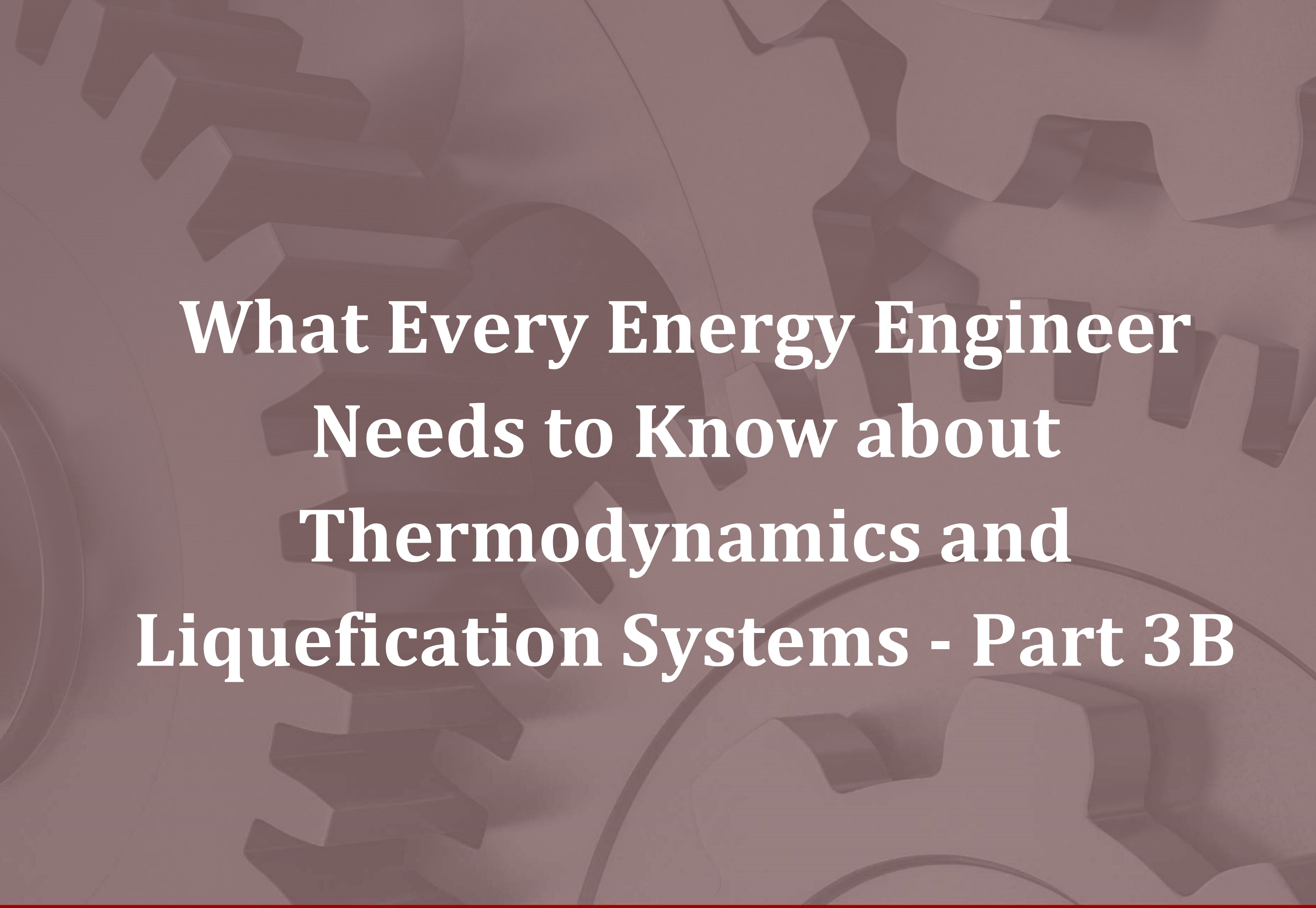

# What Every Energy Engineer Needs to Know about Thermodynamics and Liquefication Systems - Part 3B

An Online Continuing Education Course for Engineers

**Course Number: O-4007**

**Credit: 4 Hours / 4 PDH / 4 CPD**

# O-4007: What Every Energy Engineer Needs to Know about Thermodynamics and Liquefication Systems - Part 3B

Steven Vitale, P.E., PhD

## Learning Objectives

In the earlier courses, the basics of thermodynamics were covered and applied to a single-component (pure substance) refrigerant system. The car air conditioner was used as a basis for understanding the vapor compression, pressure let down, and evaporation cooling system. Later, the same concepts were applied to zeotropic mixed refrigerants, which expanded the temperature range for which liquefied natural gas could be made. It was shown that when the feed gas to an LNG plant was pretreated and cooled to -260 F, LNG could efficiently be produced and stored.

Another type of liquefaction system was explained in section 1 of 3. This was the open expansion type of liquefaction system. This system used high-pressure gas from the pipeline to power a liquefaction system by expanding the gas through expanders, which produced work. The work from the expanders was used to drive compressors, which compressed the gas to be liquefied and expanded to even higher pressures. In this section, the focus will be solely on the conceptual evaluation of a nitrogen expansion system. Then nitrogen expansion LNG liquefier is not the most efficient liquefaction process. Still, it is considered the easiest to operate, and it lends itself well to making LNG near its tank saturation temperature, which greatly lessens boil-off management problems. Many of the newer small-scale liquefiers, like those for peak shaving plants, use the nitrogen expansion process. This process has increased in efficiency over recent decades as manufacturing processes have improved, making the expanders and compressors more efficient, thus making the operating cost of this process more cost-effective.

The learning objectives of this section are to:

- Understand the thermodynamics of compression and the work required
- Understand the thermodynamics of expansion via expanders and the work delivered.
- Understand the temperature relationships that occur when nitrogen is compressed and expanded.
- Understand the methodologies used to drive expansion temperatures to low enough levels to make LNG
- Understand how to improve the efficiency of nitrogen expansion systems applied to LNG facilities.

## A Safety Moment

This learning document is meant to be at a technical level, mostly on refrigeration systems. The most important intention of every document I produce is to give you the basic technical knowledge you need to start your study on how to continue making the Liquid Natural Gas Industry a "Safe and Reliable Industry." You need technical knowledge to do that.

The image to the right is placed here as a reminder that everyone has someone who loves and needs them to come home at the end of their shift.

Reliability is also related to safety because if the LNG plant cannot make LNG into vapor when needed, the consuming public may be out of gas during the worst of cold weather times. This would put the public at severe health risk.

We, as engineers, need to ensure that our designing, planning, operating, and maintenance of LNG facilities help assure safety and reliability.

This will help ensure that everyone comes home at the end of their shift and that gas is supplied when needed by the end-user customers.

*Figure 0.1: Beautiful Granddaughter*
***Source: Self-made photo***

# 1. Introduction

Two hundred years ago, ice was harvested from frozen rivers in the winter, and large chunks of it were stored in buildings insulated by large bales of hay and sawdust. During the spring and summer, that ice was consumed but those who could afford it, and once it ran out, there was no way to produce the heat extraction needed to make ice. The only source of that cold product was to wait for the winter weather to produce it!

In 1834, Jacob Perkins invented the first vapor compression system for refrigeration, and in 1876, Carl von Lined patented a new process for liquefying gases. Today nearly every car and home are air-conditioned via various technologies; the most common is the vapor-compression–condensation–pressure-drop-evaporation system. This system is used in household refrigerators and massive liquefaction plants worldwide. The massive systems used in LNG export facilities use the same principles as most home refrigeration systems, except that some enhancements are used to make the large-scale systems more energy efficient. Also, the refrigerants needed to produce very cold temperatures differ from those used in home air-conditioning and refrigeration systems.

It is taken for granted that when a cold soda is desired, it is readily available from the refrigeration system in the house. The amazing thing is that the refrigeration systems are so well perfected that typically, the only reason they are replaced is that they go out of style and not because they need to be fixed. These systems have been running for many decades with little maintenance. These smaller systems have been reliable for so many years because, since the late 1920s, these small-scale refrigeration systems have been hermetically sealed. That means the motor and compressor are in a sealed case without the need for shaft seals that could leak and without any possibility of refrigerant contamination.

Over the past 189 years, since Jacob Perkins invented the vapor compression refrigeration system, refrigerant technology has also developed significantly. In the 1800s, refrigerants were extremely toxic, and some were inefficient. These toxic refrigerants included ammonia, methyl chloride, and sulfur dioxide. Refrigeration systems were often installed outside to avoid death from a refrigerant leak.

I had chemical pneumonia for a month due to exposure to anhydrous ammonia from a small refrigeration system. Such exposures have killed many.

In 1928, halogenated hydrocarbons such as chlorofluorocarbons (Trade-named Freons) were invented. This revolutionized refrigeration, and various Freon compounds were developed for various temperature applications. However, in the late 1900s, as it became apparent that Freon were harmful to the environment, legal restrictions were placed on using and reusing Freons. With the phasing out of older traditional Freons, newer refrigerants (hydrofluorocarbons, also trade name Freons) were introduced, such as R-134A for automobile applications and R-410a for home air conditioning applications. Even these refrigerants have associated environmental concerns, and newer refrigerants are under development.

For very low-temperature refrigeration systems (LNG production), Freons cannot be used because they cannot achieve the very low temperatures needed to liquefy natural gas. Instead, mixtures of nitrogen, methane, ethane, propane, and iso-pentane are some of the most common refrigerant mixes used for attaining ~ -260 F. In a large LNG production facility, the downside of these refrigerants is that tons of them are needed in these systems that cannot be hermetically sealed, and all but nitrogen are highly flammable. Any system that contains large quantities of pressurized flammable liquids and vapors poses a risk to the plant and its operators.

There are billions of small-size air conditioning/refrigeration systems in operation today, but only a few hundred behemoth-size systems are used in the LNG liquefaction industry. There are many other gas liquefying industries, but this work will limit its focus to understanding small, simple systems and then learn about the larger systems used for liquefying natural gas.

Although the basic technology is the same between the small-size units and the large units, the complexity of the systems and the refrigerants used differs as the desired temperatures become colder and as the capacity of the units becomes larger.

If the outside environment is at 80 F, it takes little energy, and the technology is simple to achieve the 35 F temperature needed to cool down a soda. It takes more energy to store frozen food at 0 F, but the technology is still simple.

However, suppose the outside environment is 80 F. In that case, it will take a significantly large amount of energy and more complex technology to achieve the ~ -260 F temperature needed to make Liquid Natural Gas (LNG). To achieve a temperature of ~ -424 F to liquefy hydrogen, the energy and technology required increases many-fold over that needed to make LNG. To take this to the extreme, liquid helium (the very coldest gas liquefied) can be produced at ~ -452 F and is extremely difficult and power-intensive. Keep in mind that the absolute zero temperature is -459.67 F.

Engineers need some understanding of thermodynamics to better respond to anomalies during plant operation. The thermodynamics presented in this publication are basic and based on application rather than theory. The cases studied are all steady-state (the properties of the fluid at any point do not change with time) and steady-flow (the flow rate does not change with time) type problems. All the solutions are based on some simple calculations and/or on the use of the pressure-enthalpy chart or thermodynamic software. A large-size pressure enthalpy chart for methane or thermodynamic software should accompany this publication.

This Section 3B is the last of a 3-part series (with section 3 being made of two parts, 3A and 3B) on the thermodynamics of producing LNG. In earlier sections, vapor compression systems and open expansion systems were explained. In this section, nitrogen expansion systems will be explained.

## Cautionary Note

This document is intended to teach basic concepts. To accomplish this, a simplified approach is taken to explain thermodynamic processes.

Real plants have pressure drops associated with flows through piping, exchangers, and other processing equipment. Such pressure drops are not considered in the simplified examples given herein. Parts of the plant, such as the $CO_2$ and water removal systems, were not included in the analysis because their study is outside the scope of this document.

Also, rounded-off numbers are often used throughout to allow the reader to focus on the concept without getting bogged down in numerical detail.

## Facilities in the United States and Codes that Govern Them

The Federal Energy Regulatory Commission (FERC) governs most permanent LNG facilities in the U.S. via the Federal Code of Regulations (code 49CFR193). This code requires the governed facilities to abide by the National Fire Prevention Association (NFPA) 59A consensus code. Many countries around the world also conform to NFPA 59A.

The U.S. Pipeline and Hazardous Material Association (PHMSA) collects data on LNG facilities annually. According to PHMSA, the inventory of LNG facilities as of 10/1/2022 for the 2021 annual reporting year is as follows:

https://www.phmsa.dot.gov/data-and-statistics/pipeline/gas-distribution-gas-gathering-gas-transmission-hazardous-liquids

- 71 Peak Shaver (PS) LNG Facilities (48 with liquefiers) **(Almost 70 %)**
- 23 Satellite (Sat) LNG Facilities (1 with liquefier – that is how it is reported)
- 26 Base Load LNG (liquefiers - not counted)
- 40 Mobile or temporary LNG facilities
- 8 Other LNG facilities
- Of the 94 Peak Shaver and Satellite LNG facilities, 44 (47%) facilities in the Northeast
- Of the 94 Peak Shaver and Satellite LNG facilities, 72(77%) 1960’s – 1970’s vintage
- Of the 48 PS and Sat in the Northeast U.S., 40 (83%) 1965 – 1975 vintage
- Of the 48 PS and Sat in the Northeast U.S, 12 (25%) have liquefiers

The Northeast is emphasized because it is the country’s area where local distribution companies (LDCs) are heavily dependent on LNG, as many of these facilities receive LNG via tanker truck from the Everett LNG import terminal.

# 2.0 Terms and Units of Measure for Natural Gas and LNG

## Abbreviations

The following abbreviations, terms, and units will be used in this document for natural gas and LNG:

| | |
|---|---|
| U.S. | United States |
| Peak Shaver | An LNG facility used to supplement the supply of natural gas during times of high gas demand |
| Satellite | An LNG facility used to supply gas to a localized area |
| Sendout | Natural gas or vaporized LNG sent out by a gas utility via pipelines to customers |
| Boil-off gas | The gas that boils off from an L ank as heat is into the tank from the environment (sometimes just ca |
| F | Degree Fahren |
| Psia | |
| Psig | |
| Lbm | |
| Lbf | P sec$^2$) |
| Cu.ft. | A |
| BOG | Boil-off |
| SCF | A standa x 1′ volume of gas at a standard temperature and pressure. this document, the American Gas Association (A.G.A.) definition of standard pressure and temperature of 14.73 psia and 60 F is used. |
| BTU | Btu is the amount of energy needed to raise 1 lbm of water 1 deg F. This is not a precise measure of energy because different industries and countries use different standard temperatures for the water being heated. The heat capacity of water differs with temperature. |
| HHV | Higher heating value is the heat released from burning an SCF of natural gas at 60 F with air at 60 F and bringing the combustion products down to 60 F. |
| Therm | By definition, a Therm is 100,000 Btu. |
| Dekatherm | Deca means 10, so a dekatherm is 1,000,000 Btu. |
| MSCF | In the U.S. Gas Industry, “M” means 1,000. Thus, MSCF is 1,000 SCF. |