A
Project Report
on

"LNG VALUE CHAIN & DESIGN OF STORAGE FACILITIES"

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“LNG VALUE CHAIN
&
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A thesis submitted in partial fulfillment of the requirements for the Degree of
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CERTIFICATE

This is to certify that the work contained in this thesis titled **"LNG VALUE CHAIN & DESIGN OF STORAGE FACILITIES"** has been carried out by Ankit Bharadwaj under my supervision and guidance and has not been submitted elsewhere for a degree.

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ABSTRACT

LNG is a critical energy resource today and, with numerous new LNG ventures under development; its importance is set to increase. While the market is becoming more mature, LNG trading prices remain very dynamic, due to demand-supply volatility, geopolitical concerns, regulatory issues and public scrutiny. To better manage this uncertainty, the systems making up the entire LNG value chain (from production, liquefaction and shipping in specially designed vessels, to re-gasification at the destination terminal) have to be designed and operated in an optimal, safe and reliable fashion.

This complex business climate makes it imperative that companies investing in new LNG projects have confidence in both the technical and economic models required to support optimal decision making. This report will look at some of the best practices that enable better capital investment decisions based on rigorous model based analysis of LNG value chain. It will also cover aspects of storage design and stimulation to maximize operating performance, and to ensure safe and reliable operation of the LNG assets through the use of advanced process control technologies. Industry examples and case studies will be used to illustrate the recommended practices, which will include basic design calculations.

This project report focuses on:

(1) Study of LNG value chain,
(2) Designing and simulation on LNG storage facilities.

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ABBREVIATIONS USED

APCI: Air products and Chemicals Inc.
BS: British Standards.
CNG: Compressed Natural Gas.
DES: Delivered Ex-ship.
FOB: Free On Board.
FSRU: Floating Storage and Re-gasification Unit.
GBS: Gravity Based Structure.
GSA: Gas Sale Agreement.
IHI: Ishikwajama – Harima – Heavy Industries.
IMO: International Maritime Organization.
JCC: Japan Crude Cocktail.
LFL: Lower Flammability Limit.
LNG: Liquefied Natural Gas.
MCHX: Main Cryogenic Heat Exchanger.
MMTPA: Million Metric Tons per Annum.
MR: Mixed Refrigerant.
ORV: Open Rack Vaporizer.
SPA: Sales and Purchase Agreement.
SRT: Ship Board Re-gasification Terminal.
SS: Stainless Steel.
TCF: Trillion Cubic Feet.
TOP: Take or Pay.
USD: U.S. Dollar.

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CHAPTER 1.

AN INTRODUCTION TO NATURAL GAS & LNG

1.1 Raw Natural Gas Composition

The Natural Gas is a mixture of several components. The presence of these components differ from to source, the most of the components present are:

A. Organics Substances:-
i. Methane (CH_4) - (82-96) %
ii. Ethane (C_2H_6) - (4-10) %
iii. Propane (C_3H_8) - (2-6) %
iv. Butane ($C_4 H_{10}$) - (2-4) %
v. Pantene (C_5H_{12}) - (0-1) %
vi. Hexane (C_6H_{14}) - (0-1) %
vii. Higher Hydrocarbons - (0-1) %

B. Other Inorganic Substances:-
i. Nitrogen (N_2) - (0-25) %
ii. Carbon Dioxide (CO_2) - (0-5) %
iii. Sulphur Components - 4- 50ppm
iv. Helium - Traces
v. Mercury - Traces

1.2 Properties and uses of each component of natural gas

1.2.1 Organic Substances:

1.2.1.1 Methane: is a chemical compound with the molecular formula CH_4. It is the simplest alkane, and the principal component of natural gas. Burning one molecule of methane in the presence of oxygen releases one molecule of CO_2 (carbon dioxide) and two molecules of H_2O:

$CH_4 + 2O_2 = CO_2 + 2H_2O$

Methane's relative abundance and clean burning process makes it a very attractive fuel. However, because it is a gas (at normal temperature and pressure) and not a liquid or solid, methane is difficult to transport from the areas that produce it to the areas that consume it. Converting methane to derivatives that are more easily transported, such as methanol, is an active area of research. Certain micro-organisms can affect this selective oxidation using enzymes called methane monooxygenases.

Usage:

- Power Generation: Gas based power plants
- Fertilizer: Gas based Fertilizer Plants
- Feedstock: Fertilizer, GTL, Sponge Iron, Glass, Ceramics, Hydrogen
- Automotive: Trucks, Buses, Cars, LCVs, Rickshaws, Two wheelers
- Industrial Heating Furnaces, Ovens
- Domestic Applications: Cooking, Heating air conditioning.

1.2.1.2 Ethane: is a chemical compound with chemical formula C_2H_6. It is the only two-carbon alkane, that is, an aliphatic hydrocarbon. At standard temperature and pressure, ethane is a Colourless gas.
Ethane is isolated on an industrial scale from natural gas, and as a byproduct of petroleum refining. Its chief use is as petrochemical feedstock for ethylene production.

1.2.1.3 Propane: is a chemical compound with chemical formula C_3H_8 or more structurally, CH_3CH_2 CH_3. It is colorless and can be easily liquefied. Propane can be produced from natural gas, light crude oil, and oil refinery gases. It is available as standalone liquefied propane or as a major constituent of liquefied petroleum gas (LPG). It is an important raw material for the manufacture of ethylene and for the petrochemical industry. It is also used as a refrigerant, extractant, solvent, aerosol propellant, and fuel for portable cooking appliances, torches, and lighters.

Other uses:

- It is also used as a feedstock for the production of base petrochemicals in steam cracking.
- Propane is used in some flamethrowers, as the fuel, or as the pressurizing gas.
- Propane is also used as a feedstock for propyl alcohol, a common solvent.
- It is used as fuel in hot air balloons.
- It is used as propellant along with silicone oil (for lubrication) in air-soft guns. A paintball company has made a paintball gun using propane, as opposed to the usual CO2 or Nitrogen.
- It is used in some combustion based potato guns.
- It is used in semiconductor manufacture to deposit silicon carbide

1.2.1.4 Butane, also called n-butane, is the un-branched alkane with four carbon atoms, CH3 CH2 CH2CH3. Butane is also used as a collective term for n-butane together with its only other isomer, isobutene (also called methyl propane), $CH\ (CH_3)_3$.

Butanes are highly flammable, colorless, easily liquefied gases. The name butane was derived by back formation from the name of butyric acid.

Butane gas is sold in bottles as a fuel for cooking and camping. When blended with propane and other hydrocarbons, it is referred to commercially as LPG. It is also used as a petrol component, as a feedstock for the production of base petrochemicals in steam cracking, as fuel for cigarette lighters and as a propellant in aerosol sprays.

Very pure forms of butane, especially isobutene, can be used as refrigerants and have largely replaced the ozone layer depleting halomethanes, for instance in household refrigerators and freezers. The flammability of butane is not a major issue because the amount of butane in an appliance is not enough to cause a combustible mixture given the amount of air in a room. The system operating pressure for butane is lower than for the halomethanes, such as R-12, so direct conversion of R-12 systems to butane, such as in automotive air conditioning systems, will not function optimally.

1.2.2 Other Inorganic substances:

1.2.2.1 Nitrogen: is a chemical element which has the symbol N and atomic number 7. Elemental nitrogen is a colourless, odourless, tasteless and mostly inert diatomic gas at standard conditions, constituting 78.1% by volume of Earth's atmosphere. Nitrogen is a constituent element of all living tissues and amino acids. Many industrially important compounds, such as ammonia, nitric acid, and cyanides contain nitrogen.

Nitrogen gas has a wide variety of applications, including serving as an inert replacement for air where oxidation is undesirable;

- To preserve the freshness of packaged or bulk foods (by delaying rancidity and other forms of oxidative damage)
- In ordinary incandescent light bulbs as an inexpensive alternative to argon
- On top of liquid explosives for safety.
- The production of electronic parts such as transistors, diodes, and integrated circuits.

- Dried and pressurized, as a dielectric gas for high voltage equipment
- The manufacturing of stainless steel
- Use in military aircraft fuel systems to reduce fire hazard.
- Filling automotive and aircraft tyres. It is a preferred option due to its inertness and lack of moisture or oxidative qualities, as opposed to air, though this is not necessary for normal automobiles.

1.2.2.2 Carbon Dioxide: is a chemical compound, normally in a gaseous state, and is composed of the carbon and two oxygen atoms. It is often referred to by its formula CO2. It is present in the Earth's atmosphere at a concentration of approximately 0.038% and is an important greenhouse gas due to its ability to absorb many infrared wavelengths of sunlight and due to the length of time it stays in the atmosphere. It is also a major component of the carbon cycle. In its solid state, it is called dry ice. Carbon dioxide has no liquid state at normal atmospheric pressures.

Applications:

- Transporting items that need to remain cold or frozen, such as food, without needing any mechanical cooling source
- Blast cleaning
- Freezing parts to make removal easier.
- Keeping broken or powerless refrigerators and freezers cold.
- Loosening floor tiles by shrinking and cracking them
- Carbonating water and other liquids such as beer
- Repelling mosquitoes and other insects
- Creating low-sinking dense clouds of fog for dramatic effects by putting it in water and therefore accelerating sublimation.
- Freezing water in pipes with no valves or being repaired to stop leaking
- Making ice-cream
- Minor dent repairs - dry ice can help to remove dents, by forcing a car's sheet metal to contract.

1.2.2.3 Sulphur: It is an abundant, tasteless, multivalent non-metal. Sulphur, in its native form is a yellow crystalline solid. In nature, it can be found as the pure element or as sulfide and sulfate minerals. It is an essential element for life and is found in two amino acids, cysteine and methionine. Its commercial uses are primarily in fertilizers, but are also widely used in gunpowder, matches, insecticides and fungicides.

1.2.2.4 Helium (He): is a colourless, odourless, tasteless, non-toxic, nearly inert monatomic chemical element that heads the noble gas series in the periodic table and whose atomic number is 2. It's boiling and melting points are the lowest among the elements and it exists only as a gas except in extreme condition. Extreme conditions are also needed to create the small handful of helium compounds, which are all unstable at standard temperature and pressure. It has a second, rare, stable isotope which as helium II is important to researchers studying quantum mechanics (in particular the phenomenon of super fluidity) and to those looking at the effects that near absolute zero temperatures have no matter (such as superconductivity).

Helium is the second most abundant and second lightest element in the Universe and was one of the elements created in the Big Bang. In the modern Universe almost all new helium is created as a result of the nuclear fusion of hydrogen in stars.

It is extracted from the natural gas by a low temperature process. Helium is used for many purposes that require some of its unique properties, such as its low boiling point, low density, low solubility, high thermal conductivity, or inertness. Pressurized helium is commercially available in large quantities.

- Because it is lighter than air, airships and balloons are inflated with helium for lift. In airships, helium is preferred over hydrogen because it is not flammable and has 92.64% of the lifting power of the alternative hydrogen.
- At extremely low temperatures, liquid helium is used to cool certain metals to produce superconductivity.
- For its inertness and high thermal conductivity, helium is used as a coolant in some nuclear reactor.
- Helium is used as a shielding gas in arc welding processes on materials that are contaminated easily by air.
- Because it is inert, helium is used as a protective gas in growing silicon and germanium crystals
- In rocketry, helium is used as an ullage medium to displace fuel and oxidizers in storage tanks and to condense hydrogen and oxygen to make rocket fuel. It is also used to purge fuel and oxidizer from ground support equipment prior to launch and to pre-cool liquid hydrogen in space vehicles.
- Because it diffuses through solids at a rate three times that of air, helium is used to detect leaks in high-vacuum equipment and high-pressure containers.

1.3 Definition of LNG

When natural gas is cooled to a temperature of approximately -161°C at an atmospheric pressure, it condenses to Liquefied Natural Gas (LNG). Liquefaction reduces the volume by approximately 600 times, thus making it more economical to transport over long distance across the countries. LNG weighs less than one half of water, about 45% as much. LNG is odour less, colour less, non-corrosive and non-toxic. When vaporized, it burns only in concentrations of 5-15% when mixed with the air.

1.4 Composition of LNG

Natural gas is composed primarily of methane but may also contain ethane, propane and heavier hydrocarbons. Small quantities of nitrogen, oxygen, carbon dioxide, sulphur compounds and water may also be found in natural gas.

The liquefaction process for LNG requires natural gas free from impurities like Co2, sulphur compounds, water vapour, mercury etc.

1.5 Need for LNG

LNG has been the world's fastest growing energy option over the last two decades. Its market has quadruplicated in size since 1980. A total of 143 bcm of gas was carried by ship in 2001 which is 25% of world's gas export. The remaining 75% natural gas export has been by pipeline.

The world's proven reserves of natural gas are abundant and estimated to be more than 155.8 tcm equivalent to approximately 140 btoe. This quantity is almost three quarters of the world's proven oil reserves. The geographical distribution of natural gas reserves is very different from that of oil. Whereas more than three quarters of world's oil reserves are located in OPEC countries, equivalent figure for gas is only about 1/3rd.

1.6 The drivers for the use of LNG

1.6.1 Growing demand for fossil fuel.

1.6.2 Versatility of usage.

1.6.3 Environmental awareness-Natural gas being the cleanest fossil fuel, its application is getting global preference over other fossil fuels.

1.6.4 Security of supply-LNG contracts are normally of long term with commitment for high investment on either side of the LNG value chain i.e., liquefaction, transportation and re-gasification.

1.6.5 Pricing and delivery flexibility-LNG can be delivered at any of the re-gasification terminal. Pricing can also be flexible as per agreed formulae.

1.6.6 Safer than the nuclear energy- Worldwide perception is that nuclear energy contains enormous risk that is unacceptable to most of the industrialized nations.

1.6.7 Growth rate of energy consumption world wide-The World primary energy (comprising commercially traded fuels) consumption during the year 2005 was registered at 10537.1 MTOE with a growth rate of 2.7% over the previous year. Similarly during the year 2006, energy growth has been 2.4%.Same trend continued.

1.6.8 More finds of Hydro Carbons world wide-Considering the importance of Hydrocarbons, the reserve status has been measured and updated from time to time.

1.6.9 Serving large number of customers connected to the gas supply grid.

1.7 Retarders for the use of LNG

There are a few retarders in the LNG business which also need to be addressed to have proper understanding of the trade.

1.7.1 LNG purchases involve considerable front loaded investment and therefore willingness on the part of seller and buyers for long term commitment is essential.

1.7.2 LNG supplies are mostly as a supplemental source of energy supply. Many users have been using LNG for peak load requirement; consideration needs to be given for making LNG suitable for base load requirement.

1.7.3 Linking LNG pricing with crude oil price is not the real indicator of the energy price in either countries. The crude oil price is basically driven by the demand and supply position coupled with the geo-political considerations and as such it would not reflect the market sentiments.

1.7.4 The customers using LNG for their plants are vulnerable to supply disruption in tandem with the disruption in liquefaction, shipping, re-gasification and in-land transportation.

1.8 Gas Transportation Methods

1. Cross border pipelines
2. LNG
3. CNG by ship.

1.8.1 Cross border pipelines:

The cross border pipelines are a modified form of the intra-country gas grid i.e., the pipeline in this case connects one country to other country or may be more than one. Examples for such cross border pipelines are available in abundance. For example Russia- Europe Pipeline, Russia-Turkey Pipeline, Blue stream Pipeline, Kazakhstan-China (West-East) Pipeline, Algeria-Spain Pipeline, Iran-Turkey Pipeline. The pipeline projects under active consideration are GUSA Pipeline (Qatar-Saudi Arabia-Oman -Abu Dhabi)-1100 Kms, Sakhalin-

Japan Pipeline-300 Kms, Iran-Pakistan-India Pipeline-2100 Kms, Turkmenistan-Afghanistan-Pakistan-India Pipeline-1700 Kms, Myanmar-India Pipeline-1450 Kms, Azerbaijan-Greece Pipeline-2500 Kms, NABUCCO Pipeline 3000 kms. The pipeline connectivity necessarily keeps a long term commitment with least flexibility.

1.8.2 LNG mode of gas transportation :

LNG mode of gas transportation has gained importance specifically due to growing global gas demand coupled with flexibility available to the countries both supplier and buyers because of two major reasons – firstly, the supplier can have the best and most favourable market, secondly, the LNG supplies have flexibilities with respect to destinations.

1.8.3 CNG by ship mode of transportation:

The CNG by ship option is a developing concept where gas is cooled at about (-) 100°C and compressed to approx. 100 bar pressure and then transported through the ships.

The factors responsible for such high growth of LNG trade have been:

1. High natural gas demand in the developing countries on sustained basis
2. Monetization of stranded / isolated gas reserves through skid mounted modular LNG trains
3. Technological advancement reducing unit cost of LNG production.

1.9 LNG Safety

As a liquid, LNG can not explode or burn. If LNG is spilled, the resulting LNG vapour will warm up, become lighter than air and disperse with the prevailing wind/air. Although LNG is colorless, but as it is released into the air, the cold vapour would appear as a white cloud. The lighter-than-air property actually makes it less hazardous than some other fuels such as propane or butane whose vapours are heavier than air and tend to settle closer to the ground.

1.10 Transportation & Storage of LNG

LNG is transported from producing countries in specially designed double hulled tankers to prevent leakage or rupture. The double hull provides increased structural safety and the insulation allows the ships to act like thermos bottles to keep LNG cold. The LNG is stored in a special containment system within the inner hull at atmospheric pressure.
Large LNG tankers hold up to approximately 138,000 cubic meters (or more) of LNG in liquid form.
LNG is stored as a “boiling cryogen” that is, a very cold liquid at its boiling point for the pressure at which it is stored. It is kept in liquid form by auto-refrigeration, a process in which LNG is kept at its boiling point so that any heat additions are countered by the energy lost from LNG vapour that is vented out of storage and used to power the vessel. As long as the LNG vapour boil-off is allowed to leave the tank, the temperature will remain constant.

1.11 Process along LNG value chain

Normally, the minimum train size for an LNG liquefaction plant is from 5 MMTPA to 8 MMTPA. Further, for flexibility of meeting commitment of deliveries to various customers, there will normally be 2 LNG liquefaction trains. As the LNG Plants is cost extensive, the normal design calls for a 20-25 years plant life. These important aspects for LNG production and dispatches are to be kept in mind before steps to create various facilities along LNG value chain are considered. The elaborate description of each activity along value chain is addressed in detail in chapter 5. However, we are highlighting basic process along the value chain to broadly understand the LNG.

Various stages of LNG value chain consist of the following:

1.11.1 Exploration and production –

To find natural gas and start production of the gas for delivery to gas users. In the present case the LNG liquefaction plant. For a normal LNG plant as described above, the proven reserves of gas shall have be 4-8 TCF before LNG liquefaction project is initiated.

1.11.2 Gas processing and liquefaction –

1.11.2.1 Gas processing for LNG liquefaction.

1.11.2.2 LNG Liquefaction.

1.11.3 LNG Storage –

After production of LNG in liquefaction plant, the same is stored in 9% Ni tanks specially fabricated with proper insulation between inner shell of 9% Ni and outer shell of Carbon steel or 9% Ni depending on the design. The storage tanks are cylindrical vessel constructed either above or under ground with proper safety as per the available code in practice.

LNG Storage facilities are also required at the receiving terminal where regasification of LNG takes place in a subsequent plant.

1.11.4 LNG Shipping –

The LNG transportation is carried out in specially designed ship to take LNG from liquefaction plant to its destination at regasification location.

1.11.5 Re-gasification Terminal –

To convert the LNG stored in specially built storage tanks, from liquid phase to gaseous phase for further transportation through natural gas pipeline system or for captive use in associated & integrated facilities like power generation etc. the LNG is vapourised by taking away the cold of LNG either by sea water or by blowing air or by heating.

1.11.6 LNG send out facilities and pipeline to customers –

The vapourised LNG is measured before it is supplied to a system of pipeline connecting to various customers who have contracted LNG.

The innovation for transporting LNG directly in road tankers has also generated good market for LNG.

CHAPTER 2.

LNG VALUE CHAIN

A typical LNG value chain comprises facilities starting from upstream gas field to gas processing, gas liquefaction, LNG storage, LNG shipping and LNG regasification including regassed LNG sent out or captive use as the case may be. We therefore discuss these important components of LNG value chain as outlined below:

- Gas Field
- Gas Treatment Plant
- Gas Liquefaction Plant
- Gas Transportation
- Re-gasification Terminal
- Re-gasified LNG offshore Terminal
- LNG In-land Transportation by Road Tankers

2.1 Gas Producing Fields

2.1.1 General

For establishing any LNG production facility, it is essential that the proven reserves are available to cater to the requirement of LNG liquefaction plant on a sustainable long term basis. With the continuous advancement in technology, cost reduction due to economy of scale of the plant, a bare minimum size LNG plant would not be less than 5 MMTPA capacity.

2.1.2 On shore Vs Off shore gas production cost

Offshore feed gas production always cost more per unit of the volume produced than on shore feed gas. Further the most severe offshore conditions such as-shallow water, deep water, ultra deep water, extreme weather conditions may cost up to 7 times as much as compared to onshore facilities. The global experience shows that offshore feed gas cost typically varies from 1.6 to 2.5 times more than comparable on shore facilities.

2.1.3 Gas field production and processing facilities

Gas field production and processing facility comprise well performance testing equipment, gas and condensate dehydration, water treating, purification and disposal. A trade off is normally worked out between the location of acid gas removal plant, LPG separation plant, CO2 removal plant at the field gas producing complex or at the LNG liquefaction facility.

The traditional design dehydrates gas and condensate in the field. To protect the feed gas pipeline to the liquefaction plant from corrosion, the dehydrated sour gas is less harming since natural gas containing acid gas but without free water is mildly corrosive to the carbon steel pipeline. This is the least expensive alternative. If need be, a NACE grade pipeline can be used. This approach is fairly cost effective considering that the feed gas is going to an LNG liquefaction plant where a huge complex will be built up and all facilities required to make the feed gas suitable for liquefaction can be economically installed. If there is a good market for acid gas in the local area at field installation, gas sweetening can also be located near the field facilities.

2.2 Gas treatment plant

2.2.1 General

In the context of discussions on LNG value chain, the gas produced from the field is entirely dedicated to LNG liquefaction facility. The normal gas treatment activities such as dehydration, gas sweetening (removal of sour gas), CO2 removal, mercury removal (if necessary), higher hydrocarbon removal (the fractions which do not form part of LNG specifications in terms of contracted LNG volumes) have to be suitably located between the gas producing facilities and the LNG liquefaction plant. The economic consideration coupled with system safety, the following will be a desirable combination:

1) Dehydration - Location: near gas producing field.
2) Water treatment - Location: near gas producing field & disposal
3) Gas sweetening - Location: Preferably at liquefaction plant.
4) Co_2 removal - Location: Preferably at liquefaction plant.
5) Mercury etc. - Location: Preferably at liquefaction removal plant.
6) Higher hydrocarbon - Location: Preferably at liquefaction removal and plant condensate treatment.

2.2.2 Technology

All above processes are having proven technologies and they are available on competitive cost basis. None of these technologies are LNG specific. The specification for acquiring a technology should be framed based on the LNG contract (LNG-SPA) if already entered or a typical LNG composition. The important consideration is to be given to dehydration and CO_2 removal, which create problem due to ice formation during the successive cooling of the feed gas.

In certain cases when feed gas from the field indicates high percentage of nitrogen and other undesirable elements, the provision in the process is required to be made for removal of such elements to the desired level.

2.3 Gas liquefaction plant

2.3.1 Feed Gas Preparation Technology

LNG is produced by successive cooling till liquefying all components of the feed gas. The feed gas to LNG plant may be the non-associated gas (what is mostly the case) or a mixture of non-associated gas and associated gas (as is the case of LNG plants at Das Island, Libya and a plant in Nigeria).

All the components present in the feed gas have influence on liquefaction process. The solubility, liquefaction temperature and other characteristics influence the liquefaction process. For example Carbon di-oxide (CO2) freezes at -78.5°C and may form dry ice in the process thereby chocking the heat exchangers which are employed to cool the feed gas. CO2 contents more than 50 ppm are therefore not desirable in the feed gas. The raw feed gas having higher contents of CO2 shall have to be treated for CO2 removal to bring down the contents to 50 ppm level.

Water vapour is another undesirable element in raw feed gas which needs to be removed, such that the water due point remains around (-) 80°C. Like CO2 water vapour gets crystallized at much higher temperature than LNG final temperature. Solidified water crystals may create possible choking of the heat exchangers deployed in liquefaction process.

Total sulphur compound in excess of (30 ppm) and H2S alone beyond 5 ppm may create corrosive components especially when it comes in contact of water vapours in the feed gas.

Nitrogen and other inert gases, though normally do not create any harmful effect on the process or equipment but they do not contribute any heat value to LNG. Therefore, the energy spent in cooling such components and again in re-gasifying goes waste, thus rendering both liquefaction and re-gas process, less cost effective. A trade off is therefore required to be worked out as to what extent these elements be removed from the raw feed gas. Normally 1% (max) by mole would be enough to limit such elements.

Mercury, even present in traces can cause corrosion of Aluminium heat exchangers employed in liquefaction process, if it comes in contact with free water. Mercury removal below 10 nenogram/Sm^3 of gas is recommended to avoid corrosion.

Aromatics: These are the hydrocarbon cyclic compounds. Melting point of the lowest compound namely Benzene is 5.5°C and B.P of 80°C. Higher members of this family are having higher MP. The presence of Aromatics in LNG feed gas creates congealing of the heat exchanger due to solidification of the aromatic compounds. The permissible limit of aromatics is therefore very low to the extent of 2 ppm in LNG feed gas.
The raw feed gas, after removal of impurities to the level less than or equal to specified in table, is fed to an LNG liquefaction plant to produce LNG of the quality defined in the design and specified in the LNG contracts.

Normally the LNG specifications in the contracts have flexibility to accommodate the possible variation in feed gas composition but the impurities removal is the safety and process requirement. The undesirable elements or impurities can be removed by employing suitable gas treatment technologies.

2.3.2 Liquefaction Technology

Two types of LNG facilities have been developed: 1) large base load units for continuous LNG production to export markets, and 2) small peak shaving plants for gas distribution systems. The large scale based load units are typically designed with emphasis on process efficiency. In addition to the process units involved in the liquefaction step, base load LNG plants tend to be large complex facilities which involve product storage, loading and complete stand-alone utility systems. Peak shaving facilities differ from base load units in several aspects. Peak shaving plants are much smaller, operate only a portion of the year, and are often located near the point of use for the gas. The design emphasis is thus on capital cost minimization rather than thermodynamic efficiency.

In order to produce the low temperature necessary for liquefaction, mechanical refrigeration systems are utilized. Four types of liquefaction processes can be used to accomplish this refrigeration:

1. Cascade Refrigeration Process
2. Mixed Refrigerant Process
3. Pre-cooled Mixed Refrigerant Process
4. Nitrogen Expander Process

Each of these processes has been used for liquefaction facilities with the Pre-Cooled process being the predominant technology in base load units. The Cascade and Mixed Refrigerant processes have both been used in a wide range of process sizes in both base load and peak shaving units with the Mixed Refrigerant process being the dominant technology in peak shaving units.

2.3.2.1 Cascade Refrigeration

The first LNG liquefaction units utilized the cascade refrigeration process. These facilities use the classical cascade cycle where three refrigeration systems are employed: propane, ethylene and methane. Two or three levels of evaporating pressures are used for each of the refrigerants with multistage compressors. Thus the refrigerants are supplied at eight or nine discrete temperature levels. Using these refrigeration levels, heat is removed from the gas at successively lower temperatures. The low level heat removed by the methane cycle is transferred to the ethylene cycle, and the heat removed in the ethylene cycle is transferred to the propane cycle. Final rejection of the heat from the propane system is accomplished with either water or air cooling.

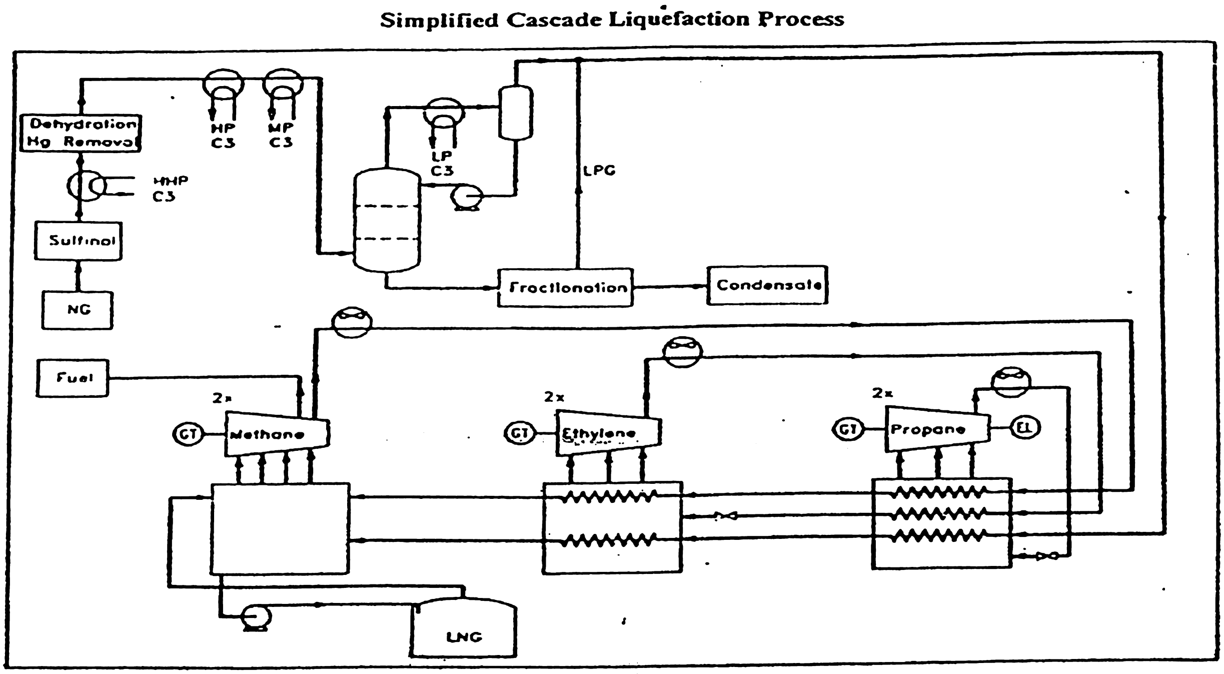


Figure 2.1: Simplified cascade refrigeration process block diagram.

Early facilities used a closed methane refrigeration loop. More modern designs use an open methane loop such as shown in Figure 2.1 where the methane used for refrigerant is combined with the feed gas and forms part of the LNG product. The efficiency and cost of the process is dependent on the number of refrigeration levels provided in each refrigeration system.

The refrigeration heat exchange units traditionally were based on shell and tube exchangers or aluminum plate fin ex- changers. Newer designs incorporate plate fin exchangers in a vessel known as "core-in-kettle" designs. A critical design element in these systems is the temperature approach which can be reached in the heat exchangers.

2.3.2.2 Mixed Refrigerant Processes

After initial developments of cascade LNG plants, the mixed refrigerant cycle was developed to simplify the refrigeration system. This system uses a single mixed refrigerant com- posed of nitrogen, methane, ethane, propane, butane and pentane. The refrigerant is designed so that the refrigerant boiling curve nearly matches the cooling curve of the gas being liquefied. The closeness of the match of these two curves is a direct measure of the efficiency of the process.

The process (Figure 2.2) has two major components: the refrigeration system and the main exchanger cold box. The cold box is a series of aluminum plate fin exchangers which provide very close temperature approaches between the respective process streams. The low pressure refrigerant is compressed and condensed against air or water in a closed system. The refrigerant is not totally condensed before being sent to the cold box. The high pressure vapor and liquid refrigerant streams are combined and condensed in the main exchanger.

The condensed stream is flashed across a J-T valve and this low pressure refrigerant provides the refrigeration for both the feed gas and the high pressure refrigerant.

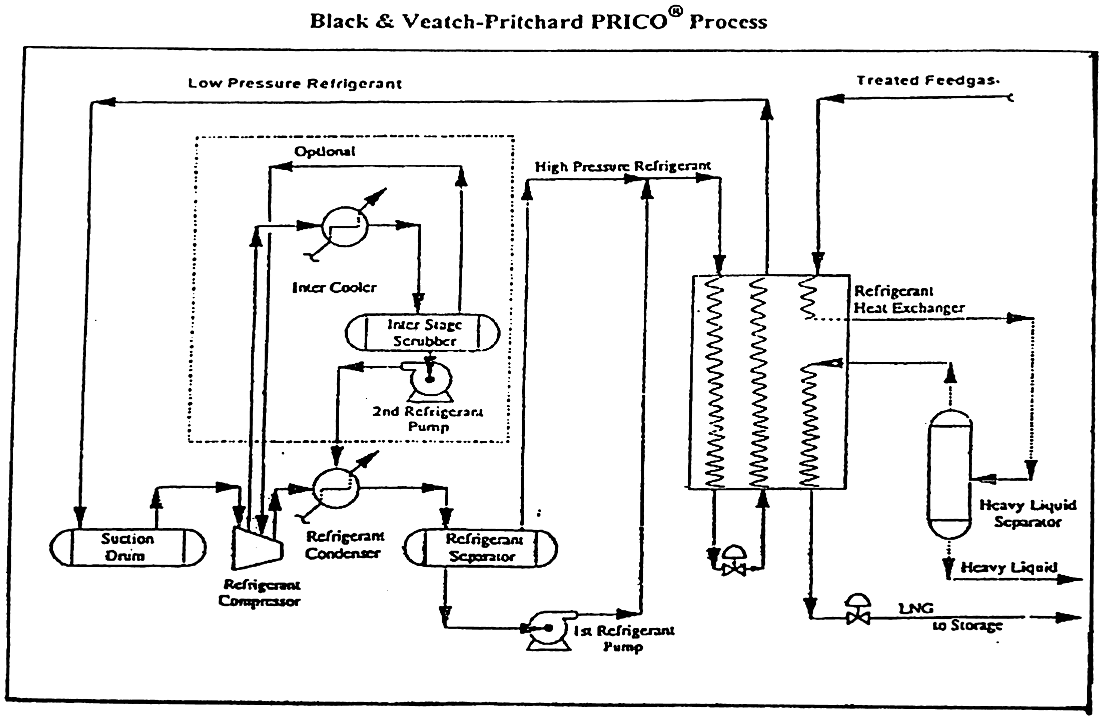


Figure 2.2: Black & Veatch-Pritchard PRICO Process $^{(TM)}$ diagram.

Removal of pentane and heavier hydrocarbons from the feed gas is accomplished by bringing the partially condensed gas out of the cold box and separating the liquid at an intermediate temperature. The liquid removed is then further processed to produce a specification $C5^{+}$ product. Light products from this separation are returned to the liquefaction system.

2.3.2.3 Pre-cooled Mixed Refrigerant Process

The propane pre-cooled mixed refrigerant process (Figure 2.3) was developed from a combination of the cascade and mixed refrigerant processes. In this process, the initial cooling of the feed gas is accomplished by using a multistage propane refrigeration system. The gas is cooled with this system to around –40°F at which point the gas is processed in a scrub column to remove the heavy hydrocarbons. The gas is then condensed in a two step mixed refrigerant process. The chilling of the gas is accomplished in a single, large, spiral-wound heat exchanger. This exchanger allows extremely close temperature approaches between the refrigerant and the gas to be achieved.

The mixed refrigerant in this process is a lighter mixture composed of nitrogen, methane, ethane and propane with a molecular weight around 25. The mixed refrigerant after re- compression is partially cooled with air or water and then further cooled in the propane refrigeration system. The partially condensed refrigerant from the propane chilling is separated and the high pressure vapor and liquid streams sent separately to the main exchanger. The liquid is flashed and provides the initial chilling of the gas. The high pressure vapor is condensed in the main exchanger and provides the low level, final liquefaction of the gas. As in the other processes, the LNG leaves the exchanger subcooled and is flashed for fuel recovery and pumped to storage.

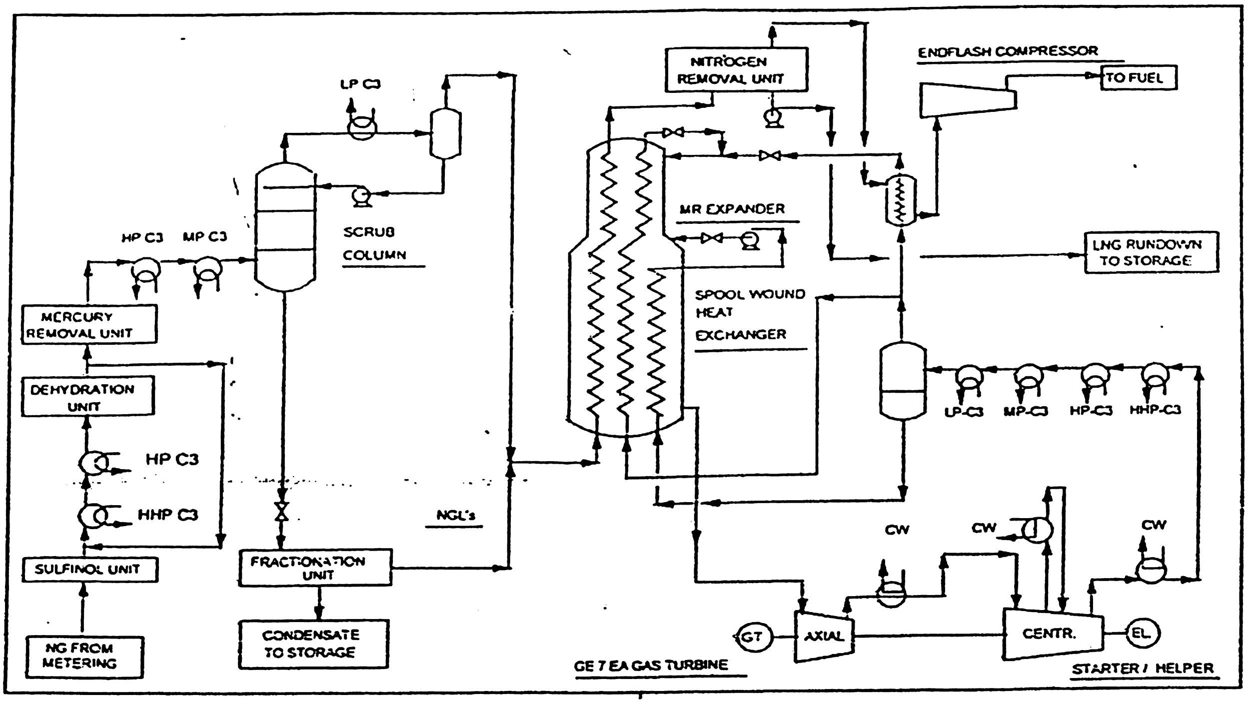

APCI Propane Pre-cooled, Mixed Refrigerant Process

Figure 2.3: APCI Propane Pre-cooled, mixed refrigerant process diagram.

2.3.2.4 Nitrogen Expander Process

Basically, in the expander-based process, a stream of gas at high pressure is expanded isentropically to a lower pressure. In this process work and refrigeration are extracted from the expansion process. This refrigeration is then used to aid the liquefaction process. The work extracted is then utilized to partially recompress the refrigerant gas.

A major benefit of using nitrogen as the cycle fluid is that it is inherently safe. Storage of hazardous hydrocarbons adjacent to or within the processing plant is avoided and there is no need for major hydrocarbon flaring if the refrigerant compressor trips.

The expander cycle (Figure 2.4) is simple and has fewer items of equipment than alternative refrigeration cycles. The nitrogen expander design is flexible to changes in feed gas conditions and requires minimal operator intervention. Expander cycles offer considerable advantages for offshore liquefaction and the use of two expanders avoids the need for pre-cooling by mechanical refrigeration with distinct benefits in terms of reliability, space and avoidance of refrigerant storage.

The double-nitrogen-expander cycle requires more power than more complex cycles but the simplicity of the process makes it cheaper and safer.

BHP Nitrogen Expander Process

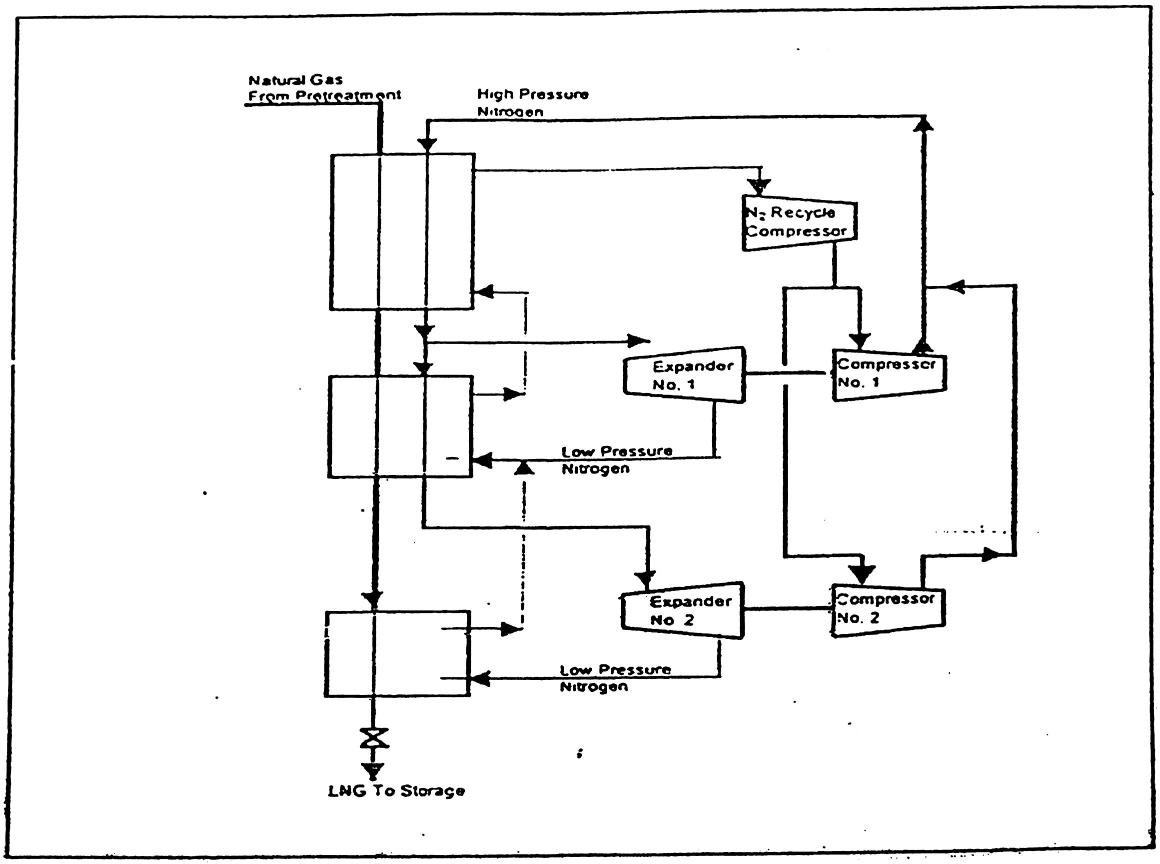


Figure 2.4: BHP Nitrogen expander process diagram.

2.4 Different technology Providers

Many process licensors have developed their proprietary technologies using some variation(s) or modification(s) in above primary processes of cooling. LNG liquefaction process licensors and technology in brief are placed below.

S. No.	Technology provider	Process used
01	Phillips Petroleum Corporation	.For optimized cascade process
02	Air Products & Chemicals Inc	For singles pressure, all mixed refrigerant process and propane pre-cooled, mixed refrigerant process.
03	The Pritchart Corporation (Black & Veatch)	Cascade process and single process, all mix refrigerant process.
04	Technip	Double pressure mixed refrigerant process.
05	Linde AG	Double mixed refrigerant process.
06	Technip / Snamprogetti	Double mixed refrigerant process
07	BHP or C-LNG (compact LNG)	Nitrogen expander cycle

Table 1.1: LNG liquefaction process licensors and technology.

Among all the above technologies, APCI, propane pre-cooled mixed refrigerant process is the dominant liquefaction process in use today.

The Technip / Snamprogetti double mixed refrigerant process, also known as Tealarc process has not picked up. It was originally selected for a Nitrogen expansion based LNG project, but subsequently replaced by APCI, propane pre-cooled mixed refrigerant process. Technip / Snamprogretti are no more pursuing this technology. The BHP process, also known as C-LNG (compact LNG) is a recent development aimed at off-shore application.

Since the end use of these technologies is production of LNG from the feed gas, all commercially available liquefaction processes therefore operate over the same temperature range i.e., from ambient to -163°C. The treatment of the feed gas is also same for all the processes. The four important commercially developed technologies are described below.

2.4.1 APCI Technology

The treated feed gas enters the main pre-cooling section of the liquefaction train where the remaining hydrocarbons are removed in a scrubber column which also provides sufficient LPG for refrigerant make up in addition to direct merchant sale. The fractionation column separates the ethane, propane, butane, pentane etc. In addition, the refrigerant (ethane and propane make up) is recovered as a separate sub-product. Each fractionation train has a de-ethanizer, de-propanizer and de-butanizer column.

The pre-cooling refrigeration is provided by multi-stage propane refrigeration system operating at minimum temperature of -37°C. The propane refrigeration is also used to partially condense the multi component refrigerant system and various cooling duties in the fractionating trains. Propane vapours from various stages of refrigeration are compressed in a multi stage centrifugal compressor. The compressor discharge is de-super heated and condensed using either sea water or air cooling. The condensed refrigerant is then expanded to various pressures and temperature levels of refrigeration. The scrubber tower overhead enriched in the C1 + fraction is liquefied and sub-cooled in a heat exchanger with a circulated multi component refrigerant system consisting of nitrogen, methane, ethane and propane.

Advantages of APCI LNG process

1. Distribution of cooling load between propane and a mixed refrigerant circuits result in less power requirement which fit proven compressor technology even for large train size.
2. Use of propane as refrigerant stabilizes front end of the process facilitating start-up and feed gas de-hydration.
3. Heat exchanger in propane circuit can be conventional shell tube type.
4. This design has high thermo dynamic efficiency.
5. API-P-MR process is the most widely used base load liquefaction process operating since last 30 years in more than one dozen plants of the existing LNG installations. The plants have been successfully operating with no major problems. Most of the plants have exceeded the design capacity.

Areas of Concern:

1. Requirement for high purity propane for refrigerant circuit both for initial quantity and make-up.
2. Cold temperature of the process may reach warm end of the plant temperature on shut down.
3. Proprietary source for the main cryogenic heat exchanger which constitutes a major cost of the plant.
4. Limited flexibility of shifting refrigeration load between propane and mixed refrigerant circuits.

2.4.2 Optimized Cascade Process – Phillips

In this process, LNG is produced by cascade refrigeration system using propane, ethylene and methane as refrigerants. The propane and ethylene are used in closed loop refrigerant systems circulated as a single component refrigerant. The methane refrigeration circuit is an open loop system with flushing of feed gas to successfully low pressure and re-compression and re-circulation of the flush and vapour. The process flow diagram is shown below with the simplification with methane circuit shown as closed loop.

Major advantages of the Cascade Process:

1. Simplicity of the operation and control because of the use of power and single component refrigerant system.
2. High thermo dynamic efficiency resulting in low horse power requirement for compressor and low fuel consumption.
3. Low requirement of refrigerant blending facilities.
4. Process configuration is simple and permits the use of proven and low cost Aluminium plate – fin type heat exchanger.
5. Ease of start-up through easily controlled refrigeration circuits with wide range of operating flexibilities.

Areas of concern:

1. Due to agreement between the licensor-Phillips and the sole EPC contractor, Bectel, leads to a situation of low competition resulting in high capex.
2. Equipments and piping complexities exist to achieve high thermo dynamic efficiency.
3. Plant cost is also high due to large number of equipments and associated piping.
4. The power required for three refrigerated systems namely propane, ethylene and methane being different leads to application of the different ratings of compressors and drivers resulting in increase of maintenance requirement.
5. The ethylene required for refrigeration is a superior quality which cannot be produced in a simple fractionation process and normally results in procurement more often on proprietary basis.

Operating experience:

'The Kenai, Alaska plant uses this technology since 1969. Another LNG project in Trinidad (Atlantic LNG) is also being operated on this technology since 1999.

2.4.3 Pritchart (Black &Veatch) Refrigerant Process

This process was originally developed by Pritchart Corporation, now known as Black & Veatch Pritchart. This is an all mixed refrigerant process operating at a single return gas pressure. The mixed refrigerant is made up of nitrogen and a range of hydrocarbons from methane to hexane. The original prico process concept utilizes a single casing axial compressor in the mixed refrigerant loop. This limits the compressor discharge pressure to about 17 bar. The modified design uses the mixed refrigerant circuit above this pressure by employing a second stage compressor which increases the thermo dynamic efficiency and also decreases the heat exchanger requirement.

Advantages of the process:

1. Simple process in absence of any intermediate refrigerant separators.
2. The important process requirement and gas liquefaction and refrigeration can be accomplished in a conventional Aluminium plate-fin heat exchanger. There is no proprietary item which leads to capex reduction.
3. The process can take wide variations in feed gas compression.
4. Ease of start-up operations.
5. Successive improvements in the process has led to higher LNG production that operate a unit of installed refrigeration power and also led to reduced heat transfer requirement.

Areas of Concern:

1. Process simplicity has led to higher power consumption.
2. Single compressor refrigeration system limits the capacity of the single operating train.
3. Due to limitations in available size, multiple plate-fin exchangers, cores are required with large amount of manifolding and associated piping.
4. Higher utility operation cost due to high power consumption in the process.

Operating experience:
Sonatrach's 4th train at Skikda Algeria employed this technology in 1971. Thereafter, for the 5th and 6th trains also, the same technology was selected. Initially there were some design and construction problems, experienced in 4th train, which were subsequently modified in 5th and 6th trains. The revised heat exchanger design which was installed in 5th and 6th trains has yielded a production figure of 110-115% of the design capacity.

2.4.4 BHP's Expander Process

This process utilizes the thermo dynamic principle that the near isentropic expansion of fluid extracts work and in equivalent amount of heat from a closed system. Expander cycles for production of LNG have been successfully employed in a much smaller LNG peak saving type plants. The expansion cycle fluid either natural gas in an open cycle or nitrogen in a closed loop system is compressed cooled and expanded to near atmospheric pressure. The cold low pressure expansion gas cools and liquefies the high pressure feed gas. The BHP process achieves improved thermo dynamic efficiency by use of a second "cold" expander to provide the lowest level of refrigeration in place of the Jule Thompson valve used in single stage process.

Advantages of the Process:

1. These types of plants have compact design and the use of nitrogen and inert gas as refrigerant fluid has much desirable applications for the off-shore liquefaction plants.

Disadvantages of the Process:

1. Application of more rotary equipments which could contribute for more plant shutdowns as compared to refrigeration cycle.
2. The turbo expander operates at a very high speed in the range of 10000 to 50000rpm. Therefore, maintenance requirements are high.
3. The expander process requires high circulation rates with accompanying large turbo expanders and compression equipment having lower thermodynamic efficiency.

2.4.5 Combined Mixed Refrigerant/Expander Process-Chiyoda

Chiyoda Corporation has recently patented a combined all mixed refrigerant expander LNG process. All heat transfer is accomplished in Aluminium plate-fin heat exchangers. High pressure LNG leaves the MCHX at a relatively warm temperature compared to the pre-cooled mixed refrigerant processes. The high pressure LNG is reduced in pressure through to stages of liquid expansion. The first stage uses an axial type turbo expander followed by a second stage re-compression type hydraulic turbine. The large amount of flash gas produced on pressure let down is re-heated and re-compressed to incoming feed gas pressure using power generated by the turbo expanders. Over 65 Aluminium plate-fin cores are required to produce approximately 2.2 MMTPA of LNG.

2.4.6 Integral Incorporated Cascade (CII)-Gaz de France

Gaz de France recently announced development of a variation of the all mixed refrigerant process with a reported efficiency equivalent to that of dual refrigerant process. Improved efficiency and reduced equipment requirement, leading to reduced capital investment, compared to existing processes is reportedly obtained by fractionating the mixed refrigerant into light and heavy fractions which are then used to cool and liquefy the feed gas in a cascade type arrangement. Pre-cooling and liquefaction is accomplished in dual Aluminium plate-fin heat exchangers placed end to end. Compression is accomplished in a first stage axial compressor followed by a second stage centrifugal compression for additional light refrigerant compression.

Design status indicate that 4 cold tanks each containing these dual cores (48 total cores) are required to produce 2 to 2.5 MMTPA.

2.5 Comparison of the thermodynamic efficiency of various LNG production (Process) cycle

A single major parameter which could be considered as indicator of the efficient LNG production process is the power consumption per tonne of LNG produced. The comparison of the 4 most used processes is given below.
APCI process is the most efficient having edge over the next best technology i.e., Prico by 10-15 percent and a further addition of about 10 percent over the Phillips cascade process.

CRITERIA	CASCADE	MRC	EXPANDER
Uses proven technology	Yes	Yes	Yes
Overall space requirement	High*	Moderate*	Low
Refrigerant storage hazard	Yes	Yes	No
Sensitivity to vessel motion	Moderate	Moderate	Low
Simplicity of operation	Moderate	Moderate	High
Ease of start-up/shutdown	Moderate	Low	High
Flexibility to feed gas changes	High	Moderate	High
Efficiency	High	High	Low
Total Capital Cost	High	Moderate	Low

* Due to requirement for hydrocarbon refrigerant storage

Table 2.2: Key selection criteria of LNG process cycle.

2.6 Selection of appropriate technology

This should be based on the overall economy to the investors taking into account Capax; OPEX and technology cost including thermal efficiency. For evaluation a life span of 25 years for the plant or up to feed gas commitment, may be taken into account.

2.7 Major components of the LNG liquefaction plant

1. Heat Exchangers: Shell and tube type, spiral wound heat exchanger (for APCI-P-MR process proprietary item), Aluminium plate-fin heat exchanger for Prico process.
2. Compressors with Steam Turbine Drivers: The refrigeration process required for all kinds of LNG processes need compressors. Mostly, centrifugal compressors are used in most of the designs including Technip / Snamprogetti design.
3. Compressor with gas turbine drivers: Post 1980s, gas turbines have found preferred usage as prime mover for compressor and electric power generator drivers. Gas turbines are simpler in design, operation & maintenance and are more efficient in terms of fuel consumption as compared to steam turbines. Use of gas turbines further eliminates the complex and costly high pressure steam systems and reduces the cooling water requirement.

2.8 LNG Storage

Another important area in the LNG value chain is LNG storage facilities. This is important because this facility is required at both the locations, i.e., at the LNG liquefaction plant as well as the re-gas plant. LNG storage typically accounts for approximately up to 5-10% of the total plant cost depending on the design both in liquefaction and re-gasification.

There are broadly two basic types of LNG storage tanks, one being above ground and the other being underground. Almost all LNG liquefaction plants have above ground storage tanks. The underground LNG storage tanks have been used in Japan and Korea specifically with a view to achieve a high degree of safety in densely populated area where land is at high premium.

The design of the above ground LNG storage tank basically varies depending on the type of insulation used and the degree of fail-safe passive components included in the tanks. On these classifications, there are three main types of above ground storage tanks namely:

2.8.1 Full Containment Tank

This design is basically consist of two complete LNG storage tanks in one. The primary inner tank is constructed of 9% nickel steel and is surrounded by an outer concrete wall with a thin 9% nickel steel insulated inner which connects as a vapour barrier. The annular space between the two tanks is filled with perlite insulations. The roof of the outer tank is constructed of pre-stress concrete and is fully insulated. In the event of inner tank failure, the outer tank is capable of containing both liquid and vapour along tank. Operation is continued even in the event of failure and the primary (inner) tank but increase in boil-off may occur. The outer wall may be re-enforced concrete surrounded by earthen embankment or pre-stress concrete to better withstand dynamic liquid forces. There is virtually no possibility of liquid LNG spillage with this type of tank.

2.8.2 Double Containment Tank

These tanks have same primary basic inner tank design as full containment tanks. The outer tank is typically of pre-stress concrete design with a thin 9% nickel steel insulated liner which acts as a vapour barrier. The annular space between the two tanks is filled with perlite insulation. The roof of the outer tanks is of carbon steel and not insulated. The outer tank is fully capable of basically containing the liquid LNG in the event of failure of the inner tank but at the expense of additional heat leak through the upper outer tank wall and roof. A high degree of tank safety is achieved with this design, but with higher boil-off gas.

An alternative double containment tank design utilizes the thin SS corrugate membrane as the primary liquid container. The membrane is attached to a load bearing insulation material, placed against inside of a pre-stress outer tank wall, the insulation placed between the membrane and the outer concrete wall is purged with nitrogen and monitored with methane vapours which might escape through minute leaks in the membrane welds. All proponents of the membrane-double containment design believe that it offers enhanced safety coupled with liquid and vapour containment comparable to full containment design.

2.8.3 Single Containment Tanks

This design has an inner tank capable of containing the LNG liquid. The carbon seal outer shell protects the insulation around the outside of the cryogenic storage tank. In the event of the inner tank failure, the outer tank cannot contain the liquid LNG and there will be liquid spillages to the area around the tank. Because of this spill potential, the tanks must be segregated from each of the surrounding plant side by containment dykes that will hold at least the volume of the tank. The surrounding facilities are placed to protect them from potential hazard of the burning liquids contained behind the dykes. This kind of tank design requires maximum land for the site, but at the lowest cost for the LNG tanks.

Cost-wise comparison of these three designs is 5: 8: 9 for single containment, double containment and full containment. The choice of storage tank design is based on the choice of the owner of the operating company particularly taken into consideration the safety and operating issues related to plant location and the applicable codes and standards.

2.8.4 Storage Volume

The storage volume of a single storage tank and total storage capacity created at either liquefaction or re-gasification terminal is a matter of the plant daily production capability and its send out rate of LNG or re-gas. However, the minimum LNG storage capacity is determined by the size of the ship or LNG exported from liquefaction plant/imported to re-gasification plant. The ship capacity will represent the minimum actual working volume of the storage tank. As a matter of standard operating procedure, the LNG should be dispatched from one tank at a time to a ship; similarly, the ship unloading should be done to a single tank. Another important factor which will have bearing on the storage capacity is condition of the sea for its ship worthiness during adverse climatic conditions. As in India, this would be mostly in the monsoon season when the sea encounters high tides and severe storms. A typical LNG export terminal achieves 40-50 tanks turnover per year, i.e., the annual capacity could be safely divided by 40 to achieve the storage capacity. Depending on the size of the tank, this will also decide number of tanks in the installation. For receiving terminal, a typical Japanese experience indicates approximately 20 turnovers per year. A typical 2.5 MMTPA plant will call for 1,25,000 m^3 of LNG storage.

The LNG storage tank capacity has undergone a change from initial small tanks of 75000 m^3 to 135000 m^3 to now 200000 m^3 capacity.

2.9 LNG transportation by ship

LNG transportation is a specialized job. The cryogenic tank design basically has two versions. The first one is a membrane design which utilizes the complete hull of the ship in a rectangular cryogenic storage tanks made of 36% nickel steel or SS 304 corrugated membrane. The inner hull of the ship provides the structural strength that withstands the static and dynamic loads resulting from transportation of LNG. The load bearing insulation is mechanically attached with the inside surface of the inner hull. The insulation is covered by a thin liquid tight secondary barrier called the membrane. Another layer of the insulation is there and finally a primary barrier, the membrane that contains the LNG. Both the primary and secondary membranes are designed and fabricated from materials operated at cryogenic temperatures without damage such as 9% nickel steel (SS 304 / 36 % nickel). The membrane containment system provides a full liquid tight secondary barrier that will contain the LNG in the event of a leak in the primary barrier. The space between the secondary and primary barrier membranes is continuously purged with nitrogen existing the inter barrier space which is monitored by gas detection system for any evidence of leakage in the primary barrier.

2.9.1 Techni Gaz Tank Design

In this design, the membrane is made of 1.2 mm thick SS-304 L with corrugations both longitude and transversely with a spacing of 0.5 mtrs apart. These corrugations absorb mechanical and thermal refrigeration shocks arising out of thermal stresses from the cold of LNG and hull refractions due to severity in the sea navigation. Because the corrugations absorb the refractions, there is minimum stress in the membrane itself.

Original load bearing insulation consisting of laminated balsa wood panels is incorporated with a plywood secondary liquid barrier. The inner hull of the ship is also covered with plywood as a barrier to sea water in the event of leak in the inner hull. Further, developed model of the insulation comprises laminated plywood and rigid polyurethane re-enforcement in two dimensions with fiber glass. The liquid tight secondary barrier is a bounded composite aluminium foil and two layers of glass cloth.

2.9.2 Gaz Transport Tank Design

This design uses 0.7 mm thin strip of invar (36 percent nickel steel alloy) for both the primary and secondary barrier. Invar has very low thermal expansion coefficient. Invar strips 500 mm wide are rolled out in single pieces over the entire length of the cargo tank, adjoining strips are welded to invar tongue, i.e., fixed to the underline installation using automatic resistance welding technique. The load bearing insulation will support the primary and secondary barriers consist of plywood boxes filled with perlite insulation material. The boxes are strong enough to absorb high impact pressure resulting from slushing of the LNG cargo when the ship is at sea. Insulation boxes are mechanically fixed to the inner hull. The thickness of the insulation boxes varies depending upon desired boil-off rate which can be utilized by the ship for its propelling power. Normally the thickness is about 200 – 250 mm.

2.9.3 Self – Supporting Tank System

2.9.3.1 Spherical Tank System Design – LNG Ship.

The self-supporting tanks are constructed independent of the hull structure and are designed with inherent strength to withstand.

1. All static loads of the tank and insulation weight, cargo weight and vapour pressure weight of cargo.
2. Dynamic loads resulting from ship motion, hull deflection and cargo slushings. These tanks are thick walled with robust construction material such as 5083-O Aluminium alloy or 9% nickel steel. The self-supporting tanks are constructed independently and assembled after completion of the hull construction. Here again, two variations are available. They are:
    i) Kvaerner Moss Spherical Tank Design: This design employs spherical tanks fabricated from 5083-O Aluminium alloys that have no internal structural support or stepney. In the later design, 9% nickel steel has also been considered. Each tank is supported by a cylindrical skirt, i.e., welded by a "specially shaped equatorial ring." This ring is called so because it assembles with the equator of a globe. The bottom of the skirt is welded to the inner bottom of the ship. The skirt incorporates two special features-a structural transition joint where the transition from Aluminium alloys used in the tank to stainless steel is made and stainless steel thermal break to reduce conduction of heat from inner hull to the cargo. In the latest design, spherical tanks of internal dia 37.5 to 40.5 mtrs - 4 to 5 numbers with a total LNG capacity of approximately 1,35,000 m^3 have been used. The principle behind this design is the leak before failure concept, that means, if construction defects would grow into a crack that will lead at a detectable rate of leakage well before it grows to a size that threatens the integrity of the tank. This design is also qualified as an international maritime organization-IMO dependent type-B containment system. The outer surface of the tank is covered with insulation typically expanded polystyrene or polyurethane foam of 300 mm thick approx. The insulation is covered by Aluminium foil vapour barrier. Nitrogen purging is continuously done through the space between the tank and the insulation. This drive nitrogen prevents moisture from ambient air from condensing and freezes on the tank surface. Also the nitrogen exiting from this space is monitored for any leakage of LNG. Even with more than 50 tanks in used of this design, no leak has been detected so far.
    ii) IHI-SBP Containment System: This design called as self-supporting prismatic independent type-B tank, was developed by IHI (Ishikwajama-Harima-Heavy Industries). This is an improved and

modernized version of Karneh design used in 1960s. The stress analysis when combined with crack and fatigue studies allows the design to predict with confidence that no crack in the shell can be detected before growing to a critical length and thus the tank is classified has IMO-dependent type-B. The prismatic shape Aluminium alloy tanks are designed to fit the dimensions of the ship hull to utilize the space efficiently. The cargo tanks are internally stiffened with webs and girders, in addition, each tank is divided by a liquid tight longitudinal bulk head and transfers swash bulk head which effectively dampens the liquid slushing.

The tanks are supported from the ships bottom by means of insulating material made of re-inforced plywood load bearing blocks. The insulating blocks raised on structural bottom support welded to the inner bottom which bears the weight to tank and cargo. The combination of plywood load bearing chokes and bottom supports allows for tank expansion and contraction when cooled from ambient to cryogenic temperature.

The polyurethane foam blocks attached on the outer tank surface provides the necessary insulation. Similar to spherical tank design, the insulation is covered with a layer of Aluminium foil to provide vapour barrier. Nitrogen is continuously purged between insulation of the tank. The existing nitrogen is monitored for LNG leaks.

2.10 LNG re-gasification

A typical LNG re-gasification terminal includes facilities like ship berthing, LNG unloading, storage and re-gasification of LNG. The basic process concept is very simple to re-gasify LNG by making use of the cold associated with LNG. In fact, there is no proprietary technology involved in this process except for some individual equipment which has found their repeated application by virtue of economy and operational ease.

There are two distinct areas of specific expertise which a typical LNG re-gas terminal shall have to create.

1. Ship unloading comprising of navigation channel with or without break water, jetty with berthing and unloading facilities and mooring facilities.
2. LNG storage, re-gas and send out facilities.

Necessary utilities comprising of water, power, air and inert gas, fire & safety provisions shall have to be accommodated in re-gas terminal.

2.10.1 LNG regasification terminal

General: LNG regasification terminals normally have the following sections, when we consider stand alone regasification terminal. However, since the LNG has cryogenic temperature of (-161) °C, the economy of operation calls for utilization of this cold for commercial purposes.

A typical LNG regasification terminal will comprise of the following facilities:

- Receiving Section
- Storage Section
- Send Out Section

In addition to the above, the terminal consists of various utilities, flare system, fire fighting facilities and other associated infrastructures.

2.10.1.1 Receiving Section: The LNG tankers are moored and berthed along the jetty especially designed for LNG handling. LNG is pushed out of the ship tanks to the land based storage tanks with the help of unloading arms connected to the ship, through an insulated cryogenic pipe.

2.10.1.1.1 The Jetty

The jetty consists of berthing facility, unloading arms and other associated facilities.

2.10.1.1.2 Berths-

i) The number and size of the berths are determined by the quantity of LNG delivered, the size of the ships, time intervals between two ships & site conditions. The berths may be installed either parallel or perpendicular to the bank at the end of the jetty depending on the water depth, prevailing wind speed and the location of the basin.

ii) The berth may include either simple dolphins or sophisticated concrete platform which includes the unloading arms. Land access to the moored ships shall be provided. If necessary, a separate road may lead to the berths in order to provide the crew with a free access to the ship.

iii) Exclusion of ignition Sources. No uncontrolled ignition source should be within a predetermined safe area, centered on the LNG carrier's cargo manifold. The minimum area from which all ignition sources must be excluded should be determined from the design considerations and dispersion studies envisaged in the risk analysis report.

iv) Mooring layout. The jetty should provide mooring points of strength and in an array which would permit all LNG carriers using the terminal to be held alongside in all conditions of wind and currents.

v) Quick Release Hooks. All mooring points should be equipped with quick release hooks. Multiple hook assemblies should be provided at those points where multiple mooring lines are deployed so that not more than one mooring line is attached to a single hook.

2.10.1.1.3 Unloading Arms

i) Unloading arms consist of pipe length connected to each other by swivel joints, moved by hydraulic actuators. The connection of the arm end to the ship crossovers flange shall be provided with a special automatic ERC device.

ii) During emergency this automatic device will come into operation and de-coupling system gets activated.

iii) Emergency Release System (ERS). Each unloading arm shall be fitted with an ERS system, able to be interlinked to the ship's ESD system. This system must operate in two stages; the first stage stops LNG pumping and closes block valves in the pipelines; the second stage entails automatic activation of the dry-break coupling at the ERC together with its quick-acting flanking valves. The ERS System should conform to an accepted industry standard.

iv) No drain shall be open to the atmosphere. Provision should be given to collect the LNG from the unloading arm to a closed system by way of providing blow down vessel or any other suitable arrangement.

v) The size of the arms depends on the unloading flow rate. Usual sizes are 10" and 12" for LNG tankers upto 75,000 m3 capacities and 16" for 120,000 m3 and above capacity tankers.

2.10.1.1.4 General Information/Consideration:

i) General cargo, other than ships' stores for the LNG tanker, shall not be handled within 30m of the point of transfer connection while LNG is being transferred through piping systems. Ship bunkering shall not be permitted during LNG unloading operations.

ii) Vehicle traffic shall be prohibited on the berth within 30m of the loading and unloading manifold while transfer operations are in progress. Warning signs or barricades shall be used to indicate that transfer operations are in progress.Prior to transfer, the officer in charge of vessel cargo transfer and the officer in charge of the shore terminal shall inspect their respective facilities to ensure that transfer equipment is in the proper operating condition

iii) Interlocking between ship and terminal control room to be established and the control of unloading operations shall be monitored from the terminal control room.

iv) Terminal Security. An effective security regime should be in place to enforce the designated ignition exclusion zone and prevent unauthorised entry of personnel into the terminal and jetty area, whether by land or by sea.

v) Operating Limits. Operating criteria, expressed in terms of wind speed, wave height and current should be established for each jetty. Such limits should be developed according to ship size, mooring restraint and hard arm limits. Separate sets of limits should be established for (a) berthing, (b) stopping cargo transfer, (c) hard arm disconnection and (d) departure from the berth.

vi) The ships should be berthed in such way that in case of emergency the ship can sail out immediately. All other instructions and procedures of Port Regulatory Authority are to be observed.

2.10.1.1.5 Unloading Line

i) The unloading and transfer lines for LNG should have a minimum number of flange joints. Consideration should be given to provide cold sensors for flanges of size 200mm and above as well as where there are clusters of flanges.

ii) Length of the unloading line is to be kept minimum. In case it is not feasible, alternative options available are:
  - To have an additional line running parallel
  - To have a booster pump
  - Increase the size of line

iii) The unloading line needs to be kept in a cold condition to avoid stress and cyclic fatigue due to frequent warm-up and cooling down operation. This is done by one of the following methods.
  - Continuous circulation of LNG (LNG goes through the unloading line and sent back to the vapourisation section through a special small diameter line).
  - Alternatively two unloading lines are installed. When unloading is not taking place, this loop is used for re-circulation for keeping the lines in chill down condition.
  - The Line is fully filled with LNG and the boil-off formed is sent to the tank or to the vapouriser section.

2.10.1.2 Storage Section

The storage section consists of LNG storage tanks, in-tank pumps, and BOG system and re-liquefaction facility.

2.10.1.2.1 Storage Tank:

The primary function of storage is to receive, hold and stock LNG for providing continuous supply to the send out section. An LNG tank is designed to ensure the following functions:

2.10.1.2.2 Liquid Retention

The storage tank shall be capable of withstanding the hydrostatic load of the liquid and low temperature of LNG. In order to meet these conditions, cryogenic materials such as low carbon austenitic stainless steels, Aluminium alloy, 9% Nickel ferritic steel, Invar (36% Ni steel) and pre-stressed concrete are generally used.

2.10.1.2.3 Gas Tightness

Tanks should be tight enough to prevent any evapouration losses and also to avoid ingress of air and moisture.

2.10.1.2.4 Thermal Insulation

Thermal insulation shall be provided to:

- Limit boil-off rates (usually between 0.06% and 0.1 % of total volume per day).
- Avoid cold spots on the outer shell.

2.10.1.2.5 Thermal Stresses

Under normal operating conditions, the tank is subjected to variation in the temperatures. Also during start up, tank temperature is required to be brought down from ambient to cryogenic temperatures. 9.3.2.6 Piping

All nozzles for the piping requirements for an LNG tank shall be from the top. The piping requirements are:

- Fill lines
- Withdrawal line
- Boil-off line to remove LNG vapor.
- Cool down line for initial cooling of tanks during commissioning of the tank.
- Nitrogen purges lines to purge the inner tank and annular space.
- Pressure make-up line.
- Pump re-circulation line.
- Purge release vent line.
- Pressure relief valve line
- Vacuum relief line

2.10.1.2.7 Boil off Gas & Reliquefaction

BOG system consists of boil-off gas recovery from the tanks, piping and to divert it into the LNG send out system or inject it into the pipeline transmission network. BOG is also used for vapour return to the ship tanks during unloading thereby avoiding pressure drop in the ship tanks.

2.10.1.2.8 BOG Recovery/Utilisation Options:

(i) Re-liquefaction & Recycle to Storage: Liquefaction process used in the LNG production plant may be used for re-liquefaction.

(ii) Pressurisation & Mixing with gas discharged from the Termina

(iii) Recondensation & incorporation into the regasified LNG: The recondensation is carried out using LNG cold released during vapourisation.

(iv) As a fuel gas in power generation process or internal use.

(v) The receiving terminal shall be provided with flare system to enhance the plant safety. The flaring of BOG should be done only as a final resort when the normal BOG handling system is not available.

2.10.1.3 Send out Section

In send out section, LNG is pumped and brought to a pressure slightly higher than the network pressure through secondary pumps and vapourised & warmed to a temperature above 0°C and metered before it is sent for distribution.

This sub section comprises of,

i. LNG Pumping,
ii. LNG Vaporization with/without gainful utilization of cold contained in LNG
iii. Sending gasified LNG (as natural gas) to pipe line system to be delivered to the customers.

2.10.1.3.1 LNG Pumping

In-Tank Pumps: The tanks are provided with in-tank submerged pumps, which are also known as primary pumps. These pumps are installed in wells, equipped with foot valves, which can be isolated to enable pump removal for maintenance.

If the network pressure is not too high, in-tank pumps alone may be sufficient to bring up to the network pressure through vaporizers.

Secondary Pumps: These Pumps are used for pumping the LNG from the intermediate pressure to the network pressure through vaporizers.

2.10.1.3.2 The re-gasification process- is basically drawl of LNG from tank, extraction of its cold with or without useful utilization of the same to produce natural gas for sending it to the desired destination. This process is basically the vaporization process. The commercially available LNG vaporization process takes care of the three distinct designs of the vaporizer.

1. Simple heat exchange with sea water or other heating sources such as river water or power plant cooling water. The popular design is the sea water based vaporizer as in most cases sea water is easily available at all LNG terminals. The only consideration where care needs be taken, is the re entry of cooled sea water to the sea.

   Open rack type sea water vaporizer: Currently this is the most commonly used LNG vaporizer. They require sea water intake and out flow system consuming electricity for circulation pump and there is no requirement of fuel gas. These are ideally recommended for base load service since they have practically low turn down capability and are stable. However, in certain locations, local environmental and ecological concerns thermal pollution may prohibit their use. In Indian context, there is no such provision as of now and in fact at RGPPL, Dabhol, sea water has been used as cooling water for power plant.

2. Gas fired vaporizer most often of the submerged combustion type: These vaporizers are of compact design which can be easily shut down and re-started. These vaporizers use up to 1.5% of the throughput, as fuel. The submerged combustion design is a preferred one since it is comparably more safe and efficient.

3. Indirect or intermediate vaporizers where LNG vaporization takes place with the heat exchange with an intermediate fluid. In this process, heat is transferred by LNG via an intermediate fuel typically propane, Glycol or Freon. Units of this design offer an alternative method for using sea water to vaporize LNG without the risk of freezing of sea water which directs sea water LNG heat exchangers have. The intermediate fluid vaporizers are also well suited for integration into cold recovery scheme.

   Out of the above re-gas methods, selection would basically based on the plant location and its integration with other plants which economically utilize the cold of LNG like power plant which uses LNG cold for cooling the inlet air to gas turbine and also cooling of the condenser cooling water. Other useful utilization could be to prepare a brine solution to be used for cold storage.

2.10.1.3.3 LNG Cold Recovery

General: LNG cold recovery system may be optional in an LNG Terminal. It aims at recovering the part of the potential cold energy available in LNG so as to use it effectively in cold utilizing plants.

LNG cold utilization process has two options namely:

(i) When LNG is rich, the fractionation process is employed to extract high value fractions like Ethane, Propane, Butane or LPG. This process can also make use of pressurizing the LNG to a pressure of 140 bar and absorb heat from integrated power plant and then expand the vapors to 90 bar which fits in the pipeline system pressure.

(ii) Cold is used directly to cool down another element, by simple heat transfer. Some of the schemes under this category are:

- Re-liquefaction/re-condensation of BOG
- Cooling of industrial fluids
- Air Liquefaction plants
- Food Freezing
- Power plant turbine inlet air and condenser cooling

Both above measures are described below as an academic exercise to make the subject simple to understand. In view of the growing LNG market and global awareness about energy efficiency, it is essential that a proper energy balance is worked out to make use of full cryogenic temperature benefit from LNG.

While designing LNG regas terminal a combination of the above options can be used depending upon the project projects.

2.10.1.4 Ship tanker receiving facilities and minimum port facilities and Berthing conditions:

i) Approach Channels. Harbor channels should be of uniform cross sectional depth and have a minimum width, equal to five times the beam of the largest ship.

ii) Turning Circles. Turning circles should have a minimum diameter of twice the overall length of the largest ship to be received where current effect is minimal.

iii) Tug Power. Available tug power, expressed in terms of effective Bollard pull, should be sufficient to overcome the maximum wind force generated on the largest ship using the terminal. under the maximum wind speed permitted for harbor maneuvers and with the LNG carrier's engines out of action.

iv) Traffic Control. A Vessel Traffic Service (VTS) System should be a port requirement and this should be able to monitor and direct the movement of all ships..

v) Operating Limits. Operating criteria for maximum wind speed, wave height and current should be established for each terminal and port approach. Such limits should match LNG carrier size maneuvering constraints and tug power.

vi) Speed Limits. Speed limits should be set for areas in the port approach presenting either collision or grounding risks. These limits should apply not only of LNG carriers but also to any surrounding traffic.

A separate Jetty shall be earmarked for LNG unloading. A minimum distance of 500 meters from other cargo jetties should be kept.

Minimum depth of the sea required to accommodate the large LNG tankers is of order of 13-14 meters. (This is for general reference; ship operators/manufacturers specify their minimum draft for the ships).

2.10.1.5 Terminal layout

2.10.1.5.1 Philosophy

Terminal lay out philosophy must consider location of the facilities at a site of suitable size. Before selecting a site, all site related characteristics which could affect the integrity and security of the facility shall be determined.

2.10.1.5.2 Basic Information

Information on following items should be collected before proceeding with the development of overall plot plan.

- Terminal capacity
- Process units and capacities
- Process flow diagram indicating flow sequence
- Utility requirements
- Unloading system along with tanker berthing system with capacity
- LNG storage tanks, sizes and type of storage tanks
- Other storage tanks
- LNG transfer and vapourisation
- No. of flares
- Provision for spill containment and leak control
- Inter distances between the equipment
- Operating and maintenance philosophy for grouping of utilities
- Plant and non-plant buildings
- Environmental considerations
- Scrap yards and dumping ground
- Fire station
- Chemical storage
- Ware house and open storage areas.

Information related to each item should include, but not limited to, following:

- Extreme temperatures and pressures for normal operations as well as emergency conditions.
- Concrete structures subject to cryogenic temperatures

- Fail safe design
- Structural requirement
- Requirement of dike and vapour barrier.
- Shut off valves and relief devices. Data on the following infrastructure facilities should be identified and collected before detailed layout activity is taken up. Due consideration should be given for the same while deciding/finalising the terminal layout.
- Site location map
- Seismic characteristics and investigation report.
- Soil characteristics
- Prevailing wind speed and direction over a period
- Meteorological data including corrosive characteristics of the air and frequency of lightening
- Area topography contour map
- High flood level in the area and worst flood occurrence.
- Source of water supply and likely entry / exit point
- Electric supply source and direction of entry point
- LNG entry point/ Gas exit point
- Minimum inter distances between facilities as well as between facilities & boundaries
- Storm water disposal point and effluent disposal point
- Approach roads to main terminal areas
- Surrounding risks
- Air routes and the proximity to the Airports.

2.10.1.5.3 Layout of Blocks/Facilities associated with regasification terminal

2.10.1.5.4 Roads-The access road to LNG ragas-terminal and the moored ships shall be provided. If necessary, a separate road may lead to the berths in order to provide the crew with a free access to the ship.

2.10.1.5.5 Location - The receiving terminal should be as close as possible to the unloading jetty.

2.10.1.5.6 Future Expansion - Future expansion requirement shall be assessed and provision of space for the same should be made.

2.10.1.5.7 Spacing Requirements of LNG Tanks and Process Equipment.

2.10.1.5.8 LNG Tank Spacing - LNG tanks with capacity more than 265M3 should be located at a minimum distance of 0.7 times the container diameter from the property line but not less than 30 meters. Minimum distance between adjacent LNG tanks should be 1/4 of sum of diameters of each tank.

2.10.1.5.9 Vaporizer Spacing - Vaporizers and their primary heat sources unless the intermediate heat transfer fluid is non-flammable shall be located at least 15 m from any other source of ignition. In multiple vaporizer installations, an adjacent vaporizer or primary heat source is not considered to be a source of ignition heated vaporizers a clearance of at least 2m shall be maintained.

2.10.1.5.9.1 Process Equipment Spacing

i) For Process equipment spacing Table 2 of OISD-STD-118 as applicable shall be followed.

ii) Fired equipment and other sources of ignition shall be located at least 15m from any impounding area or container drainage system.

2.10.1.5.9.2 Control Room and Substation:

i) Control Room shall be constructed as per OISD-STD-163.

ii) The minimum distance of 60 m shall be maintained between LNG Storage Tank and Substation.

2.10.1.5.9.3 Unloading Facility Spacing

i) A pier or dock used for pipeline transfer of LNG shall be located so that any marine vessel being loaded or unloaded is at least 30 m from any bridge crossing a navigable waterway. The loading or unloading manifolds shall be at least 60m from such a bridge.

ii) LNG and flammable refrigerant loading and unloading connections shall be at least 15m from uncontrolled sources of ignition, process areas, storage containers, control room and important plant structures. This does not apply to structures or equipment directly associated with the transfer operation.

2.10.1.5.9.4 Electrical Classification- Classification of areas for Electrical Installations in LNG Terminal shall be as per OISD-STD-113 as applicable.

CHAPTER 3.

ENGINEERING DESIGN ASPECTS

3.1 Liquefaction terminal

3.1.1 General: The simplest way to produce LNG is by cooling the natural gas. The natural gas feed for cooling is to be treated in a gas processing plant so that the unwanted constituents are removed from feed gas.
Each component of the feed gas has a definite influence on the basic liquefaction process. Of particular importance are the non-hydrocarbon components, such as: carbon dioxide, hydrogen Sulphide and organic sulphur compounds, inert gases such as nitrogen and helium, water vapour and possible traces of mercury.

The composition of natural gas, as feed, to the LNG liquefaction plant varies from source to source from where the natural gas is produced. Again the extent of these impurities depends on the source of the natural gas supply and the extent of field treatment.

Carbon dioxide contents are typically in the range of 2 to 15 mole % Ethane and heavier hydrocarbon contents are in the range of 10 to 15 mole %. Nitrogen contents vary from 0.1 to 19 mole % maximum.

The desirable level of the impurities in the feed gas is again depends on the process employed for liquefaction and the contracted specifications of LNG. However the experience has shown that for cost effective and safe operation there must be limits on the presence of various impurities, such as:
Mercury – to be contained within 10 ng / Nm^3 (nanograms per normal cubic meter)
Carbon dioxide – to be contained within 50 ppm (part per million)

A typical LNG product specification is shown in table 3.1 below:

Component	Mole %
Nitrogen	1.0 (max0
Butanes+	2.0 (max)
Pentanes+	0.1 (max0
Impurities	As per unit specified against each
Carbon dioxide	50 ppm (vol) (max)
Hydrogen Sulphide	5 mg/ Sm^3 (max)
Total Sulphur	30 mg/Sm^3 (max)
Aromatic	2 ppm (vol) max
Water	Less than (-) 73 degree Celsius
Quality	As per unit specified against each
Heating value	1040 to 1150 Btu/ Scf, or 9000 to 10,000 kcal/ Scm

Table 3.1 : LNG product Specification

3.1.2 Gas Treatment Plant- The natural gas as produced from the wells, whether produced as associated gas with oil or from a gas well, needs treatment to make it suitable for a particular application. In respect of LNG feed, gas treatment refers to as removal of all unwanted element/ components upto their acceptable limits.
There could be two choices to locate such facilities. Some of the facilities can be located at the production well site and some can be located at a place adjacent to or within LNG liquefaction plant battery limit. Gas treatment plant (including appropriate location and the technology selection) has been described in detail in section 5.2 of this book.
3.1.3 LNG liquefaction plant- The treated gas suitable for successive cooling is fed to the liquefaction plant. The liquefaction plant is designed in modular concept for the purpose of over all economy. These modules are called the "Trains".

3.2 Re-gasification terminal

3.2.1 General - LNG regasification terminal comprises of three main sections namely:

(i) LNG receiving facilities- comprising of marine facilities including LNG unloading facilities
(ii) LNG storage facilities, and
(iii) LNG vapourization facilities including gas send out facilities.

These facilities are separately described in following section for the purpose of design.

3.2.2 Regasification terminal components

The major components of each section of LNG regasification terminal are described below:

3.2.2.1 Major components of LNG receiving facilities (the shipping facility is considered as a separate facility. This can be owned by the LNG supplier in case of ex- ship sale of LNG or it could be hired by the regas terminal owners in case of fob sale of LNG)

(i) Approach channel
(ii) Break water (optional)
(iii) Dolphins (mooring and berthing)
(iv) Berthing platform
(v) Unloading arms (including quick releasing coupling)
(vi) Control system
(vii) LNG carrier pipeline to storage (cryogenic pipeline)
(viii) Vapor return pipeline (connecting storage system to the LNG ship)

3.2.2.2 Major components of LNG storage system

(i) LNG storage tanks
(ii) LNG pumps (submersible type mounted inside LNG tank)
(iii) Connected piping

3.2.2.3 Major components of vapourization facilities and gas send out facilities

(i) Vaporizers (sea water heating, Air heating, Gas fired heating or a combination of these).
(ii) Glycol and /or methanol system (for indirect heating of LNG or cold recovery process employed for better economy of operation.

3.3. Ship Building

Basic design approach: The conceptual basic design starts from the design capacity of the regasification terminal in terms of LNG to be regasified. Each section needs specific consideration. Let us start from marine facilities than for storage and finally for the regas and send out facilities.

3.3.1. Designing Marine facilities-

(a) Preparation for Jetty: now days the common LNG carrier (ship) size is 135,000 m^3. (Although ships of size upto 250,000 m^3 are on order, when such ships are commercially available we may consider such capacity).

Taking density of LNG as 0.45 tonne/cubic meter, we get, with 90% fill of the LNG ship, a weight of LNG in each shipment or the voyage, equal to:

135,000 x 0.9 x 0.45 tonne, or;

54675 tonne.

Therefore for 1 mmtpa capacity of LNG, we need 1000000/54675 sorties or the voyage, this is equal to 18 voyages.

The berthing time for a ship is approximately 6 to 12 hrs. depending upon the length of approach channel and berthing facilities at the location. Similarly the unloading time required is approximately 14 to 24 hrs. and the unberthing time including send off time is also 10 to 16 hrs. Safely we may assume that 3 days will be required to unload a ship.

Thus the maximum number of ships which can be unloaded shall depend on;

(i) The weather window for unloading, rainy season high tides or seasonal rough weather conditions which may prevent berthing of the ship.

(ii) Normal maintenance of unloading facilities.

(iii) Dredging of approach channel.

(iv) Any unforeseen circumstances

Normally a margin of 15 days should be kept for such eventuality.

Therefore the number of ships that can be unloaded is,

(365 – 15)/3 = 116.67, say 117 max.

Thus with one jetty maximum LNG unloading possible is,

= 117/18 mmtpa

=6.5 mmtpa

Thus for a LNG terminal of capacity more than this we need to make provision for another jetty.

(b) Draft requirement: For LNG ship of size we have considered, a minimum draft of 12 meter is required.

(c) Dolphins requirement: Dolphins are the piled concrete structures created to help in berthing LNG ship and to keep the ship in position after berthing and during unloading. Dolphins are required to lash or tie the ship while berthed and unloading operation is in progress. These dolphins are termed as berthing dolphins.

(d) Unloading arms: These are the equipments which get connected to the ship for unloading of LNG. There can be one, two or more of such arms for unloading operation. The vapour return line is also essential to complete the circuit so that there is no vacuum created in the unloading operation. The unloading arms are intern connected to LNG tanks.

(e) Tug boats: These are the boats with pulling capability of desired bollard pull. They are used to navigate the LNG ship through approach channel. For better control and maneuvering main engine of the ship is switched off at the entry point of the approach channel. From that point onward, tug boats are used to pull the ship to its placement called the navigation and the berthing operation.

(f) Break water: Depending on the condition of the sea, there may be a requirement of break water. Break water is primarily meant to create the tranquility in the approach channel so that the movement of ships can be without any hindrance due to tidal situation.

(g) Number of ships required: The total voyage time of the ship from LNG liquefaction plant to the regasification plant is first calculated. This again will depend on the distance between liquefaction plant and the regasification plant. The berthing and unloading time is further added to it, to get the total time for a sortie.

Suppose the voyage time is = "D "days between the liquefaction and the regasification terminals.

Then, the total time required to receive one cargo of LNG = (D+3) days.

And the total cargoes received in a year, C = (350/ D+3)

Now if D=1 day, then, C=87

D=2 days, then, C= 70

D=3 days, then, C= 58

D=4 days, then, C= 50 and so on.

This means, with one ship, one could receive 4756725, 3827250, 3171150, 2733750 tonnes of LNG respectively. This intern will specify the regas terminal capacity as, 4.75 mmtpa, 3.8 mmtpa, 3.15 mmtpa, 2.70 mmtpa respectively.

3.3.2. Design of LNG Ship

LNG ships basically have LNG storage facilities and the ship propulsion facilities. Their design criteria are though compatible yet they follow different design basis.

3.3.2.1 Design of onboard LNG storage facilities: There are two types of design namely, the membrane type and spherical type.

The LNG storage capacity is first selected based on the requirement of the owners' and the technology available at the time of design and construction. The typical sizes vary from 135,000 to 250,000 m^3.

3.3.2.2 Design of ship main: LNG ships containing LNG cargo are to have all necessary accessories which are required for a normal sea worthy ship except that the main engine powering the ship is natural gas fired reciprocating engine and the power generator is mostly a gas turbine. This is to utilize the boil off gas from LNG evaporation. For black- start purpose, a diesel engine is also installed.

3.3.3. LNG Vaporizer

3.3.3.1. General: The conventional LNG vaporizers can be classified into two types:

- (i) Open Rack type vaporizer (ORV) –
- (ii) Submerged combustion type vaporizer (SCV) –
- (iii) Steam Ejector type vaporizer (SEV) –
- (iv) Indirect or intermediate vaporizers in which LNG vaporization takes place in heat exchange with intermediate fluid.

Design of vaporizer: - this can be covered in two sections. The first section covers the thermal design and the second section covering structural design.

Thermal and process design:

The cold removal of LNG or the teat supplied for vaporization is the primary consideration of vaporizer design. The heat transferred to LNG, is used both, for vaporizing it from liquid phase to gaseous phase and then for increasing its temperature from LNG temp to desires temperature which is mostly 0 degree Celsius.

The thermodynamic equation in its simplest form is:

$$H = L\,m + m\,C_p\,dT$$

Where,
H = heat required
L = latent heat of vaporisation
m = mass of LNG vaporized
Cp = specific heat at constant pressure for natural Gas (Methane Cp = 2.2 KJ/Kg. deg Kelvin)
dT = temperature difference deg. Kelvin

Example of the steam ejector type vaporizer:

LNG design rate (tonnes per hour)	= 105
Heat load (MW)	= 25
LNG in/out Temperature	= (-) 161/0 deg. C)
LNG turn down ratio	= Over 20
Heating source	= Steam at over 0.7 MPa

Bath water temperature = from 30 to 40 deg.C

(This is a live example of the design of a steam ejector type heat exchanger used in vaporizer used by Chiyoda.)

Engineering and Structural design:
This primarily involves the plant layout, equipment sizing, piping, support structure and insulation.
The open- rack type sea water vaporization is the most common type of LNG vaporizer currently in use. They require no net fuel consumption, but do need a sea water intake and outflow system that consumes electricity for the circulation pumps. They are best used in continuous, base load service, since they have only limited turndown capability. While designing such a system, one should take in to account the environmental factor, such as thermal pollution or other ecological concerns.

Gas- fired direct vaporizers, on the other hand, are compact and can easily be shut down and restarted. These vaporizers however consume 1.2% to 1.5% of throughput as fuel. The submerged combustion design is the preferred design, since it is inherently safe and has high thermal efficiency. As such, the submerged combustion unit is well suited for peaking and other short term operation.

Intermediate fluid vaporizers transfer heat to LNG via an intermediate fluid, typically Propane or Freon. This design offers an alternative method for using sea water to vaporize LNG without the risk of freezing with direct sea water-LNG heat exchange. Intermediate fluid vaporizers are most suited for integration into cold recovery systems.

General notes:-

(i) The vaporizer design is preferred in modular concept. It helps to control cost and provide much needed flexibility of expansion of LNG terminal capacity.
(ii) While designing regasification terminal efforts should be made to utilize the cold of LNG for useful purposes, such as:
    a. Plan for a power generation plant where inlet air to gas turbine and condenser water cooling can be achieved by heat transfer with intermediate fluid.
    b. Provision of cold storage
    c. Refrigeration and air conditioning within terminal
    d. Dry-ice plant, etc.

3.3.4. Re-gasified LNG send out facilities

There are mainly three kind of sent out which need design consideration, namely:

(i) Natural gas pipeline system- Normally LNG plant serves several of the customers on land. The connectivity to such customers is through a natural gas pipeline with several spur lines connecting. There are proven design for such pipelines, however for LNG terminal point of view it should be ensured that the evacuation pipeline comes matching the completion schedule of the terminal.
(ii) Internal or captive use- To get better efficiency in cold recovery and saving in transportation, it is common to locate facilities requiring gas, near to the LNG terminal. For such situation send out facilities would be well under the control of the terminal owner.
(iii) As new advancement, LNG transportation by road tanker has become a practical solution for evacuation of LNG. However such evacuation is limited due to the capacity of the tanker which is mostly about 18 tonnes. This type of evacuation may only be considered as additional to other facilities.

CHAPTER 4.

LNG STORAGE DESIGN

4.1 Introduction

LNG (Liquefied Natural Gas) has the cryogenic temperature of –163 °C to ensure the minimum storage volume when stored in LNG tank. Among various types of LNG storage tanks, the full containment above-ground type (Figure 4.1) is widely used nowadays and is the main concern of this study. Typical full containment tank has a double safety system: outer concrete tank; and inner steel tank.

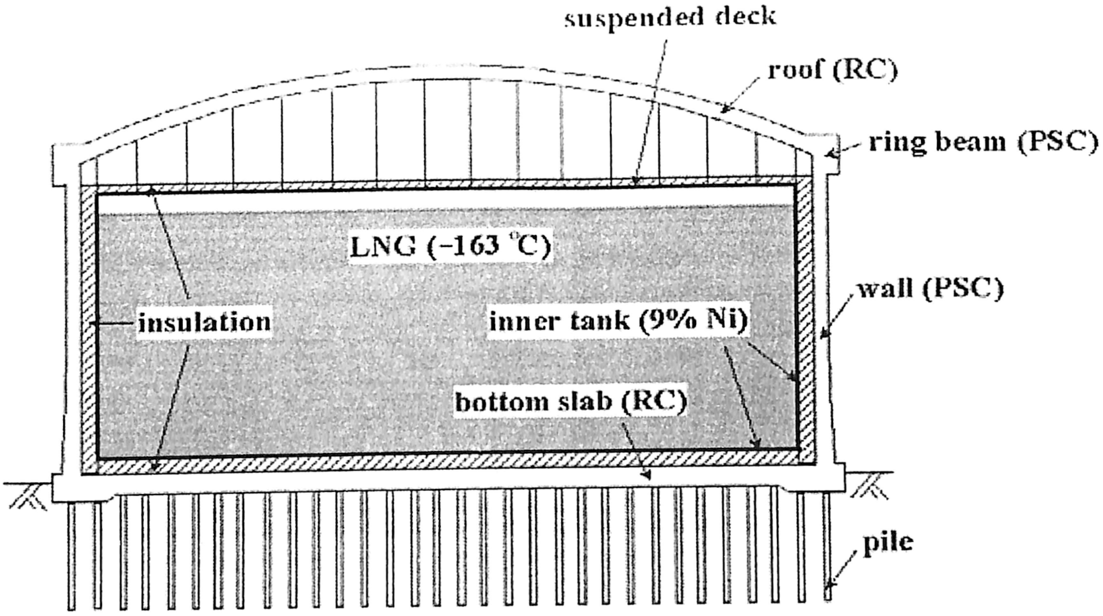


Figure 4.1: Full containment LNG storage tank

4.2 Thermal analysis of LNG tank

The structural details of a LNG tank are very complicated as shown in Figure 4.1. So, the full thermal analysis modelling including all the components inside the LNG tank may involve cumbersome tasks and even be impractical. The proposed model considers the outer tank and the effects of the suspended deck and the insulation layers for the temperature distribution are separately formulated into the boundary conditions. General-purpose structural analysis program ANSYS [1] is used to analyze a sample LNG tank with 200,000 kl capacity, which has a typical wall thickness of 750mm, roof thickness 600mm and bottom slab thickness 1800mm.

Inner face of the concrete roof is not directly exposed to the cryogenic temperature due to the suspended deck and deck insulation. The equilibrium condition of heat flow rates through the roof part (Figure 4.2) is employed to estimate the inner face temperature (T_b). In Figure 4.2, Q_0 and Q_2 are the heat flow rates due to conduction and Q_1 due to radiation, which can be set up as follows.

$$Q_o = \left(\lambda_c \frac{T_a - T_b}{t_c} \right) A_{roof} \tag{1}$$

$$Q_1 = \left\{ \varepsilon\sigma\left[(T_b + 273)^4 - (T_c + 273)^4 \right] \right\} A_{roof} \tag{2}$$

$$Q_2 = \left(\lambda_r \frac{T_c - T_d}{t_r} \right) A_{deck} \tag{3}$$

Where, λ_c and λ_r are the thermal conductivities of concrete and deck insulation, respectively; t_c and t_r thicknesses of concrete roof and deck insulation, respectively; A_{roof} and A_{deck} areas of concrete roof and suspended deck, respectively; εemissivity; and σ Stefan-Boltzmann constant. When a heat balance is achieved in the equilibrium condition, the equality of above three equations can be established. One can find the temperatures shown in Figure 4.2 by solving these nonlinear systems of equations.

Inner face boundary condition of the wall and bottom slab can be obtained by the following procedures. The insulations of the wall and bottom slab have multiple layers that consist of different materials. When the LNG smears into the insulations during the leakage, not all these insulation layers are lost but some of them still remain. For example, provided that PUF (Poly-Urethane Foam) is attached to the inner face of wall, it behaves as a cold resistance relief for the leakage. The effect of remaining insulations can be effectively converted into the boundary conditions by the following proposed scheme. First, the effect of each insulation denoted by subscript i is converted into the equivalent convection coefficient ($h_{ci,eq}$) by expressing actual heat conduction through the insulation (left side of Eq. (4)) as the equivalent heat convection (right side of Eq. (4)).

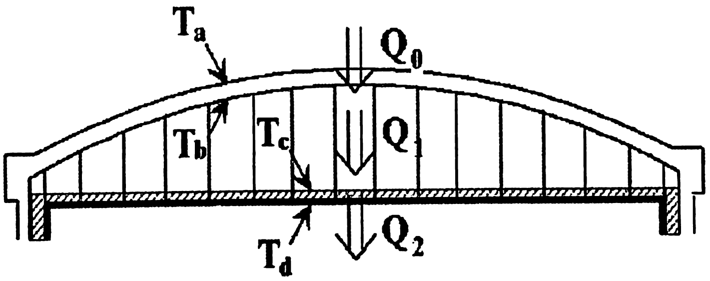


Figure 4.2: Heat flow rates through the roof

$$\lambda_i \frac{\Delta T}{t_i} = h_{ci,eq} \Delta T \qquad (4)$$

Where, λ_i and t_i are the thermal conductivity and thickness of an ith insulation, respectively. Since the total n insulation layers are arranged in a series, the overall equivalent convection coefficient ($h_{c,eq}$) that should be applied to the inner face of concrete can be obtained by Eq. (5).

$$\frac{1}{h_{c,eq}} = \sum_{i=1}^{n} \frac{1}{h_{ci,eq}} = \sum_{i=1}^{n} \frac{t_i}{\lambda_i} \qquad (5)$$

According to the proposed schemes, the inner face temperatures of outer concrete tank for the case of leakage are 11.0 °C for the roof, -13.8 °C (with PUF) or -163 °C (without PUF) for the wall and 4.6 °C for the bottom slab when a steady state is attained assuming the ambient temperature of 15 °C.

Once the temperature boundary conditions are obtained, the heat transfer and the thermal stress analyses are performed in an ordinary manner to produce the resulting section forces. Change of the concrete properties under the cryogenic temperature should be considered as necessary.

4.3 Liquid tightness design of LNG tank

One of the important points that should be considered in a design of liquid storage tank including the LNG tank is to maintain liquid tightness from the serviceability's view point. Normally, the inner tank contains LNG (Figure 4.1), but when the LNG leaks from the inner tank, the outer concrete tank comes into contact with LNG. Under this accidental case, it is indispensable for the outer tank to keep the liquid tightness in order to safely contain the LNG before taking any countermeasure. The cryogenic temperature-induced stresses may seriously deteriorate the liquid tightness property of concrete. Therefore, the thermal analyses should be preceded to assess the liquid tightness considering the cryogenic temperature.

4.3.1 Design parameters

The conditions commonly referred in the specifications can be classified into three categories.

(1) Residual compressive stress

Residual compressive stress is the compressive stress introduced by the prestressing tendons, which is still effective even after canceling out the main design loads. It provides against the shrinkage or temperature variation which is not easy to predict. Design codes [3, 4] recommend that the residual compressive stress of 1.0~1.4 N/mm^2 should be maintained in the hoop and vertical directions of the wall.

(2) Residual compression zone

Residual compression zone is a depth of the section that maintains compression state when the design loads are applied. For example, prEN 265002 recommends the residual compression zone of 100mm. It is an important provision for the crack not to penetrate the section.

(3) Crack width

The allowable crack width is most widely used specifications in relation to the serviceability design including the liquid tightness. The calculation methods and allowable crack widths have a wide range of variation depending on the codes. More strict allowable crack widths are generally applied to the liquid storage tanks and prestressed concrete members.

4.3.2Design practice and suggestions

(1) Hoop direction

Judging from some design documents of actual LNG tanks, we can conclude that the design practice of prestressing tendons in LNG tank usually follows that of the ordinary liquid storage tank which contains the fluid with normal temperature. Figure 4.3 shows the typical arrangement of hoop tendons in LNG tank that counteracts the design loads of liquid and gas pressure except the cryogenic temperature-induced load.

The following questions can be raised with regard to the above-mentioned design practice. First, the design practice deviates from the original intention of residual compressive stress that counteracts *all* the main design loads, since the cryogenic LNG temperature produces severe section forces thus cannot be disregarded in the design loads. Second, the conventional provision of residual compressive stress is not sufficient to cover the cryogenic temperature-induced tensile stresses but can only cover ambient temperature-induced stresses.

Therefore, one conceivable alternative is to design the hoop tendons to counteract all the design loads including LNG temperature also with some additional residual compressive stress. It suggests the *full prestressing* concept in a hoop direction of the wall as is often the case for the prestressed liquid storage tanks which contain the fluid with normal temperature. The full prestressing may ensures the liquid tightness and no additional checks needs to be accompanied since full depth of the section maintains compressive stress state and thus cracks may not occur. In this case, however, main difficulties arise when determining the arrangement of the hoop tendons. Hoop tendon design that counteracts the simple distribution of the liquid and gas pressure (Figure 4.3) is rather straightforward (the space between tendons gets close downward) thus even can be carried out by a hand calculations.

On the other hand, LNG temperature develops such a severe and irregular loading condition that the tendon design to counteract the effect of LNG temperature can be obtained only through the detailed analyses. Therefore, full prestressing of LNG tank in the hoop direction would produce densely and irregularly spaced tendons thus are not recommendable from the view points of practical and economical design although conceivable.

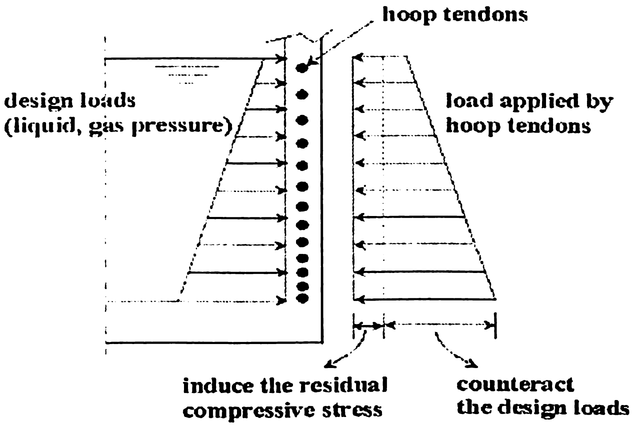


Figure 4.3 Typical arrangement of hoop tendons in LNG tank

Some previous studies have pointed out that liquid tightness is ensured when the specifications for the residual compression zone and crack width are satisfied although the residual compressive stress is lost. Taking notice of this point, we can find a useful and practical design basis of prestressing tendons for the LNG tank by adopting *partial prestressing* concept. It would be a strategy that the conventional design practice of hoop tendon arrangement in Figure 4.3 is similarly employed and the liquid tightness is controlled by the residual compression zone and crack width in accordance with the partial prestressing concept.

(2) Vertical direction

In the vertical direction of LNG tank wall, the code-specified residual compressive stress is not sufficient to keep full depth of the section in compression state when subjected to the vertical bending moment. It naturally leads to the design of partial prestressing.

4.3.3 Cracked section analysis

For the partially prestressed wall of LNG tank, cracked section analysis should be performed to predict the residual compression zone and crack width as related to the liquid tightness in each direction. It is conceptually convenient to divide the axial force (*N*) and bending moment (*M*) into two parts [8].

$$N = N_1 + N_2 \quad \text{and} \quad M = M_1 + M_2 \qquad (6)$$

Where, N_1 and M_1 are the decompression forces that make the section zero stress state by canceling out the prestressing-induced compressive stresses. Uncracked section analysis is performed for the N_1 and M_1 and cracked section analysis for the N_2 and M_2. In the cracked section analysis that ignores the tension part of the concrete section, the depth of neutral axis from the extreme compression fiber corresponds to the residual compression zone. During the analysis, steel stresses usually required to calculate the crack width can also be obtained.

For the case of LNG tank, it would be convenient to express the Eq. (6) into a more concise form of Eq. (7) that clearly shows the effect of residual compressive stress and cryogenic LNG temperature.

$$N_2 = N_p + N_{pr} + N_t + N_e \quad \text{and} \quad M_2 = M_p + M_{pr} + M_t + M_e \qquad (7)$$

Where, subscript *p* represents the prestress except residual compressive stress; *pr* the portion of residual compressive stress; *t* LNG temperature; and *e* external design loads except LNG temperature. Eq. (7) can further be arranged into a simpler yet different form in each direction since the structural behavior differs in the hoop and vertical directions of cylindrical wall.

$$N_2 = N_{pr} + N_t \quad \text{and} \quad M_2 = M_{pr} + M_t \quad \text{for the hoop direction} \tag{8}$$

$$N_2 = N_{pr} + N_t \quad \text{and} \quad M_2 = M_t + M_c \quad \text{for the vertical direction} \tag{9}$$

4.3.4 Consistent design procedure

Based on the above discussions, a consistent design procedure for the liquid tightness of LNG tank is proposed as shown in Figure 4.4. Here, the section forces by the cryogenic LNG temperature and other external design loads are separately taken into account and the residual compressive stress is provided only against the external loads. Checks for the residual compression zone and crack width follow, which actually indicates the partial prestressing strategy.

4.4 Description of LNG Storage Tank

According to BS7777, LNG tanks are classified in three different types. Single containment tank is either a single tank or a tank comprising an inner tank and outer container designed and constructed so that only the inner tank is required to meet the low temperature ductility requirements for storage of the product. A double containment tank is a tank designed and constructed so that both the inner tank and the outer tank are capable of independently containing the refrigerated liquid stored. And full containment tank (Figure 4.4) is described as a double tank designed and constructed so that both the inner tank and the outer tank are capable of independently containing the refrigerated liquid stored. The difference between the double containment and full containment is that the outer tank of a full containment tank is intended to be capable of both containing the refrigerated liquid and of controlled venting of the vapour resulting from product leakage after a credible event. Among these three types of LNG tanks, the full containment type is regarded as the most advanced type. The tanks are also classified by the elevations from the ground level: above-ground type, inground type and under-ground type.

The large tank developed by KOGAS is an above-ground, full containment type which consists of inner and outer tank. The inner tank is manufactured with 9% nickel steel and the outer tank is composed of reinforced concrete and pre-stressed concrete. The 9% nickel steel is widely used as a material for the inner tank since it has the strength and toughness enough for the cryogenic uses. The inner tank also has a function of preventing the LNG from leakage. Meanwhile, the concrete outer tank is designed to resist all the external loads including seismic load. Insulating materials are placed between the inner and outer tank to preserve the stored LNG.

4.4.1 Specifications of the 200,000m^3 LNG storage tank

The technical specifications of the tank were determined on the basis of the KOGAS' ITB as follows:

- Type of tank : above-ground, full containment
- Inner tank : 9% nickel steel
- Outer tank : pre-stressed concrete
- Roof : concrete dome with suspended ceiling deck
- Secondary barrier : 9% nickel steel corner protection system up to 5m high from the tank bottom then polyurethane foam (PUF) coating
- Type of base : brine heating system (BHS)
- Seismic requirements: SSE 0.2g, OBE 0.1g
- Gross capacity : 200,000 m3
- Design pressure : 29 kPa
- Design boil-off rate: 0.05 vol%/day

The tank is of an above-ground, 9% nickel steel full containment type with a pre-stressed concrete outer tank and a corner protection system of 9% nickel steel as a secondary barrier. The base of the tank has a bottom heating system (BHS) using ethylene glycol as brine fluid. The roof has a suspended ceiling deck and a steel lined concrete dome.

First of all, different hydraulic calculations and process simulations from ship to tanks were carried out for determining the maximum elevation of the tank top. With the results of the calculations and simulations and the technical requirements above, the size of the tank to be developed was determined. Figure 4.4 shows the sectional view of the LNG storage tank of 200,000m^3.

- Diameter of inner tank : 84.0 m
- Design liquid level : 36.22 m
- Maximum operating level : 35.92 m
- Height of inner tank : 37.61 m
- Thickness of shell insulation: 1200 mm
- Diameter of outer tank : 86.4 m
- Height of outer tank : 52.4 m

taken from company

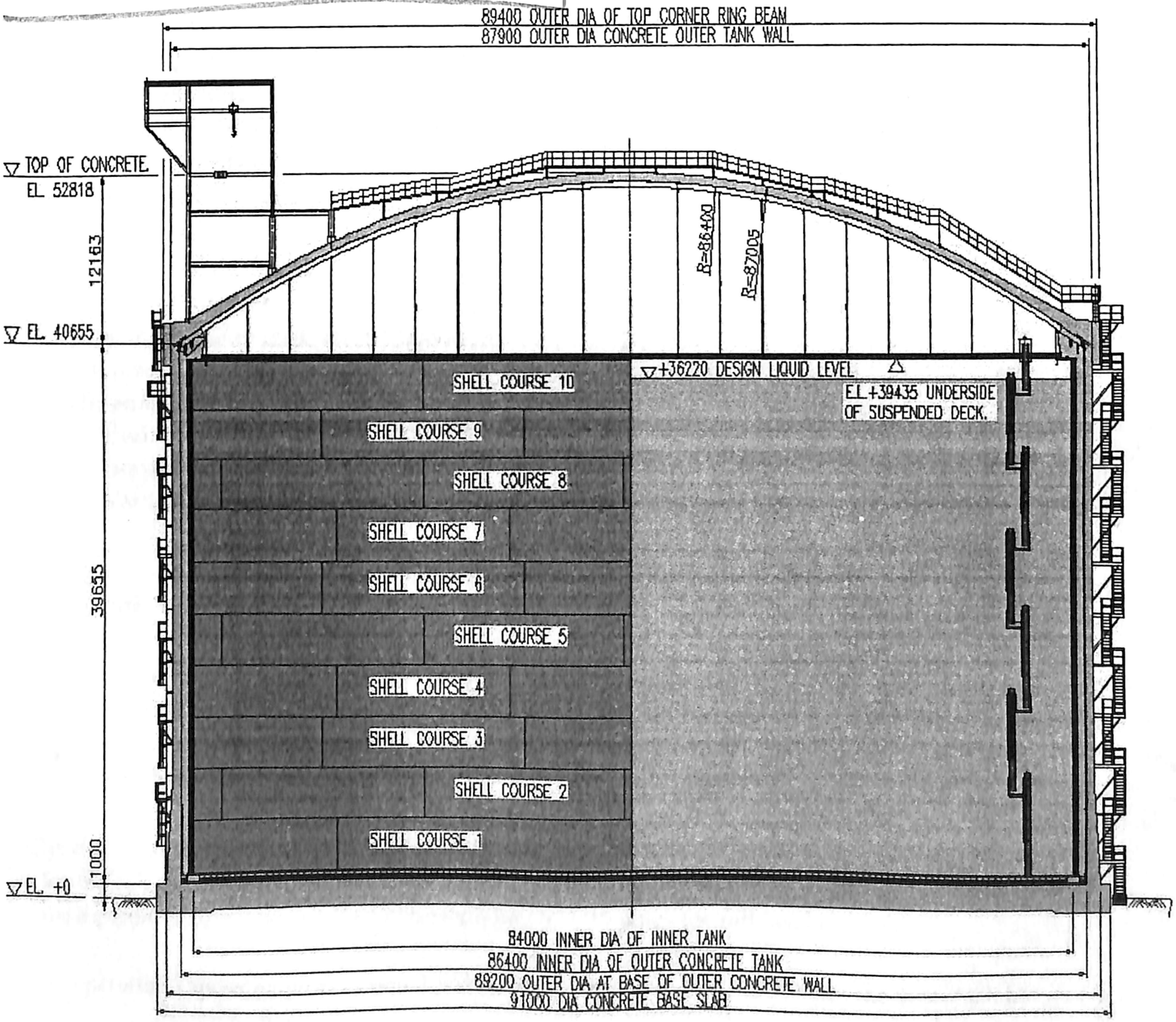


Figure 4.4: Sectional view of the 200,000m$_3$ full containment LNG storage tank

The LNG is stored in the 9% nickel steel inner tank. The steel liner installed on the inside surface of the outer concrete tank provides the gas tightness. The boil-off rate is determined by the insulation system.

In case of an LNG leakage, liquid may impact on the outer tank. Accordingly, the liquid tightness must be guaranteed by the corner protection system as well as the polyurethane foam coating installed on the inside surface of the concrete wall. The concrete outer tank protects the inner tank in case of emergency come from the outside. The bottom heating system is installed in order to avoid frost heave.

The roof liner consisting of a 5mm thick steel membrane stiffened with rafters in radial and tangential directions acts as formwork for the concrete sphere. The steel structure is fabricated on the bottom slab and lifted by air pressure to its final position. Rafters and roof liner plates are connected with a steel compression ring anchored in the concrete roof ring-beam by welding.

4.5 Design of Inner Tank

The principal design codes applied to the design of the inner tank are API 620 and NFPA 59A.

Figure 4.5 shows a general procedure for the design of 9% nickel steel inner tank and the basic design data applied in the design are as follows:

4.5.1 Basic Design Data

- Type of tank : 9% nickel steel full containment
- Gross capacity : 200,000 m$_3$
- Design pressure : 29 kPa
- Design temperature : -170$_o$C
- Specific gravity of LNG: 0.48
- Design boil-off rate : 0.05 vol%/day
- Design vacuum : -0.5 kPa
- Diameter of inner tank: 84.0 m
- Height of inner tank : 37.61 m
- Maximum liquid feed rate: 11,000 m^3/hr
- Number of shell courses: 10
- Seismic loads
    Horizontal SSE : 0.2g
    Horizontal OBE : 0.1g
    Vertical seismic response: 2/3 of horizontal values

4.5.2 Static Design

The inner tank is sized to contain 200,000m3 of LNG at a specific gravity of 0.48 in cold condition. An additional dead space for the in-tank pump NPSH of 2.0m has been given at the bottom of the inner tank and the allowance for seismic slosh plus free board has been made above the design liquid level to determine the height of the inner tank.

The thickness of 9% nickel steel plates of the inner tank shell is designed:
- for the full head of LNG corresponding to the design liquid level; and
- for a partial hydrostatic test load corresponding to 1.25 times the full head of LNG.

The operating vapour pressure is equalized on both sides of the tank shell since the inner tank has an open top.

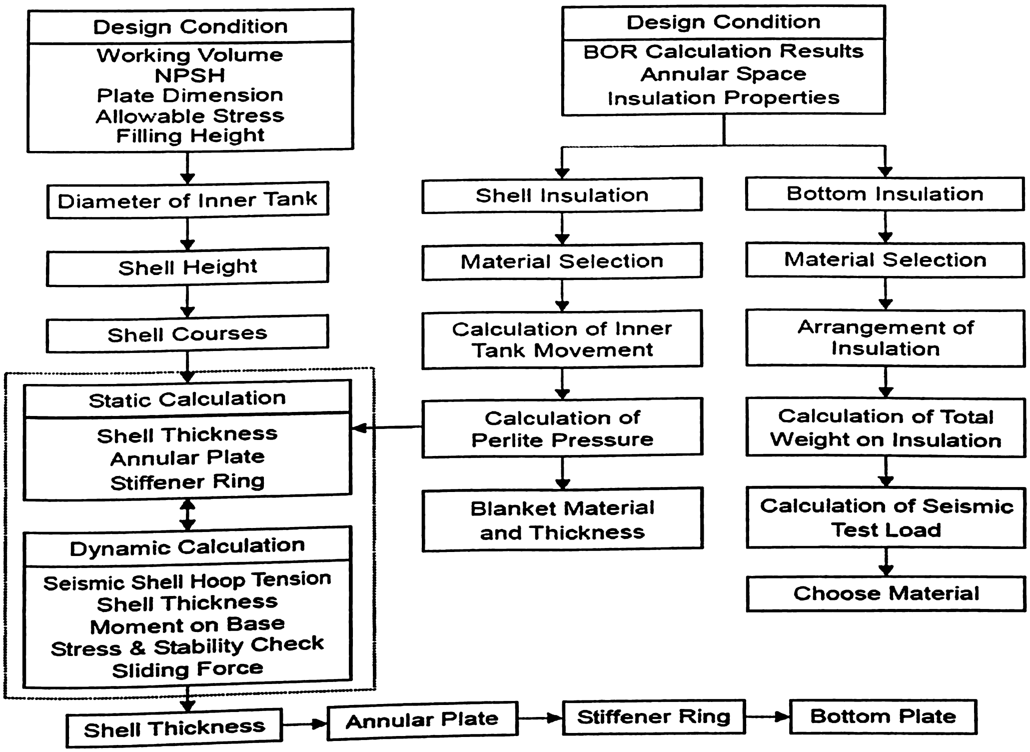


Figure 4.5: General design procedure for 9%nickel inner tank

4.5.3 Seismic Design

The inner tank is designed as an unanchored and unstrained tank to resist the OBE and SSE level design accelerations given in basic design data.

4.5.4 Hoop Loadings

The hoop forces on the inner tank shell are a combination of the static pressure due to the product liquid, the impulsive pressure due to the action of the impulsive component of the liquid, the convective pressure due to the action of the convective component of the liquid, and the vertical (or barrelling) pressure caused by the vertical component of the seismic loading.

4.5.5 Resistance to Overturning

The calculation of the resistance to overturning caused by contained liquid action on the annular plate and the width and thickness of the annular plate are based on the requirements of API 620 Appendix L paragraph L4.1 and L4.2.

4.5.6 Shell Compression

The shell compression is calculated using the procedure in API 620 Appendix L Section L.5.1 for unanchored tanks. The maximum allowable shell compression is in accordance with API 620 L5.3.

4.5.7 Seismic Sloshing

The seismic slosh height is calculated using the formula from API 620 L.8. An addition for shell run up is made in accordance with the requirement of API 620 paragraph L.8.1.

4.5.8 Secondary Bottom

If the secondary bottom is located at the top of the base insulation, it will be almost at the same temperature as the inner tank bottom in service. In the event of an inner bottom leak, no thermal shock to the secondary bottom will be given.

If the secondary bottom is located at the middle of the base insulation, it will be at a higher temperature than the inner tank bottom in service. Leakage from the inner tank bottom will give a local thermal shock to the secondary bottom. More severe considerations than the code requirements for allowable stress and joint factors must be taken in this circumstance.

4.5.9 Corner Protection System

In case of a leakage from the inner tank, LNG may accumulate in the annular space between the inner and outer tanks and cool the wall/bottom corner. In order to prevent the LNG from cracking of the lower concrete wall section, a liquid tight protection system thermally isolated with cellular glass insulation and shielded with 9% nickel steel plates will be provided as shown on Figure 4.6. The design will be carried out using finite element analysis taking into account pressure loads and thermal stresses/movements.

The outer tank shall be capable of containing the full inner tank contents. Minor and major leak cases shall be checked by finite element analyses and combined with the maximum pressure in the analyses.

4.5.10 Suspended Deck

The suspended deck is designed to resist the loadings of self weight, insulation weight, differential vapour pressure, construction traffic and seismic loadings. The design code applied in the design is British Standard Code of Practice CP 118.

An aluminium suspended deck with concentric ring stiffeners is used and the thickness of the deck plate is 5mm. The deck plate is thermally isolated by glass fibre blankets of 6 layers (see Figure 4.7 for the top corner arrangement).

4.5.11 Roof Sheeting

Roof sheeting design is in accordance with the rules of API 620 or RPLAS. The design pressure for the roof sheeting will be maximum air pressure for either air-lift or during concreting of the roof.

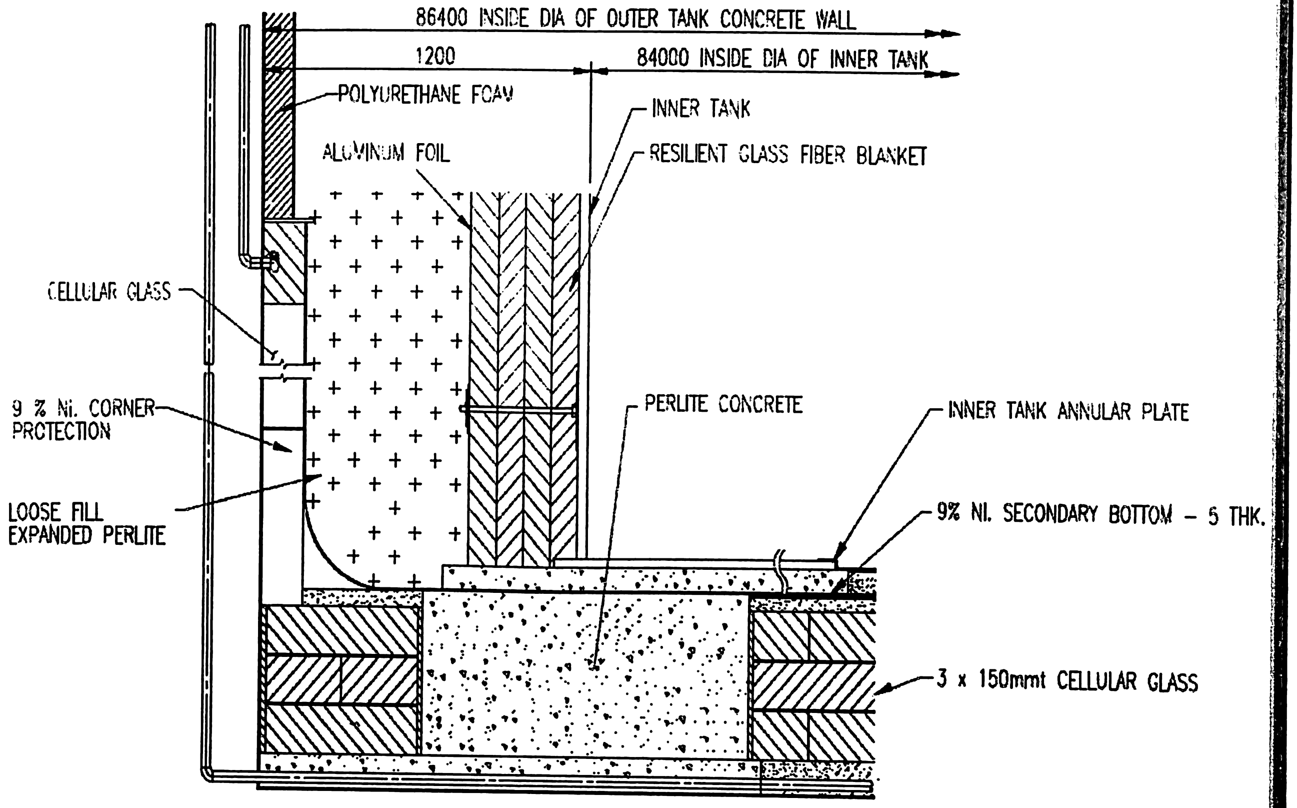


Figure 4.6: Insulation and corner protection system

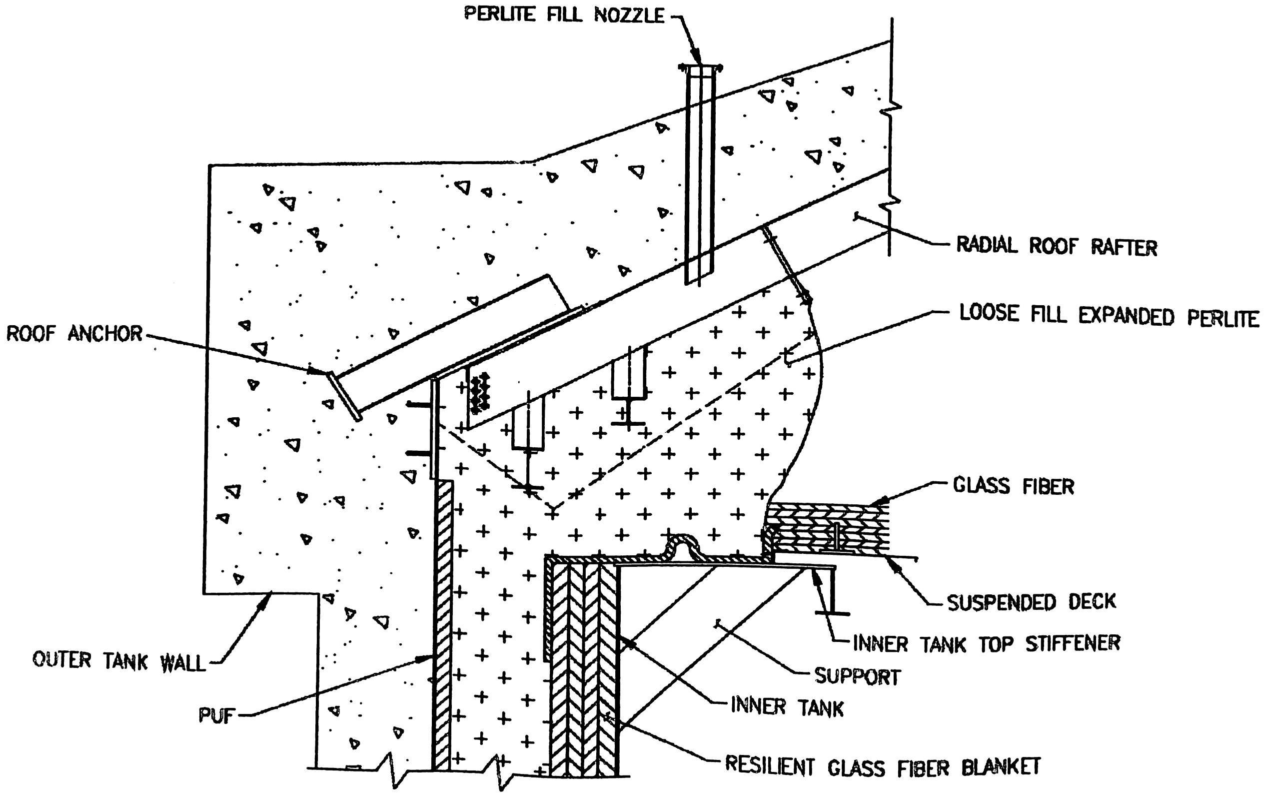


Figure 4.7: Top corner arrangement

4.5.12 Roof Fittings

The reinforcement of the roof plates for the roof fittings is designed in accordance with the rules of API 620. If heat breaks are fitted, they shall be designed in accordance with BS5500. The loadings to be considered include self weight, product weight, seismic loadings, loadings arising from the action of seismically induced liquid motions and wind loading on associated external and internal pipe work.

4.5.13 Thermal Design

The thermal insulation system of the tank is designed to have a boil-off rate less than 0.05% of the full tank contents per day due to atmospheric heat leakage. The heat leak calculation is based on a maximum ambient air temperature and the product design metal temperature of -170°C. The concrete base slab temperature is assumed to be +10°C due to the bottom heating and solar radiation effect is taken into consideration.

4.6 Design of Outer Tank

The outer container consists of an entirely closed monolithic concrete structure – bottom slab, wall ring beam and roof. The concrete containment is designed for all possible combinations of normal and emergency loads which may occur during construction, testing, commissioning, operating and maintenance of the tank. Design load combinations include the most severe combinations of loads. The general procedure for the design of outer tank is shown in Figure 6, and the principal design code applied in this design is the British Standard BS8110: Structural use of concrete.

4.6.1 Description of the Concrete Structure

The circular bottom slab of the container has a diameter of 91m and a thickness of 1.8 to 2.1m. The bottom slab is supported by 1277 steel pipe piles. The cylindrical wall is made of prestressed concrete and has a height of 38.055m up to the ring beam. The pre-stressed concrete tank wall has a uniformly tapered part from the base slab up to 7.5m and the wall thickness of the tapered part varies from 1400mm at the base/slab junction to 750mm at 7.5m above the base slab. The lower section of the wall must be thicker than the upper section to resist the higher bending and shear effects. The tank is parallel sided from the height of 7.5m to the roof ring beam. The inner diameter of the cylindrical shell is 86.4m. A ring beam of 3.2m high and 1.5m thick made of pre-stressed concrete completes the wall. The function of the ring beam is to restrain the tensile forces which result from the dome structure.

4.6.2 Design Criteria

The concrete containment is designed for the conditions of 4 stages: construction, operation, test and emergency. The concrete structures is designed on the ultimate limit state (ULS) and the serviceability limit state (SLS) for all normal situations and for the emergency situations of liquid spill in order to ensure containment for the liquid. For all other emergency situations the concrete structure is designed on the ULS. The design was carried out according to the partial safety-factored design method of BS 8110. For the reasons of durability, the cracks at the concrete surface are limited.

Units : kgf/cm²

Types of LNG tank		Dimensions of dome		Internal pressure (3.7 tf/m²)	Self-weight	Externally distributed loads (0.5 tf/m²)	Total stress (severer case)	Safety factor (allowable stress /total stress)	Remark
		Radius of curvature	Thickness (at the crown)						
Conventional design	A	1.0d	0.6m	26.5	-7.1	-1.8	19.4	1.25	
	B	1.0d	0.45m	28.8	-5.8	-1.9	23.0	1.05	
Proposed design	C	1.0d	0.6m	28.4	-7.6	-1.9	20.8	1.16	
	D	0.8d	0.6m	22.7	-4.0	-0.7	18.7	1.29	Acceptable
	E	0.58d	0.6m	16.5	2.2	1.1	19.8	1.22	
	F	1.0d	0.5m	34.0	-7.6	-2.3	26.4	0.92	
	G	1.0d	0.65m	26.2	-7.6	-1.8	18.6	1.30	Acceptable

Table 4.1: Stress check for the concrete roof dome(hoop stress)

Units : kgf/cm²

Types of LNG tank		Dimensions of ring beam		Prestressing	Dome loadings		Total stress	Remark
		Width	Height		Self-weight	Externally distributed loads		
Conventional design	A	1.5m	3.2m	-40.3	53.6	16.7	30.0	
	B	1.1m	2.6m	-67.8	44.7	18.5	-4.6	
Proposed design	H	1.5m	3.2m	-60.6	46.4	13.8	-0.4	Insufficient space for tendons
	I	2.0m	4.3m	-33.8	25.9	7.7	-0.2	Acceptable

Table 4.2: Stress check for the ring beam (hoop stress)

4.6.3 Loadings Considered in Design

The loadings to be considered in the design of outer tank for operation and test are:

- Dead Weight of the Tank Structure: Concrete, Inner Steel Tank, Steel Liners, Suspended Deck
- Pre-Stressing Including Creep and Shrinkage
- LNG Filling Inner Tank
- Operating Design Gas Pressure
- Hydrostatic Test of Inner Tank
- Pneumatic Test Pressure
- Piping and Installation on Roof
- Live Load on the Dome
- Wind
- Snow
- Temperature Operation
- Temperature Difference Slab-Wall-Roof For Emergency
- Earthquake Obe
- Earthquake Sse
- LNG Leakage

- Temperature Leakage
- Increased Overpressure
- Thermal Radiation from An Adjacent Area
- Missile Impact
- Cold Spot

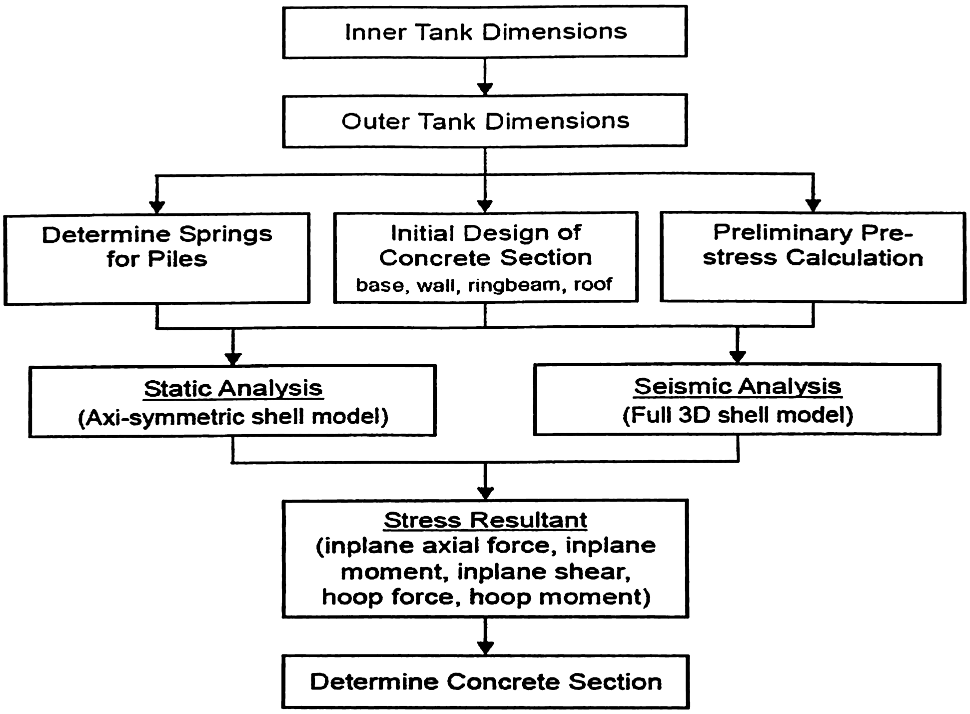


Figure 4.8: Design procedure for concrete outer tank

4.6.4 Static Analysis

For the static analysis of linear sectional forces, the main concrete tank structure is modeled using a semi-finite element computer program for axis-symmetric systems. The model comprises the bottom slab, the wall, the roof ring beam and roof. Spring elements were used to model the pile foundation in order to take into account the interaction between the tank structure and the sub-soil.

4.6.5 Nonlinear Analysis

In emergency cases in which the concrete is exposed to extreme temperatures due to heat radiation, non-linear effects of the concrete behaviour caused by the reduced stiffness due to crack formation is taken into account. The linear analysis, where the individual single load cases can be superposed, a non-linear analysis must be carried out for load combinations determined previously. For non-linear calculations the reinforcement is an input data.

4.6.6 Dynamic Analysis

The seismic calculations for OBE and SSE were done in two stages:

- Tank structure: modal analysis of an axis-symmetric model using acceleration response spectra as excitation input. The whole system is required to remain in the elastic limit, no physical or geometrical nonlinearities shall occur.

- Roof: additional modal analysis of a 3 dimensional finite element model (roof) using response spectra as excitation input.

Figure 4.9 shows an example of full seismic analysis model including the outer tank, internal structures and liquid. Figure 4.10 shows a seismic analysis result obtained on the model of Figure 4.9.

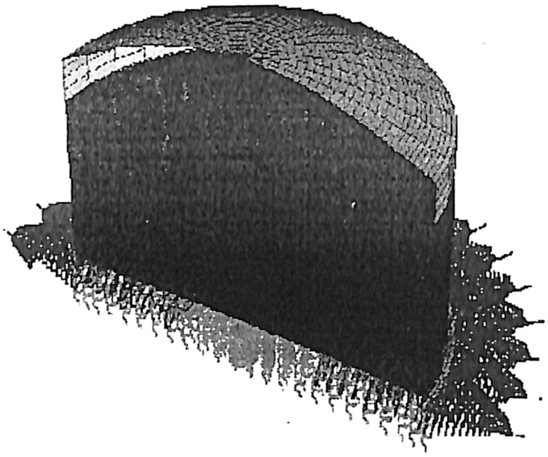


Figure 4.9: Full model for 3D seismic analysis

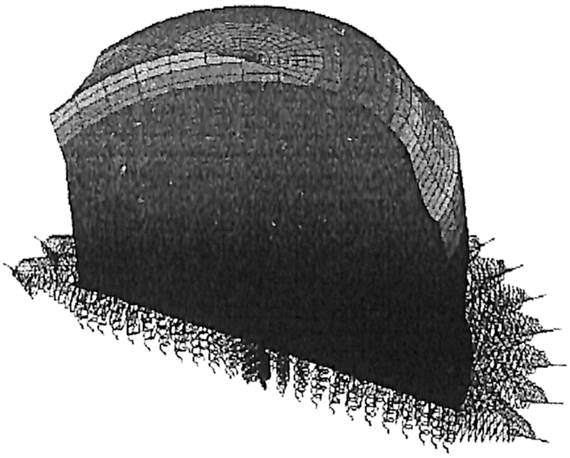


Figure 4.10: Seismic analysis result

4.7 Density Stratification in LNG Storage

4.7.1 Introduction

If LNG cargoes of different densities are stored in the same tank and are adequately not mixed, separation of LNG into distinct layers of different densities can occur. This process is called stratification. In the event of stratification, there is a possibility of tank "roll over" which occurs due to sudden mixing of two layers till their densities equalize.

4.7.2 Rollover

A significant safety concern in the storage of LNG is a phenomenon known as "rollover". If this occurs, pressures inside the storage tank may rise to excessive levels. The tanks are equipped with safety vent valves that are designed to keep the pressures from rising to levels that could cause structural damage. However, when these valves operate, LNG is vented to the atmosphere at an uncontrolled rate, which is an additional safety concern.

LNG is heavier than air and could settle in pockets of explosive mixtures. Perhaps the most well known case of rollover is that which occurred in La Spezia, Italy, in 1971. The actual pressures realized are and gas vented uncontrolled in a highly populated area for several hours. Fortunately, there was no explosion and no major damage was done to the tanks. The possibility of both potential problems was very evident, and much attention to detecting and preventing a similar occurrence has taken place since that time.

Rollover occurs under certain conditions as stratified LNG comes to equilibrium. Stratification occurs when the product in the tank forms in layers with different densities and different temperatures. Sudden mixing of LNG in any storage tank occurs as two or more layer densities approach equality. Any heat trapped in the system is released rapidly during mixing, generating a vapor which may exceed the venting capability of the tank.

The exact conditions that lead to rollover are somewhat complex. If layering occurs (discussed below), each layer is initially uniform, with the upper layer lighter than the lower. Heat entering the top layer comes through the walls of the tank. The liquid next to the tank walls warms slightly, becomes less dense and rises to the top, where it evaporates. Since light gases evaporate first, the liquid in the top layer tends to become denser.

At the same time, the liquid in the lower layer gains heat through the floor and walls of the tank with a convection flow similar to the top layer. But because of the hydrostatic pressure of the upper layer, the rising liquid does not evaporate but superheats. Thus the lower layer becomes warmer and less dense. When the two layers approach the same density, the interface between the two becomes unstable and mixes rapidly. When this occurs, the liquid from the lower layer that is superheated gives off a large amount of vapor that rises to the surface. It is this phenomenon that is known as rollover.

4.7.3 Layer Detection

The most effective method of preventing rollover is to detect layering by means of instrumentation, and if layering is present, take action to mix the layers under controlled conditions before the final conditions leading to rollover develop. If the size and composition of the layers can be detected, the potential danger can be accurately determined and the most cost-effective approach can be chosen. This action may be the operation of recirculation pumps (if available), or by mixing with liquid in other tanks. Some installations that have the capability of recirculation within a tank choose to operate these pumps on a regular basis as a preventive measure. Operation of these pumps is expensive, however, and some facilities do not have a simple method of recirculation.

Layer detection is best accomplished by means of a temperature sensor and density sensor that are run through the entire depth of the liquid. In the absence of this, multiple temperature sensors located at fixed intervals will also give an indication of layering. The disadvantage to multiple sensors is the difficulty of accurate calibration. The cost of multiple density sensors is prohibitive.

4.7.4 Instrumentation

One instrument currently available for layer detection and installed at a number of facilities around the world is the M6280 LTD series from Scientific Instruments, Inc. It is specifically designed to detect temperature and density layering in LNG tanks. To accomplish this, a single probe with installed temperature, density and liquid level sensors is driven over the entire depth of the liquid in the tank. The data is collected at fixed intervals as specified by the customer.

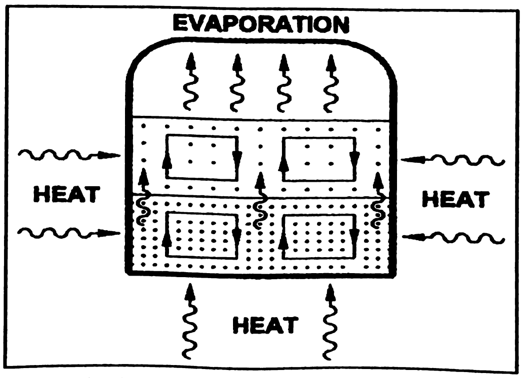


Figure 4.11: Typical display from M6280 Ltd. system showing stratification

Simple data analysis is performed to alert the operator of apparent temperature or density layering. If certain areas of the tank are suspect, a feature known as "Top Scan" is available to examine a potential layer in more detail, providing an accurate picture of the suspected layer. As mentioned previously, because a single sensor is used for data collection, calibration errors are eliminated and an accurate relative profile is obtained. With an accurate temperature and density profile, detailed calculations can be performed to properly determine the extent of the danger, and to enable cost-effective action in a timely manner to prevent rollover.

4.7.5 Mathematical Modeling of Rollover

LNG or other cryogens in static storage are in state of dynamic and thermodynamic equilibrium. The heat being absorbed by the tank is dissipated by evaporative cooling at the surface. When the system is distributed by pressure changes in the vapor space above the liquid, the system reacts to reestablish equilibrium. Evaporation of LNG in a large insulated storage tank occurs essentially on the liquid surface with no visible bubble formation.

Experiments with water and other liquids indicate that the temperature of the evaporating liquid at the surface is extremely close to the equilibrium saturation temperature of the vapor phase. However, about two millimeters below the surface the liquid temperature should be higher than the surface temperature in order to effect any appreciable surface evaporation. For any temperature difference between the surface and the liquid below the surface there is a constant steady state evaporation rate and a condition of supersaturation of the subsurface liquid.

Previous models for rollover in LNG storage tanks have been developed by Chatterjee and Geist [1] and by Germeles [2]. In these models the liquid in the tank is assumed to be stratified into a number of "cells" with heat in-leak from the sides and from the bottom of the tank as shown in Figure 4.4. The model consists essentially of the unsteady-state heat and mass balance equations for these cells and of supporting correlations. Both of these models used the thermohaline experiments of Turner [6] as a basis for treating the hat and mass transfer between cells. Both of the models simplify the problem to consideration of methane and a non-volatile heavy component. Unfortunately these adjustments have the effect of shortening the time to rollover in both models [10]. Another relation used in the Germeles model is the boil-off model by Hashemi and Wesson [7] as follow:

$$b = 0.328 \frac{\rho_0 C_p}{H_v} \frac{(g \alpha k^2)^{1/3}}{\rho \mu C_p^2} (T_n - T_s)^{4/3}$$

Where b is the boil-off mass flux, Cp is the specific heat of the liquid, g is the acceleration due to gravity, Hv is the latent heat of vaporization of methane, k is the thermal conductivity of the liquid, Tn is the absolute temperature of the top or nth cell, Ts is the absolute saturation temperature of methane in LNG, μ is the viscosity of the liquid, ρ is the density of the liquid and ρ_0 is the average reference density of the liquid.

In the Germeles model, equilibration of the liquid densities is taken as the necessary and sufficient criterion for mixing. In this aspect his model differs from that of Chatterjee and Geist, which requires equilibration of both temperature and composition. Some results from a simulation of the La Spezia rollover obtained by Germeles using his model are given in Figure 4.13. As Figure 4.13 shows, there is at rollover equilibration of density, but not necessarily of temperature or composition. Figure 4.13 shows the rapid increase in boil-off. The computed time to rollover is 34 hours, which compares with a time of 31 hours in the actual incident. Clearly the previous models while containing the general features required are inadequate for prediction and development of rollover revention strategies.

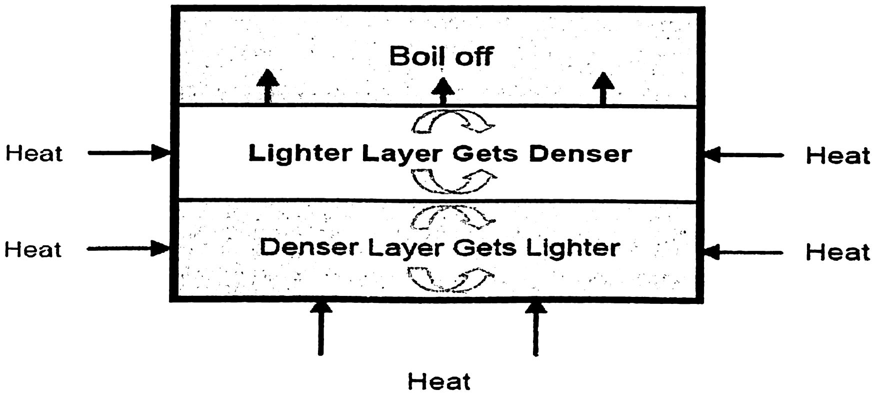


Figure 4.12: An LNG Storage Tank with the Liquid Stratified into n Cells [2]

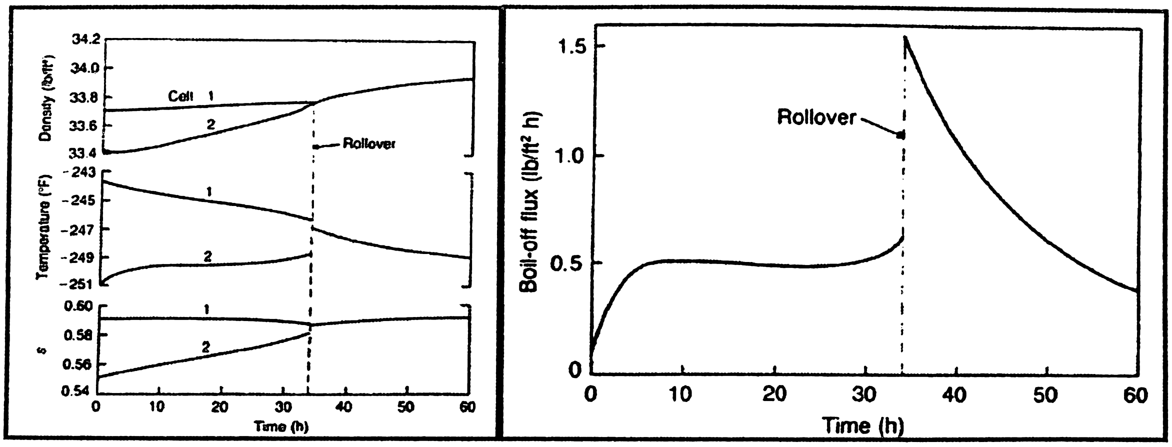


Figure 4.13: Simulation of the Rollover in the LNG tank at La Spezia Incident: Density, Temperature and Impurity Concentration (Left), Boil off flux (Right)

4.7.6 Basis of Proposed Analysis

This work present an integrated thermo-physical model for the stored LNG, which is capable of predicting for boil off gas rates as well as the ageing properties for the bulk LNG over time, from initial conditions within an LNG tank. From the numerical prediction, we analyze how the boil off gas rates depends on the degree of super saturation of the stored LNG, in terms of the tank pressure and the initial temperature of bulk LNG. In addition reliability of the predictive model is tested using the real data of tank operation. In a typical LNG storage tank, the heat from outside gradually leaks into LNG, warming the liquid near the bottom relatively buoyant and causes upward liquid flow in a boundary layer along the walls. When slightly superheated liquid arrives at the free surface, it flashes in part at the top of LNG surface under a thermodynamic condition of the vapor space.

Here, due to a decrease in hydrostatic pressure, super-saturation may become greater under the same thermodynamic condition. Then, the flash-cooled liquid (denser liquid) flows across the surface to sink back toward the bottom, and mixing with the bulk core of LNG and thus maintaining most of the bulk at an essentially uniform composition and temperature. In order to predict vapor evolution rate as well as compositional change of the LNG, it is assumed that a state of thermodynamic equilibrium is imposed on an arbitrarily film where a convective circulation flow enters and evaporation take place. Table 4.3 represents general features of proposed model for rollover prediction.

The net rate of escape of a liquid into the vapor phase depends on the degree of supersaturation of the liquid phase on the vapor-liquid interface. The experimental data obtained by many investigators of fluids of vastly different properties demonstrate that for a horizontal fluid layer heated from below:

$$Nu = C.Ra^{1/3}$$

Where Nu is Nusselt Number (Dimensionless), Ra is Rayleigh Number (Dimensionless) and C is a dimensionless constant. The computed vaporization rate with proposed model is compared with that reported by Sarsten in Figure6. At this time only one rollover incident has been reported in the open literature with sufficient detail for testing a computer model. Sarsten carefully documented a rollover event at La Spezia, Italy [9]. These data represent the experiment against which any model must be tested. The successful model will match the experimentally observed rates of vapor evolution and the time from loading to the observed rollover event with the initial conditions given by Sarsten.

Model Feature	Present Work
Chemical Species Considered	Methane, Ethane, Propane, Butane and Nitrogen
Rollover Criterion	Equalization of Density between cells
Mass Transfer between Liquid Cells	Equimolar Counter Diffusion
Saturation Conditions of the Top Layer Temperature	Film Liquid and Vapor at Equilibrium in Film Temperature
Vapor Liquid Equilibria Model	Peng Robinson Equation of State
Boil off Rate Expression	Hashemi Wesson Correlation with minor Modification

Table 4.3: General Features of Proposed Model for Rollover Simulation

4.8 Optimum Tank Operation System for LNG Receiving Terminal

(at Nihonkai LNG Co. Ltd.'s Niigata LNG Receiving Terminal)

4.8.1 Introduction

In an LNG receiving terminal, the liquefied natural gas (here in after referred to as "LNG") transported by LNG Carriers from foreign countries is unloaded by pumps installed on the LNG carriers and stored in LNG storage tanks onshore, and there after supplied as city gas or fuel gas for power plants after regasification.

For operation of LNG receiving terminal storage tanks, stable supply of correct amount of LNG corresponding to Changes in the ship rotation plan due to influences of weather and seasonal demand variations is indispensable. Moreover, as LNG is imported from several sources to meet the recent increase in its demand, it is necessary to store the LNG in separate tanks depending on the source because of the difference in density. To accept a different source into a tank, one needs to empty the tank before loading the new LNG from the different source. Since reducing tank level takes several days, the capacity of the receiving terminal is reduced temporally for that period because the tank does not accept a new shipment. The duration of this low capacity varies based on its operating schedule. For the operators, it becomes rather complex to plan the operation control of the tanks by estimating various such conditions depending only on their empirical rules. The operation method consists of unloading LNG from LNG carriers to receiving tanks, discharging from all tanks depending on demand, and transferring LNG from receiving tanks to transfer tanks.

Effective operation of this facility requires adequate control of each tank level taking into consideration constraints such as equipment capacity (pump capacity) and non mixture of LNG from different sources with the objective to determine and optimize the receiving and discharge ratio of each tank so as to minimize the transfer of LNG.

4.8.2 Outline of an LNG receiving terminal facility

Taking an example of 'Niigata Receiving Terminal' facility (Nihonkai LNG Co., Ltd.). The LNG storage tank facility of this terminal consists of six receiving tanks and two transfer tanks which do not receive LNG directly from ships. Table 4.4 shows the outline of the storage tanks in the terminal. LNG discharged from the storage tank by the LNG pump is vaporized by an LNG open rack vaporizer (ORV) and is supplied as fuel for gas turbine combined cycle power plants and city gas.

The LNG storage tanks are of the aboveground type and the receiving system has a bottom— and top-feed system. In this terminal, LNG is received in the receiving tank through the bottom feed and can be transferred to the transfer tank by changeover of the bottom and top feeds. LNG stored in the storage tanks can be discharged from all tanks depending on the demand.

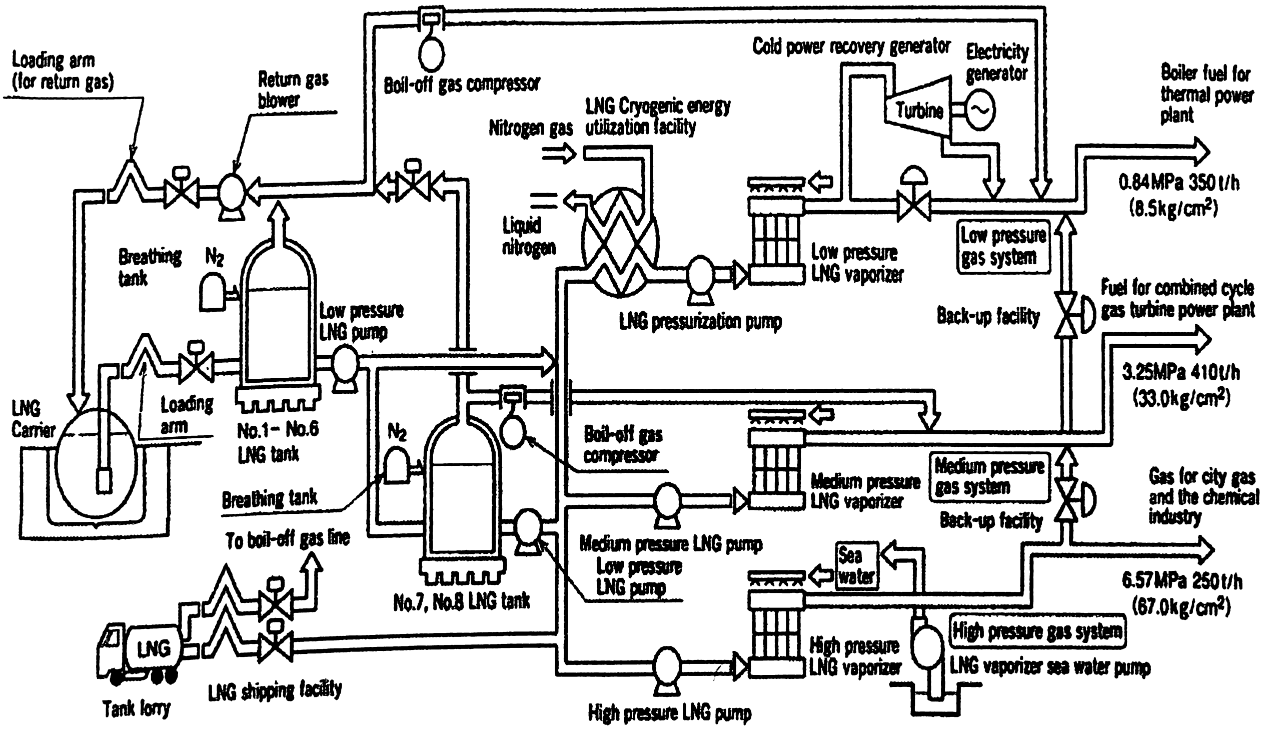
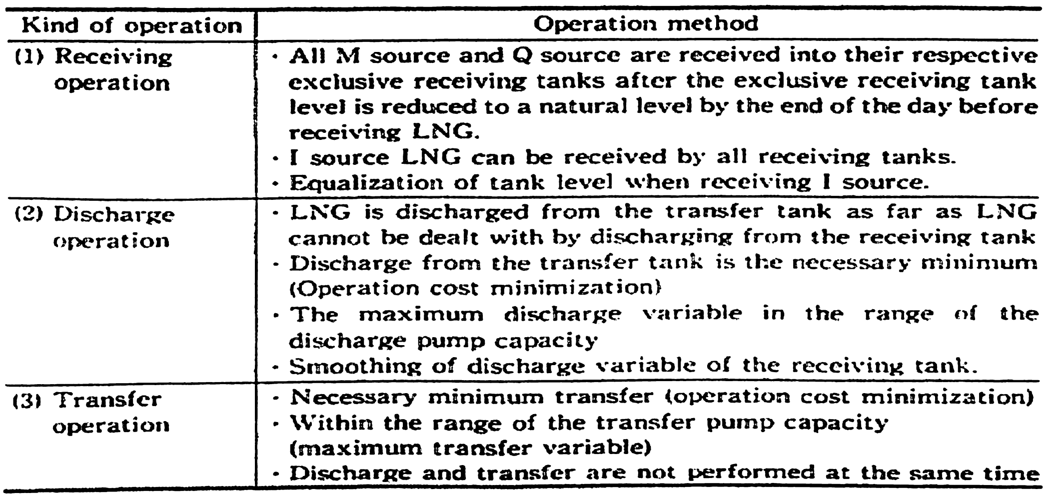


Figure 4.14: Schematic diagram of Niigata LNG receiving terminal, Nihonkai LNG Co.

Division	Equipment name	Capacity	Quantity
Storage facility	LNG receiving tank	100 000 kl	2 Units
		80 000 kl	4 Units
	LNG transfer tank	100 000 kl	2 Units
Discharge facility	LNG pump	120 t/h	22 Units (Receiving 18 units/transferring 4 units)
	LNG source		Number of times of ship arrival
LNG carrier	I source	About 125 000 m³	About 55 ships/year
	M source		About 9 ships/year
	Q source		About 10 ships/year

Table 4.4: Outline of LNG storage facility



Kind of operation	Operation method
(1) Receiving operation	· All M source and Q source are received into their respective exclusive receiving tanks after the exclusive receiving tank level is reduced to a natural level by the end of the day before receiving LNG. · I source LNG can be received by all receiving tanks. · Equalization of tank level when receiving I source.
(2) Discharge operation	· LNG is discharged from the transfer tank as far as LNG cannot be dealt with by discharging from the receiving tank · Discharge from the transfer tank is the necessary minimum (Operation cost minimization) · The maximum discharge variable in the range of the discharge pump capacity · Smoothing of discharge variable of the receiving tank.
(3) Transfer operation	· Necessary minimum transfer (operation cost minimization) · Within the range of the transfer pump capacity (maximum transfer variable) · Discharge and transfer are not performed at the same time

Table 4.5: Tank operation for application

When LNG stratification occurs due to difference in LNG density in the storage tank, an unstable phenomenon (LNG rollover) can occur in which the upper layer and lower layer reverse with the passage of time and a large quantity of LNG is gasified as BOG (BOG : Boil-off Gas) with the possibility of abrupt rise in the internal pressure of the tank. At present Niigata terminal receives LNG from three sources; I, M and Q. To prevent LNG rollover when receiving LNG from these different sources having different LNG density, following Operation is applied.

Since the receiving tank receives LNG through the bottom feed, heavy LNG of M and Q source are received in their respective designated receiving tanks at all times and different kinds of LNG are not mixed. Furthermore, because the 'I' source LNG is light compared to the other two kinds, it can be fed through the bottom feed line into the tanks and all six receiving tanks may receive source LNG. On the other hand because the transfer tank can changeover to bottom or top feed, LNG in the tank can be mixed and LNG from all receiving tanks can be transferred. Moreover, in the transfer tank, composition change of LNG is prevented by transfer from the receiving tank at the minimum flow rate which prevents boil down of LNG and regular discharge of same quantity of LNG from the transfer tank.

CHAPTER 5.

CALCULATION

5.1 Design Basis of a LNG Storage Tank

Design Code : BS7777

5.1.1 Tank dimensions

Inner tank dia	:	79.0 m
Design liquid level inner	:	32.82 m
Hydrotest level	:	19.692m
Product density	:	480 kg/m^3
Operating temperature	:	-160^{0}C
Max. design ambient temperature	:	45^{0}C
Corrosion allowance inner tank	:	0(zero) mm
Inner tank material	:	9% Ni Steel
Youngs modulus	:	20800 kg/mm^2
Coefficient of linear expansion	:	9.2 X 10^{-6}

5.1.2 Thickness & height of each course of side wall

No. of Course	Nominal Thickness (mm)	Height (mm)
9	12	3730
8	12	3730
7	12	3730
6	12	3730
5	13.2	3730
4	15.6	3730
3	18.2	3730
2	20.8	3730
1	23.5	3730

Table 5.1: Thickness & height of each course of side wall

(From BS7777)

Inner tank shell plate thickness : minimum i.e. 12.0 mm

5.1.3 Maximum allowable design stress

The maximum allowable design stress is as following:
For operating : 260 N/mm^2
For testing 331.5 N/mm^2

Maximum allowable stress under hydrostatic test shall be determined by the following expression :
Minimum (UTS/2.35 , 0.2% PS/1.5 , 260 N/mm^2)

& Maximum allowable stress under hydrostatic test shall be determined by the following expression:
Minimum (0.2%PS X 0.85 , 340 N/mm^2)

In this case, welding metal is weaker than the base metal & yield strength & the ultimate tensile strength of welding metal are considered.

Their values at room temperatures are as following

UTS = 660 N/mm^2

0.2 % PS = 390 N/mm^2

5.2 Calculation Method

Under operating condition

$$T = D/20 \times S \{98\, W\, (H - 0.3) + P\} + C$$

Where;

T = calculated minimum thickness (mm)

H = height from bottom of course under consideration of highest liquid level (m)

D = tank inside dia. (m)

W = maximum density of liquid under storage condition (g/m^3)

B = allowable design stress (N/mm^2)

P = design pressure

C = corrosion allowance

Under testing condition

$$T_t = D/20 \times S_t \{98\, W_t\, (H-0.3) + P_t\}$$

Where,

T_t → Calculated minimum thick (mm)

H → Height from bottom of course considered

W_t → Maximum density of liquid under storage conditions (g/m^2)

S_t → Allowable design stress (N/mm^2)

P_t → Design pressure (mbar)

5.2.1 Calculated results

No. of Course	Liquid level (m)	Calculated thickness (mm)	Liquid level (mm)	Calculated thickness(mm)	Design thickness(mm)
9	2.980	2.0	-	-	11.8
8	6.710	4.6	-	-	-
7	10.44	7.3	-	-	-
6	14.17	10.0	1.042	0.9	-
5	17.9	12.6	4.772	5.3	13.0
4	21.63	15.3	8.502	9.6	15.4
3	25.38	18.0	12.232	14.0	18.0
2	29.09	20.6	15.962	18.3	20.6
1	32.82	23.3	19.692	22.7	23.3

Table 5.2: Calculated results for tank thickness

Note:-- *Fabrication allowance of 0.2 mm taken into consideration*

5.3 Boil Off Calculations

5.3.1 Properties of insulation materials

Material	Thickness (mm)	Thermal conductivity (kcal/hr m c)
Dry sand	$T_{b1} = 0.4$	$K_{b1} = 0.5$
Foam glass	$T_{b2} = 0.408$	$K_{b2} = 0.039$
Base glass	$T_{b3} = 1.0$	$K_{b3} = 2.0$
Concrete ring beam	$T_{b11} = 0.3$	$K_{b11} = 2.3$
Leveling perlite concrete	$T_{b21} = 0.508$	$K_{b21} = 0.18$
Base slab	$T_{b31} = -1.0$	$K_{b31} = 2.0$
Concrete wall	$T_{s1} = -0.8$	$K_{s1} = 2.0$
Perlite	$T_{s2} = 0.8$	$K_{s2} = 0.0378$
Fibre glass	$T_{s3} = 0.2$	$K_{s3} = 0.033$
Roof concrete	$T_{r1} = 0.4$	$K_{r1} = 2.0$
Fibre glass	$T_{r2} = 1.0$	$K_{r2} = 0.033$

Table 5.3: Properties of insulation materials for calculation

5.4 Heat Influx Calculation

$Q = Q_b + Q_s + Q_r = Q_{bi} + Q_{bii} + Q_s + Q_r$

Where,

Q = heat flux

Q_b = heat flux through the bottom part

Q_{bi} = heat flux through the centre part of bottom

Q_{bii} = heat flux through the ring part of bottom

Q_s = heat flux through the side wall part

Q_r = heat flux through the roof part

At day time

a) **Heat flux through bottom Q_b**

(i) **Centre part**

$Q_{bi} = U_{bi} \times A_{bi} \times (T_1 - T_2)$

$= 0.0851 \text{ X } 4347.5 \text{ X } 213.0$

$= 78804.09$ kcal/hr

Where,

U_{bi} = any heat transfer coefficient

$= (T_{b1}/k_{b1} + T_{b2}/k_{b2} + T_{b3}/k_{b3})^{-1}$

$A_{bi} = 4347.5 \text{ m}^2$

$T_1 - T_2 = 45.0 - (-168.0) = 213^0C$

(ii) **Ring part**

$Q_{bii} = U_{bii} \times A_{bii} \times (T_1 - T_2)$

$= 0.288 \text{ X } 805.54 \text{ X } 213$

$= 49415$ kcal/hr

Where,

$U_{bii} = (T_{b11}/k_{b11} + T_{b21}/k_{b21} + T_{b31}/ k_{b31})^{-1}$

& $A_{bii} = 805.54\ m^2$

(b) Heat flux through side wall Q_s

$Q_s = U_s \times A_s \times T_{diff}$

$= 0.0362 \times 8884.04 \times 229.1$

= 7368 kcal/hr

Where,

$U_s = (T_{s1}/k_{s1} + T_{s2}/k_{s2} + T_{s3}/k_{s3})^{-1}$

$\Delta T = 97702 -(-168) + 45 - (-168)/2$

$= 229.1^0C$

(c) Heat influx through roof

$Q_r = q_1 x A_r$

$= 7.6 \times 4901.67$

= 37435 cal/hr

Assuming spherical dome to be horizontal, plane heat input $q_1 x A_r$ through the roof is determined through heat balance $q_1 = q_2 = q_3$

$Q_1 = U_{r1} \times \Delta T_1$

$= 5 \times 1.53 = 7.65$ kcal/hr m^2

U_{r1} = average heat transfer coefficient

$U_{r1} = (T_{r1}/k_{r1})^{-1} = 5$ kcal/hr $m^2\ {}^0C$

$\Delta T_1 = T_r - T_i = 82.2 - 80.67 = 1.53\ {}^0C$

Q_2 = heat transfer between inside of roof & upper surface of suspended deck insulation by heat radiation

Q_2 = 4.88 kcal/hr $m^2\ {}^0C$

Q_3 = heat transfer through suspended deck insulation by thermal conduction

$= U_{r2} \times \Delta T_{r2}$

$= 0.033 \times 231.09$

= 7.6 kcal/hr m^2

$U_{r2} = (T_{r2}/K_{r2})^{-1} = 0.033$ kcal/ hr $m^2\ {}^0C$

$\Delta T_{r2} = T_u - T_d = 63.09 - (-168) = 231.09\ {}^0C$

T_r = Temperature at outer surface of roof 82.8^0C

T_i = Temperature inside roof

T_u = Temperature at upper surface of suspended insulated deck

T_d = Temperature at lower surface of suspended insulated deck

A_r = Area of spherical domes

A_d = Area of suspended deck insulation

(d) Total heat flux (Q)

$Q = Q_{bi} + Q_{bii} + Q_s + Q_r$

$= 78804 + 49415 + 73680 + 37435$

= 239,334 kcal/hr

(c) Boil off rate at day time

Rate $= 240\ Q_t / (V\ \rho\ L)$
$= 2400 \times 239334 / (160873 \times 425 \times 122)$
$= 0.0689$

Where,
V = Tank content volume,
ρ = dia density,
L = Latent heat

At night time

(a) Heat influx through bottom (Q_b)

Same as day time
Thus,
(i) central part $Q_{bi} = 78804$ kcal/hr
(ii) ring part $Q_{bii} = 49415$ kcal /hr

(b) Heat flux through side wall (Q_s)

$Q_s = W_s \times T_s \times \Delta T_{s1}$
$= 0.0362 \times 8884.04 \times 213$
$= 68504$ kcal/hr
$\Delta T_{s1} = 45 - (-168) = 213\ ^0C$

(c) Heat flux through roof Q_r

$Q_r = q_1 \times A_r$
$= 6.303 \times 4901.67$
$= 30896$ kcal/hr

(d) Total heat influx

$Q = Q_{bi} + Q_{bii} + Q_s + Q_r$
$= 78804 + 49415 + 468502 + 30896$
$= 227617$ kcakl/hr

(e) Boil off rate at night time

Rate $= 2400\ Q_t / (V\rho L)$
$= 2400 \times 22761 / (160873 + 425 + 122)$
$= 0.0655$

Boil off rate all day long
At day time = 0.0689 (wt % / day)
At night time = 0.0655 (wt %/day)
Assuming day time & night time would go on for 12hr each, boil off rate is equal to 0.0672 < 0.08 (wt% /day)
Boil off gas produced $= (138000 \times 0.64 \times 600 \times 0.0672) / (3.8 \times 24 \times 100)$
= **360 kg/hr**
= 0.5 mmscfd

Assuming two tanks implies total BOG generated is equal to 1mmscfd.

Since amount is less & pressure ratio is more we go for reciprocating compressor.

5.5 Heat Transfer Analysis

The thermal characteristics of ORVs are very complex due to the spread of icing growth or other unknown factors. Thus, we made our approach with two assumptions:

1. ORVs are operated under no icing conditions and
2. Any boiling in star-finned tubes has not occurred.

The total resistance for ORV can be expressed as

$$\frac{1}{UA} = \frac{1}{h_t A_t} + \frac{1}{h_s A_s} + R_W \qquad (1)$$

Where, *t* and *s* denotes the LNG side and the seawater side, respectively, and R_w is the resistance of the tube wall. Generally, the convective coefficients can be obtained from *Nu* numbers of the LNG side and seawater side. The *Nu* number of seawater gives

$$Nu_s = C_s\, Re_s^d Pr_s^{0.4} \qquad (2)$$

Where, C_s, Pr_s and Re_s denote the constant. Prandtl number and Reynolds number, respectively. The Reynolds number of the seawater side can be found with the flow of model on falling fim. The Re_s becomes

$$Re_s = \frac{4\Gamma}{\mu}\ , \quad \Gamma = \frac{\delta^3 \rho g}{3\nu} \qquad (3)$$

Where, μ, ν, δ, ρ and g are viscosity, kinematic viscosity, flow thickness, density, and gravity, respectively. The *Nu* number of the LNG side is also expressed as

$$Nu_t = C_t\, Re_t^a Pr_t^{0.4} \qquad (4)$$

The wall resistance for a tube side can be calculated from

$$R_W = \frac{\ln(D_o/D_i)}{2\pi k L} \qquad (5)$$

Where, D_o, D_i, k and L denote outer diameter, inner diameter, thermal conductivity and tube length, respectively.

If the LNG side correlation and the wall resistance are known, the following expression can be used to calculate the seawater side parameters C_s and d.

$$\ln(1/y_s) = \ln(C_s) + d\ln(Re_s) \qquad (6)$$

Where, y_s is expressed as

$$y_s = \left[\frac{1}{UA} - R_w - \frac{1}{C_t[(R_e)^a (P_r)^{0.4} Ak/D]_t}\right][(Pr)^{0.4} Ak/D]_s \qquad (7)$$

Where, *A* is the area of heat transfer. From Eq. (6), the seawater side graph should therefore yield a straight line.

The slope and intercept can then be used to calculate *d* and C_s respectively.if the seawater side correlation and the wall resistance are known, the following expression can be used to determine the LNG side correlation

$$\ln(1/y_t) = \ln(C_t) + a\ln(Re_t) \qquad (8)$$

Where y_t can be written as

$$y_t = \left[\frac{1}{UA} - R_W - \frac{1}{C_s[(R_e)^d (P_r)^{0.4} Ak/D]_s}\right][(Pr)^{0.4} Ak/D]_t \qquad (9)$$

The above equation should therefore yield a straight line that can be used to calculate both a and C_t.

Assuming that both the seawater side and LNG side resistance are known, the tube wall resistance can be calculated from

$$\frac{1}{UA} = \frac{1}{h_t A_t} + \frac{1}{h_s A_s} + R_w \qquad (10)$$

The above equation should result in a straight line with a slope equal to unity and an intercept equal to wall resistance value. From the calculations, a, d, C_t and C_s were converged at 1.0325, 0.806, 0.0018, 0.000489, respectively. Also, R_w was converged at 4.20 K/kW.

CHAPTER 6.

CONCLUSIONS

Conclusion

The major global investment in new LNG liquefaction and re-gasification capacity is creating substantial new competition in the natural gas market. Companies that can optimize the performance of their production assets will be well placed to improve their margins and achieve a significant competitive advantage.

Construction costs of the LNG storage tanks occupy major portion of the LNG terminal's total construction costs. Thus, there is a clear tendency toward LNG tanks of higher capacity since it has been recognized as the desirable method for maximizing cost efficiency. Encouraged with revisions of existing codes that may restrict the economical design, it is expected that above-ground LNG tanks that have higher capacity will be constructed. Design procedure of above-ground prestressed concrete (PC) LNG storage tanks of full containment type with 200,000 m^3 capacity has been investigated.

Together with basic design of the tank, distinct features of increased structural efficiency and so induced material saving is pursued over the existing above-ground type tanks.

We also see that, cryogenic temperature of LNG significantly affects the liquid tightness of the outer concrete wall of LNG tank. Prestressing tendon design is of a primary importance to ensure the liquid tightness. Validity of the conventional design practice of tendons has been discussed considering the residual compressive stress. A more consistent design procedure for the liquid tightness is proposed based on the partial prestressing strategy. To obtain the reliable section forces induced from the LNG temperature, reasonable yet simple heat transfer analysis model is also proposed. The proposed schemes are expected to provide an efficient way of serviceability design of LNG tank that satisfies the various requirements for the liquid tightness.

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