.e.

- Ship's name
- Date
- Voyage from/to
- Gas detection readings from each primary and secondary spaces
- Use of nitrogen purge or sweeping system

The following information may also be considered useful in the process of monitoring the condition of the primary barrier over long periods:

- Nitrogen supply pressure and quality
- Primary insulation space pressure
- Secondary insulation space pressure
- Atmospheric pressure
- Temperature readings from secondary spaces/inner hull
- Vapour header pressure
- Oxygen content at outlet
- Date of last calibration of the gas detection system and when next due

Within the format of the record, the following, whilst not relevant to the requirement to monitor the primary barrier, may be convenient to record:

- Cargo liquid temperatures
- Cargo volumes onboard at commencement and completion of loading and discharge operations
- Date last conducted and next due date for routine inspections and tests of safety equipment and systems associated with the cargo tanks.

8.1.1 Recommendations

The following measures should be considered when compiling gas concentration records:

- Clearly identify the units of any recorded measurements.
- Carry out the recording once per day, at the same time each day (to eliminate any diurnal effects).
- Use one sheet to cover a laden/ballast voyage cycle.
- Records may either be hard copy, handwritten or in the form of a computer spreadsheet.
- Use a manual recording process rather than an automatic system; this will ensure that somebody really looks at the figures on a daily basis.
- Use a common format, as far as is practicable, for a fleet of LNG ships.
- Include a blank space for 'Remarks' and encourage staff to use it.

8. 2 Monitoring primary barrier condition

Having established an efficient process of recording the essential data, it is important that a formal review process for monitoring the results of the recordkeeping and, hence, the condition of the primary barrier is undertaken on a regular basis. Such a process may be scheduled to coincide with routine visits to the ship by a superintendent, engineer or manager. Alternatively, it could coincide with a visit to the head office by senior staff members when going on leave. The exact format of the review may be flexible, the critical element is that it is undertaken regularly and rigorously.

Generally, the evolution of a leakage source takes place over many months, if not years. There may, however, be marked variability from voyage to voyage for reasons that may not always be clear. Any sudden, dramatic changes in gas concentration readings should, of course, be brought to the attention of the managers as soon as it occurs, rather than wait for a review meeting.

8.2.1 Interpretation of results

These comments are intended to give an overview on the interpretation of the results of gas concentration recordkeeping. It seems there are few, if any, hard and fast rules. In fact, personal experience and expertise are key elements when reviewing the results.

As noted above, there may be considerable variability in the results on a day-to-day basis and on a voyage-to-voyage basis. For this reason, when trying to assess trends, the full records going back five years or more should be reviewed. This is because the reasons for large degrees of variability may not always be clear. Large fluctuations may be a function of any or all of the following:

- Increased hull deflections due to bad weather
- Bad weather causing LNG to 'wet' parts of the tank membrane which are normally only contact with cargo vapour
- The relative locations of the nitrogen supply and spill connections, the sampling points for the gas detector and the leakage source.
- Atmospheric pressure and temperature changes

CHAPTER 9

Membrane Testing

9.1 Integrity testing

The integrity of LNGC membranes is assessed at the construction stage as well as during the lifetime of the ship. The tests that are carried out are of the non-destructive type, using either pressurised or evacuated methods of detecting defects. In this context the word 'defect' means a physical hole, crack, crevice, fissure or a passageway in the membrane that, contrary to what is intended, permits a fluid or a gas to flow through. If such a defect compromises either safety or the performance of an engineered system, it can have very serious implications.

Integrity testing of LNGC membranes is performed for three basic reasons:

1. To prevent material loss that interferes with the operation of the system.
2. To prevent fire, explosion and environmental contamination and similar incidents.
3. To detect unreliable components and other parts of the containment system which give rise to leaks exceeding acceptable limits.

The integrity testing of large vessels or systems is concerned with the determination of the rate at which a liquid or gas penetrates through their pressure boundaries.

The flow-rate through a boundary depends on:

- the geometry of the defect
- the nature of the fluids
- the prevailing conditions of fluid pressure, temperature and type of flow

In theory nothing can be considered to be absolutely tight and there are certain gases which permeate through metal, crystals, polymers and glasses. In practice the degree of tightness can only be established in comparison to a specification or standard. For practical purposes, a small defect is often defined as one having a low flow-rate, i.e. less than that which ensures water tightness, or about $10^{-5} \text{ Pa}\cdot\text{m}^3\cdot\text{sec}^{-1}$.

GTT has specified integrity tests to be carried out on membranes and has defined a maximum permissible flow rate through each of its membrane insulation systems.

9.2 Membrane containment systems - leak detection

The tightness of membrane containment systems is ensured by the use of approved material, good welding or adhesive bonding procedures and highly qualified workers. In addition, fabrication work involving membrane systems is carried out according to an appropriate and efficient quality control system, based on numerous tests and inspections conducted at all stages of the production sequence.

Testing of the secondary barrier of both Mark and NO membrane systems using vacuum decay techniques is a two-stage process; the first stage is drawing a vacuum on both the primary and secondary insulation systems simultaneously to test the integrity of the overall envelope and thus provide a reference for the second stage of the test, which is to draw a vacuum on the secondary insulation spaces to assess the porosity level of the secondary membrane only.

9.2.1 Leak detection for NO containment systems

The tightness or the permeability of the primary and secondary membranes for the NO-type containment system is checked during construction and prior to ship's delivery. Helium tests are carried out on each membrane, and any defect that is detected is repaired before a vacuum test is conducted on each membrane.

9.2.1.1 Helium test

For the NO containment system 100% of the welded joints (manual and automatic welds) on the primary and secondary barriers are checked using helium gas as a tracer, under the following conditions:

1. a differential pressure of 20 mbar is applied on the membrane;
2. a 20% concentration of helium by volume is used (the minimum acceptable is 10%);
3. the admissible flow rate is $9.3 \times 10^{-6} \text{ Pa.m}^3.\text{sec}^{-1}$;
and
4. a speed of 1 metre/min is used for the non-destructive test apparatus.

9.2.1.2 Vacuum decay test

The integrity of the membranes of the NO type containment system is deemed to be acceptable when the pressure decay recorded during the vacuum test is generally less than 3.5 mbar for the primary and secondary insulation spaces together and 2.6 mbar for the secondary insulation space alone, depending on the thickness of the insulation space immediately behind the membrane under test.

$$\Delta P \frac{0.8}{Insul_{thickness}}$$

where:-

*Insul*_{thickness} is expressed in metres, and ΔP is expressed in mbar

In fact all shipyards have achieved far better results than the above threshold. Experience has shown that newly built ships with NO containment systems do not exhibit gas concentrations in their primary barriers sufficiently high to be read by the gas detection apparatus installed onboard the ships.

For future reference, operators of membrane ships should consider establishing a "Vacuum Decay Test Signature" of the permissible porosities per tank after a number of voyages for each of their ships.

This signature will be the "target" to reproduce after repairs on primary membranes.

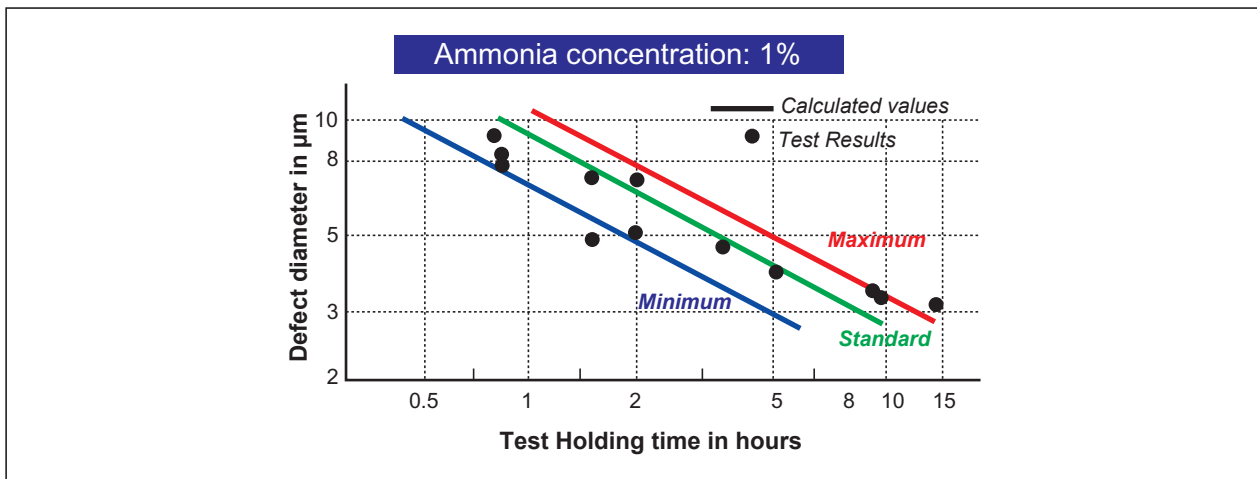
9.2.2 Leak Testing for Mark containment systems

9.2.2.1 Ammonia test

The tightness of the primary membranes of the Mark type containment system is checked by carrying out an ammonia test. For this test all the weld seams on the primary membrane are painted with a reactive yellow paint and ammonia is injected in the bottom of tank under test. The following concentration shall be observed 25% at the bottom and at least 1% at the top of the capacity under test.

If the paint in contact with ammonia turns purple or blue, all defects shall be repaired. The test is conducted during 20 hours (after all the reference leaks left on purpose in the tank have reacted).

Nippon Kaiji Kyokai (NKK) has conducted numerous tests and has established the curves shown below which relate the porosity size to the holding time of the tests.



Similarly and in view of the simplicity of conducting tests using a tracer gas, helium tests are performed to locate the possible defects on the corrugated membrane of existing vessels.

9.2.2.2 Secondary Barrier Testing for Mark Systems

The integrity of the Mark systems primary and secondary barriers is also by vacuum testing and follows the same general principles as described in 9.2.1.2 for NO systems, though the details of the tests are different.

Once all defects detected by ammonia testing have been repaired the primary membrane can be considered as perfectly tight; a Vacuum decay test is conducted during the whole time where scaffolding are dismantled from the tanks.

The secondary membrane of the Mark type containment systems requires a proof of tightness that is different to that for the secondary membrane of the NO type systems, since the former is designed to be liquid-tight but not gas-tight.

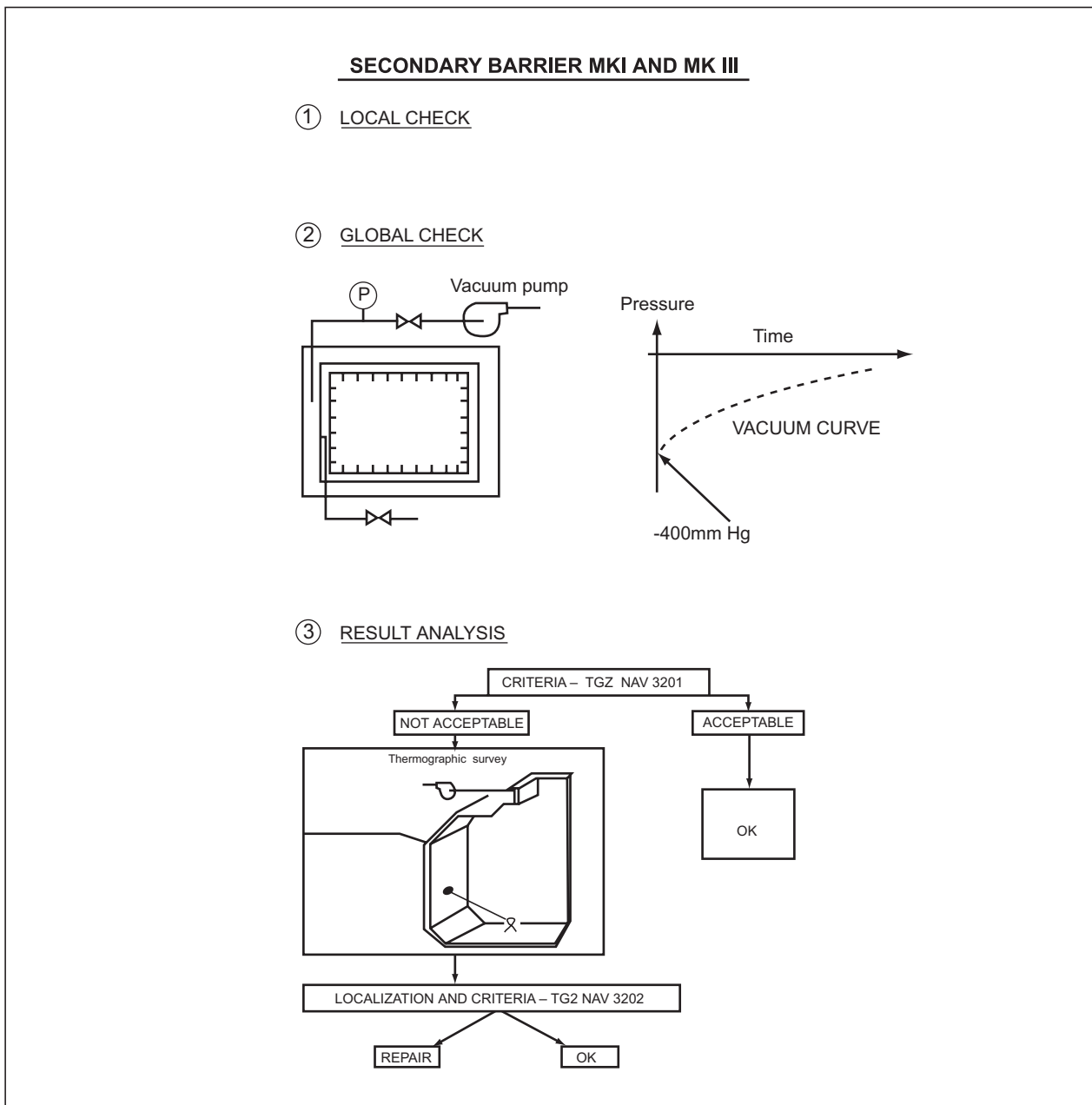
The test is performed by creating a differential pressure between the primary space and the secondary space and recording the behaviour over a certain period of time. The data obtained prior to ship's delivery are kept as reference and utilised for comparison purposes during the vessel's lifetime.

9.2.2.3 Acceptable porosity of the Mark secondary membrane

From actual experience onboard LNGCs and from laboratory testing, it has been demonstrated to the satisfaction of maritime administrations that a normalised porosity area (NPA) of 14.5 cm² per 5,000 m² of secondary membrane is an acceptable safe threshold, provided that this area is spread throughout the area of the containment system and there are no local failures of the secondary barrier.

A higher NPA is permitted for ships in service, in accordance with GTT procedures, to allow for gradually increasing porosity that may be experienced with increasing numbers of thermal cycles experienced by the tanks. As stated in 5.3.6.2 a more stringent value is applied to Mk III vessels.

For ships in operation the procedure shown below will be followed if, during the global checking of the secondary membrane, the NPA obtained does not fall within the reference locus, further investigations utilising a thermographic camera may be undertaken. Recently “multi-probe acoustic tests” have been conducted with some success. The test consists of installing ultrasonic probes in a pre-defined pattern on the inner hull, cofferdam bulkheads and primary membrane and then pulling a vacuum on the insulated space to be tested.



9.3 Conclusions

A global test of the secondary membrane is probably the best way to periodically check the condition of the secondary membrane.

The associated criteria are very conservative when the likely unsafe events, e.g. high temperatures on inner hull, are considered.

Global tests must be performed with all the necessary precautions at intervals of approximately five years and conducted in accordance with the methodologies described the latest versions of GTT's Ext Doc 182 and Ext Doc 1136. (ref bibliography B9 & B10)

Note: Some of the material used in this chapter is extracted from the American Society for Non-destructive Testing's "Non-destructive Testing Handbook". (ref bibliography B11)

CHAPTER 10

Vetting and Condition Assessment

Extending the use of older LNG carriers and the development of the LNGC spot trades as a supplement to the traditional long-term base-load projects, with dedicated ships on dedicated routes, have, inter alia, brought a greater involvement on the part of charterers in the implementation of risk assessments as the basis of the acceptability of a vessel. Vetting inspections are, therefore, now required as part of normal business practice more so than ever before. Further information is given on this subject in the SIGTTO publication “*Ship Vetting and its Application to LNG*” (ref bibliography B12).

Additional tools may be used where the proposed vessel use, and hence exposure, is for a longer period, as in the case of time charters, contracts of affreightment, consecutive voyage charters or simply for frequently used vessels/companies. In such cases, additional criteria may be applied before a vessel is accepted, and a more intensive inspection regime applied.

10.1 Vessel Inspection Questionnaires for LNG ships

SIGTTO promotes the use of the Oil Companies International Marine Forum (OCIMF) Ship Inspection Report (SIRE) inspection program for the inspection of LNG ships and that the OCIMF guidelines on the conduct of a SIRE inspection be followed.

For LNG ships, vetting inspections are generally carried out when the vessel is in service, during loading and discharging operations.

SIRE inspections utilise a document called “*Vessel Inspection Questionnaire*” (VIQ) and inspectors must use this document when undertaking an inspection.

Maintaining the tightness of the membrane containment system is imperative for the safety of operations. As such, the VIQ has been recently reviewed for LNG tankers in order to address the issue of void and interbarrier spaces more adequately.

According to Chapter 8 of the revised VIQ, the ship inspector should record whether:

1. The oxygen and hydrocarbon content of the interbarrier (primary) spaces is regularly monitored and the results recorded. He should also record whether a log of gas readings is maintained and specify whether the readings are expressed as % of the lower flammable limit (LFL) or % by volume. Records should be kept to demonstrate the levels and any apparent trends or changes in the level on the loaded and heel (ballast) passages.
2. The interbarrier (primary) space nitrogen purging system is in good order. He should review the records of nitrogen consumption and the running hours of the nitrogen generator to confirm the efficiency of the interbarrier (primary) space.
3. The pressure in the interbarrier (primary) spaces is being maintained at a sufficient level to prevent ingress from the atmosphere. The secondary barrier should be capable of being periodically checked for its effectiveness, by means of a pressure/vacuum test or another suitable method acceptable to the administration (as laid down in Section 4.7.7 of the IGC Code). The interbarrier (primary) spaces should be maintained at positive pressure and records of the pressure should be maintained.

The abovementioned trend records should be collected both on the loaded and heel (ballast) passages.

Due to the porosity of the primary membrane, it may be possible that a small amount of heavier hydrocarbons is found in the primary space.

Gas sensors are more sensitive to the C₂+ fractions. As a result, the readings of the global gas concentration, when they exist, will be slightly overestimated.

10.2 LNG carriers and CAP

Several classification societies have proposed a Condition Assessment Program (CAP) that has been developed specifically for LNG carriers. This LNGC CAP is a voluntary scheme, independent of classification society rule compliance, and is aimed at assigning a rating for defined areas. If the condition of the cargo containment system is adequately examined during the CAP some vetting departments could consider the use of CAP results in their vetting decisions.

CHAPTER 11

Training Requirements for Crew Responsible for the Operation of Membrane LNG Containment Systems

11.1 General requirements

General guidance on the training of crew for LNGCs can be found in the SIGTTO publication “*Crew Safety Standards and Training for Large Gas Carriers*” (ref bibliography B1) This publication highlights the statutory requirements for crew training under the provisions of the International Standards of Training and Watchkeeping Conventions (STCW) ref B13, as it applies to the crews of LNGCs. It does not, however, cover training for individual systems and equipment that may be found on a particular type of vessel.

Section 18.3 of the IGC Code requires:-

- Personnel involved in cargo operations should be adequately trained in handling procedures.
- All personnel should be adequately trained in the use of protective equipment provided on board and have basic training in the procedures appropriate to their duties, necessary under emergency conditions.
- Officers should be trained in emergency procedures to deal with conditions of leakage, spillage or fire involving the cargo and a sufficient number of them should be instructed and trained in essential first aid for the cargoes carried.

Furthermore, the ISM Code requires the shipowner, ship manager or bare boat charterer to structure a Safety Management System (SMS) meeting the requirements of the ISM Code. Part of the requirements of the SMS is the provision of cargo operations manuals and the identification of training needs for seafarers.

In November 2005 SIGTTO published operational competency training standards for all officer ranks on board LNG carriers. This standard is considered to be the industry recommended best practice minimum standard for the training of officers serving on LNG carriers (ref bibliography B2)

11.2 Operations manuals

To assist crew with operational responsibility for the cargo handling system it is essential that operations manuals are well produced by a company that specialises in technical writing and not just a conglomerate of manufacturer’s handbooks. These manuals should describe both routine and emergency operational procedures. Detail should be such that a person qualified, to serve in their particular rank, but not experienced on a particular type or class of vessel can, by following the manual, carry out his operational duties in a safe and efficient manner. Where necessary, in the light of experience, these should be supplemented with written procedures.

11.3 Membrane-specific training

It is strongly recommended that staff with direct responsibility for the operational aspects of the cargo containment system, i.e. the master, chief engineer, cargo engineer and chief officer, should attend one of the specialised training courses held by the membrane designers. This enables key personnel to gain experience in the design and construction of the cargo containment system that it is impossible to gain at sea, giving them detailed background knowledge to assist with the safe operation of the system. Computer-based training programs (CBT) are also available for onboard and shore training.

CHAPTER 12

Control of Emissions

12.1 Background

In response to concern about changes in the earth's climate as a result of human activities, the United Nations began a negotiating process in 1990 that resulted in the adoption of the UN Framework Convention on Climate Change (UNFCCC) in 1992. Since the adoption of the convention, the parties have continued to negotiate in order to agree on decisions that will advance the implementation of his framework. The third session of these negotiations resulted in the adoption of the Kyoto Protocol in December 1997. This protocol was finalised at Marrakech in 2001 and the next step is ratification at national level.

Most industrialised countries, i.e. the so-called 'Annex 1' countries, have agreed to reduce their greenhouse gas emissions by at least 5% on average relative to 1990 levels by the years 2008 to 2012.

It should be noted that mobile sources of emissions, i.e. aircraft and ships, are excluded from the Kyoto Protocol. However, to completely ignore the Protocol may be viewed as provocative and expose the industry to unilateral regulation. Therefore, the following comments are written as if the provisions of the Kyoto Protocol did apply to shipping.

12.2 Greenhouse gases

Trace gases in the atmosphere have a major impact on the effectiveness of the atmosphere to act as a 'blanket'. These gases are referred to as greenhouse gases (GHG) and they are essential to render the earth habitable. The main, naturally occurring GHG is water vapour. The next most significant is carbon dioxide (CO₂).

CO₂ has always occurred naturally in the atmosphere. However, human activities have resulted in the release of unprecedented levels of CO₂ to the atmosphere through the burning of fossil fuels. This additional CO₂ is currently considered to be responsible for 60% of the so-called 'enhanced' greenhouse effect.

It is as a result of these fossil fuel burning activities that CO₂ plays such an important part in the implementation of the Kyoto Protocol and, hence, the development of carbon accounting methodologies for use with emissions trading schemes. These methodologies put a value on the released CO₂. This is typically expressed as US\$/tonne of CO₂e, where the suffix 'e' denotes equivalent. The actual value per tonne will ultimately be determined by the market pressures resulting from the trading schemes.

12.3 Methane emissions

The Kyoto Protocol regulates a total of six GHGs. In addition to carbon dioxide, there are methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride. In this discussion on LNG ships, the only two of relevance are CO₂ and methane.

The main 'new' sources of methane emissions are agricultural, i.e. rice paddy fields and larger herds of cattle, but the natural gas industry is also a recognised contributor. Methane is a powerful greenhouse gas and, to enable it to be included in a carbon accounting system, 1 tonne of methane released to the atmosphere is deemed to be equivalent to 21 tonnes of CO₂. Should that 1 tonne

of methane be incinerated, then the contribution would be based on the CO₂ produced by the combustion and this equates to 2.75 tonnes CO₂e.

12.3.1 Methane releases from the operation of insulation spaces

The operation of the insulation spaces of membrane LNG ships typically results in a small leakage of LNG into the spaces. This natural gas subsequently gets released to atmosphere, either as a result of the normal breathing process or of purging. From the point of view of evaluating the emissions in a carbon accounting scheme, these emissions need to be quantified for each particular case.

Simplistic calculations lead to an order-of-magnitude type of figure of 10-100 tonnes per annum of LNG vapour being released from a membrane ship, the higher figure being the case for a ship with an identified problem. These figures may be compared with the consumption of fuel and gas for propulsion purposes. An older type of LNG vessel operating on natural gas boil-off plus heavy fuel oil (HFO) consumes approximately 15,500 tonnes/annum (tpa) of HFO and approximately 30,000 tpa of natural gas as fuel. Such a ship would emit about 130,000 tpa of CO₂. A modern equivalent vessel with a lower boil-off rate will consume about 21,000 tpa of HFO and 25,000 tpa of fuel gas and emit 135,000 tpa of CO₂.

For the assumed range of emissions from the insulation spaces, the CO₂e. covers a span of 210-2,100 tpa, if untreated. Assuming that the exhaust from the spaces can be incinerated, then this falls to 27.5-275 tpa.

From the foregoing, an assessment can be made on a case-by-case basis to assess the value of the emissions from the insulation spaces.

Theoretically, the value of the emissions could be reduced by arranging for incineration of the exhaust from the insulation spaces. However, at the time of writing, nobody has designed a system to do this and nobody has tried to assess such a design against the requirements of classification society rules and the IGC Code.

CHAPTER 13

Conclusions

13.1 Significant hazards

The two most significant hazards that were identified for analysis by the SIGTTO Working Group on Gas Concentrations in the Insulation Spaces of Membrane LNG Ships were fire or explosion in the insulation spaces and brittle fracture of the vessel's inner hull caused by contact with LNG that had permeated through the containment system.

The risk assessment carried out considered there to be an order of magnitude difference between the probabilities of occurrence of the two events. The former event is extremely unlikely and the possibility can be reduced further by additional instrumentation and attention to maintenance and condition monitoring. The latter event is difficult to quantify for a well-maintained vessel. However, it is considered to be in the same order of magnitude as other catastrophic events such as a serious collision or grounding resulting in loss of containment.

13.2 Maximum gas concentrations

Section 13.6.11 of the International Maritime Organization's IGC Code lays down requirements for the maximum permitted gas concentrations in way of the primary and secondary spaces, specifying a figure equivalent to 30% of the lower flammable limit, (LFL). However, there is an allowance for a variation on this figure, as follows:-

"Alarms should be activated when the vapour concentration reaches the equivalent of 30% lower flammable limit in air or other such limit as may be approved by the Administration in light of particular cargo containment arrangements."

Current practice by many classification societies is to use the terms of this clause in the Code and set the level at 30% by volume in the primary space of membrane containment systems. The detailed risk analysis undertaken as part of the research into producing this document shows that, given an oxygen concentration of less than 5% by volume and a gas concentration of 30% CH₄ by volume, there is no inherent risk of fire or explosion in these spaces. It is therefore suggested that this level is accepted as the arbitrary maximum limit.

13.3 Monitoring the condition of the cargo containment system

Data analysed as part of this study by the SIGTTO Working Group on Gas Concentrations in the Insulation Spaces of Membrane LNG Ships shows that gas concentrations in the interbarrier spaces may vary between loaded and ballast passages and may also be affected by the motion of the vessel in a seaway. It is therefore suggested that a formalised and efficient recording system should be in place and used in order to monitor the condition of the cargo containment system. Main parameters to be recorded include nitrogen consumption, oxygen content and gas content in each insulation space (secondary and primary spaces), local temperatures in insulation, loaded condition and weather conditions.

The purpose of keeping records of these main operating parameters is to enable monitoring of the condition of the insulation spaces over long periods such that trends can be detected and appropriate intervention planned and implemented.

13.4 Remedial measures

Gas concentrations in primary spaces should remain broadly the same for each voyage, after the operating parameters have stabilised. Any trend should be carefully monitored. If the gas

concentration cannot be controlled, even by increasing the nitrogen flow rate, the following action should be taken:

1. significant rate of change in gas concentration, e.g. leading to a doubling of gas levels between refits, should be investigated if the concentration exceeds 10% CH₄ by volume;
and
2. if the gas concentration alarm frequently exceeds 30% CH₄ by volume, the classification society should be informed in order to establish a plan of action.

It should be noted that experience has shown that leaks leading to relatively stable concentrations below 10% by volume are virtually impossible to locate.

A gas concentration in the secondary spaces is indicative of defects in both primary and secondary barriers and raises the possibility of liquid coming into contact with the inner hull. Therefore, this gas concentration value must always be less than 1.5% CH₄ by volume. Should this level be exceeded, the tank should be taken out of service at the earliest opportunity. Whenever an abnormally high gas concentration is present in the secondary spaces, it is imperative that particular attention is paid to the temperature in these spaces. The decision to take the tank out of service should be expedited should there be a significant drop in temperature.

In service a defect in the secondary membrane may only become apparent following leakage through the primary barrier. With the vessel out of commission a global test may be undertaken to prove the integrity of the secondary membrane. It is therefore strongly recommended that global tests be performed in accordance with Gaz Transport & Technigaz's test procedures given in their external documents, i.e. Ext Doc 182 Ext Doc 1093 or Ext Doc 1136, at intervals not exceeding five years.

The SIGTTO Working Group also found that confusion is often caused by the use of terms such as percentage gas by volume and percentage LFL. It is therefore suggested that when referring to gas concentrations in the insulation spaces of membrane LNGCs, the unit of percentage volume of methane, i.e. % CH₄ by volume, is used.

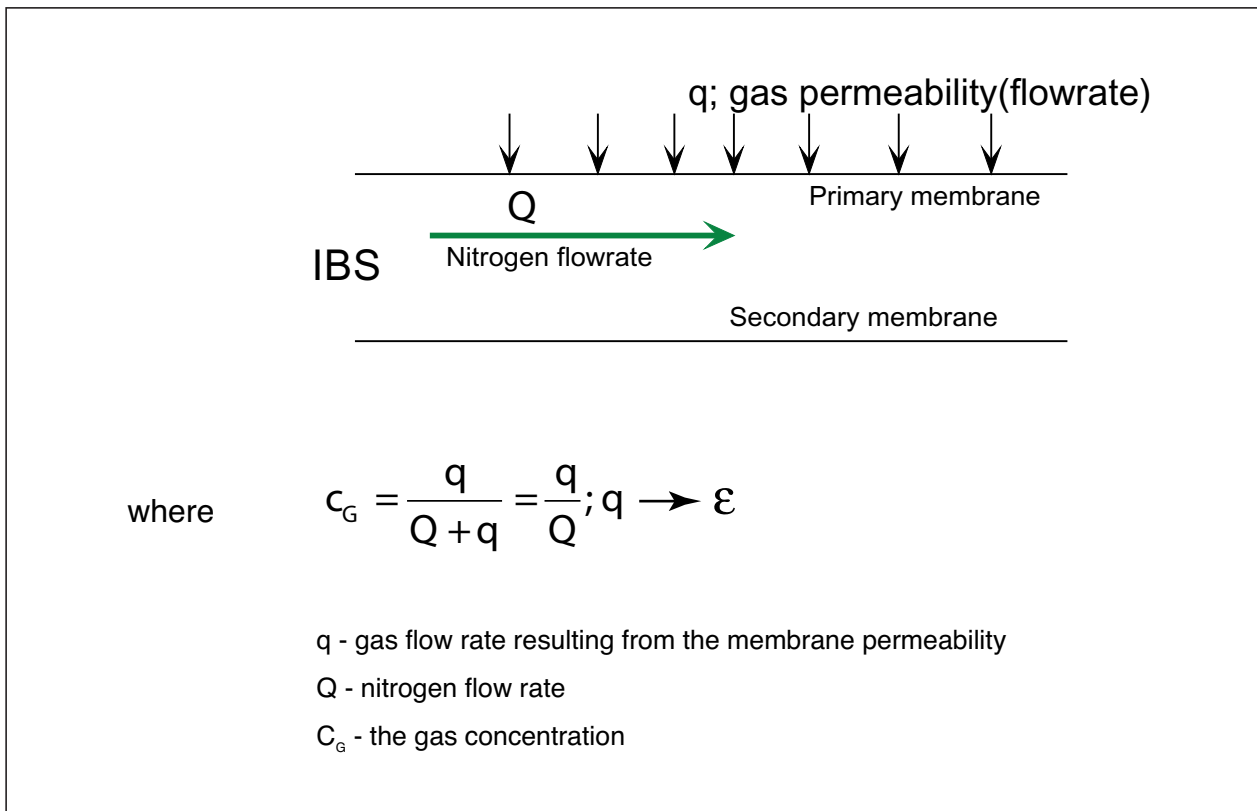
Appendix 1

Substantiation of Gas Concentration Criteria

1. Interbarrier space (IBS)

1.1 Historical background

The condition of the primary membrane is monitored by checking the gas concentration in the flow of nitrogen (N₂) sweeping the IBS. The permeability of the membrane, the N₂ flow rate and the gas concentration are linked.



Thus, the product Q x C_G determines the condition of the primary membrane. This remains theoretical and in reality is more complex. For the same average N₂ flow rate (see Appendix 4 section 3), the gas concentration shows important short-term fluctuations due to parameters such as atmospheric pressure and temperature. The average value for ballast voyages is not the same as that for laden voyages because the insulation is not at the same temperature. The initial gas concentration signature is usually established during the first 10 voyages. Such a number allows this dispersion of measurements to be taken into account.

When the first Mark I LNG carrier was built, the IGC Code was still under discussion at IMO and at the time a criterion was discussed with the US Coast Guard. The criterion is described in the USCG Letter of Compliance (LOC) issued on May 5, 1974 to the LNGC "Descartes". The enclosure to the LOC states that "for the interbarrier leak detector alarm setting at" either "30% by volume" or "30% LFL", and that the nitrogen flow rate has to be adapted accordingly.

- 30% of the LFL in air with a N₂ flow rate of 4m³/h,
- or
- 30% of gas by volume with a N₂ flow rate of 0.2m³/h

Technigaz selected the first criteria based upon 30% LFL for their mono- metallic corrugated membrane system, while Gaz Transport, designer of the NO type insulation, utilising two identical metallic membranes, preferred the second given alternative; that is to say 30% methane by volume

In 2001, some years after the merged of the two French companies, the resulting entity GTT (Gaztransport & Technigaz) approached the major Classification Societies to unify the gas concentration monitoring for a single level of concentration in the Interbarrier spaces(IFS) at 30% by volume, irrespective of the containment system considered.

The approval received was based on the same philosophy of nitrogen flowrate that has governed the Letter of Compliance issued for the “Descartes” in 1974.

From then on , the gas concentration criteria became 30% by volume for the Mark III system, but the nitrogen flow rate was reduced accordingly in order to maintain the sensitivity of gas detection.

In both cases, the product of Q x C_G. is the same value

To the best of the group’s knowledge it is only most recently that one Mark III type vessel has been delivered from its shipbuilding yard with its gas concentration alarm set at 30% by volume for its IFS.

1.2 The meaning of gas concentration in the interbarrier spaces

1.2.1 GTT NO membrane systems

In GTT NO membrane containment systems, the Invar primary and secondary membrane barriers are both manufactured using the same technology. Tests have been performed to assess the consequences of a pinhole leak in the Invar membrane and also to assess the acceptable criteria when checking the tightness of the primary membrane by vacuum test.

This criterion is

$$\Delta p \leq \frac{0.8}{e_p}$$

Where, Δp (mbar) is the vacuum decay of the primary space is in 10 hours and

e_p is the thickness of the interbarrier space (m).

For a given thickness of the primary insulation space of the NO 96 system (0.23 meter), the pressure decay must be less than 4 mbar, which can be achieved through a single circular hole of 0.6 mm diameter.

The safety margin is consistent and several events have been experienced with more serious defects and high levels of gas concentration but no significant change in temperature.

For example, in 1975 during the gas trials onboard one LNG carrier, after partial loading of one tank in less than 24 hours, the gas concentration went up to 57% by volume in the primary space with:

1. no variation of temperature sensors of the secondary membrane
2. no rise of pressure in the primary space

The cause was found to be a 7 mm long cut in one Invar strake. The origin of the damage was unknown but it was presumed that it had been caused by a sharp tool. Even with this type of defect, the liquid vaporises immediately and is eliminated by the nitrogen flow rate, without significant change of temperature or pressure, and even though the gas concentration may be very high.

Experience shows that when the gas concentration in the interbarrier space is less than 10% by volume, it is virtually impossible to locate the defect responsible.

Provided the ship operator is satisfied that the secondary barrier is tight, high gas concentrations in the primary space do not, in themselves, represent a hazard. The reason for wanting to be able to control the concentration is that it is essential to monitor the state of the primary membrane.

1.2.2 GTT Mark membrane systems

Calculations were performed in 2001 in order to determine temperature consequences of the maximum leak rate based on the gas concentration criteria at the beginning of this Appendix 1. The rationale is based on a typical 140,000 m³ LNG carrier with four cargo tanks and a daily boil-off rate (BOR) of 0.15%. It should be noted that the same order of magnitude will be obtained for NO membrane systems using this type of calculation.

This area has to be compared with the 1,200 m² area of the tank bottom of the reference ship. This shows that the criteria which governs the primary membrane tightness quality is a very conservative value and that doubling the accepted product $Q \times c_G$ would not significantly change this statement.

1.3 Gas concentration assessment and alarm set-point

Historical background shows clearly that the main concern in gas concentration assessments is the condition of the primary membrane and that the risk of a flammable mixture is considered as very unlikely. The product $Q \times c_G$ is a very simple theoretical statement and experience shows that the same ship could display fluctuations between voyages, depending on many parameters and environmental conditions.

Given that there is no rigorous scientific approach to setting the alarm limit, a practical approach based on experience would seem the most appropriate. A 100% by volume is obviously an impractical limit because a liquid leak could be dissimulated until temperature sensors start to show a significant drop. At the other extreme, setting the limit very low is undesirable because, if this results in frequent alarms, then the operator will tend to ignore the alarm state.

An alternative principle to use when there is no obvious limit is to work on the basis that the alarm setting should be abnormal before dangerous. It is clear from the discussion that the exact value of the gas concentration is not critical, as long as the general principles described above are maintained.

This is also true for the nitrogen flow-rate. The ship must be able to maintain this flow rate with a high confidence, according to the redundancy level of the ship's nitrogen production plants and/or storage tanks.

For the insulation or secondary spaces, two specific features have to be taken into consideration, i.e.

- failure of the integrity of the inner hull (cases have been experienced with potential ingress of water or air from the adjacent compartments)
- outlet of the pressure relief system on the deck.

Thus, it is suggested that the maximum gas concentration of these spaces be specified as 1.5% CH₄ by volume.

Appendix 2

Substantiation of Criteria for the In-Service Control of the Secondary Membrane

The primary function of the secondary membrane is to prevent a significant drop in the inner hull temperature should the primary spaces become flooded with LNG.

Testing the tightness of the secondary membrane using liquid is not possible. The only proven method of demonstrating the integrity of the secondary membrane is by a vacuum decay test. If there is a serious defect in the secondary membrane which could, in the event of failure of the primary membrane, lead to a liquid leak into the secondary insulation spaces, this defect will be detected by a vacuum decay test.

If there are numerous micro-porosities spread over the secondary membrane, gas can permeate from the primary space to the secondary space. However, liquid cargo will not pass through the membrane if these micro-porosities have very small dimensions. Thus, vacuum decay tests are more rigorous than liquid tests.

1. NO-type membrane containment systems

The underlying principles for the global test of the secondary membrane are as follows:

- the secondary space is evacuated to minus 525 mbarg (primary space at minus 50 mbarg)
- the vacuum decay in the secondary space and pressure drop in the primary space are recorded for at least 12 hours
- a vacuum decay of 2.6 mbar over the most stable 10-hour period is the maximum acceptable.

The objective of this global test is to check the tightness of the secondary membrane. Tests in laboratories have demonstrated that for NO membranes a leak through a pinhole of less than 1.3 mm diameter results in no significant change of steel temperature. This criterion is similar to the criteria for the primary space (see Appendix 1/Paragraph 1.2.1) and is the following:

$$\Delta P \leq \frac{0.8}{e_s}$$

where, “ e_s ” is the secondary insulation space thickness.

This criterion is conservative and the safety coefficient (referenced to the area of a pinhole) is greater than 4.

2. Mark-type membrane containment systems

2.1 Experimental data

Tests have been performed to determine the maximum diameter hole in the secondary membrane of a Mark I system which will pose no threat of liquid contacting the inner hull.

The results of these tests demonstrated that, provided the porosity is distributed over a surface of 5,000 m², the corresponding safe normalised porosity area (NPA) is more than 14.5 cm².

2.2 Mark I containment system

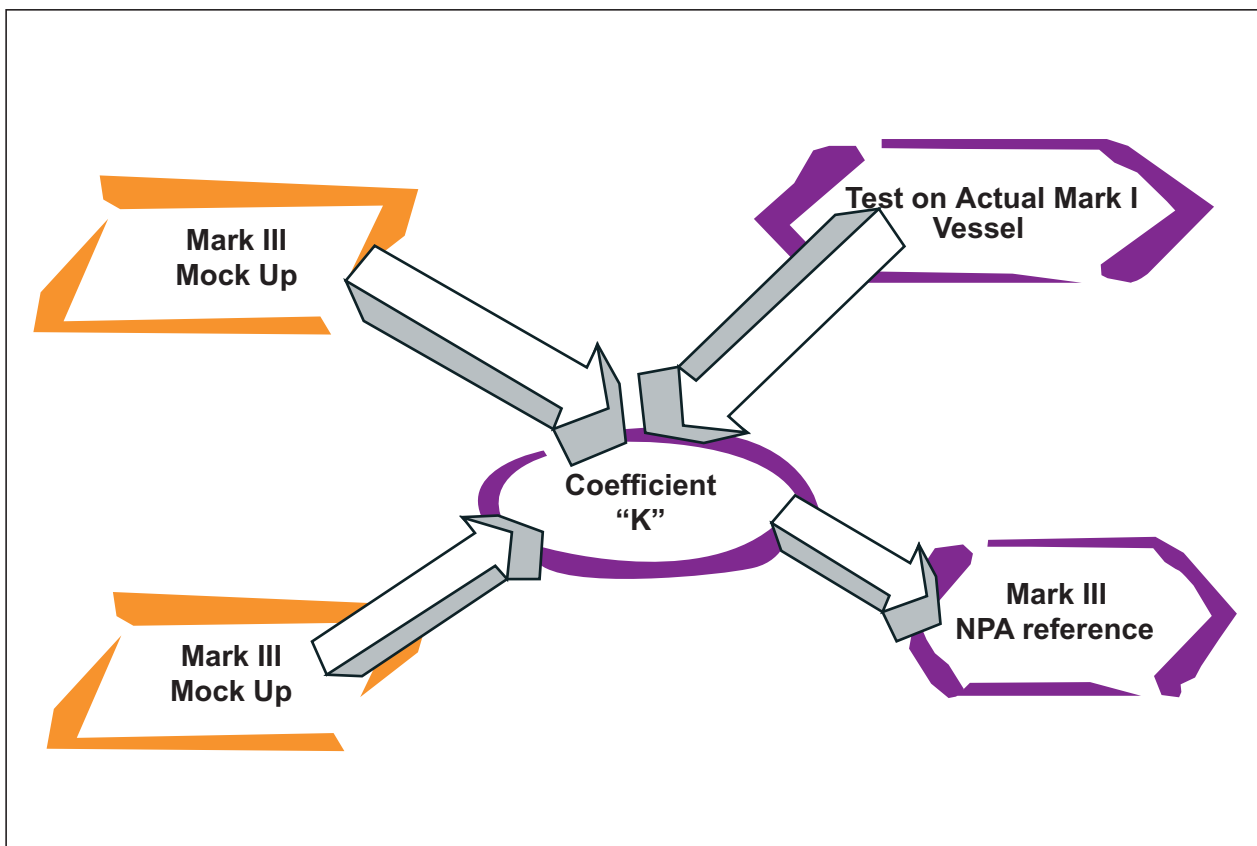
The primary objective of the test program was to build a NPA reference curve, taking into account what is reasonably achievable with good quality control on a newly built ship.

The first ship to be tested was “Descartes”, an LNG ship with a Mark I membrane, and tests led to a reference NPA of 0.509 cm². That means that the safety coefficient for the initial NPA was found to be greater than 27.

2.3 Mark III containment system

The secondary membrane of the MARK III system is made of Triplex and the porosity of Triplex is significantly lower than that of the secondary membrane material of the Mark I system. The following approach was used to assess the reference NPA prior to the construction of the first Mark III ship:

This gives a significantly lower NPA than for Mk I vessels.



Appendix 3

Risk Assessment for Gas Discharge-Induced Static Electricity (including carbon dioxide-blown polyurethane foams)

1. Gas discharges

Dry gases discharged at high velocity through an orifice, with neither liquid droplets nor solid particles present, rarely acquire sufficient static charge to result in the possibility of ignition. However, when the gases contain liquid droplets or solid particles, or when these are formed during the discharge, a charge sufficient to ignite flammable vapours can accumulate. This latter situation may be encountered when steam, wet compressed air and carbon dioxide are discharged through an orifice. It is for this reason that CO₂ should not be used to inert a space containing a flammable atmosphere.

If the gas discharging through an orifice is itself flammable, then clearly the hazards highlighted above are even greater. A particular example is liquefied petroleum gas (LPG), which readily produces charged droplets when released through an orifice. A static charge arising in this manner may well present a hazard.

2. Carbon dioxide (CO₂) in polyurethane foams

Subsequent to the manufacture of carbon dioxide-blown polyurethane foams, the composition of the gases entrapped in the material's closed cell structure will change as a function of time. The CO₂ will reduce, whilst that of N₂ and O₂ will rise at a rate determined by the rate of diffusion through the material. In general, in an uncontrolled atmospheric environment at ambient temperature, the exchange of gases will invariably lead to an internal gas composition equivalent to that of air, with a total CO₂ concentration of about 0.04%.

Considering the time necessary for the fabricating, transporting and installing of reinforced polyurethane foam panels onboard an LNG carrier and the cycles carried out during a tank's construction, it is most likely that this compositional quantity of CO₂ will prevail.

In service an LNG carrier's insulation system will operate within the temperature range of ambient temperature and -163°C. Furthermore, it will continually operate whilst under a continued nitrogen gas flow. This latter gas flow should augment the compositional percentage of nitrogen present in the foam panels while simultaneously reducing that of oxygen and carbon dioxide.

The solidification of CO₂ will occur between the temperatures of -100°C and -140°C.

Considering the thermal gradient of the insulation system and its continued "flushing" with nitrogen, should there be any CO₂ still present within the foam panels, it is most likely that it would be concentrated in small quantities in its solid form in the primary insulation layer.

The reheating of the cargo tank by the passage of warm inert gas is normal before an inspection. The time taken for such a heating cycle for a Mark III vessel is 42 hours. During such reheating any solid CO₂ present within the foam panels will vaporise and diffuse through the insulation panels, eventually departing from the foam's cellular structure.

3. Conclusion

Considering the low pressure gas rate used for the flushing of the polyurethane insulation panels and the low probability of the presence of airborne solid CO₂ particles during a gaseous discharge, there is little danger of a static charge sufficient to cause the ignition of possible flammable vapours.

Appendix 4

Probability Analysis - Tentative Approach

1. Likelihood ratings

1.1 General

The following classification for the probability of an event occurring, commonly adopted in nuclear industry, is used in this study:

Likelihood	Frequency	Comment
Highly unlikely	$F \leq 10^{-6}$	Such event should never happen
Unlikely	$10^{-4} \geq F \geq 10^{-6}$	Such event should not be encountered except if the studied set is very large (i.e. 10 000 equipments x years)
Rare	$10^{-2} \geq F \geq 10^{-4}$	Such event has been encountered once or several times
Common	$10^{-2} < F$	Such event has been encountered very often

Where, F is defined as the annual frequency of an undesirable event per ship (or ship's equipment)

f is defined as the hourly frequency $f \cong 10^{-4} \cdot F$

1.2 Application to membrane LNG carriers

The corresponding set for membrane LNG carriers is about 1,000 ships x years. It can be considered as a mean set for the probability analysis, and the confidence level when frequencies becomes much lower when $F < 10^{-3}$.

In the simplest qualitative form:

- A common event has been encountered many times. It is the case for gas leaks, without any serious consequence.
- Rare events have been encountered only a very few times, for instance:
- For ship groundings: the estimated frequency per ship and per year is $F \cong 10^{-3}$. Two events are documented, i.e. "El Paso Paul Kayser" and the "LNG Taurus", the latter being a spherical tank LNGC.

- For liquid leaks: seven events are known. The frequency can be assumed to be $F \cong 7.10^{-3}$ with a good confidence level. Actual liquid leaks can be caused by the following: cargo pump failure, cargo pump not properly secured after repairs, loose electrical cables leading to membrane failure, membrane failure, shipyard error, and weld defect for unknown reason.
- There have been no known cases whereby a gas leak in the primary barrier has subsequently developed to give 100% gas in the interbarrier space, which would be indicative of a liquid leak.

- An unlikely event should not be encountered, e.g. a collision at sea leading to very dangerous consequences.

- It is logical that a highly unlikely event has never happened.

2. Calculated and estimated frequencies

2.1 Calculated frequencies

The reference document is *“Risk and Dependability Analysis of Large Membrane Methane Tankers”* by S. Boucher and B. Dabouis of Bureau Veritas and F. Hannon and J. Pauthier of Gaz Transport and Technigaz, (ref bibliography B14)

EVENT	F	f
	General	
Grounding	$3.2. 10^{-3}$	
Collision at sea	$3.2. 10^{-3}$	
Cargo Containment & Cargo Handling System		
Damage to membrane	$1.8. 10^{-3}$	2.10^{-7}
Failure of a nitrogen generator		7.10^{-5}
Loss of electrical safety characteristics in hazardous areas	7.10^{-6}	8.10^{-10}
Failure of piping valve (individually)		from $4.5. 10^{-6}$ to $7.6. 10^{-6}$
Damage to secondary insulation caused by water ingress	$1.5. 10^{-7}$	

2.2 Complementary assumptions

The following assumptions are made:

- N₂ pressurisation system: a minor leak on the system is assumed as a common event. It has happened many times without any noticeable consequences except quantities of nitrogen (N₂) are

wasted. A catastrophic rupture of this network is assumed to be a rare event with $f \approx 10^{-8}$. It is an acceptable assumption for low pressure networks which are properly maintained. The test pressure is 10 bars while the service pressure is equal to or less than 500 mbar.

- The occurrence frequency of a failure of an oxygen (O₂) detector is assumed to be $f \approx 10^{-4}$, that is to say $F=1$. That means that one or several repairs per chain are predicted per year. It is a conservative assumption for instrumentation.

2.3 Discussions

Liquid leak

The measured occurrence frequency is $F \approx 7 \cdot 10^{-3}$, while, in 1994, the calculated frequency used by the authors of the Gastech paper was $F \approx 1.8 \cdot 10^{-3}$. Thus, the calculated frequency seems to be slightly optimistic, but it is also known that not all membrane damage leads to an actual liquid leak.

Loss of electrical safety characteristics in hazardous areas

This has been found by calculation to be a very low frequency event and close to a highly unlikely event. It should be emphasised that electrical safety is one of the main safety considerations for the insulation spaces. It must be also noted that it is also a common rule for other types of hazardous areas, e.g. pyrotechnic storage. This point is detailed in Chapter 5.5.

Water ingress into secondary spaces

Actual data leads to a measured occurrence frequency F higher than $2 \cdot 10^{-3}$. Several events of this kind have happened, two of them leading to the need for considerable repairs to the cargo containment system. There is a noticeable discrepancy between calculation and actual events, probably because the calculation assumed that the hull structure was properly maintained and that periodical global tests are performed in order to assess the tightness of the inner hull, as well as the secondary and the primary membranes. Tightness of inner hull and the secondary membrane are key issues for the safety of LNG carriers.

Control valve failure

An individual annual occurrence frequency F in a range of 10^{-2} to $5 \cdot 10^{-2}$ is to be expected for this type of equipment in most of industrial fields.

3. Calculation of the risk of fire or explosion in primary space

The basis is the fault tree as given in Chapter 5.4.2.

3.1 Frequencies of occurrence

- Total loss of nitrogen production (event A)

$$f < 5 \cdot 10^{-9}$$

This is a conservative value because the buffer tank capacity is neglected. This capacity allows time to repair many types of failures of the nitrogen plants.

- Total loss of control of the pressurisation (event B)

$$f < 2.5 \cdot 10^{-11}$$

This is a pessimistic assumption because the possibility of using the sweeping valve is not taken into account.

- No nitrogen flow rate in a tank (event C)

$$f < 1 \cdot 10^{-8}$$

It is determined only by the frequency of the event C, which is a conservative assumption.

- Air ingress in the insulation space (event D)

It is determined only by the frequency of the event C, which is a conservative assumption.

- Accidental pollution of nitrogen by oxygen (event E)

$$f \cong 7 \cdot 10^{-9}$$

- Risk of oxygen ingress into the insulation space (event F)

$$f < 2 \cdot 10^{-8}$$

It is determined by the frequencies of two events D or E which have almost equal individual frequencies.

- Risk of fire/explosion in the insulation space

$$f \cong 2 \cdot 10^{-8} \times 8 \cdot 10^{-10} = 1,6 \cdot 10^{-17}$$

$$\text{and } F < 1.4 \cdot 10^{-13}$$

or, considering five tanks per ship, $F \cong 10^{-12}$. This event is highly unlikely. Even if the risk “ignition source” has been underestimated by several tens, this conclusion is still valid as long as $F \cong 10^{-6}$.

3.2 Discussion

This simplified analysis does not take into account human error, carelessness, irresponsibility, intentional actions, terrorism or lack of maintenance.

The principal means of improving safety, if necessary, are:

- to monitor oxygen levels at the point of nitrogen production level to minimise the frequency of event F
- to install a nitrogen flow meter for each tank (prevention of event C)
- to operate the system properly and according to the designer documents
- to maintain the system properly

4. Calculation of the hull integrity risk

The calculations here are based on the fault tree shown in Chapter 5.8. It is very difficult to assess an occurrence frequency for the secondary barrier failure, but the worst situation is the case where the secondary barrier is presumed to be broken, either because the global test is not satisfactory or because it has not been performed. This is the situation of a creeping or dormant event.

When such a situation has been become established over a long period of time, the frequency of the undesirable event becomes the frequency of a liquid leak through the primary membrane, $F \cong 7.10^{-3}$.

Other potentially catastrophic events are:

1. Collision at sea: $F \cong 7.10^{-3}$, with only 3% of ship collisions leading to serious or catastrophic consequences. Thus, the occurrence frequency for the loss a ship due to collision at sea would be $F \cong 3.10^{-5}$.
2. Grounding: $F \cong 3.10^{-3}$ but all grounding events do not lead to catastrophic consequences, as is illustrated by the case of the LNGC “El Paso Paul Kayser” mentioned above.

Even if the primary membrane is in perfect condition, operating with an inefficient secondary barrier is obviously unsafe and unacceptable because the risk, which equals frequency times consequences, is too high.

5. Conclusions

This simplified approach to probability risk analysis confirms commonsense thinking.

Two events have been considered, i.e.

1. fire/explosion in the insulation space; and
2. LNG coming into contact with the inner hull.

The probability of these two events is not at the same scale. A fire or explosion in the insulation space is very unlikely and safety can be improved, if necessary, by additional instrumentation. As regards the likelihood of LNG coming into contact with the inner hull of the ship, it is difficult to quantify an occurrence frequency for a ship presumed to be in good condition. However, it is expected that the frequency has the same order of magnitude as that for other potentially catastrophic events, e.g severe collision at sea or grounding.

However, if it is thought that the secondary barrier is damaged, or if there is any doubt about its integrity, the occurrence frequency, F , becomes much closer to $F(10^{-2})$. This means that it is a common event capable of giving rise to dangerous consequences. As such, it is unacceptable.

Appendix 5

Care of Membrane Cargo Tanks During Refit

Introduction

Historically, considerably more damage has been done to membranes as a consequence of refit activities than have occurred during service. Therefore, to ensure a successful re-entry into service after refit work has been carried out and to guarantee a long life for the membrane system, various steps need to be taken before and during refit. The following outlines various procedures which experience has shown to be important. They encompass the time from the last discharge to completion of the first loading and apply to what may be described as routine refit, i.e. cargo tanks open for inspection but no membrane repair or replacement work planned.

Planning

From experience, a key essential for a successful refit is to ensure that all operations are carefully planned and conducted as per written procedures and that any repairs are treated to the same level of meticulous planning and execution. This latter part demands very close liaison between shipyard, ship's staff and the superintendent engineer responsible for the refit.

Clear lines of authority and responsibility must be established and actions for staff to take in event of deviation must also be explicitly described.

Period prior to refit

The scope of work for all items associated with the cargo system is to be reviewed and a member of the ship's staff appointed as responsible person for each item. This member of staff is to familiarise himself with the detail of the work to be done and to clearly understand any special precautions or procedures required. During the refit, he is to monitor progress and ensure agreed procedures are followed.

The following paragraphs relate to operations leading up to refit.

Last discharge

This is to be planned to include manipulation of the ballast in order to trim the ship and facilitate stripping of the cargo tanks. When trimming the vessel, the operator must take care not to exceed the maximum allowable trim permissible for the cargo tank pipe tower.

Warming-up

To be planned as per documented procedures. Care should be taken not to exceed maximum temperature or damage to soft sealing elements of valves and insulation can result. Pressure in the insulation spaces is to be carefully monitored. Membrane and insulation space temperatures are to be regularly monitored and accurate records maintained in the form of an operations log.

Inerting and gas-freeing

To be planned and executed as per written procedures. A key point to watch is that the inert gas plant product is as per specification, particularly in respect of carbon monoxide and dew point. IG plants which are slightly out of adjustment can produce sufficient carbon monoxide such that, after aeration and even though the oxygen content is 21%, there are still dangerously high levels of carbon monoxide remaining in the tanks.

Entry to refit

As soon as possible after entry into the refit area, the following is suggested:

- Fixed tank hatches to be removed and temporary weatherproof closures installed
- Establish small flow of dried air through all the cargo tanks (dry air supply by refit yard)
- Insulation spaces pressure control regime to be established (see note below)
- Cargo tank access procedures to be established (see below)

Insulation spaces pressure control

During refit, the ship services which support the insulation space pressure control systems are normally shut down. To preserve the integrity of the system, keep the insulation spaces (both primary and secondary) under vacuum (absolute pressure about 800 mb) throughout the refit. The barrier space relief valves are replaced with deadweight relief valves to protect against inadvertent overpressure. Continuous monitoring of the pressure is an assurance that the primary membrane is undamaged. Any sudden reduction of vacuum indicates a problem to be investigated.

Cargo tank access

In addition to any procedures for enclosed entry normally established, the following is good practice:

- Access to be restricted to authorised people
- Protective overshoes are to be put on immediately prior to tank entry and removed after exit
- Pockets are to be emptied of any loose items before entry. The only acceptable 'loose item' is a torch carried on a lanyard round the neck
- Safety helmets to have chin straps fitted

As soon as safe access is available, a preliminary inspection is conducted. This is to identify any unanticipated problem and to look for dust and debris in the tank bottom. Any items of debris should be tagged to identify which tank it was in and removed for inspection with a view to identifying source. Excessive dust may indicate a problem with the IG plant driers.

During refit

In the case of any mechanical work to be performed in the cargo tank, e.g. removal of a cargo pump for overhaul, a bottom protection system should be laid around the work site. The protection system consists of plywood sheets with offset pads. The offset pads are designed to ensure that the sheeting clears the weld seams (Gaz Transport (NO) membranes) or knots (Technigaz (Mark) membranes) and hence the loads are applied to the flat parts of the membrane only.

On a daily basis during refit, the atmosphere in each cargo tank should be checked (as all enclosed spaces should be) and the vacuum in the insulation spaces checked for unusual variation.

End of refit

After completion of any work in the cargo tank, all work tools are removed and the bottom protection system lifted and removed. The tank bottom should be subject to a final cleanup of any dust/debris accumulated during refit and then the tank subjected to a final inspection. The final inspection

should confirm that all in-tank fittings are in place and correctly secured. Checks should also confirm that no foreign material, tools, etc have been left in the cargo tank.

This final inspection should particularly look for any indentation damage on the bottom of the tank and after bulkhead in way of the pipetower. Any fresh indentation damage is to be inspected and its location recorded. The inspection should assess the damage against criteria established by GTT for repair. Should repair be deemed necessary, this should be planned and executed as soon as possible. For this reason, as far as is practical, work in cargo tanks should be completed as early as possible in the refit planning.

Once a tank has passed its final inspection, it should be closed up as quickly as possible.

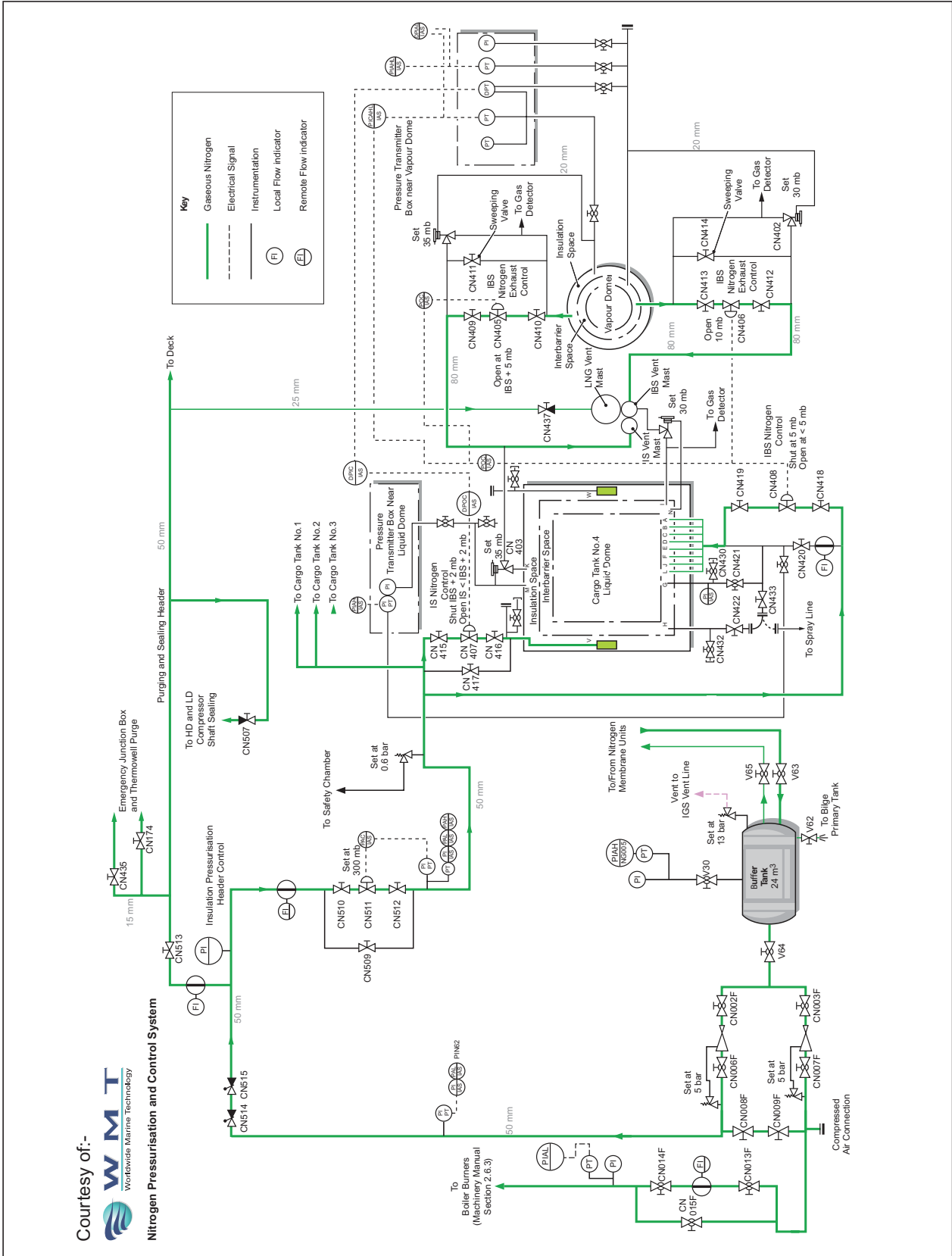
When all normal ship services are available, the nitrogen system for supplying and maintaining the insulation spaces can be re-commissioned. The vacuum in the spaces can be broken by feeding nitrogen. When the pressure is at ambient, the deadweight relief valves can be removed and the service valves refitted.

Post refit

The post refit operations - inerting, gassing-up, cooldown and first loading - are to be planned and conducted strictly according to written procedures. All systems are to be carefully monitored when brought back into service to check for normal functioning. Particular attention should be paid to the isolation of the IG system from the cargo system.

Appendix 7

Typical P & I diagram for a nitrogen distribution system



Definitions

Applicable to LNGC insulation space atmosphere control

Breathing

The tendency for cyclic nitrogen make-up and spill to occur during normal operations. This cyclic behaviour is caused by natural external effects such as diurnal temperature variation, effects of solar radiation (on the deck) and changes in atmospheric pressure. It is also influenced by the warming and cooling of cargo tanks due to successive ballast and loaded voyages.

Insulation Spaces

The insulation spaces comprise:-

- The primary insulation space or Interbarrier space (IBS) which refers to the space between the primary membrane in contact with the LNG and the secondary membrane or barrier.
- The secondary insulation space or insulation space (IS) refers to the space between the secondary membrane and the inner hull

NB: Terms; Interbarrier Space and Insulation Space generally refer to the original Technigaz designs.

Inerting

The introduction of an inert gas into the insulation spaces with the object of reducing the oxygen content to a level at which combustion cannot take place. This may be achieved by the successive pulling of a vacuum and the introduction of nitrogen.

Permeability

The rate of diffusion of a gas or liquid under a pressure gradient through a porous membrane. Not to be confused with the IGC Code definition, which defines permeability as the percentage of a given volume of a space that, for stability purposes, may be occupied by water.

Porosity

The amount of “void space” in a material, particularly welds, that will result in a given gas or liquid passageway.

Purging

Also known as gassing up. Purging is a general term used in gas shipping for the introduction of cargo vapour into a space with the object of displacing the existing tank atmosphere. It is not, in the context of this document, synonymous with nitrogen purging (see “Sweeping” below and also the *“Tanker Safety Guide – Liquefied Gas”* ICS (ref bibliography B15)).

Sweeping

Also known as nitrogen purging. The continuous flow of dry nitrogen through the insulation spaces to ensure that a flammable atmosphere never exists and also to provide the means for sampling the atmosphere for hydrocarbon gases.

Venting

The release of cargo vapour or inert gas from cargo tanks and associated systems. Thus, in the context of this document, venting is the release of the nitrogen and cargo vapour that is discharged as a result of sweeping (ref bibliography B15).

Bibliography

B1	“Crew Safety Standards and Training for Large Gas Carriers”	SIGTTO
B2	“LNG Shipping Suggested Competency Standards”	SIGTTO
B3	“International Code for the Construction and Equipment of ships Carrying Liquefied Gases in Bulk (IGC) Code”	IMO
B4	“The Safety of Life At Sea (SOLAS) Convention”	IMO
B5	(46 CFR 154) “Safety Standards for Self-Propelled Vessels Carrying Bulk Liquefied Gases”. US Government Printing Office	
B6	“The Limiting Oxygen Concentration required to Inert Jet Fuel vapours Existing at Reduced Fuel Tank Pressures” – Steven M. – Summer – 2003	
B7	“Protection des structures contre la foudre”	AFNOR
B8	“Fire Prevention in the Cargo Containment Systems of Liquefied Vessels Carrying Bulk”	SIGTTO
B9	Ext Doc 182	GTT
B10	Ext Doc 1136	GTT
B11	“Nondestructive Testing Handbook”. Am..Soc.for Nondestructive Testing’s	
B12	“Ship Vetting and its Application to LNG”	SIGTTO
B13	“International Standards of Training and Watchkeeping Conventions (STCW)”	IMO
B14	“Risk and Dependability Analysis of Large Membrane Methane Tankers” S. Boucher and B. Dabouis of Bureau Veritas and F. Hannon and J. Pauthier of Gaz Transport and Technigaz, Gastech 94	
B15	“Tanker Safety Guide – Liquefied Gas”	ICS