Containerized Compressed Natural Gas Shipping

by

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Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Mechanical Engineering

at the

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ABSTRACT

In the last decades, the demand for energy is increasing. It is necessary to develop new ways to distribute the energy using economically feasible solutions. In this project an Ultra Large Container Ship is used that can carry more than 12,000 TEUs. Inside each TEU, four cylinders are installed that can store compressed natural gas at 250 bar. Two types of cylinders are tested: cylinders made of steel and cylinders made of carbon fiber. Carbon fiber cylinders were chosen because they are lighter. In addition, two types of compressors are used: centrifugal and reciprocating compressors. Centrifugal compressors are used to increase the initial pressure from 10 bar to 50 bar. Reciprocating compressors are used to increase the pressure from 50 bar to 250 bar. A model is developed using thermodynamics and MATLAB, in order to determine the total power required for a compressor to fill the entire vessel in one or more days. Furthermore, by using valuation metrics, a model is created to find the value of the project and to generate sensitivity analyses. It is concluded that leasing the ships is more profitable than buying them.

Thesis Supervisor: Paul D. Sclavounos
Title: Professor of Mechanical Engineering and Naval Architecture

Dedication

This thesis is dedicated to my parents, Vasilis and Maria, whose support, guidance and constant love have sustained me throughout my life and have provided me the opportunity to pursue my dreams.

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1. Introduction

1.1 The Natural Gas Market

Natural gas will play an important role worldwide for the next several decades. Natural gas accounts for 14% of the total world energy supply. That share is expected to rise especially in North America and Europe.

Natural gas is a gaseous-phase fossil fuel and is lighter than air. It is used for residential purposes such as space heating, water heating and cooking. In the last decade, gas is also used to generate electricity. It is cleaner than conventional fossil fuels such as coal (solid substance) and oil (liquid substance). Gas is also more efficient and has lower levels of dangerous byproducts that are released into the atmosphere (Wang and Economides 2009).

There are many large deposits of natural gas around the world. Gas consumption is rapidly increasing, and the International Energy Agency (IEA) states that the global gas demand will rise by more than 50% between 2013 and 2035. According to IEA, gas will make to 32% of the global energy supply.

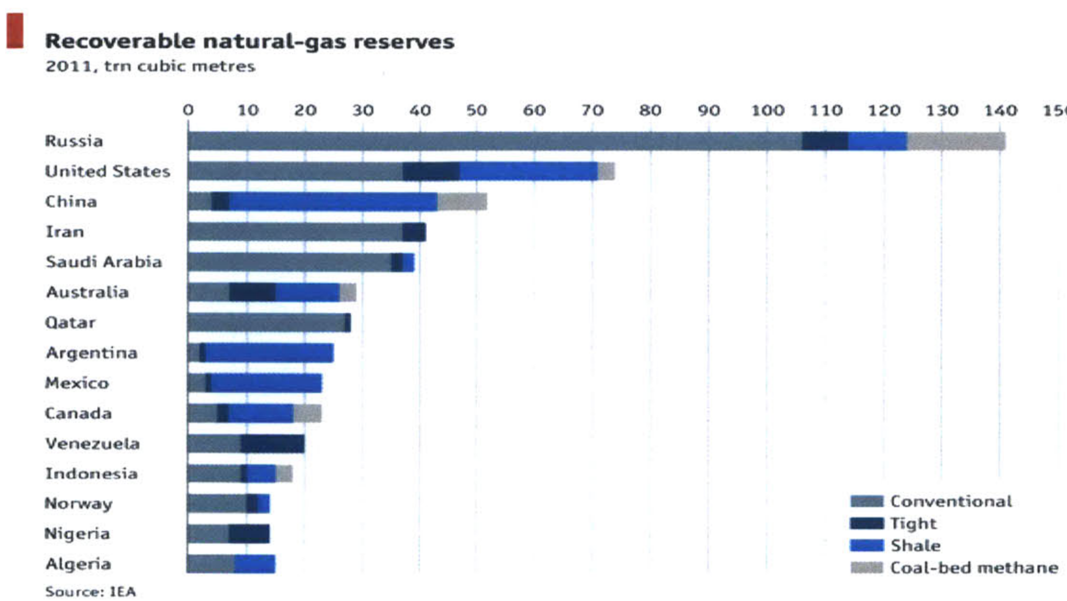


Figure 1: Recoverable natural-gas reserves

One drawback to natural gas is the difficulty in transporting it. Because of increased demand, there has been a substantial development in natural gas exploration and transportation

On the global natural gas market, USA and Russia account around 40% of the natural gas supply as can be seen from the graph below.

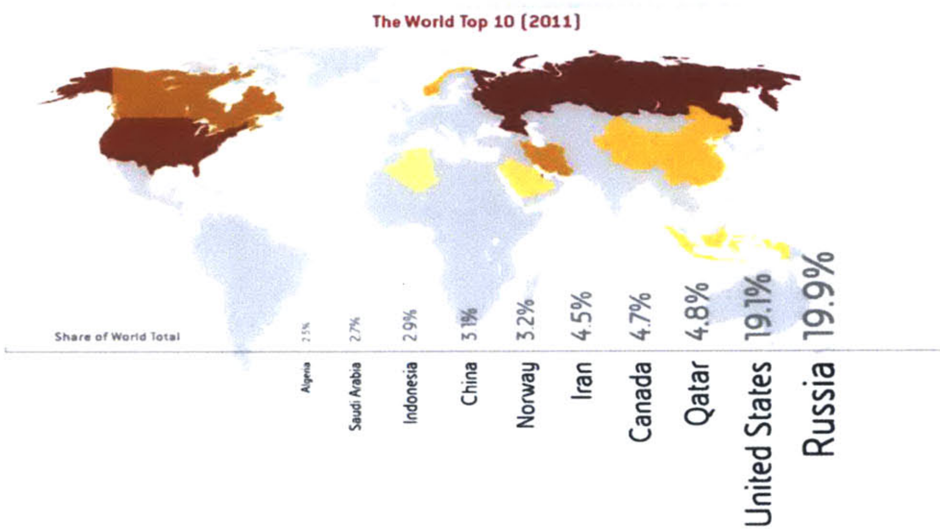


Figure 2: Top 10 Producers of Natural Gas

The following graph clearly shows that North America and Europe are the leading regions in natural gas consumption.

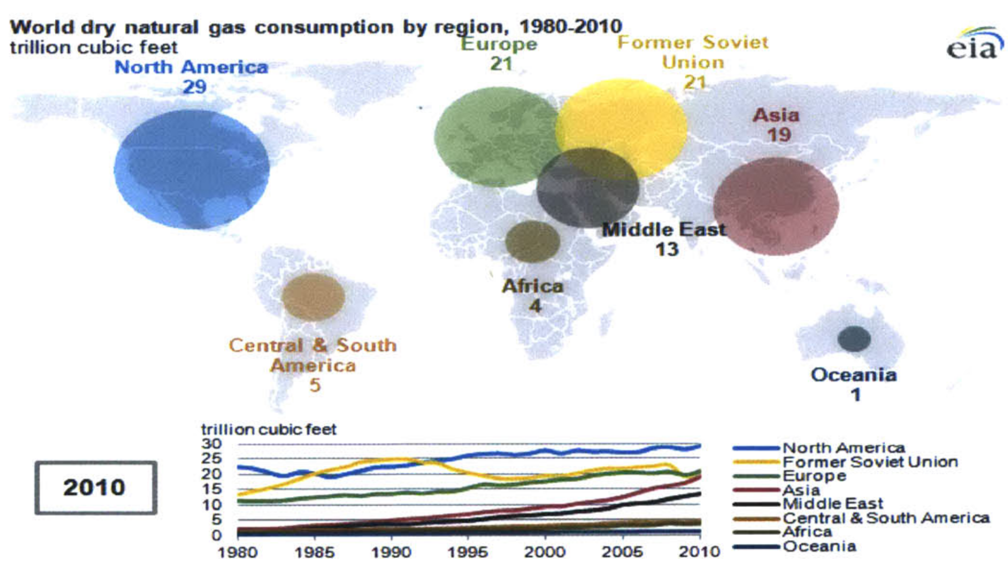


Figure 3: Natural Gas Consumption by region

Over the last years, Asia had a high growth rate in gas consumption and is approaching the level of Europe and North America. This growth is shown in Figure 3. This is due to the shutdown of Nuclear reactors in Japan after the Fukosima accident and the increased Chinese demand for the Russian natural gas.

1.2 Natural Gas Transportation

Due to rising environmental concerns and low price, natural gas is a front-runner in energy preference by customers worldwide. Hence, the transportation of it over long distances is a major issue for the majority of governments and the energy sector.

Two well established modes of transportation are used to carry natural gas over long distances from the sources to the consumers: pipelines and liquefied natural gas (LNG) ships. According to BP statistical review of World Energy, pipelines account for 70% of the transported gas and LNGs for the remaining 30%. Many countries construct LNG terminals for re-gasification in order to be able to get this fossil fuel directly from the LNG ships. Some LNG ships have already installed small re-gasification stations on them, in order to be able to transport greater gas volume from the port. These stations make LNG ships more competitive against the pipelines. The following figure clearly depicts LNG ships domination in the sea transport market of natural gas (Wang and Economides 2009).

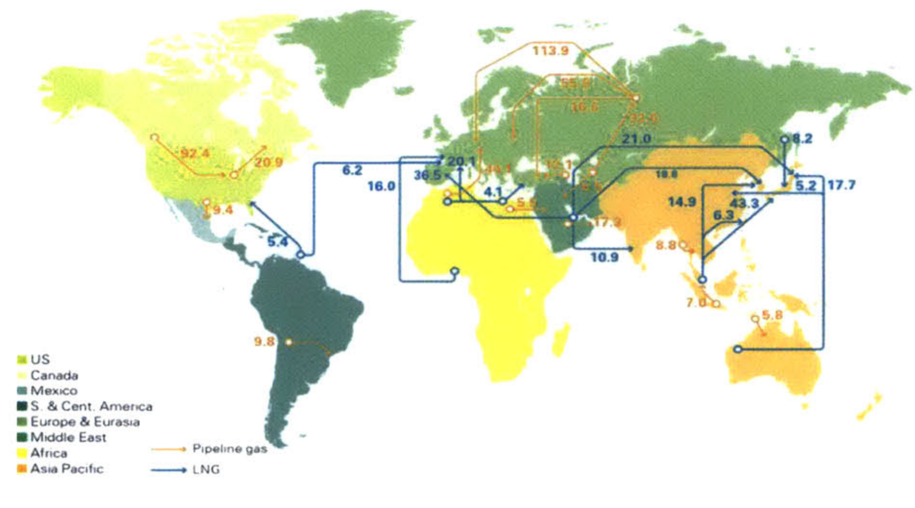


Figure 4: Use of LNG carriers and Pipelines around the world

1.2.1 Pipelines

Pipelines are less expensive than the LNG vessels. Underwater pipelines are also an option, but are very expensive. Pipelines are the common and efficient ways to transport natural gas on land. Of course, pipelines have political, technical and economical obstacles. High capital investment is needed for large-diameter pipelines and significant proven reserves for the next years. Larger pipelines mean that more compressor stations are necessary for the operation of the pipelines. Compressor stations require fuel and specialized workers to run. It is estimated that a pipeline costs around $1 billion to $1.5 billion per 1000 km. Pipeline transportation is less complex than the LNG process. In the last decade, the development of the underwater pipelines and offshore pipeline technology make pipelines a viable way of transportation. Pipeline usage reduces the unit costs of gas transportation thus making it more competitive to LNG vessels usage (Wagner and Wagensveld 2002).

Figure 5: Alaskan Pipeline

1.2.2 LNG Carriers

LNG ships are very expensive. They cost around $200 million to build and their maximum capacity is 160,000 cubic meters.

Figure 6: Liquefied Natural Gas Carrier

The obvious benefit of LNG carriers is the relatively easy access to distant markets. Generally, beyond 3,000 kilometers is too great and expensive of a distance for pipelines to cover (Wand and Economides 2009). The environmental concerns for oil transportation pipelines have frequently been more widely debated than for liquefied natural gas pipeline transportation. Pipeline projects such as the Baku-Tblisi Ceyhan, Chad-Cameroon, Camisea and the Yadana have become important landmarks for ecological activism. On the other hand, if the pipeline infrastructure can be moved underground then the environmental impacts can be reduced.

The advantage of LNG ships over pipelines and other modes of transportation for natural gas is clearly depicted by the following figure.

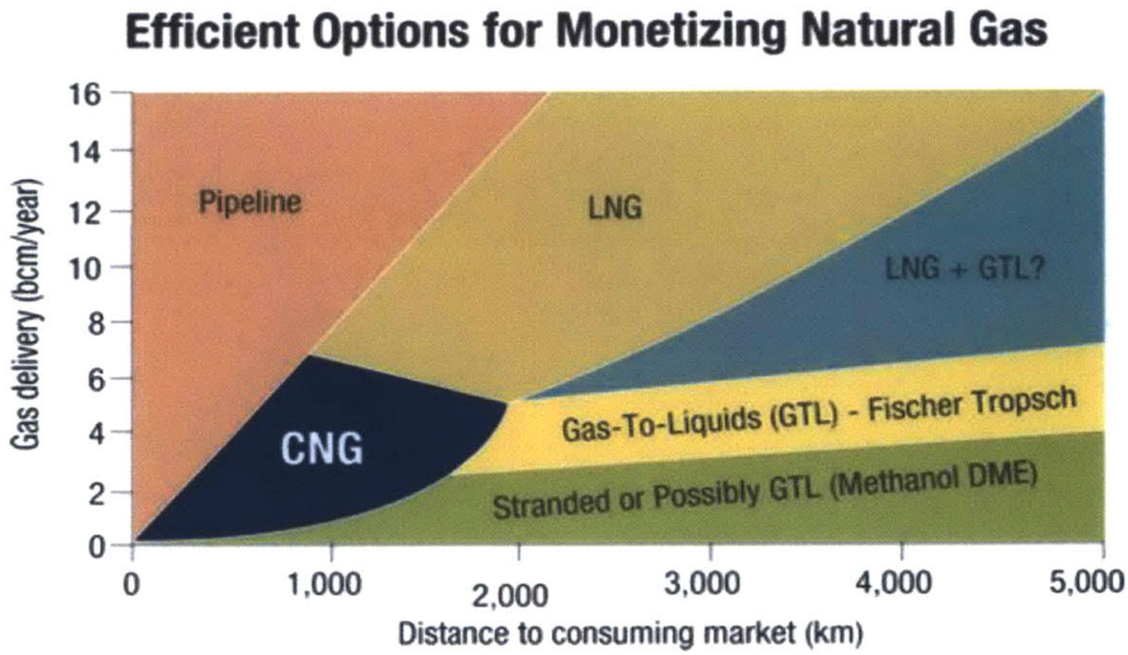


Figure 7: Options to transport Natural Gas according to the distance to consuming market

1.3 Compressed Natural Gas (CNG)

CNG is a natural gas compressed at pressures of 100 to 250 bar in order to reduce its volume. Ships, trucks and barges can transport it. It has been used to fuel buses, cars and other vehicles around the world. There are several maritime companies that use CNG vessels to transport compressed natural gas throughout the seas. These ships can be called "floating pipelines" (Wang and Economides 2009).

The first ship was constructed in the 1960's for the transportation of CNG. The name of the ship was Columbia Gas' SIGALPHA. This ship was capable of carrying compressed natural gas. Of course, this ship was uneconomical due to the low selling price of natural gas. This high transportation cost and low gas prices meant low returns for the investors (Wang and Economides 2009).

Today LNG ships are the leaders in sea transportation of natural gas because they can carry larger quantities for a considerable distance. Thus they can pick up and transport natural gas from any port.

Comparison of natural gas delivery by LNG and CNG tanker	LNG	CNG
Proved / stranded gas (10^{12} m³)	161	127
Capacity (million m³)	100 - 250	1,4 - 22
Reach (km)	6000 - 12,000	200 - 5,500
Upstream infra costs	very large	low
Downstream infra costs	very large	low
Number potential export sites	low	large
Global gas commodity market?	no	yes
Energy balance delivered gas	very strong	stronger
Public acceptance	low	unknown

Biopact 2007, cc

Table 1: Advantages of LNG Carriers over CNG Carriers

1.4 CNG Carriers and Shipping Companies

CNG carriers' technology is very simple. At an ambient temperature, natural gas is compressed to higher pressures (100-250 bar). A common CNG ship has a containment system of cylindrical, vertical or horizontal pipes to store the compressed natural gas. The pipes are made of steel in order to sustain the high temperature of natural gas intake.

In the last decade, many investors and shipping companies have shown interest in CNG projects. Some of the most famous shipping companies that own CNG carriers are: SeaNG Corporation, Knutsen OAS Shipping Company, Trans Ocean Gas Company and Enersea Transport LLC.

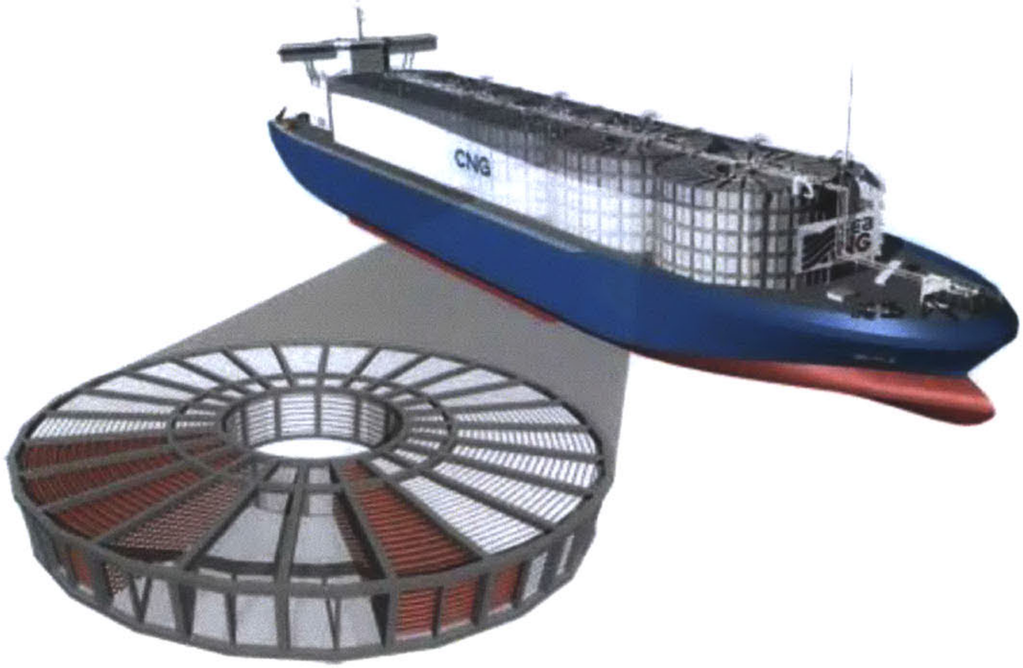


Figure 8: SeaNG Corporation's carrier

1.4.1 Sea NG Corporation

Sea NG Corporation is based in Canada. It has a model that stores compressed natural gas in coils of pipe wound into cylindrical containers called coselles. Coselles have a diameter of 17 meters and 4 meters in height. Every coselle weighs around 600 tons and has a capacity of 3 million MMscf of compressed natural gas. They can be stacked in the holds and on the deck. This type of CNG vessel combines safe and efficient loading and unloading facilities with the gas compressed at an onshore terminal. American Bureau of Shipping was the first classification society, which approved the first CNG carrier of Sea NG Corporation. Cost savings are achieved because these types of ships use their own natural gas, as a fuel thus the ship owner does not need to purchase heavy fuel oil, which is expensive.

1.4.2 Knutsen OAS Shipping Company

Knutsen OAS is a Norwegian maritime company, which developed a pressurized natural gas system. This system consists of pipes enclosed in cylindrical containers. Det Norske Veritas the Norwegian classification society approved this vessel. In this model, the natural gas is stored on-board at 250 bar at ambient temperature in vertical cylinders. The capacity of these ships varies from 2 million cubic meters to 30 million cubic meters. Their advantage is that they use natural gas as fuel so they have low cost. Their disadvantage is that the unloading of natural gas could be far away from shore and this increases the delivery cost.

The technology behind the Knutsen's ship is simple. It is a combination of a crude oil tanker and a container vessel. The ship's pressurized natural gas system is based on pipeline construction principles.

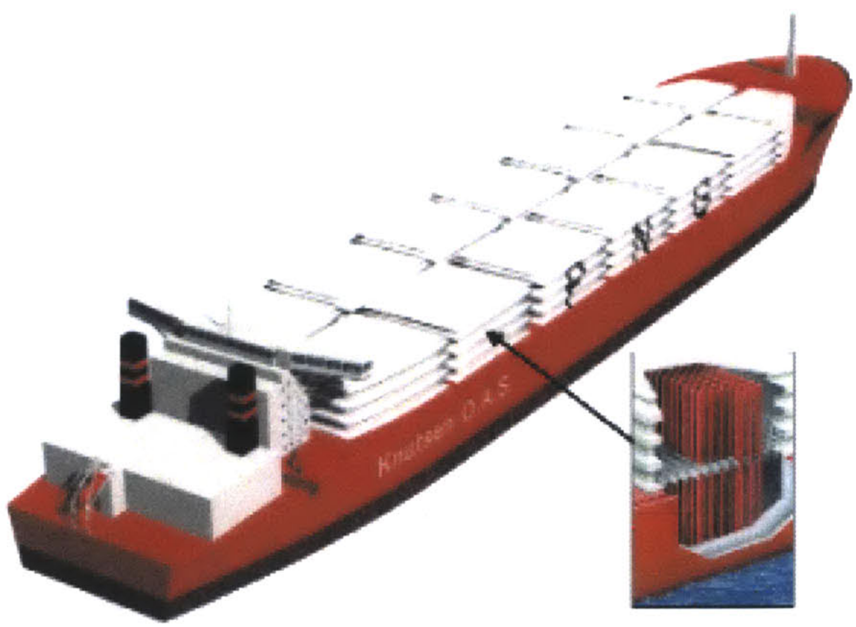


Figure 9: PNG Carrier of Knutsen OAS

1.4.3 Trans Ocean Gas Company

Trans Ocean Gas Company is based in Canada and uses fiber reinforced plastic pressure vessels to transport compressed natural gas at high pressures.

Fiber pressure vessels are considered safe and trustworthy and have various applications in different industries such as aerospace, offshore shipping and public transportation. Using fiber pressure vessels eliminates all the disadvantages of using conventional steel pressure vessels.

The Trans Ocean Gas CNG containment system is easier to install because it is developed in cassettes. The cassette system carries fiber pressure bottles vertically and manifolds are connected on the top and bottom of each cassette. In order to reduce their instability from vibrations and hydrodynamic movements, the cassette frames are made of steel. In addition, manifolds and pipes are manufactured by duplex stainless steel in order to be corrosion resistant (Trans Ocean Gas. July, 2010).

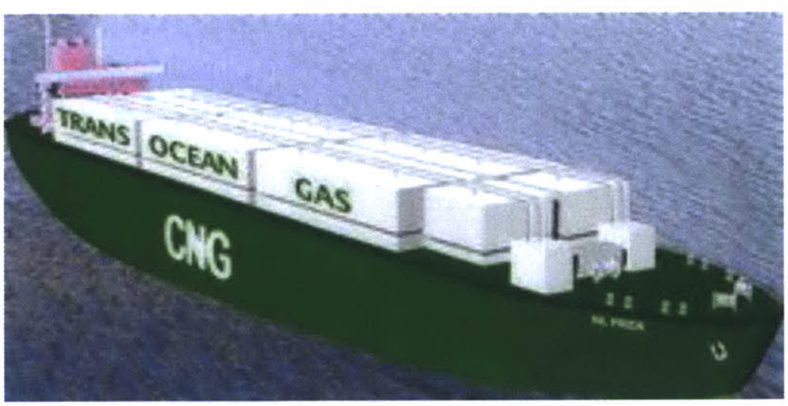


Figure 10: Trans Ocean Gas CNG Carrier

1.4.4 EnerSea Transport

EnerSea Transport is a US maritime company and has developed a cargo containment system known as 'VOTRANS' (Volume Optimized Transport Storage).This system includes compressed natural gas bottles made from large-diameter steel pipe sections. Optimizing pressure and temperature and using this containment method can achieve improved storage efficiencies of more than 60%.

Reducing the vessel's weight reduces wall thickness due to the operating pressure of 120 bar and in that way the volume of natural gas is increased.

The vessel's draft was designed to guarantee that the ship could be constructed and the cargo containment system could be fitted in dry dock. In addition, the vessel can be dry docked in many ports worldwide for servicing and maintenance.

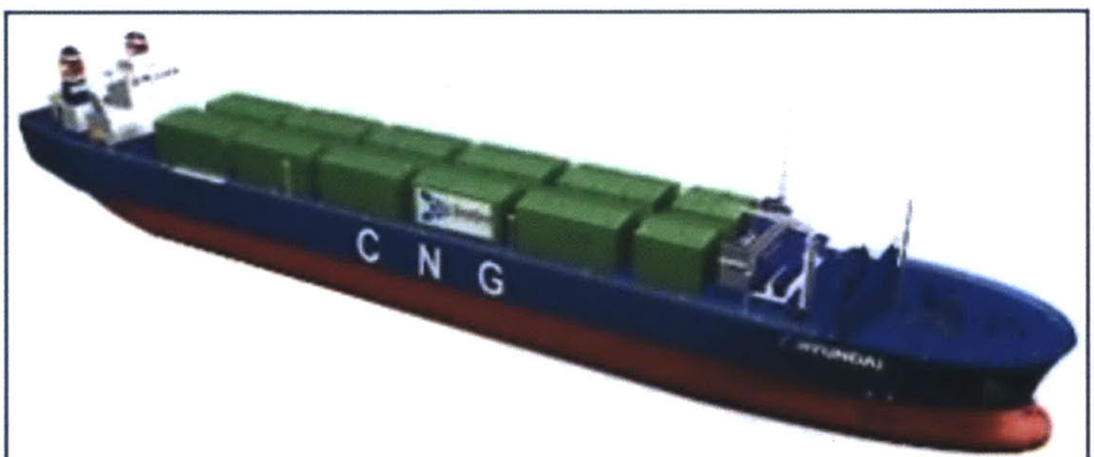


Figure 11: EnerSea Transport CNG Carrier

1.5 Containerization

Containerization is the technique of transporting cargo by placing it in large containers. It is an essential cargo-moving method established in the last century. Sealed boxes were used until the 1960s. Afterwards, containerization became a vital factor in maritime industry. Ships were constructed for carrying containers. These types of ships are fast and large and can hold boxes inside the bulkheads and above deck. Containers can be easily loaded and unloaded with less lost time in ports. Their speed makes them able to make more voyages compare to traditional cargo vessels. Of course, port infrastructure plays a key role for the fast handling of the boxes. The container can be transported by a ship, truck and rail. The container, developed after the Second World War, resulted in a rapid increase of international trade and reduced transport expenses (Stopford 2009).

Containerization caused a revolution in the global logistics system and shipping industry. Its introduction did not have an easy passage and it took about ten years before ships used it widely. One important issue was the high cost of infrastructure in ports and railroad stations for the handling of the containers. Moreover, trade unions were worried about the massive loss of jobs of port employees.

Figure 12: Container Terminal

In 2010 approximately 90% of non-bulk cargo worldwide was moved by container ships. Today, several container ships can carry over 14,000 TEU. One example of a modern container ship with a length of 396 meters is the Emma Maersk. Container ships can be limited in size only by the depth. Enhanced cargo safety is also a significant advantage of containerization. It is very difficult for someone to steal the shipment because the doors of the containers are sealed. In addition, a number of containers are fitted with electronic monitoring devices and can be remotely monitored for changes in air pressure, which happens when the doors are opened. Containers have developed into widely accepted technique to move vehicles overseas .By using TEU or FEU containers for simple international transportation; container ships have decreased shipping expense and shipping time.

1.5.1 ISO Standards

There are five common standard container lengths worldwide: 20-ft, 40-ft, 45-ft, 48-ft, and 53-ft. The United States uses standard containers of 48-ft and 53-ft for domestic purposes. Cargo capacity of container ships is expressed in twenty-foot equivalent units or forty-foot equivalent units (FEU).

The maximum gross mass for a loaded TEU container is 24 tons, and for a FEU is 30 tons. The maximum payload mass is reduced to approximately 22 tons for TEU and 27 tons for FEU due to truss weight.

Figure 13: TEU Container

1.5.2 Container Ships

Container ships are merchant vessels that carry their load in standard intermodal containers. They carry the majority of sea-going non-bulk cargo.

Container ship capacity is measured in twenty-foot equivalent units.

These ships remove their hatches and hold more than the traditional merchant vessels. The hull of a container ship is divided into cells by vertical guide rails. These cells are designed to store cargo in standard dimensions of a TEU or FEU. Containers are usually made of steel to be able to hold up to 24 tons.

Recent container ships can carry up to 16,000 twenty-foot equivalent units.

Figure 14: Marco Polo Container Ship (16,000 TEU)

Today's largest container ships have a length of 400 meters. The hull is comparable to bulk carriers and is built around a strong keel. The holds are topped by hatch covers, on which more boxes can be loaded. A lot of container ships have their own cargo cranes, and safety systems for securing the stability of boxes during the voyages.

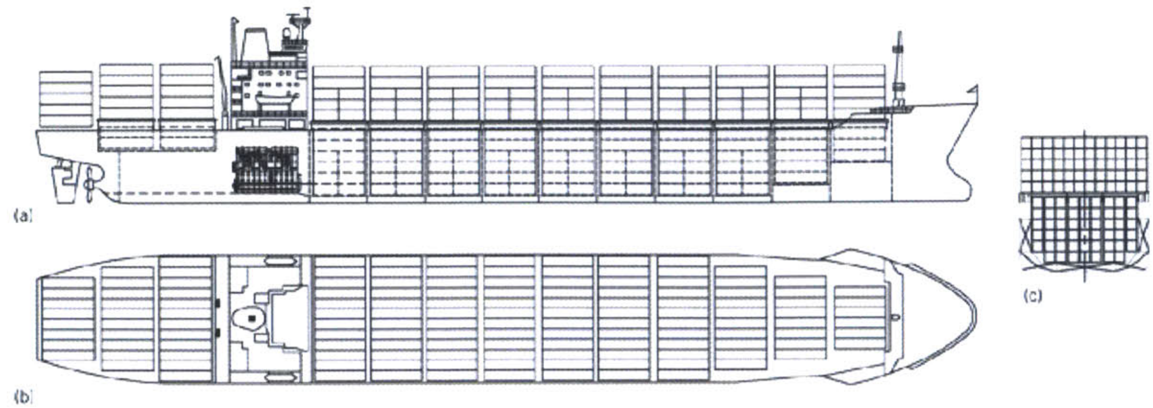


Figure 15: General Arrangement of a Container Ship

In 2010, container ships made up 14% of the world's fleet in terms of deadweight tonnage. The container ship deadweight tonnage is around 170 million. The average age of container ships worldwide is 11 years, making them the youngest merchant type of vessel.

The top 20 liner companies controlled 65% of the world's container capacity, with 2,700 ships and German ship owners dominate the liner shipping trade.

1.5.3 Evolution of Container Ships

Since the mid 1950s, the size of the container ships has been increasing by different periods. Each period represents a different generation. There are five generations:

1) First generation

The first generation of container ships consisted of small bulk vessels with speeds of 18 knots that could carry up to 1,000 TEUs. Due to the lack of infrastructure in port terminals, these vessels had cranes onboard. Once the container began to be adopted, the construction of the first fully cellular container ships started. All containerships are composed of cells. Cellular containership also offered the benefit of loading the cargo below the deck as well as on the deck. Many ports started to use specialized cranes for loading and unloading boxes. In addition, the fully cellular vessels were much faster with speeds of more than 20 knots.

2) Second Generation - Panamax

In the 1980's larger containerships were constructed to meet the economies of scale. More boxes means less cost per TEU. The main purpose of naval architects and ship owners is to build ships that can pass the Panama Canal (32 meters beam limitation) and this was achieved in 1985 with containerships of about 4,000 TEUs.

1) Third Generation – Post Panamax

The target was to overcome the beam restriction of Panama Canal and to construct bigger ships by increasing the length and keep the beam constant. In 1996, the first Post Panamax ship was constructed with a capacity of 6,500 TEUs. Ship size increased with a capacity of 8,000 TEUs due to the rapid growth of international trade. Post Panamax Containerships require deep-water ports with excellent handling systems.

2) Fourth Generation - New Panamax

These are ships designed to be able to pass Panama Canal after its expansion in 2014. They have the ability to carry around 12,500 TEUs. These vessels can service the USA either from Asia and Europe.

3) Fifth Generation - Post New Panamax

In 2006, Maersk shipping company introduced the containership Emma Maersk having capacity of 11,000 to 15,000 TEUs. These ships cannot pass the Panama Canal even after its 2014 expansion but can load up to 18,000 TEUs. In addition, shipyards are trying to design container ships of 30,000 TEUs. These ships will be very useful for the transportation of large commodities between Europe and Asia.

Containership speeds range from 20 to 25 knots. Due to high-energy consumption, many shipping companies are using slow-steaming method (up to 21 knots) to reduce their fuel costs. As a result, the design of fast containerships will not continue for the next few years.

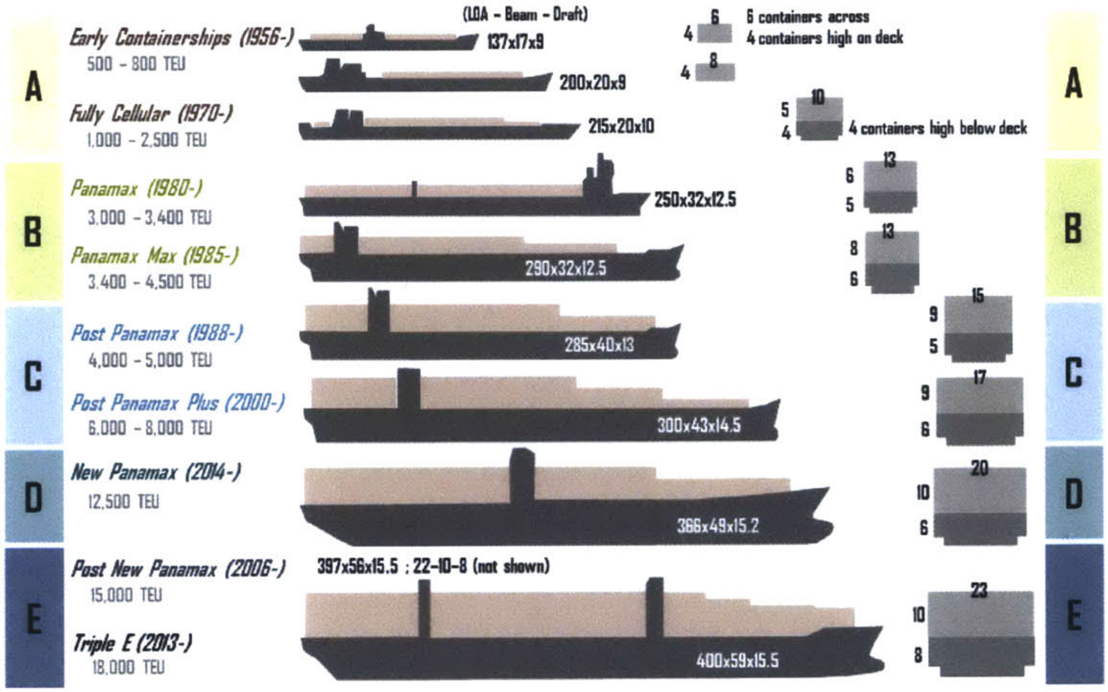


Figure 16: Evolution of Container Ships

In order to reduce the operating cost per TEU, economies of scale play an essential role in containerships sizes. The major issues for the construction of larger ships are, the lack of large low speed diesel engines, the size limitations of sea passages such as Suez Canal and Singapore Strait and the lack of sufficient ports organized to handle large container ships.

Of course, the low draft of large container ships gives substantial room for ships growth. Hence, a 20,000 TEUs ship can be constructed by increasing its length and its beam.

1.5.4 Cargo Cranes

There are two types of container ships: geared container ships that have cargo crane on-board and gearless container ships that do not have cranes. The majority of the container ships are ungeared. Geared ships account for only 8% of the container ship capacity and are vessels of 1,500-2,500 TEUs.

Geared container ships are flexible and can load and unload TEUs in every port, but they have a number of disadvantages such as:

- Higher new building cost
- More maintenance and fuel costs
- Suitable only for less-developed ports
- Some of the cranes are slower than the ports cranes

The development of port cranes has been a key to the success of containerization. Today, some ports can load or unload around 700 TEUs per hour. Singapore's port is the world's busiest harbor with 26 million of TEUs annually and the total estimated container traffic is around 465 million TEUs.

Figure 17: Port Crane

1.5.5 Cargo Holds

Cargo holds for modern container ships are mainly constructed to increase the speed of loading and unloading the cargo, and to hold containers stable while at sea. The hatch openings are vital for the operation of the vessel through its entire life. They are enclosed by a steel arrangement which is the hatch coaming. Hatch covers are on the top of hatch coamings and are metal plates that can be moved hydraulically or lifted by cranes (Stopford 2009).

Vertical arrangements made by metal or cell guides, are installed in each cargo hold. They keep the containers in well-organized rows and give extra protection against movement during sea turbulence. The main difference between the structure of container ships and other merchant vessels such as oil tankers and bulk carriers is that container ships have cell guides.

A method of three dimensions is used in the loading and unloading process to explain the location of a container aboard the ship.

The first coordinate is the row, which starts in the front of the container ship.

The second coordinate is a tier. The first tier is at the bottom of the cargo holds and it increases across the height of the cargo hold.

The third coordinate is the slot. Slots on the starboard side are given odd numbers and those on the port side are given even numbers. The slots at the centerline are given low numbers, and the numbers increase for slots near the end of the edges of breadth.

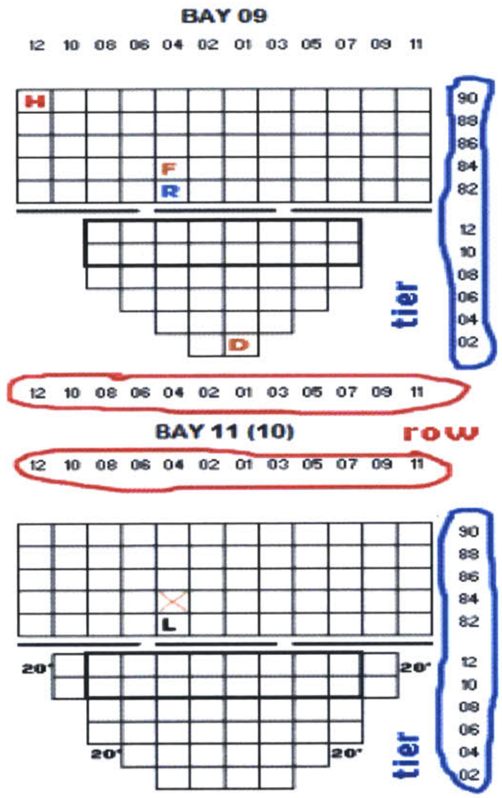


Figure 18: The three dimensions of the cargo hold

Figure 19: Container Ship's Cargo Hold

1.6 Freight Market of Container ships

The act of hiring a ship to carry commodities is called chartering.

In the freight market, the following types of freights and contracts apply:

- Voyage Charter

In this case, the ship owner agrees to transport a given quantity of a commodity with a predefined vessel from a given port, A, to a given port, B, within a stated time period. The price is defined as $/tonne of commodity. The freight weight depends upon the quantity of the cargo loaded in the ship, except when the vessel is fixed on dead weight charter (Alizadeh and Nomikos 2009).

The ship owner pays every operational expense related to the vessel (fuel, crew, port charges, etc) with the only exception, probably, being the loading and unloading expenses.

The voyage charter may be:

1. Direct: this is performed within a few weeks after signing the contract, while the respective freight is called spot rate.
2. Forward charter: this is performed in the future, e.g. within two months after signing the contract.
3. Consecutive: this refers to a number of similar, repetitive vessels.

- Time Charter

In this case, the vessel and the crew are leased for a specific time period. The ship owner provides the crew, the maintenance and guarantees that the vessel meets various performance criteria (speed, consumption, etc). In this case, the rate is determined differently, in $/day or DWT/month.

In addition, the charterer pays separately the following: Fuel, port expenses, loading and unloading expenses. During the specified charter period, the charterers may use the vessel at their discretion; they may even sub-charter it. A time charter fixture report will detail the name of the vessel, its description, its delivery date, the rate of hire and the name of charterer.

There are three charters categories:

1. Direct
2. Forward charter
3. Bareboat charter: the charterer, apart from the fuel, port expenses, loading and unloading expenses, also provides the crew. In addition, a ship owner buys a vessel and does not wish to manage it but hands it over the charterer for a specific period, usually 10-20 years. The owner cannot be active in the operation of the ship and he acts as an investor.

The time charter market is less transparent for calculating the general market on a particular route. It is a very suitable measurement for charterers, ship owners and bankers because they are able to consider the ship's income and compare it to the breakeven cost (Alizadeh and Nomikos 2009).

- Contract of affreightment

- A Contract of affreightment is similar to a repetitive chartering contract but the name of the vessel is not defined in it. The ship owner is allowed to use any vessel, at his discretion, in order to comply with his contractual obligations. He can even use a vessel that is not under his control when signing the contract (e.g. he may fulfill his obligations by participating in the time charter as a buyer). Companies, which are using contract of affreightment, illustrate their industry as "industrial shipping" because their objective is to provide a service. Most of these shipping companies that are using this type of chartering, own bulk carriers that transport iron and coal and the major consumers are the steel mills of Europe and Far East.

The ship owner covers every operating expense of the vessel. The freight is calculated in a fixed price $/tonne of the commodity. One problem of this contract is that the volume and time schedule of the cargo is not usually known in advance.

The container shipping prices are divided into two categories: the first is the price to time-charter one TEU on a container ship, and the other is the freight rate which is the daily cost to distribute one TEU. The liner maritime companies use the Hamburg Index and Shanghai's Containerized Freight Index to determine the charter prices of containers. These indexes show the average daily cost of a TEU for a weight of 14 tons.

In addition, UNCTAD keeps a record of container freight rates expressed as the price for a charterer to move one TEU along a given route. There are three main routes for liner sector: Europe-Asia, USA-Europe and USA-Asia. In recent years the freight rate of USA-Asia route is higher than the other routes due to the high demand of Chinese products in USA.

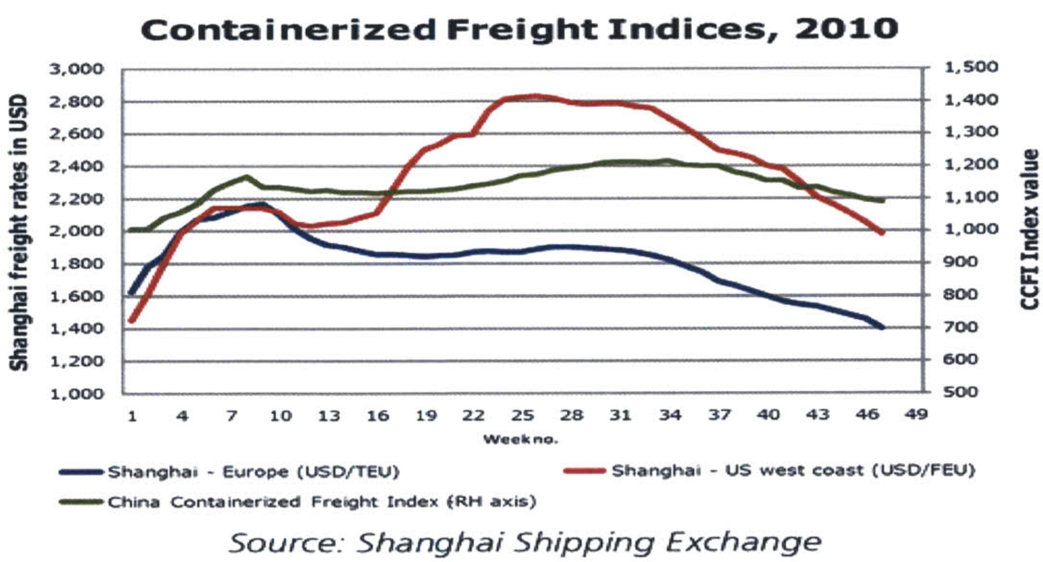


Figure 20: Shanghai's Containerized Freight Indices

2. Transportation of Natural Gas inside a TEU

2.1 Twenty Equivalent Unit (TEU)

The twenty-foot equivalent unit is the most common unit of cargo capacity regularly used to illustrate the deadweight of container ships. It is a standard-sized metal box which has the ability to be transported easily by sea (ships) and land (trucks and trains). The height of TEU ranges from 1.30 meters to 2.90 meters. The most common height is 2.59 meters.

The maximum gross weight for a TEU container is 24tons. Subtracting the empty container weight, the maximum load a TEU can carry is reduced to 21.8 tons.

Figure 21: Dimensions of a TEU Container

Inside a TEU, four cylinders can be installed to carry compressed natural gas. In this project, two materials are examined for the manufacture of the cylinders. The materials are Steel (X120 steel grade) and composites (Carbon Fiber Type 4).

2.2 Steel- X120 grade

The first Compressed Natural Gas (CNG) project, using steel pressure vessels mounted on the deck of a ship, was conducted off the coast of New Jersey in 1966. It was concluded that it was not feasible because the weight of steel pressure vessels required, would be too heavy for the host ship to carry. Thus, CNG development stagnated for thirty years.

Since then, the demand of Natural gas has been increasing rapidly. Pipeline Companies try to reduce the gas transportation costs. These expenses can be reduced by high strength operating pressure and thin wall pipes. Conventional steel lacks strength. The technological advancement of plate manufacturing helps these companies to exploit the high strength of steel. Over the last decades, engineers increased transportation efficiency by increasing the diameter of pipelines. Today, the highest pipeline uses X100 grade. In 1993 ExxonMobil accelerated the improvement of X120 pipeline technology (Valsgard, Lotsber, Sigurdsson and Mork 2010).

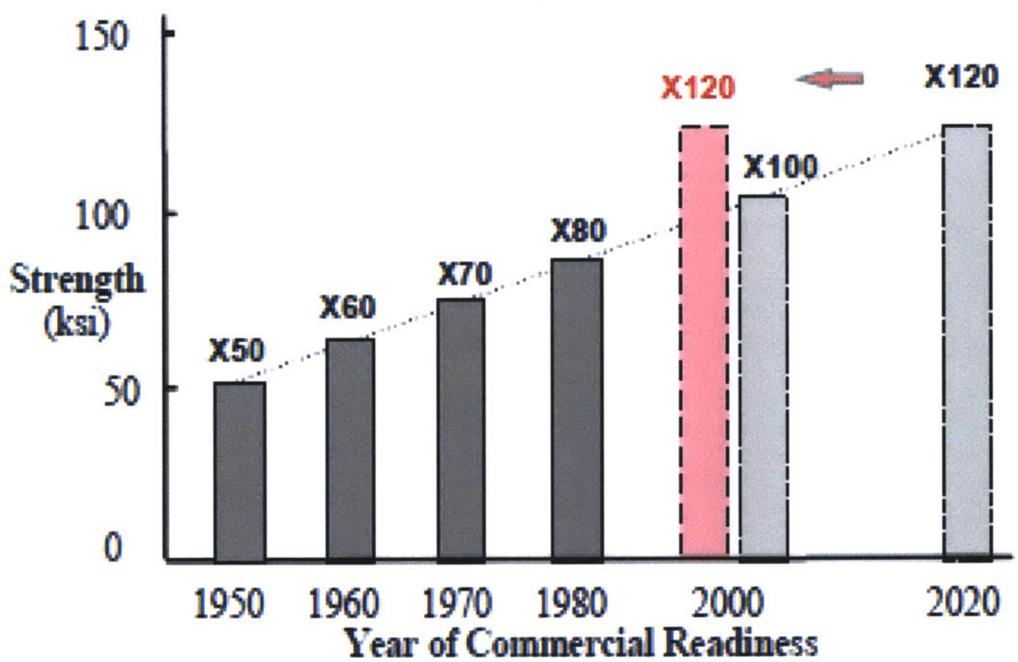


Figure 22: The rapid improvement of X120

The growth targets were set to create a minimum yield stress of 827 MPa. The initial X120 target properties were for dry gas transportation and stress-based design with wall thickness up to 20 mm.

Property	Base Pipe	Seam and Girth Welds
Yield Strength Tensile Strength	≥ 827 MPa ≥ 931 MPa	≥ 827 MPa ≥ 931 MPa
CVN Toughness @ -30°C	≥ 231J	≥ 84J
CTOD@ -20°C	≥ 0.14mm	≥ 0.08 mm (seam) ≥ 0.13 mm (girth)
DBTT (vTre)	< -50°C	
BDWTT (SA%)@ -20°C	≥ 75%	
Yield / Tensile Ratio	< 0.93	

Table 2: Properties X120 steel grade

2.3 Carbon Fiber Type 4

In 1999, Mr. Steven Campbell developed a technique of CNG transportation that overcame all the steel pressure vessels drawbacks. He used composite pressure vessels for Trans Ocean Gas and concluded that these vessels were safe and cost efficient. These vessels have been used by various industries such as aerospace, automotive and defense. Since composite pressure vessels have been successfully utilized to carry natural gas for fuel on public busses, they can also be used in a ship-based CNG transportation system.

The most important advantages of using carbon fiber pressure vessels over steel pressure vessels for the transportation of compressed natural gas are:

1) Better rupture characteristics

2) Corrosion resistant

3) Much lighter

4) Long life expectancy

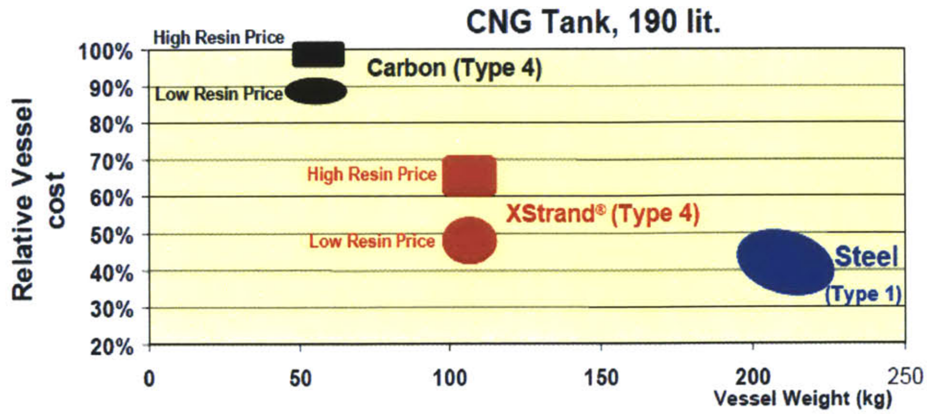
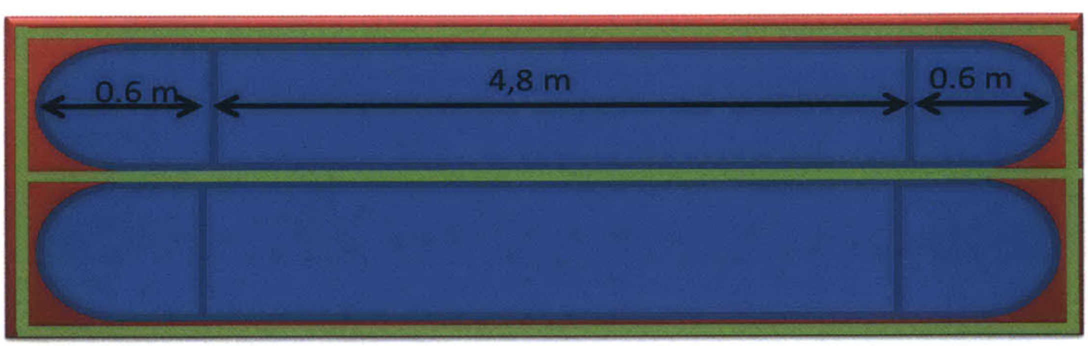


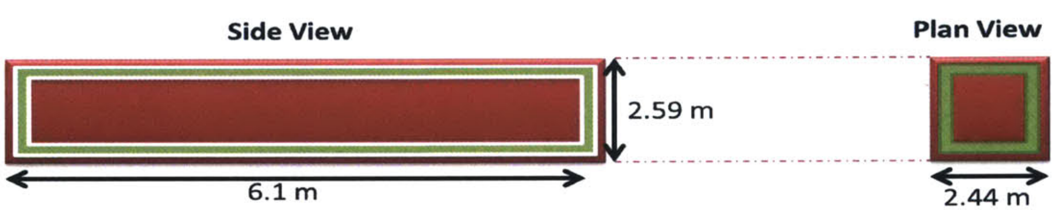
Figure 23: Comparison of the weight and cost of each material

2.4 Dimensions of the TEU

TEU		
Length	6,1	meters
Width	2,44	meters
Height	2,59	meters
Volume	39	cubic meters
Weight	2,2	tons

2.5 Sketch of the TEU





2.6 Analysis of the cylinders

2.6.1 Determination of the steel cylinders thickness

The pressure inside the cylinder pushes against the area that is equal to the inside diameter of the cylinder. The pressure times the diameter is equal to the force produced by internal pressure. That force has to be balanced, otherwise the cylinder would rupture. The area of the metal in the cylinder is equal to twice the thickness and creates another force. These two forces must be equal and hence the minimum thickness can be determined.

$$\mathrm{F} = \mathrm{P} \cdot \mathrm{D} = 2 \cdot \mathrm{f}$$

$$\mathrm{f} = \sigma_{\mathrm{yield}} \cdot \mathrm{t}$$

$$\mathrm{P} \cdot \mathrm{D} = 2 \cdot \sigma \cdot \mathrm{t}$$

$$t = \frac{\mathrm{P} \cdot \mathrm{D}}{2 \cdot \sigma}$$

Diameter of a cylinder = 1.2 meters

Maximum Pressure = 250 bar = 25 MPa

σ_{yield} of X120 steel grade $= 827$ MPa

Hence,

$$t = \frac{\mathrm{P} \cdot \mathrm{D}}{2 \cdot \sigma} = \frac{25 \cdot 1.2}{2 \cdot 827} = 0.018\, meters = 1.8\, cm$$

A safety factor of 1.1 is used for the steel and the thickness used is 2.0cm.

2.6.2 Dimensions of the cylinders

Pressure inside the cylinders	250	bar
Cylinder's length	6	meters
Material	X120	Steel grade
Thickness	0,020	meters
Diameter of the Cylinder	1,2	meters
Diameter of the Inner Cylinder	1,16	meters
Yield Strength of steel	827	MPa

2.6.3 Calculation of cylinders volume

Cylindrical Section		
Length	4,8	meters
Outside Height	1,2	meters
Inside Height	1,16	meters
Inner Volume	5,1	cubic meters
Total Volume	5,4	cubic meters

Volume of Cylindrical Section	0,4	cubic meters

Semicircular Sections	2	
Outer Radius	0,6	meters
Inner Radius	0,58	meters
Inner Volume	2,11	cubic meters
Total Volume	2,26	cubic meters

Volume of Semicircular Sections	0,15	cubic meters

Total Volume of Steel	0,50	cubic meters

2.6.4 Calculation of Weight of cylinders without CNG

Density of steel	7850	kg/cubic meters

Weight of Steel in one cylinder	3946	kg	4	tons

Weight of 4 cylinders in an TEU	15,8	tons

2.6.5 Determination of the Compressed Natural Gas inside the four cylinders

Density of Natural Gas	0,7	kg/cubic meters		
Total Volume of Inner Cylinders in FEU	7,18	cubic meters		
Weight of Natural Gas (4 Cylinders)	5029	kg	5,0	tons

2.6.6 Total Weight of a TEU

Weight of the TEU+Cylinders+NG	23	tons

As it is mentioned in a previous section of this thesis, the maximum weight of a TEU 24 tons. Hence, using steel cylinders is reliable and valid for this project.

2.6.7 Determination of the Carbon Fiber (Type 4) cylinders weight

According to the following figure and the composite cylinders company the ratio of the CNG/Total weight is 57.7% or a ratio of 0.577. The weight of the compressed natural gas is 5 tons this gives a weight for the composite container of 3.66 tons. This lowers the weight of the TEU by 4.32 tons which is 34%.

	Type 1	Type 2	Type 3	Type 4
Market Share (%)	93%	4%	< 2%	< 2%
Structure	Metal	Metal Liner reinforced with resin Impregnated continuous filament (hoop Wrap)	Metal Liner reinforced with resin Impregnated continuous filament (fully Wrap)	Resin impregnated continuous filament with a non-metallic liner
Most commonly used	CrMo steel	CrMo steel with Glass Fiber	Aluminium with HP Glass &/or Carbon	HDPE liner with Carbon
Indicative cost - US$/litre	$3 to $5	$5 to $7	$9 to $14	$11 to $18
Indicative weight - Kg/litre	0.9~1.3	0.8~1.0	0.4~0.5	0.3~0.4

Sources: CompositeMarketReports.com
CompositeWorld.com

Figure 24: Weight and cost of each material

Therefore, the total weight of a TEU by using composites cylinder us 11.7 tons.

Weight of the NG	5	tons
CNG/Total Weight	0,577	
Weight of the composites cylinders	3,67	tons
Weight of NG	5	tons
Weight of frame + TEU	3	tons
Weight of a loaded TEU	11,7	tons

2.7 Strength Analysis of the TEU

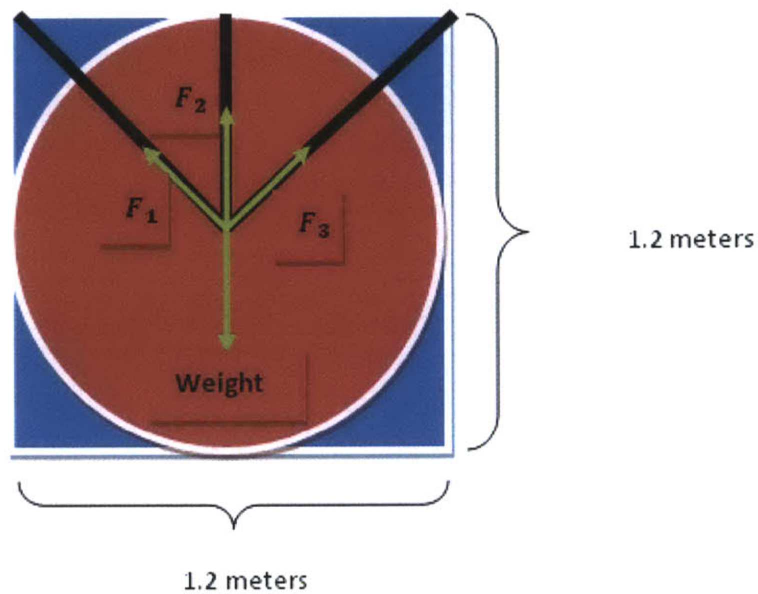


Figure 25: Free Body Diagram of the cylinder

Mass of Natural gas inside the cylinder = 1250 kg

Mass of cylinder's steel = 3950 kg

Total mass = 5200 kg

Weight = 5200 * 9.81 = 51012 N

Weight at each edge is = 51012/2 = 25506 N

$\theta = 45^o$

$l_1 = \frac{l_2}{cos\theta} = l_3$

$$\Sigma F_x = 0$$

$$F_{3x} - F_{1x} = 0$$

$$F_3 \cdot cos\theta = F_1 \cdot cos\theta$$

$$F_3 = F_1$$

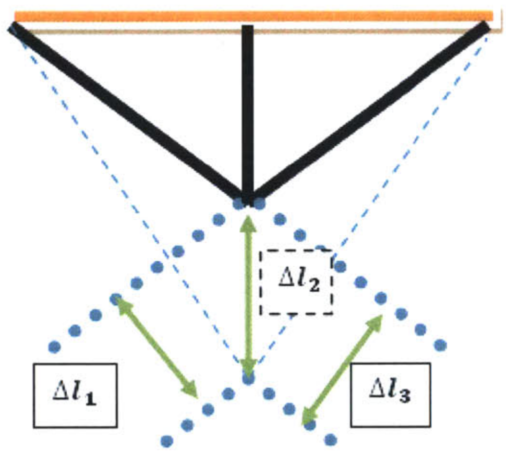
$$\Sigma F_y = 0$$

$$Weight = F_2 + F_{1y} + F_{3y}$$

$$25506 = F_2 + F_1 \cdot sin\theta + F_3 \cdot sin\theta$$

$$25506 = F_2 + F_1 \cdot sin45^o + F_3 \cdot sin45^o$$

$$25506 = F_2 + F_1 \cdot \frac{\sqrt{2}}{2} + F_3 \cdot \frac{\sqrt{2}}{2}$$



$$\Delta l_1 = \Delta l_2 \cdot cos\theta = \Delta l_3$$

$$Euler's formula\ states: \Delta l = \frac{F \cdot l}{A \cdot E}$$

$$\frac{F_1 \cdot l_1}{A \cdot E} = \frac{F_2 \cdot l_2}{A \cdot E} \cdot cos\theta$$

$$F_1 \cdot l_1 = F_2 \cdot l_2 \cdot cos\theta$$

$$F_1 \cdot \frac{l_2}{cos\theta} = F_2 \cdot l_2 \cdot cos\theta$$

$$F_1 = F_2 \cdot cos^2\theta = F_3$$

$$F_1 = F_2 \cdot \left(\frac{\sqrt{2}}{2}\right)^2 \leftrightarrow F_1 = F_2 \cdot 0.5 = F_3$$

Hence,

$$25506 = F_2 + F_1 \cdot \frac{\sqrt{2}}{2} + F_3 \cdot \frac{\sqrt{2}}{2}$$

$$25506 = F_2 + \left(F_2 \cdot 0.5 \cdot \frac{\sqrt{2}}{2}\right) + \left(F_2 \cdot 0.5 \cdot \frac{\sqrt{2}}{2}\right)$$

$$F_2 = 14941\ N$$

$$F_1 = F_3 = 7492N$$

2.7.1 Tensile Stresses

$l_1 = l_3 = 0.84\ meters$

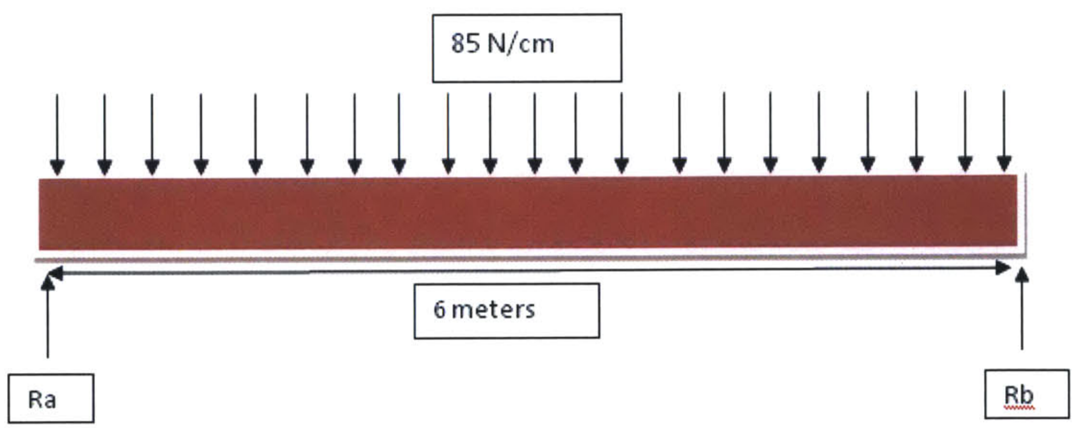
$l_2 = 0.6\ meters$

Thickness = 0.03 *meters*

$$\sigma_1 = \sigma_3 = \frac{F_{1,3}}{A} = \frac{7492}{0.84 \cdot 0.03} = 297302\ {}^{N}/_{m^2}$$

$$\sigma_2 = \frac{F_2}{A} = \frac{14941}{0.6 \cdot 0.03} = 830111\ {}^{N}/_{m^2}$$

2.7.2 Beam Analysis



Total Weight of a cylinder = 51012 N

Length of the beam = 6 meters

Hence, 8500 N/m = 85 N/cm

$\Sigma F_x = 0$

$\Sigma F_y = 0 \quad \leftrightarrow \quad R_a + R_b = 85 \cdot 600 = 51000\ N$

Hence, $R_a = R_b = 25500\ N$

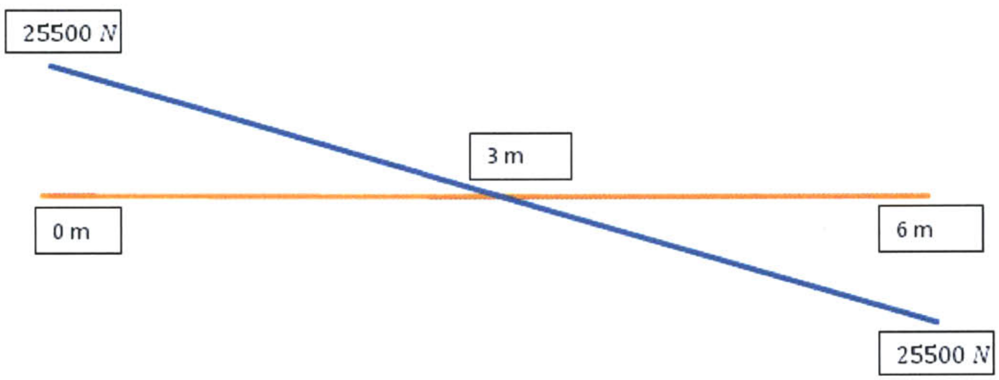
$\Sigma M = 0$

x=0 M=0

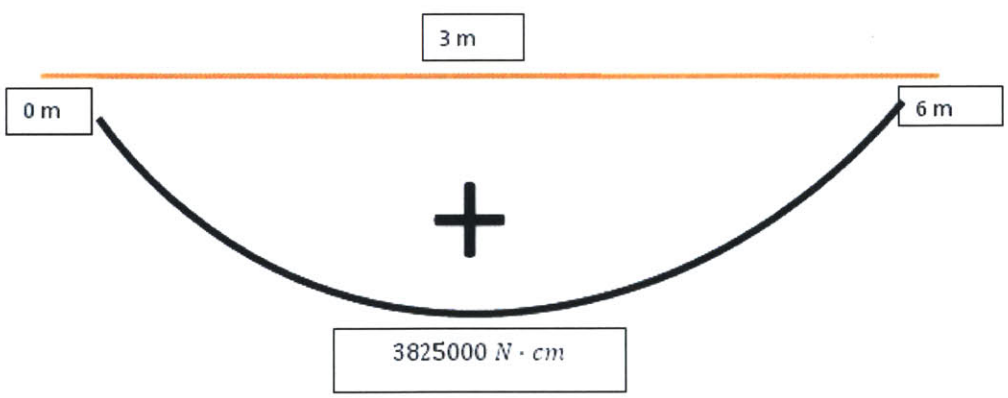
x=3 $M = (25500 \cdot 300) - \left(85 \cdot \frac{300^2}{2}\right) = 3825000\ N \cdot cm$

x=6 M=0

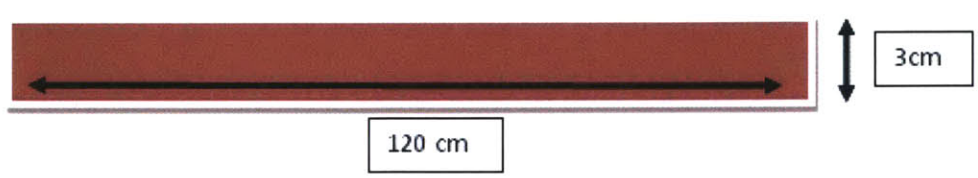
2.7.3 Shear Force and Bending Moment Diagrams



Bending Moment Diagram:



Cross-Section:



A36 steel is going to be used.

Force = 51012 N

Length = 600 cm

Young Modulus of A36 steel = 29000000 psi = 19994796 N/cm^2

$$\Delta l = \frac{F \cdot l}{A \cdot E} = \frac{51012 \cdot 600}{19994796 \cdot 600 \cdot 3} = 8.5 \cdot 10^{-4} cm$$

2.7.4 Compression Stresses on the beam

$$\sigma = \frac{F}{\mathrm{A}} = \frac{51012}{600 \cdot 3} = 28.34\ \mathrm{N/cm^2}$$

A36 steel in plates, bars, and shapes with a thickness of less than 8 inches have minimum yield strength of 36,000 psi.

36000 psi = 24821 N/cm^2

2.7.5 Maximum Bending stress

$$\mathrm{W_X} = \text{Moment of Resistance} = \frac{\text{thickness} \cdot \text{width}^2}{6} = \frac{3 \cdot 120^2}{6} = 7200\ cm^3$$

$$\sigma = \frac{M}{W_x} = \frac{3825000}{7200} = 531.25\ N/cm^2$$

Allowable bending stress for A36 steel: 22000 psi = 15168 N/cm^2

$$\sigma_{allowable} > \sigma_{bending\ moment}$$

Hence, it is accepted.

2.7.6 Critical Buckling Point

In our case, Euler's formula for critical buckling point cannot be applied.

Safety factor of A36 steel = 1.67

$$F_{critical} = safety\ factor\ \cdot Force$$

$$F_{critical} = 1.67\ \cdot 51012 = 85190\ N$$

Of course we can reduce the thickness of the cross-section in order the total weight of the FEU to be decreased

3. Compressors

A gas compressor is a mechanical device that increases the pressure of a gas by reducing its volume.

Types of Compressors:

The most important types of gas compressors are presented on the following figure (Bloch 2006):

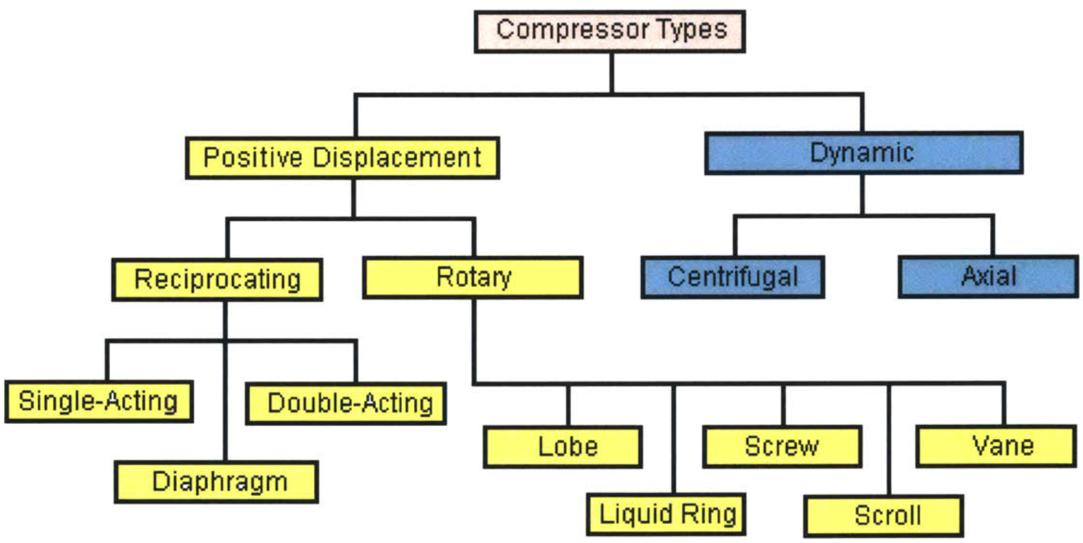


Figure 26: Compressors Types

3.1 Reciprocating Compressors

Reciprocating compressors make use of pistons driven by a crankshaft. Their characteristics are:

- They are stationary or portable
- They are single or multi-staged
- Internal combustion engines or electric motors drive them

They are used by many industries such as automotive, oil and gas industries. Their benefit is the potential to reach discharge pressures up to 200 MPa and for that reason they are the most efficient type of compressors. On the other hand, their big size and high capital cost are their main disadvantages (Bloch 2006).

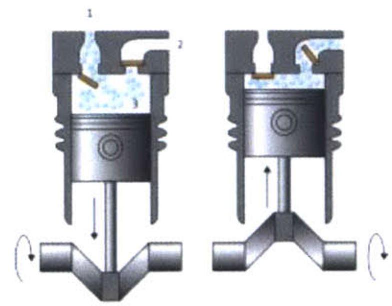


Figure 27: Reciprocating Compressor

3.2 Centrifugal Compressors

Centrifugal compressors make use of an impeller to force the gas to the rim of the impeller, increasing the velocity of the gas. A diffuser section is used in order to convert the kinetic energy to pressure energy. These compressors are mainly used in the oil industry and in natural gas processing plants. They are single and multi-staged compressors. They can reach pressures up to 70 MPa (Bloch 2006).

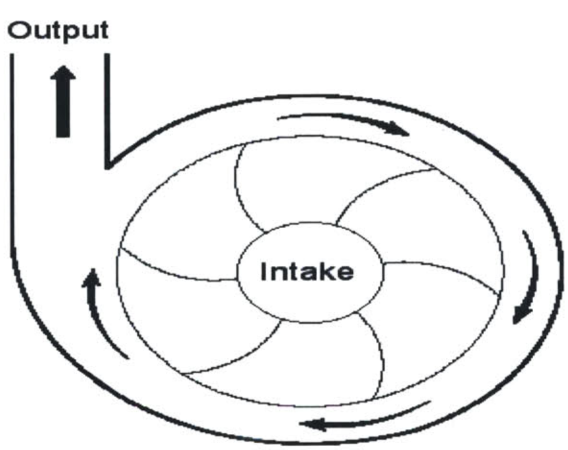


Figure 28: Centrifugal Compressor

3.3 Axial Compressors

Axial-flow compressors are dynamic rotating compressors that use arrays of fan-like airfoils to compress the gas. They are perfect for high flow rates of gases. They are multi-staged compressors (more than 5 stages). One important advantage of axial compressors is their high efficiency which reaches 90% at design conditions. Of course, for that reason they are expensive and need careful maintenance. Natural gas pumping stations use these types of compressors (Bloch 2006).

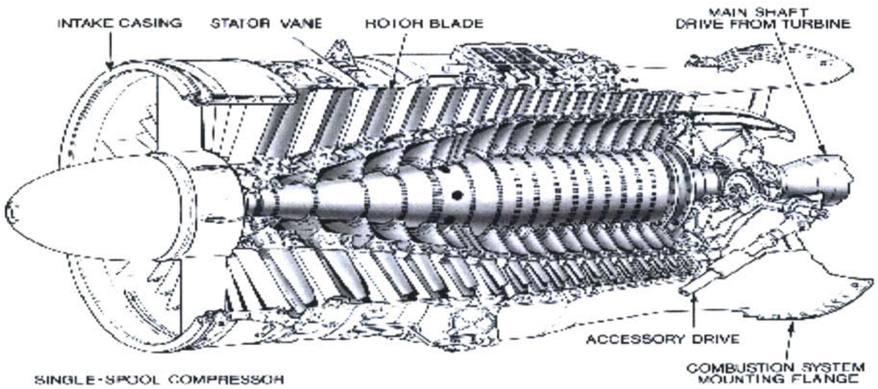


Figure 29: Axial Compressor

3.4 Rotary Compressors

Rotary screw compressors use two meshed, rotating, positive-displacement helical screws to force the gas into a smaller space (Bloch 2006). Their features are:

- Continuous operation
- Stationary or portable
- They produce a power up to 900 kW
- Their discharge pressure can be up to 8 MPa

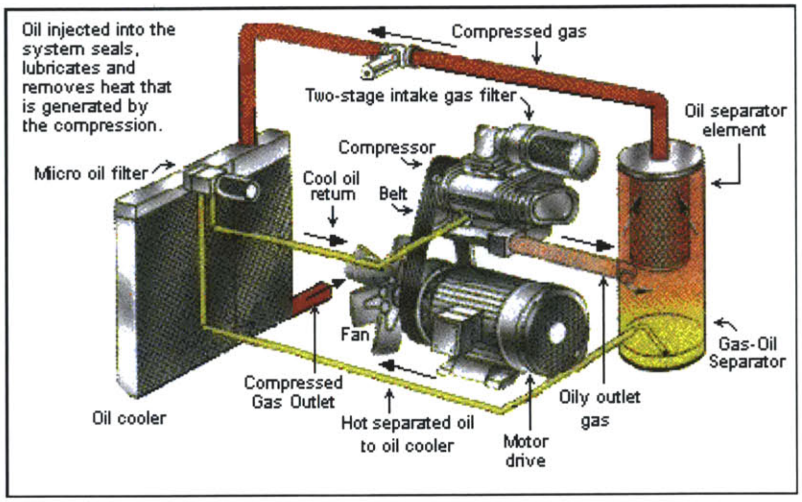


Figure 30: Rotary Compressor

3.5 First Law of Thermodynamics

The first law of thermodynamics states that energy cannot be created or destroyed during a process, although it may change from one form of energy to another in a closed system (Borgnakke and Sonntag 2009).

$$\Delta E = Q - W$$

The change in internal energy of a system is equal to the heat added to the system minus the work done by the system.

The first law of thermodynamics can be expressed from the conservation of energy for an open system.

$$\dot{Q} + (e + pu)_{initial} \cdot \dot{m}_{initial} = (e + pu)_{final} \cdot \dot{m}_{final} + \dot{W}$$

e is the energy, u is the specific volume and p is the pressure.

For constant flow of mass: $\dot{m}_{initial} = \dot{m}_{final} = \dot{m}$

Hence, the above equation can be written as:

$$\dot{Q} + (e + pu)_{initial} \cdot \dot{m} = (e + pu)_{final} \cdot \dot{m} + \dot{W}$$

It is known that energy e is the addition of the kinetic, potential and internal energy of a substance.

Hence, e+pv can be represented as:

$$e + pv = u + pv + \frac{v^2}{2} + gz$$

Enthalpy h is equal to u+pv.

By multiplying the above equation by the mass, it is obtained that:

$$h = u + pv$$

$$mh = mu + mpv$$

$$H = U + PV$$

$$which\ is\ the\ enthalpy\ of\ the\ whole\ mass\ that\ flows\ inside\ the\ system$$

Therefore,

$$\dot{Q} + (e + pu)_{initial} \cdot \dot{m} = (e + pu)_{final} \cdot \dot{m} + \dot{W} \quad can\ be\ written\ as$$

$$\dot{Q} + \left(h + \frac{v^2}{2} + gz\right)_{initial} \cdot \dot{m} = \left(h + \frac{v^2}{2} + gz\right)_{final} \cdot \dot{m} + \dot{W}$$

3.6 Ideal Gas Laws

A perfect gas is one that obeys the laws of Boyle, Charles and Amonton. In reality, there are no truly ideal gases, but these laws are used and corrected by compressibility factors based on experimental data (Bloch 2006).

Boyle's Law:

At constant temperature the volume of a perfect gas varies inversely with the pressure. This is the isothermal law.

$$\frac{V_2}{V_1} = \frac{P_1}{P_2}$$

$$P_2 \cdot V_2 = P_1 \cdot V_1 = constant$$

Charles' Law:

The volume of a perfect gas at constant pressure varies as the absolute temperature:

$$\frac{V_2}{V_1} = \frac{T_2}{T_1}$$

$$\frac{V_2}{T_2} = \frac{V_1}{T_1} = constant$$

Amontons' Law:

At constant volume the pressure of a perfect gas will vary with the absolute temperature.

$$\frac{P_2}{P_1} = \frac{T_2}{T_1}$$

$$\frac{P_2}{T_2} = \frac{P_1}{T_1} = constant$$

3.7 Perfect Gas Formula

Using Charles' and Boyles' laws, the following formula is developed which is the perfect gas equation:

$$P \cdot V = n \cdot R \cdot T$$

Where P is pressure in Pascal, V is the gas volume in m^3 , n is the number of moles of the gas, T is the absolute temperature in Kelvin and R is the universal gas constant and equals to 8.31 $\frac{J}{mol \cdot K}$.

3.8 Compressibility

All the gases deviate from the above ideal gas laws. It is essential that these deviations be considered in many compressor calculations in order for the results to be reliable. Compressibility is taken into account from the records on the real performance of a particular gas under pressure-volume-temperature changes. Hence, Z factor becomes a multiplier in the perfect gas equation (Cravalho, Smith, Brisson and McKinley 2005).

The ideal gas formula can be written as:

$$P \cdot V = Z \cdot n \cdot R \cdot T$$

Or

$$Z = \frac{P \cdot V}{n \cdot R \cdot T}$$

Compressibility factor Z is defined as the ration of the actual volume (at a given pressure and temperature) to the ideal volume of a perfect gas. In addition, it determines how real gas diverges from actuality.

Z factor can be calculated by PVT laboratories and from published charts such as the one shown in the following figure.

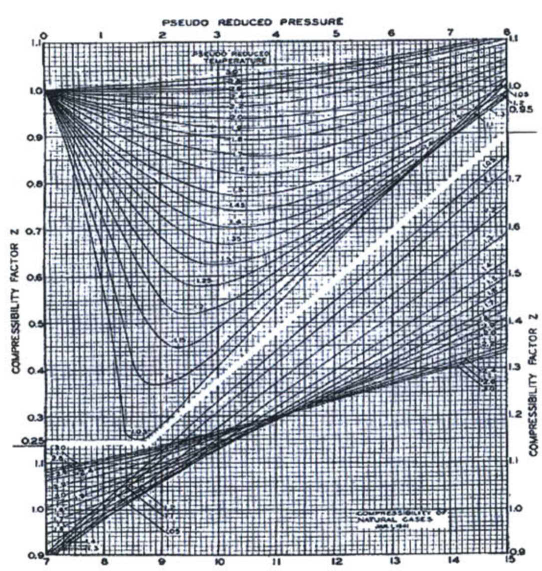


Figure 31: Diagram of Compressibility Factor

3.9 Theoretical Compression cycles

There are two types of compression cycles that are valid to compressors.

Isothermal Compression is when the temperature is kept constant as the pressure increases. Of course, this is an ideal compression cycle and cannot be implemented easily on a compressor. This needs constant removal of the heat of compression. Isothermal compression obeys the following equation:

$$P_1 \cdot V_1 = P_2 \cdot V_2 = constant$$

Adiabatic compression is obtained when there is no heat added or removed from the gas during compression. It obeys the following formula

$$P_1 \cdot {V_1}^k = P_2 \cdot {V_2}^k$$

where k is the ratio of the specific heats.

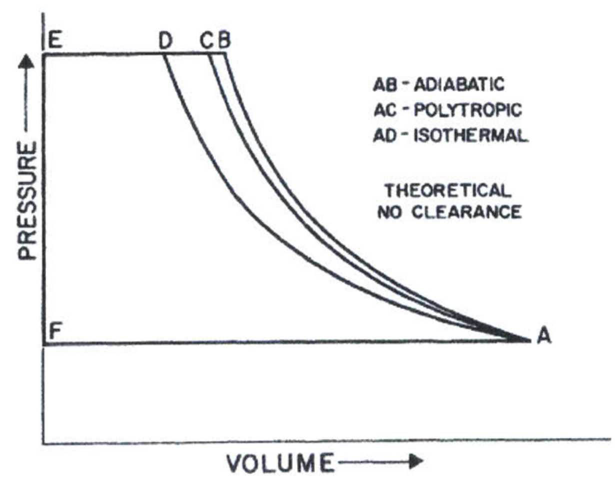


FIGURE 1.7 A p–V diagram illustrating theoretical compression cycles. *(Dresser-Rand Company, Painted Post, N.Y.)*

Figure 32: Pressure-Volume Diagram

The above figure shows the theoretical isothermal and adiabatic cycles on a pressure-volume diagram. The area represents the work required from a compressor. It is observed that the work required for the isothermal process is less than the work required for the adiabatic process.

Isothermal and adiabatic processes are never obtained closely because heat is constantly added or rejected.

Therefore, actual compression takes place between the above two processes and it is known as polytropic cycle. Polytropic compressions obey the following equation:

$$P_1 \cdot {V_1}^n = P_2 \cdot {V_2}^n$$

The exponent n is given by the compressors manufacturers and it is close to the adiabatic exponent k. For positive displacement compressors, n is less than k.

It should be mentioned that polytropic cycle is irreversible, whereas adiabatic and isothermal are reversible cycles.

3.10 Heat transfer

Heat is defined as the form of energy that is transferred across the boundary of a system at a given temperature to another system at a lower temperature. Heat transferred to a system is considered positive and heat transferred from a system is considered negative. The symbol Q represents heat. Q is equal to zero when the process is adiabatic (Holman 2010).

$$Q = q \cdot m \qquad where, q = c_p \cdot \Delta T$$

$$Q = m \cdot c_p \cdot \Delta T$$

In order to calculate the work required for a compressor, heat should be determined by the above equation. Heat inside the compressor is increasing because when the volume increases, temperature also increases.

3.11 Heat mode

1) Conduction:

Is the transfer of heat between elements that are in direct contact with each other.

$$Q = -k \cdot S \cdot [T - T_A]$$

Where Q is the heat transfer, k is the thermal conductivity of the material and S is the surface area.

The conduction process can be seen in the following sketch:

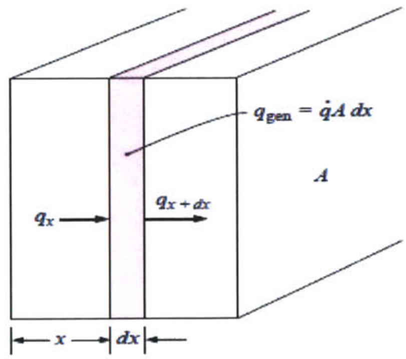


Figure 33: Conduction Process

Energy conducted in the left side + Heat created within the element = Change in internal energy + Energy conducted out right side

3.12 Heat Capacity

Heat Capacity is a feature of a matter, the amount of heat required to change its temperature by one degree. For gases, there are two heat capacities (at constant pressure and at constant volume) (Holman 2010)..

The heat capacity for constant pressure Cp is the change of specific enthalpy of a gas when the pressure is constant and temperature varies.

Cp can be obtained by:

$$C_p = \frac{h_2 - h_1}{t_2 - t_1}$$

The heat capacity at constant volume Cv is the change of specific internal energy of a gas when the volume is constant and temperature varies.

$$C_v = \frac{u_2 - u_1}{t_2 - t_1}$$

The relationship between Cp and Cv can be represented by the following equation:

$$R = C_P - C_v$$

Hence, the difference between the two specific heat capacities is equal to the universal gas constant R.

In addition, many times in thermodynamics the ratio of Cp and Cv can be written as:

$$\gamma = \frac{C_p}{C_v}$$

3.13 Work Done Calculation for the whole Process

The purpose of our compressors is to increase the volume from 10 bar to 250 bar. This can be achieved by using centrifugal compressors to increase the pressure from 10 bar to 50 bar and then using reciprocating compressors to increase the pressure from 50 bar to 250 bar. In addition, an inter-cooler is used to reduce the temperature in order any melting issue to be avoided. Our process is divided into three stages and all the above thermodynamics equations were used for the determination of the total work done by the compressors and the inter-cooler.

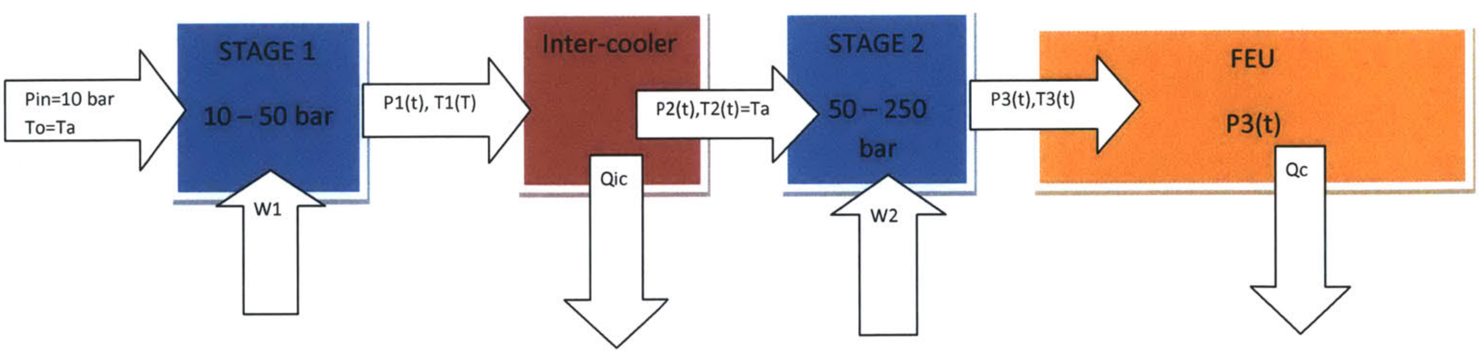


Figure 34: Two-stage process to reach 250 bar inside the cylinders of the TEU

First Law around Stage 1 (10-50 bar):

$$\dot{W} = \dot{m} \cdot c_p \cdot (T_1 - T_A)$$

First Law around Stage 2 (50-250 bar):

$$\dot{W} = \dot{m} \cdot c_p \cdot (T_3 - T_2)$$

First Law around Inter-Cooler:

$$\dot{Q}_{IC} = \dot{m} \cdot c_p \cdot (T_1 - T_2)$$

First Law around FEU container:

$$\dot{Q}_C + \dot{m} \cdot h_{IN} = \frac{dE}{dt}$$

1) $\dot{Q}_C = -k \cdot S \cdot [T(t) - T_A]$
2) $h_{IN} = c_p \cdot T_3(t)$
3) $E(t) = m(t) \cdot c_v \cdot T(t)$

Substitution:

$$\dot{Q}_C + \dot{m} \cdot h_{IN} = \frac{dE}{dt}$$

$$-k \cdot S \cdot [T(t) - T_A] + \dot{m} \cdot c_p \cdot T_3(t) = \frac{d[m(t) \cdot c_v \cdot T(t)]}{dt}$$

$$-k \cdot S \cdot [T(t) - T_A] + \dot{m} \cdot c_p \cdot T_3(t) = \dot{m} \cdot c_v \cdot T(t) + m(t) \cdot c_v \cdot \dot{T}(t)$$

First Law around FEU container:

$$\left.\begin{array}{l} \dot{Q}_{IC} = \dot{m} \cdot c_p \cdot (T_1 - T_2) \\ \\ \dot{Q}_{IC} = (k \cdot S)_{IC} \cdot (T_1 - T_A) \end{array}\right\} \quad \dot{m} \cdot c_p \cdot (T_1 - T_2) = (k \cdot S)_{IC} \cdot (T_1 - T_A)$$

or

$$\dot{Q}_{IC} = (k \cdot S)_{IC} \cdot \left(\frac{T_1 + T_2}{2} - T_A\right) = \dot{m} \cdot c_p \cdot (T_1 - T_2)$$

Hence,

$$W_{Total} = W_1 + W_2 = \dot{m} \cdot c_p \cdot (T_1 - T_A + T_3 - T_2)$$

Calculation of T2:

$$\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^a = \left(\frac{P}{P_2}\right)^a = \left(\frac{P}{P_1}\right)^a \quad \rightarrow \quad T_3 = \left(\frac{P(t)}{P_1(t)}\right)^a \cdot T_2 \qquad T_2 \approx T_A$$

Let's substitute on the following equation:

$$(k \cdot S)_{IC} \cdot \left(\frac{T_1 + T_2}{2} - T_A\right) = \dot{m} \cdot c_p \cdot (T_1 - T_2)$$

$$(k \cdot S)_{IC} \cdot \left(\frac{T_1 + T_2}{2} - T_A\right) = \dot{m} \cdot c_p \cdot T_1 - \dot{m} \cdot c_p \cdot T_2$$

$$(k \cdot S)_{IC} \cdot \frac{T_1}{2} + (k \cdot S)_{IC} \cdot \frac{T_2}{2} - (k \cdot S)_{IC} \cdot T_A = \dot{m} \cdot c_p \cdot T_1 - \dot{m} \cdot c_p \cdot T_2$$

$$(k \cdot S)_{IC} \cdot T_1 + (k \cdot S)_{IC} \cdot T_2 - 2 \cdot (k \cdot S)_{IC} \cdot T_A = 2 \cdot \dot{m} \cdot c_p \cdot T_1 - 2 \cdot \dot{m} \cdot c_p \cdot T_2$$

$$(k \cdot S)_{IC} \cdot T_2 + 2 \cdot \dot{m} \cdot c_p \cdot T_2 = 2 \cdot \dot{m} \cdot c_p \cdot T_1 - (k \cdot S)_{IC} \cdot T_1 + 2 \cdot (k \cdot S)_{IC} \cdot T_A$$

$$T_2 \cdot [(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p] = 2 \cdot \dot{m} \cdot c_p \cdot T_1 - (k \cdot S)_{IC} \cdot T_1 + 2 \cdot (k \cdot S)_{IC} \cdot T_A$$

$$T_2 = \frac{2 \cdot \dot{m} \cdot c_p \cdot T_1 - (k \cdot S)_{IC} \cdot [T_1 - 2 \cdot T_A]}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}$$

By knowing the following equation:

$$T_3 = \left(\frac{P_3}{P_2}\right)^a \cdot T_2$$

$$T_3 = \left(\frac{P}{P_1}\right)^a \cdot \left[\frac{2 \cdot \dot{m} \cdot c_p \cdot T_1 - (k \cdot S)_{IC} \cdot [T_1 - 2 \cdot T_A]}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right]$$

One other principle equation is:

$$\frac{T_1}{T_A} = \left(\frac{P_1}{P_A}\right)^a \rightarrow \quad T_1 = \left(\frac{P_1}{P_A}\right)^a \cdot T_A \rightarrow \frac{T_1}{(P_1)^a} = \frac{T_A}{(P_A)^a} \rightarrow \quad \frac{T_1}{(P_1)^a} \cdot (P)^a = \frac{T_A}{(P_A)^a} (P)^a$$

$$T_3 = \left(\frac{P}{P_1}\right)^a \cdot \left[\frac{2 \cdot \dot{m} \cdot c_p \cdot T_1 - (k \cdot S)_{IC} \cdot [T_1 - 2 \cdot T_A]}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right]$$

$$T_3 = \left[\left(\frac{P}{P_1}\right)^a \cdot \frac{2 \cdot \dot{m} \cdot c_p \cdot T_1}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right] - \left|\left(\frac{P}{P_1}\right)^a \cdot \frac{(k \cdot S)_{IC} \cdot [T_1 - 2 \cdot T_A]}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right|$$

$$T_3 = \left[\left(\frac{P}{P_1}\right)^a \cdot \frac{2 \cdot \dot{m} \cdot c_p \cdot T_1}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right] - \left|\left(\frac{P}{P_1}\right)^a \cdot \frac{(k \cdot S)_{IC} \cdot T_1}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right| + \left|\left(\frac{P}{P_1}\right)^a \cdot \frac{(k \cdot S)_{IC} \cdot 2 \cdot T_A}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right|$$

$$T_3 = \left[\left(\frac{P}{P_1}\right)^a T_1 \cdot \frac{2 \cdot \dot{m} \cdot c_p - (k \cdot S)_{IC}}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right] + \left|\left(\frac{P}{P_1}\right)^a \cdot \frac{(k \cdot S)_{IC} \cdot 2 \cdot T_A}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right|$$

$$T_3 = \left[\frac{T_A}{(P_A)^a} (P)^a \cdot \frac{2 \cdot \dot{m} \cdot c_p - (k \cdot S)_{IC}}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right] + \left|\left(\frac{P}{P_1}\right)^a \cdot \frac{(k \cdot S)_{IC} \cdot 2 \cdot T_A}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right|$$

From,

$$\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^a = \left(\frac{P}{P_2}\right)^a = \left(\frac{P}{P_1}\right)^a$$

$$T_3 = \left[\frac{T_A}{(P_A)^a} (P)^a \cdot \frac{2 \cdot \dot{m} \cdot c_p - (k \cdot S)_{IC}}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right] + \left|\frac{T_3}{T_2} \cdot \frac{(k \cdot S)_{IC} \cdot 2 \cdot T_A}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right|$$

Assume that T2=Ta or that the inter-cooler brings the exit temperature down to atmospheric.

$$T_3 = \left[\frac{T_A}{(P_A)^a} (P)^a \cdot \frac{2 \cdot \dot{m} \cdot c_p - (k \cdot S)_{IC}}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right] + \left|\frac{T_3}{T_A} \cdot \frac{(k \cdot S)_{IC} \cdot 2 \cdot T_A}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right|$$

$$T_3 = \left[\frac{T_A}{(P_A)^a} (P)^a \cdot \frac{2 \cdot \dot{m} \cdot c_p - (k \cdot S)_{IC}}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right] + \left|T_3 \cdot \frac{(k \cdot S)_{IC} \cdot 2}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right|$$

$$T_3 - \left|T_3 \cdot \frac{(k \cdot S)_{IC} \cdot 2}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right| = \left[\frac{T_A}{(P_A)^a} (P)^a \cdot \frac{2 \cdot \dot{m} \cdot c_p - (k \cdot S)_{IC}}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right]$$

$$T_3 \cdot \left[1 - \frac{(k \cdot S)_{IC} \cdot 2}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right] = \left[\frac{T_A}{(P_A)^a} (P)^a \cdot \frac{2 \cdot \dot{m} \cdot c_p - (k \cdot S)_{IC}}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right]$$

$$T_3 = \frac{\left[\frac{T_A}{(P_A)^a} (P(t))^a \cdot \frac{2 \cdot \dot{m} \cdot c_p - (k \cdot S)_{IC}}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right]}{\left[1 - \frac{(k \cdot S)_{IC} \cdot 2}{[(k \cdot S)_{IC} + 2 \cdot \dot{m} \cdot c_p]}\right]}$$

Perfect Gas Law:

$$P(t) \cdot V = m(t) \cdot R \cdot T(t)$$

Hence,

$$T_3 = \frac{\left[\frac{T_A}{(P_A)^a}\left(\frac{m(t)\cdot R\cdot T(t)}{V}\right)^a \cdot \frac{2\cdot \dot{m}\cdot c_p - (k\cdot S)_{IC}}{[(k\cdot S)_{IC} + 2\cdot \dot{m}\cdot c_p]}\right]}{\left[1 - \frac{(k\cdot S)_{IC}\cdot 2}{[(k\cdot S)_{IC} + 2\cdot \dot{m}\cdot c_p]}\right]}$$

Substitution:

$$\dot{Q}_C + \dot{m}\cdot h_{IN} = \frac{dE}{dt}$$

$$-k\cdot S\cdot [T(t) - T_A] + \dot{m}\cdot c_p\cdot T_3(t) = \frac{d[m(t)\cdot c_v\cdot T(t)]}{dt}$$

$$-k\cdot S\cdot [T(t) - T_A] + \dot{m}\cdot c_p\cdot T_3(t) = \dot{m}\cdot c_v\cdot T(t) + m(t)\cdot c_v\cdot \dot{T}(t)$$

$$-k\cdot S\cdot [T(t) - T_A] + \dot{m}\cdot c_p\cdot \frac{\left[\frac{T_A}{(P_A)^a}\left(\frac{m(t)\cdot R\cdot T(t)}{V}\right)^a \cdot \frac{2\cdot \dot{m}\cdot c_p - (k\cdot S)_{IC}}{[(k\cdot S)_{IC} + 2\cdot \dot{m}\cdot c_p]}\right]}{\left[1 - \frac{(k\cdot S)_{IC}\cdot 2}{[(k\cdot S)_{IC} + 2\cdot \dot{m}\cdot c_p]}\right]} = \dot{m}\cdot c_v\cdot T(t) + m(t)\cdot c_v\cdot \dot{T}(t)$$

$$\frac{-k\cdot S\cdot [T(t) - T_A] + \dot{m}\cdot c_p\cdot \frac{\left[\frac{T_A}{(P_A)^a}\left(\frac{m(t)\cdot R\cdot T(t)}{V}\right)^a \cdot \frac{2\cdot \dot{m}\cdot c_p - (k\cdot S)_{IC}}{[(k\cdot S)_{IC} + 2\cdot \dot{m}\cdot c_p]}\right]}{\left[1 - \frac{(k\cdot S)_{IC}\cdot 2}{[(k\cdot S)_{IC} + 2\cdot \dot{m}\cdot c_p]}\right]} - \dot{m}\cdot c_v\cdot T(t)}{m(t)\cdot c_v} = \dot{T}(t)$$

Total Work done

$$\dot{W_{Total}} = \int_0^{t_f} (\dot{W}_1 + \dot{W_2})dt = \int_0^{t_f} [\dot{m}\cdot c_p\cdot (T_1 - T_A + T_3 - T_2)]dt$$

3.14 Calculation of the above constants

3.14.1 Calculation of Z factor

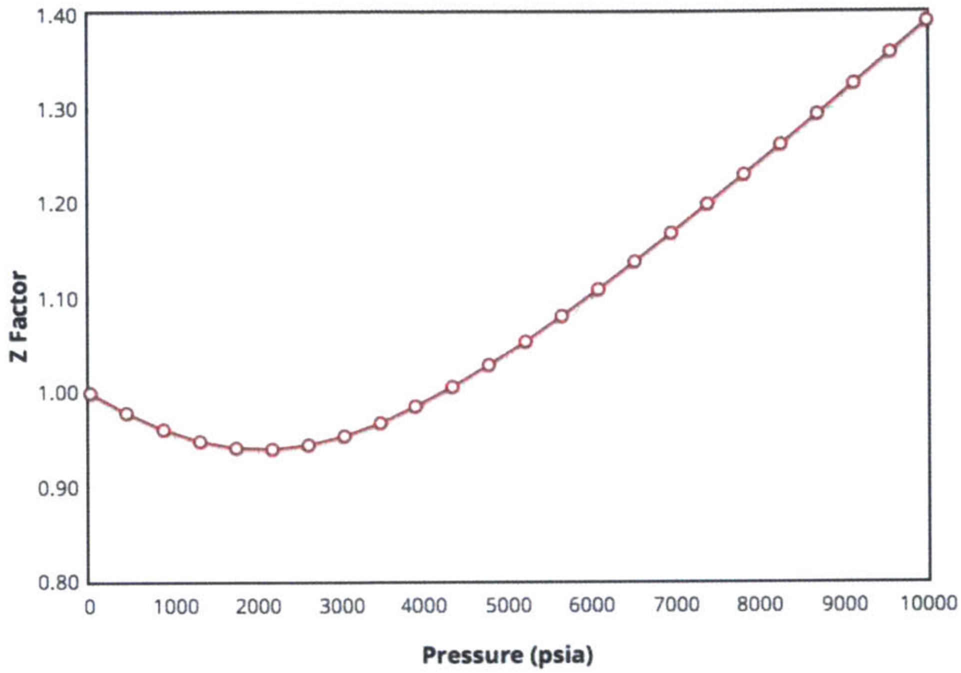


Figure 35: Z factor Diagram

Our initial pressure from the drilling well is 10 bar and the final pressure, which is the pressure that exits the cylinders, is 250 bar. The above graph is logarithmic and by using linear interpolation, the following equations were obtained for the average calculation of the compressibility factor.

$$P_{initial} = 10\ bars = 145\ psia$$

$$for,\ \ 15 \leq psia \leq 2815$$

$$Z_1 = a(logP_1)^2 + b(logP_1) + c$$

a= -0.0322

b= 0.0833

c= 0.9468

$$Z_1 = 0.9764$$

$$P_{final} = 250\ bars = 3625\ psia$$

$$for, \qquad 2815 \le psia \le 4015$$

$$Z_2 = a(logP_2)^2 + b(logP_2) + c$$

a= 0.9214

b= -6.6837

c= 12.9418

$$Z_2 = 0.8254$$

Hence, the average of Z_1 and Z_2 is taken

$$Z = \frac{Z_1 + Z_2}{2} = \frac{0.9764 + 0.8254}{2} = 0.9 \approx 1$$

3.14.2 Calculation of the Surface Area of the cylinders

R=0.6 m

r=0.58 m

h=6.1-1.2 = 4.9 m

t=0.02 m

$$Surface\ Area_1 = (2 \cdot \pi \cdot R^2) + (2 \cdot \pi \cdot R \cdot h)$$

$$Surface\ Area_2 = (2 \cdot \pi \cdot r^2) + (2 \cdot \pi \cdot r \cdot h)$$

$$Total\ Surface\ Area = Surface\ Area_1 - \ Surface\ Area_2$$

Now we should consider the the 2 semicircles of our cylinder

$$Surface\ Area\ of\ semicircles = \lfloor(\pi \cdot R^2) - (\pi * r^2)\rfloor \cdot 2$$

$$Surface\ Area\ of\ the\ four\ cylinders = (Total\ Surface\ Area + Surface\ Area\ of\ semicircles) \cdot 4$$

$$Surface\ Area\ of\ the\ four\ cylinders = 3.6\ m^2$$

3.14.3 Specific Heat Capacities and Gas Constant of Methane

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TABLE A–2

Ideal-gas specific heats of various common gases

(*a*) At 300 K

Gas	Formula	Gas constant, R kJ/kg · K	c_p kJ/kg · K	c_v kJ/kg · K	k
Air	—	0.2870	1.005	0.718	1.400
Argon	Ar	0.2081	0.5203	0.3122	1.667
Butane	C_4H_{10}	0.1433	1.7164	1.5734	1.091
Carbon dioxide	CO_2	0.1889	0.846	0.657	1.289
Carbon monoxide	CO	0.2968	1.040	0.744	1.400
Ethane	C_2H_6	0.2765	1.7662	1.4897	1.186
Ethylene	C_2H_4	0.2964	1.5482	1.2518	1.237
Helium	He	2.0769	5.1926	3.1156	1.667
Hydrogen	H_2	4.1240	14.307	10.183	1.405
Methane	CH_4	0.5182	2.2537	1.7354	1.299
Neon	Ne	0.4119	1.0299	0.6179	1.667
Nitrogen	N_2	0.2968	1.039	0.743	1.400
Octane	C_8H_{18}	0.0729	1.7113	1.6385	1.044
Oxygen	O_2	0.2598	0.918	0.658	1.395
Propane	C_3H_8	0.1885	1.6794	1.4909	1.126
Steam	H_2O	0.4615	1.8723	1.4108	1.327

Note: The unit kJ/kg · K is equivalent to kJ/kg · °C.

Source: Chemical and Process Thermodynamics 3/E by Kyle, B. G., © 2000. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.

Table 3: Ideal-gas specific heats of various gases

$$c_p = 2253.7\ \frac{J}{kg \cdot K} \qquad c_v = 1735.4\ \frac{J}{kg \cdot K} \qquad R = 518.2\ \frac{J}{kg \cdot K}$$

$$\gamma = \frac{c_p}{c_v} = \frac{2253.7}{1735.4} = 1.299$$

3.14.4 Mass flow rate

One TEU can carry 5 tons (5,000 kg) of compressed natural gas.

Hence,

The mass flow rate depends on time (hours needed to load the whole vessel).

To load one TEU in one day,

$$\dot{m} = \frac{5000}{86400} = 0.056\ kg/sec$$

To load one TEU in two days,

$$\dot{m} = \frac{5000}{172800} = 0.029\ kg/sec$$

To load one TEU in three days,

$$\dot{m} = \frac{5000}{259200} = 0.019\ kg/sec$$

3.15 Calculation of Work done using Matlab

3.15.1 Case 1: Load a TEU in one day

Stage 1: To increase the pressure from 10 bar to 50 bar

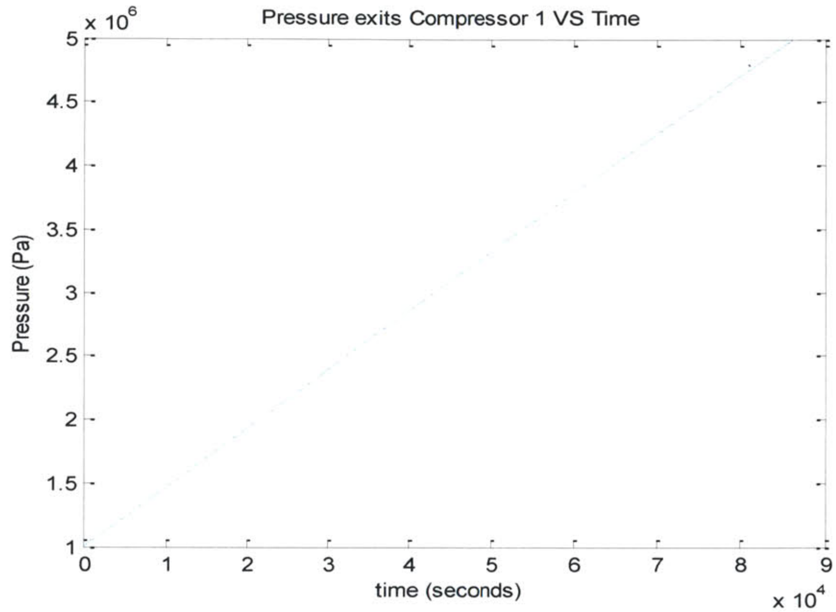


Figure 36: Pressure (10 bar-50 bar) over Time graph

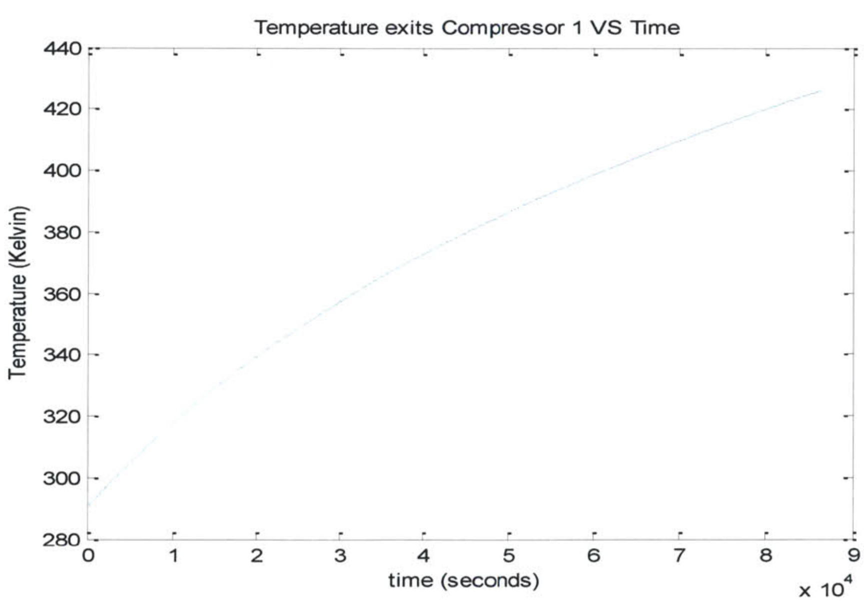


Figure 37: Temperature over Time graph

Stage 2: To increase the pressure from 50 bar to 250 bar

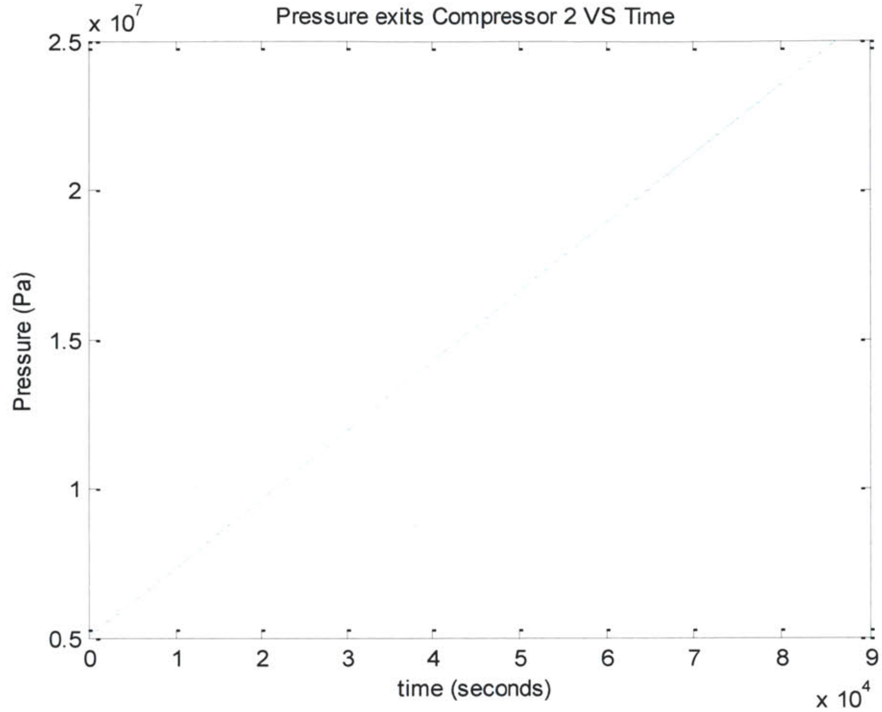


Figure 38: Pressure (50 bar-250 bar) over Time graph

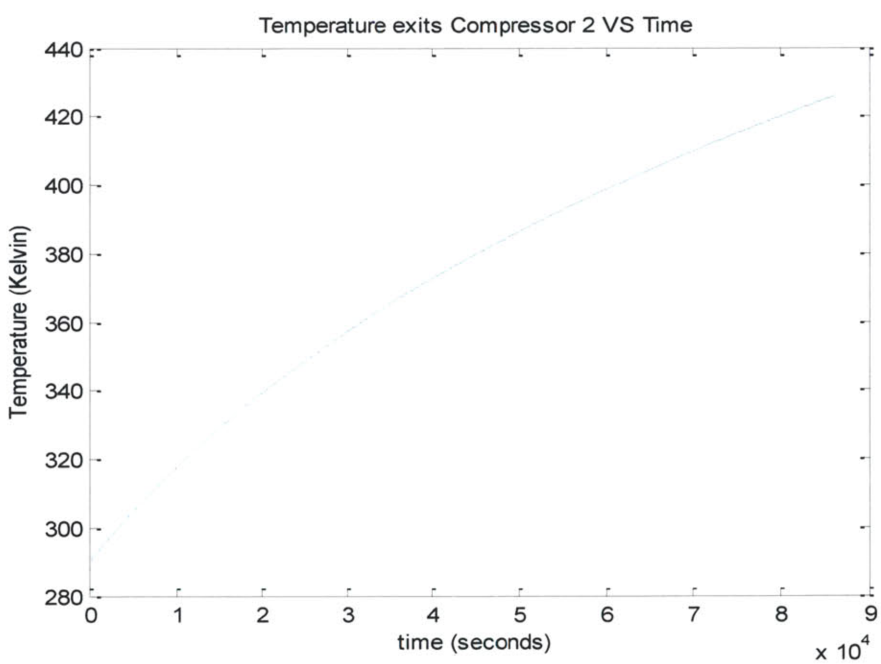


Figure 39: Temperature over Time graph

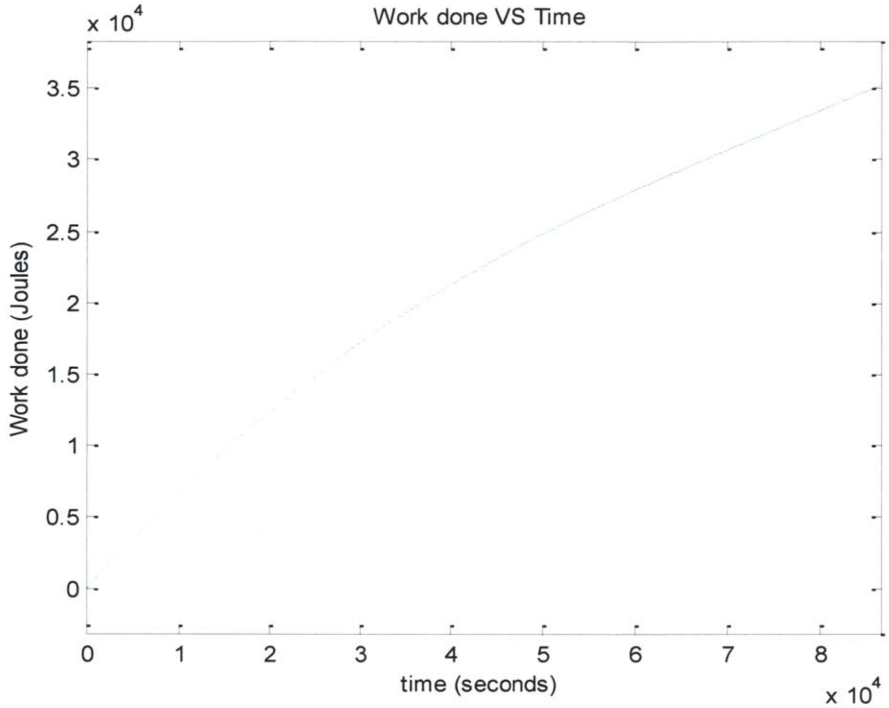


Figure 40: Work done to reach 250 bar in one day

$$Total\ Work\ required = 1.8039 \cdot 10^{9} Joules$$

Hence, a 20.8 kW rated compressor is needed to load one TEU in one day.

3.15.2 Case 2: Load a TEU in two days

Stage 1: To increase the pressure from 10 bar to 50 bar

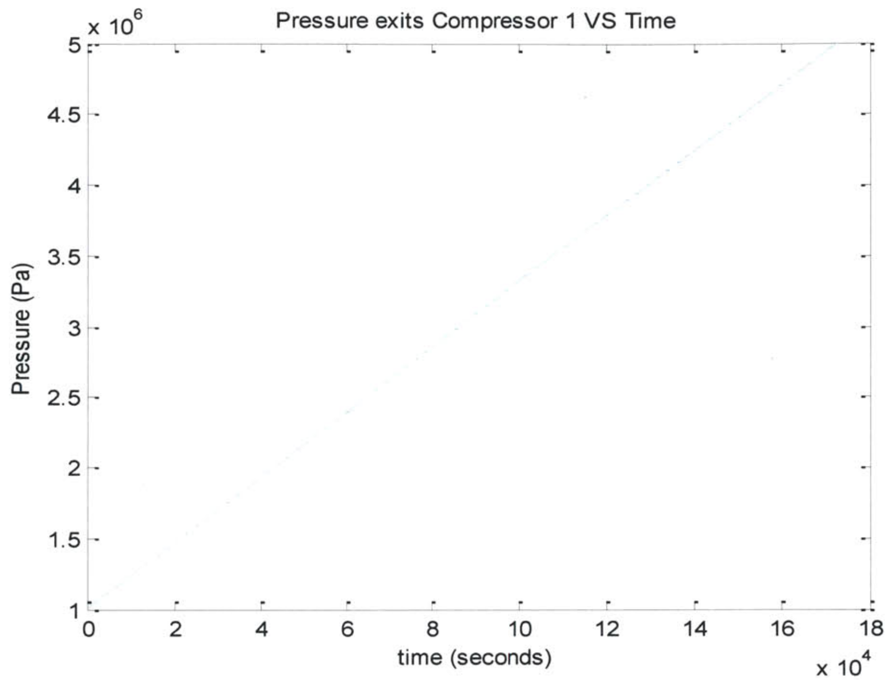


Figure 41: Pressure (10 bar-50 bar) over Time graph

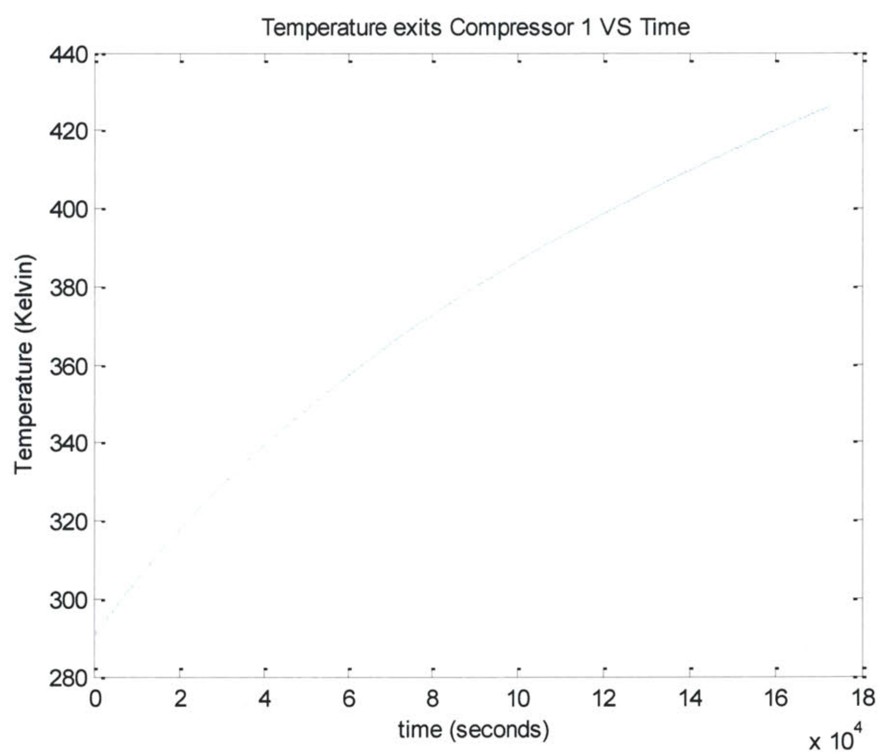


Figure 42: Temperature over Time graph

Stage 2: To increase the pressure from 50 bar to 250 bar

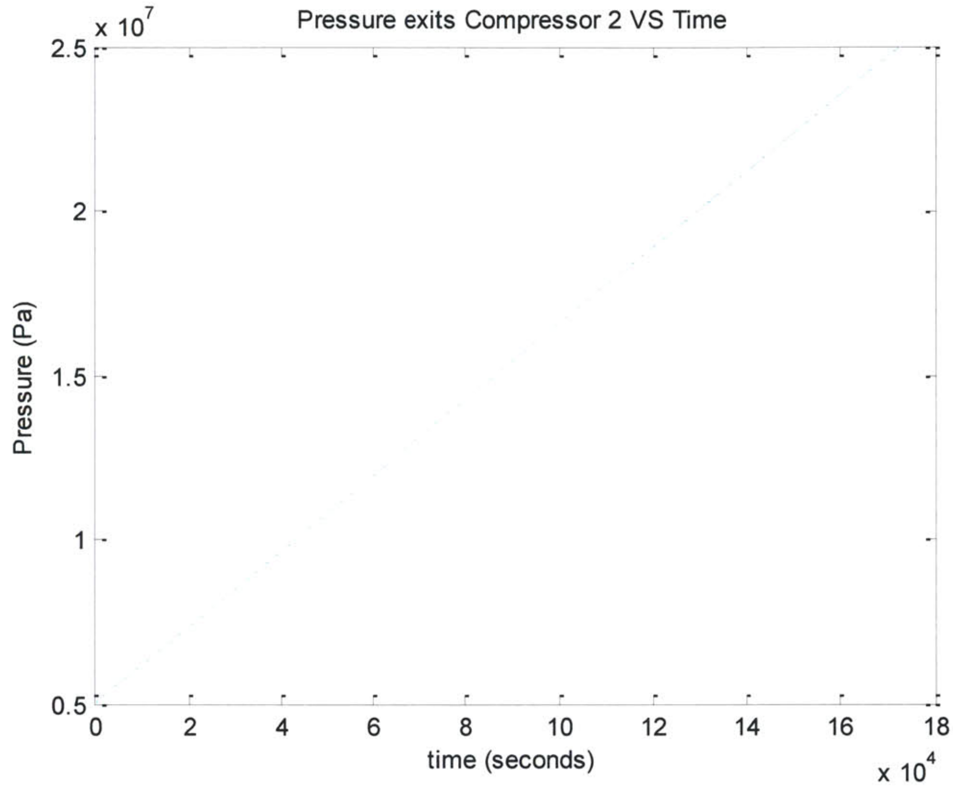


Figure 43: Pressure (50 bar-250 bar) over Time graph

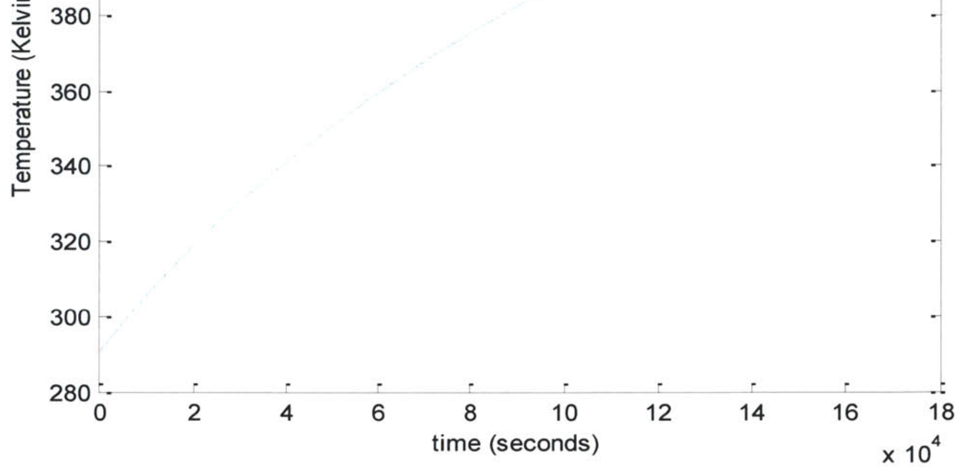


Figure 44: Temperature over Time graph

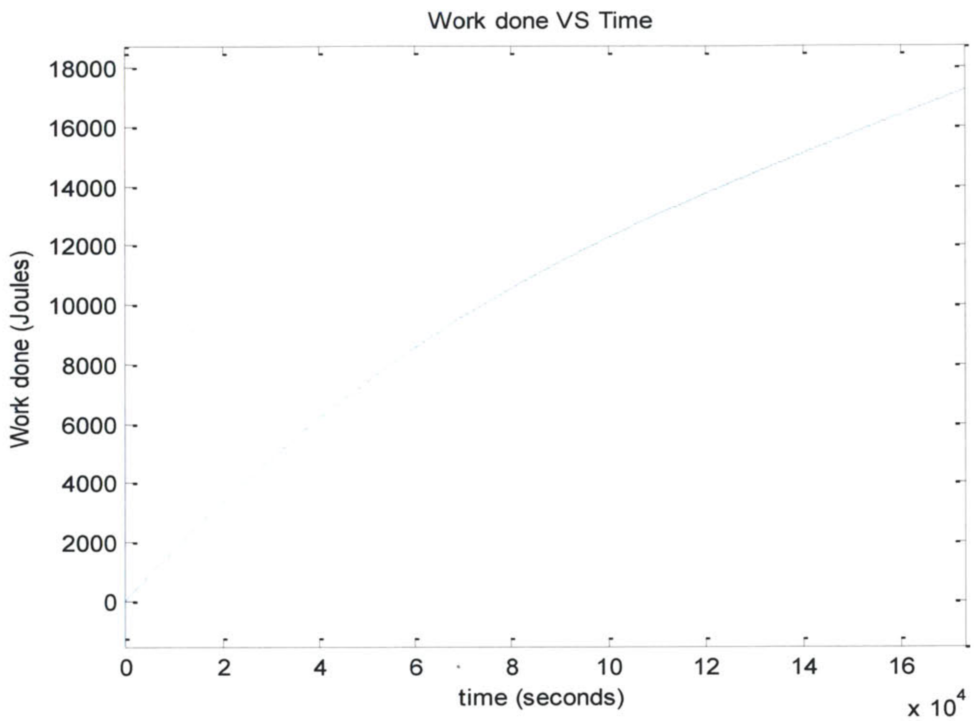


Figure 45: Work done to reach 250 bar in two days

$$Total\,Work\,required = 1.7814 \cdot 10^{9} Joules$$

Hence, a 10.31 kW rated compressor is needed to load one TEU in two days.

3.15.3 Case 3: Load a TEU in three days

Stage 1: To increase the pressure from 10 bar to 50 bar

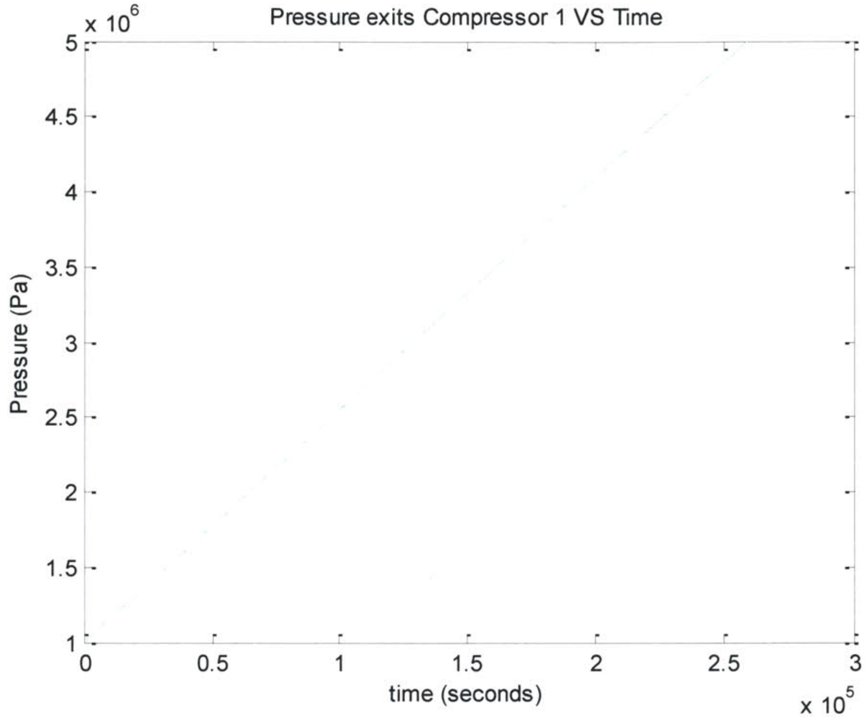


Figure 46: Pressure (10 bar-50 bar) over Time graph

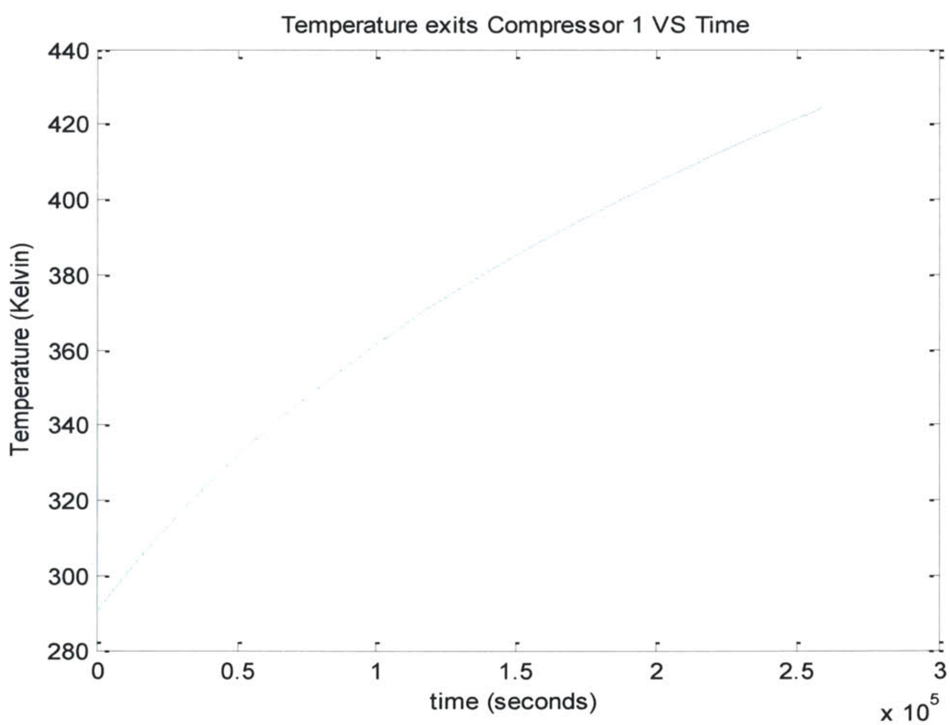


Figure 47: Temperature over Time graph

Stage 2: To increase the pressure from 50 bar to 250 bar

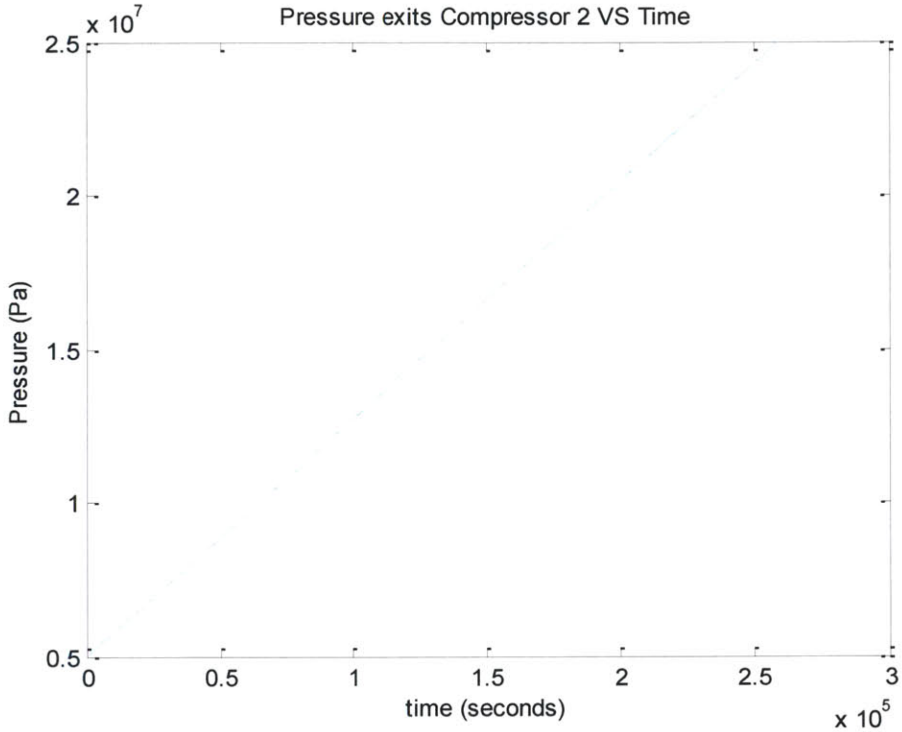


Figure 48: Pressure (50 bar-250 bar) over Time graph

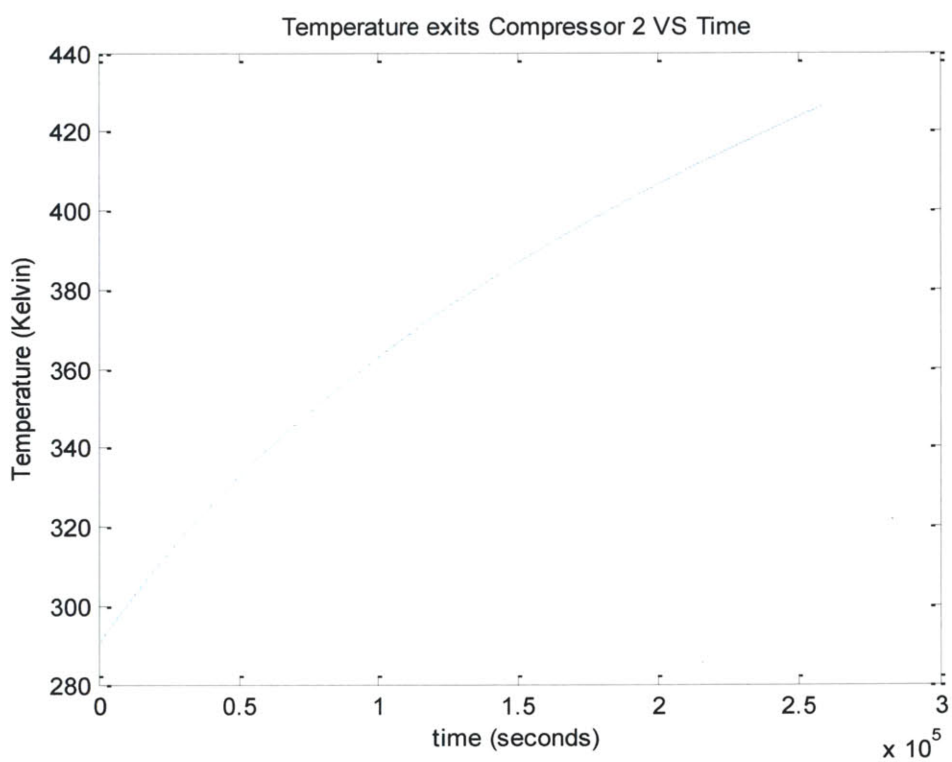


Figure 49: Temperature over Time graph

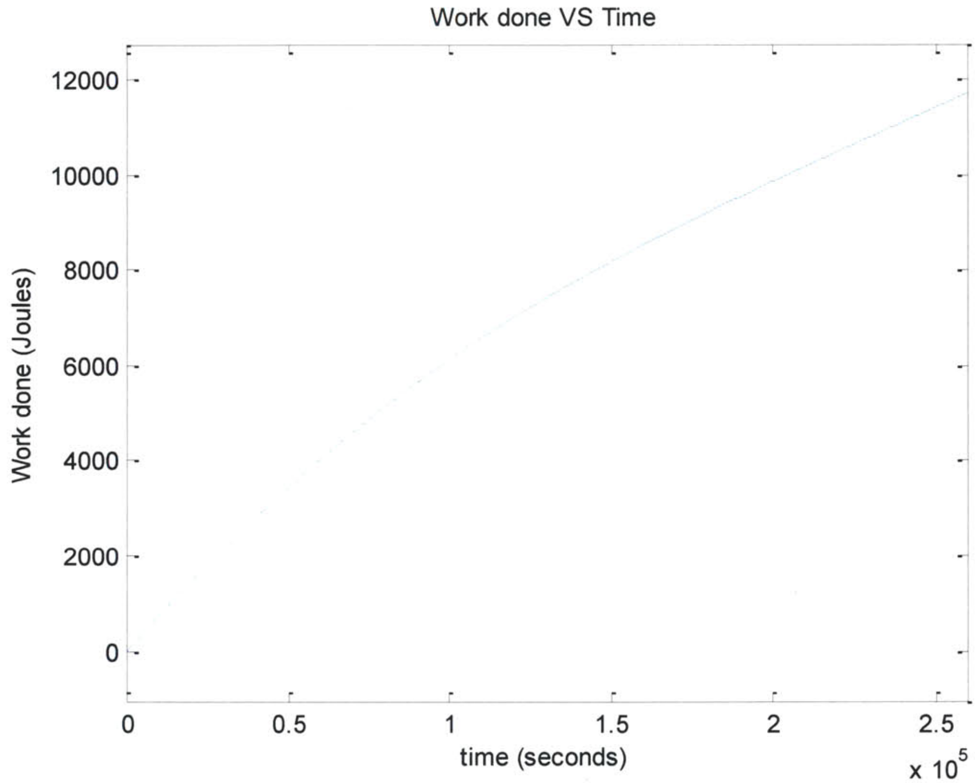


Figure 50: Work done to reach 250 bar in three days

$$Total\,Work\ required = 1.7857 \cdot 10^9 Joules$$

Hence, a 6.9 kW rated compressor is needed to load one TEU in two days.

3.16 Graphs of the above results

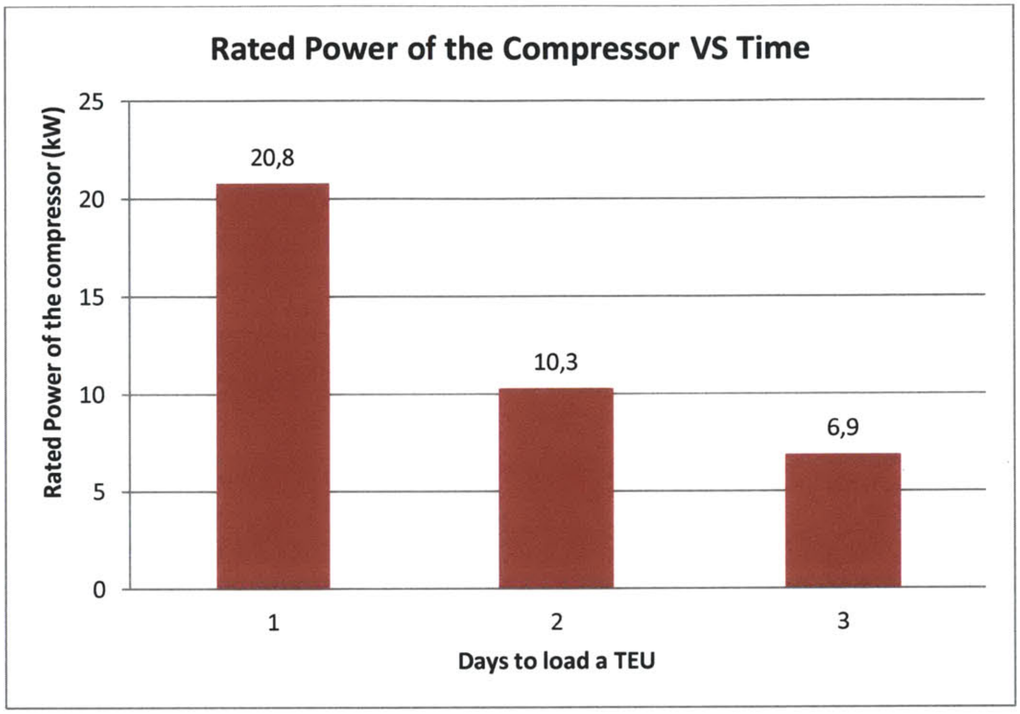


Figure 51: Rated Power of the Compressor over Time

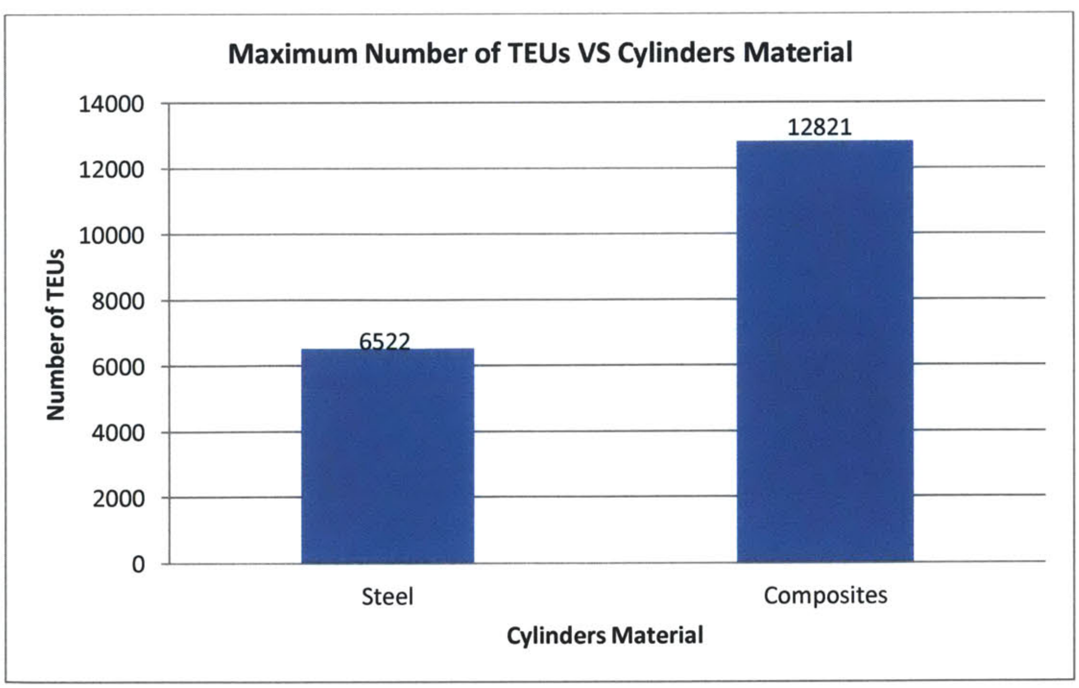


Figure 52: Maximum number of TEUs over Cylinders Material

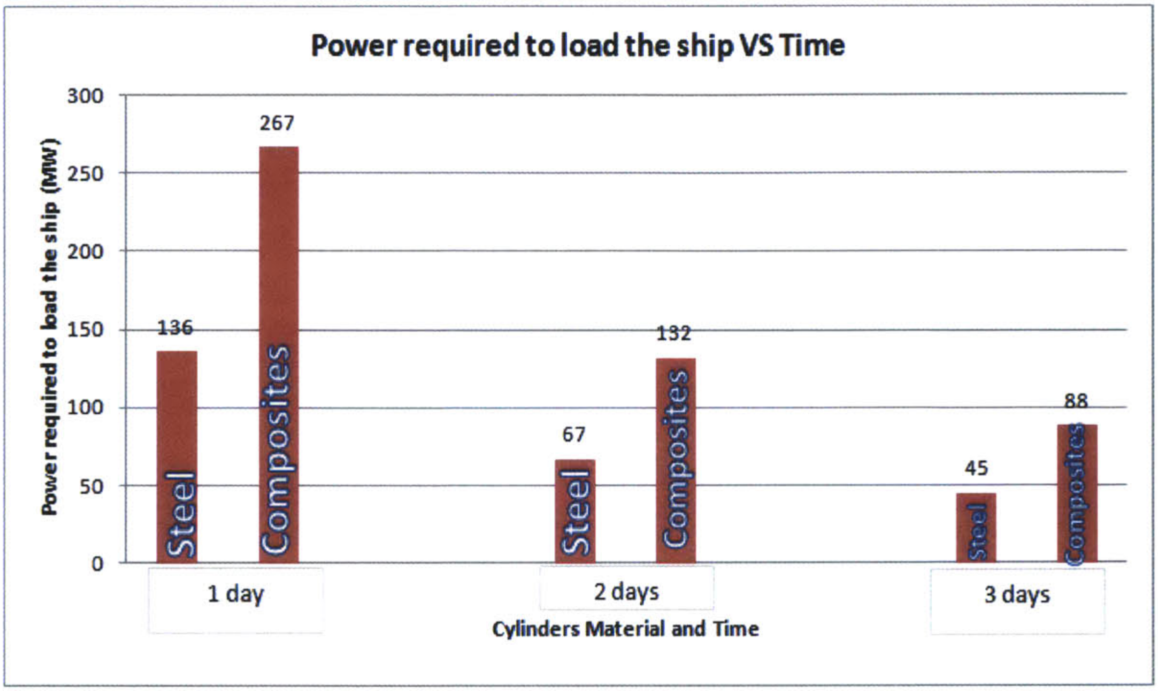


Figure 53: Total Power required for a compressor to load a ship over time

4. Economic Valuation

4.1 Ultra large Container Ship (ULCS)

The dimensions of containership have a propensity to be large as world trade increases and cargo movements and demand raise. The expansion of containership size started after 1990. In the last decade, containerships of more than 12,000 TEU operate into Asia-Europe and Asia-USA. DNV says that a construction of a 22,000 TEU containership will be held in the forthcoming years.

Ultra Large Containerships have the benefit of economies of scale where operating expenses decreases as vessel's size increases. It is proven that bigger vessels capital cost is 20% less and fuel expense 40% less. Of course, frequency of voyages and cargo demand play an important role for a profitable large ship. In addition, these types of ocean carrier are dependent on ports infrastructure.

Moreover, ULCS are green ships by the idea that fuel consumption per TEU carried is lower.

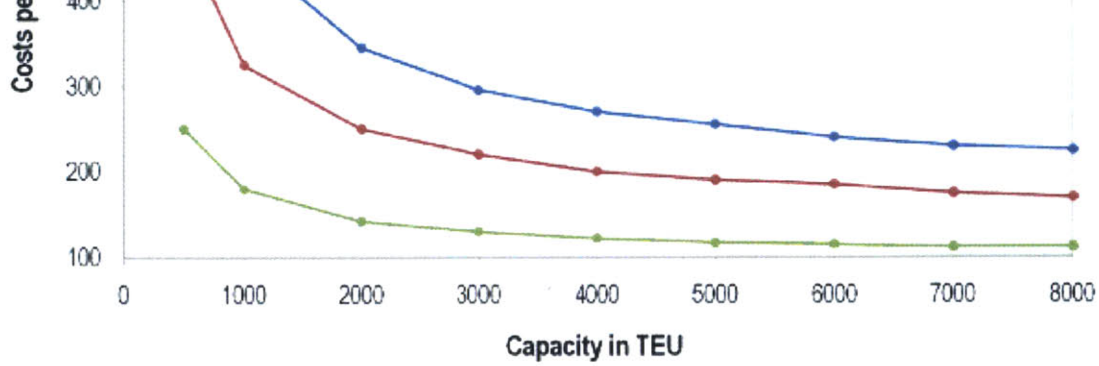


Figure 54: Cost per TEU over Capacity in TEU

4.1.1 Ultra Large Containership Details

Deadweight	150,936	tons
Length	368	meters
Beam	51	meters
Depth	30	meters

Newbuilding Price	$ 130.000.000
Cargo Overview	13,900

4.1.2 Number of CNG TEUs loaded in the ULCS

$$\text{Number of TEUs} = \frac{150{,}000}{11.7} = 12{,}821\ \text{TEUs}$$

4.1.3 Voyages and Fleet of the Shipping Company

A distance of 5000 nautical miles is taken which is the distance between USA (West Coast) to Japan. It is known that containerships have the ability to run up to 25 knots.

Hence,

$$Days\ to\ go\ from\ USA\ to\ Japan = \frac{5000}{25 \cdot 24} = 8\ days$$

The ship stays around 3 days at each port for loading and unloading of compressed natural gas.

Therefore, the whole trip takes around 22 days for the ship.

$$Annual\ Voyages\ per\ vessel = \frac{365}{22} = 17\ voyages$$

Furthermore, a fleet of seven Ultra Large Containerships is required, in order for the shipping company to have continuous operation.

4.2 Capital Costs for the Shipping Company

Capital costs are fixed expenditures on the purchase of land, buildings, ships and equipment. It accounts for about 40% of the total cost. When a vessel is built, its capital expenses are obligations, independent of the ship's operation cost. In our case, there are three initial capital costs: 1) the purchase of the ship, 2) the purchase of Composites cylinders and TEUs 3) the purchase of the centrifugal and reciprocating compressors.

Weight of Composites	4,7	tons per TEU
Total Weight of Composites for the fleet	421795	tons
Cost of Composites	$ 100.000	per TEU
Total Cost for the fleet	$ 8.974.358.974	

Compressor Rater Power	267	MW
Cost	$ 500.000	per MW
Cost to buy the Compressors	$ 133.500.000	
	$ 1.488	per TEU

Newbuilding Price	$ 100.000.000	per ULCS
Total Cost to buy the fleet	$ 700.000.000	
	$ 7.800	per TEU

Total Capital Costs	$ 9.807.858.974

4.2.1 Annual Costs

Annual Costs account for about 15% of the total costs and are divided into Operating expenses and Voyage costs. Operating costs for a maritime company are crew, insurance, maintenance, and administration. Voyage expenses are variable expenses such as fuel costs, port charges, tugs and canal charges, and account for 40% of the total costs of a shipping company.

4.2.2 Fuel Costs

According to shipyard's data, an Ultra Large Containership needs a low speed diesel engine of 68,000 kW in order to reach a speed of 25 knots.

It is known that the brake power is proportional to the speed to the power of three.

$$Power = Resistance \cdot Speed = C \cdot Speed^3$$

Where, C is a constant.

By using the above formula, useful charts and an average specific fuel consumption of 170 g/kWh are used to estimate the fuel costs for different speeds and the amount of emissions generated.

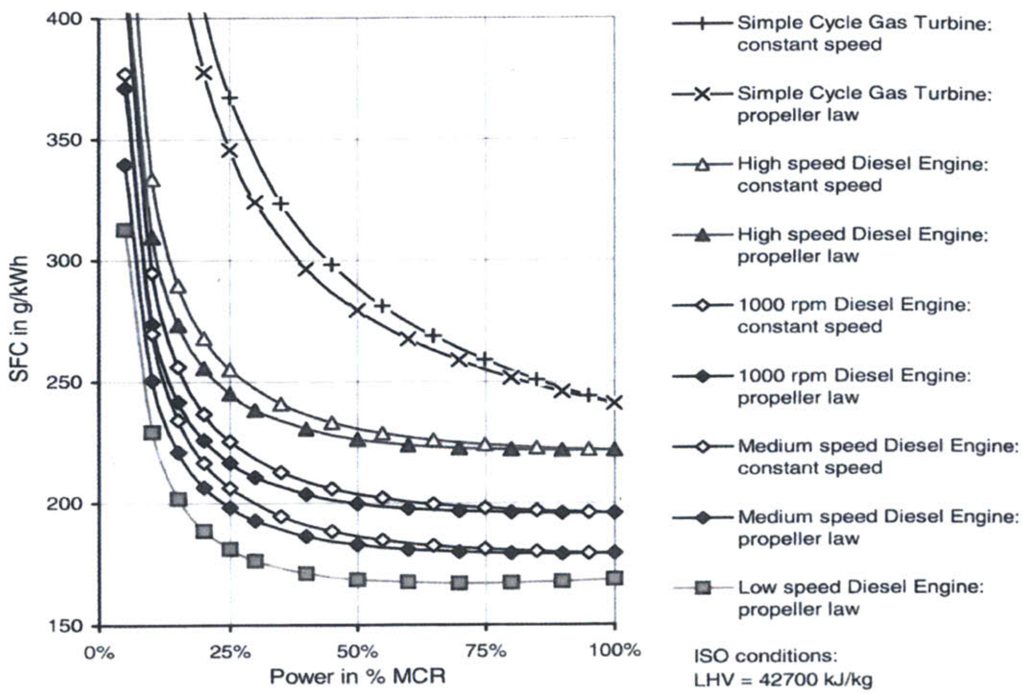


Figure 55: Specific fuel consumption over Power

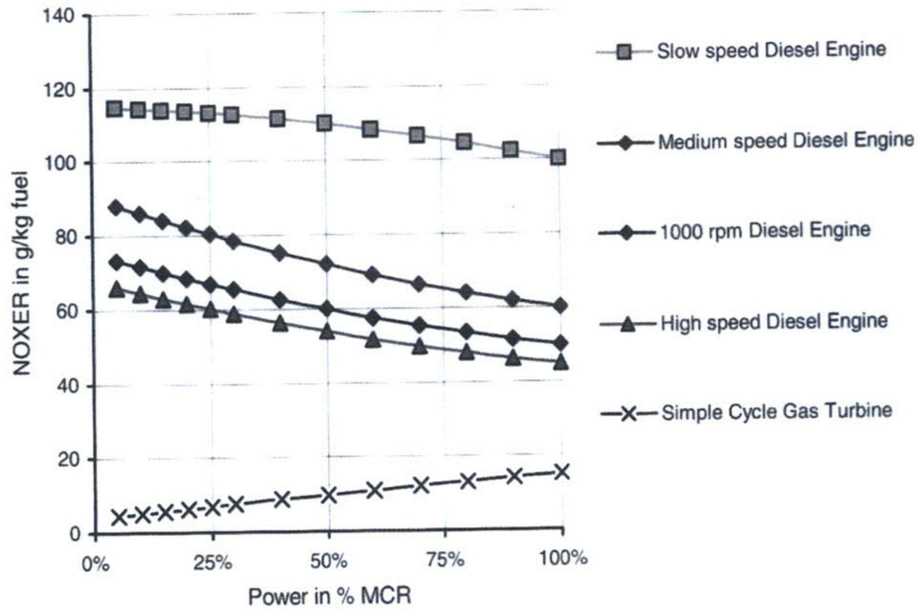


Figure 12.9 NO_x emission ratio for prime movers.

Figure 56: NOx emission ratio for prime movers

Speed (knots)	MCR	SFC (g/kWh)
25	100%	171
24	96%	171
23	92%	170
22	88%	170
21	84%	170
20	80%	170
19	76%	170
18	72%	170
17	68%	170
16	64%	170
15	60%	170
14	56%	170
13	52%	170
12	48%	170
11	44%	170
10	40%	170

Brake Power (kW)	mass fuel rate (kg/hour)	mass rate (tonnes/day)
68640	11737	282
60728	10385	249
53449	9086	218
46776	7952	191
40683	6916	166
35144	5974	143
30131	5122	123
25620	4355	105
21583	3669	88
17994	3059	73
14826	2520	60
12054	2049	49
9651	1641	39
7591	1290	31
5847	994	24
4393	747	18

Noxer (g/kg fuel)	kg of Nox per day
100	281,70
102	249,23
103	218,07
105	190,85
107	165,99
110	143,39
112	122,94
115	104,53
117	88,06
120	73,41
122	60,49
125	49,18
127	39,38
130	30,97
132	23,86
135	17,92

Route	Long Beach to Tokyo	Speed (knots)
Distance (nautical miles)	5000	25
		24
		23
		22
		21
		20
		19
		18
		17
		16
		15
		14
		13
		12
		11
		10

Days to go to Tokyo	Fuel Consumption (tonnes)	Price of HFO 380cSt
8	2347	710
9	2163	710
9	1975	710
9	1807	710
10	1647	710
10	1494	710
11	1348	710
12	1210	710
12	1079	710
13	956	710
14	840	710
15	732	710
16	631	710
17	538	710
19	452	710
21	373	710

Cost of Fuel ($)	Cost of Fuel per day ($)
1666716	200006
1536046	176952
1402459	154831
1283157	135501
1169158	117851
1060461	101804
957066	87284
858973	74215
766183	62521
678695	52124
596509	42949
519626	34919
448045	27958
381766	21990
320789	16938
265115	12726

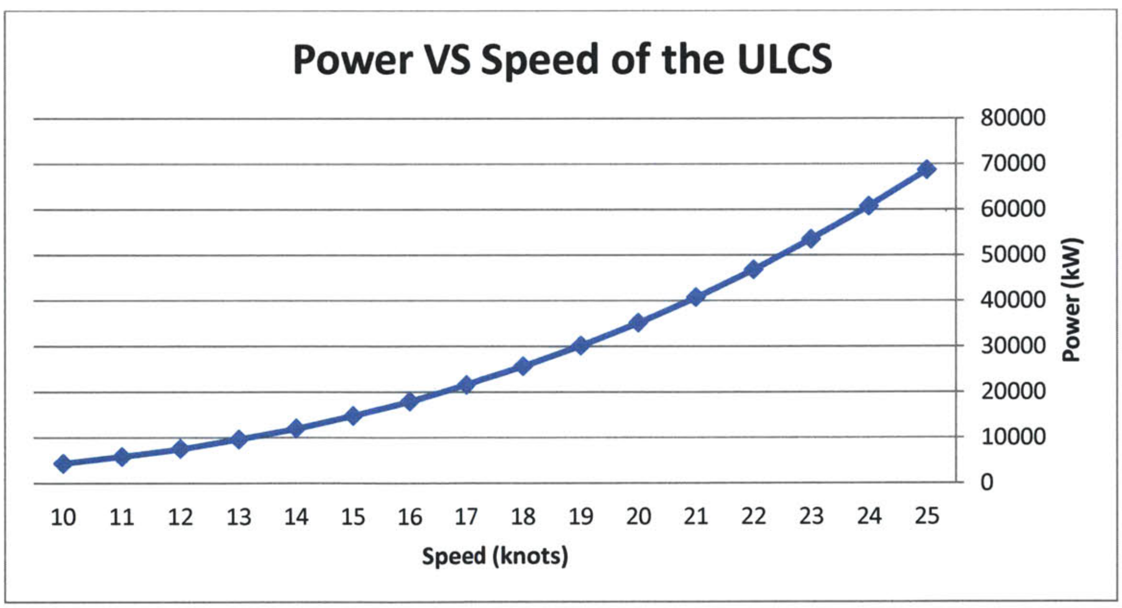


Figure 57: Power over Speed of the Ultra Large Containership

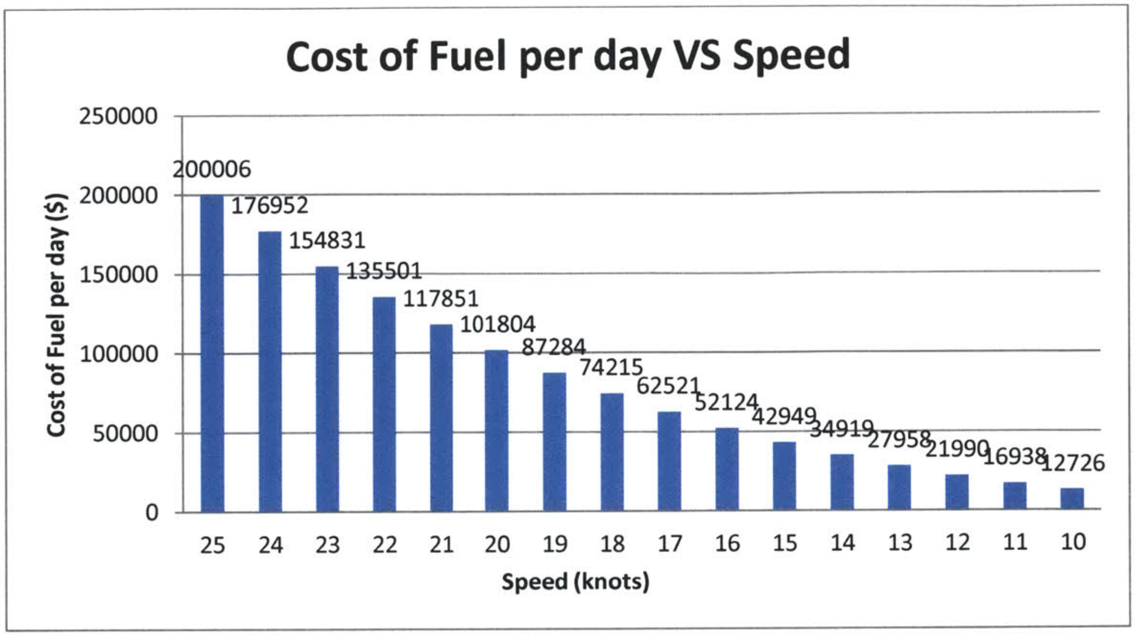


Figure 58: Cost of Heavy Fuel Oil per day over Speed of the ULCS

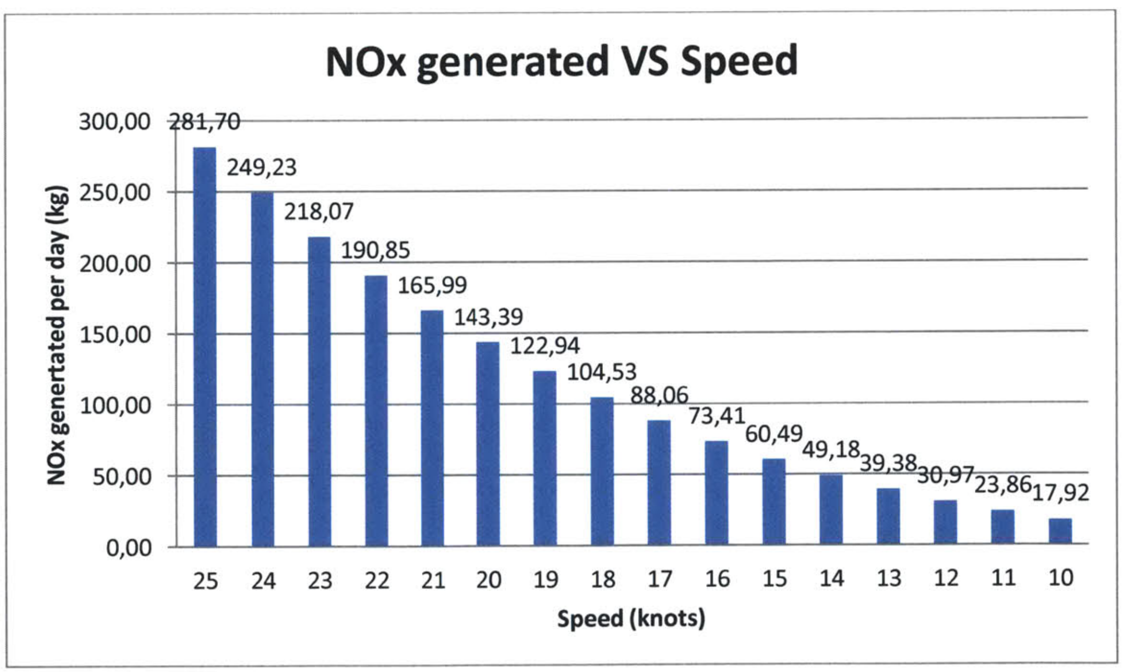


Figure 59: NOx generated over speed of The ULCS

The ULCS carries 12,821 TEUs of compressed natural gas.

$$NOx = \frac{281.70}{12{,}821} = 0.022\ kg\ of\ NOx\ per\ TEU$$

4.2.3 Electricity Costs

In the previous chapter, it is calculated that a 267 MW rated compressor is need to fill the entire speed in one day. The cost of electricity in USA is \$0.10 cents per kWh.

Hence,

$$Electricity\ Costs = 267 \cdot 1000 \cdot 0.10 \cdot 24 = \$640{,}800\ per\ voyage$$

4.2.4 Port Charges

Port charges correspond to a major part in voyage expenses for the use of facilities and services provided by the port. The actual port charges depend on the pricing policy of the port's administration, the ship's size, the time spent in port and the type of cargo loaded or unloaded. Of course, the shipping company has less control over these charges, since they vary from port to port.

4.2.5 The deployment of containers

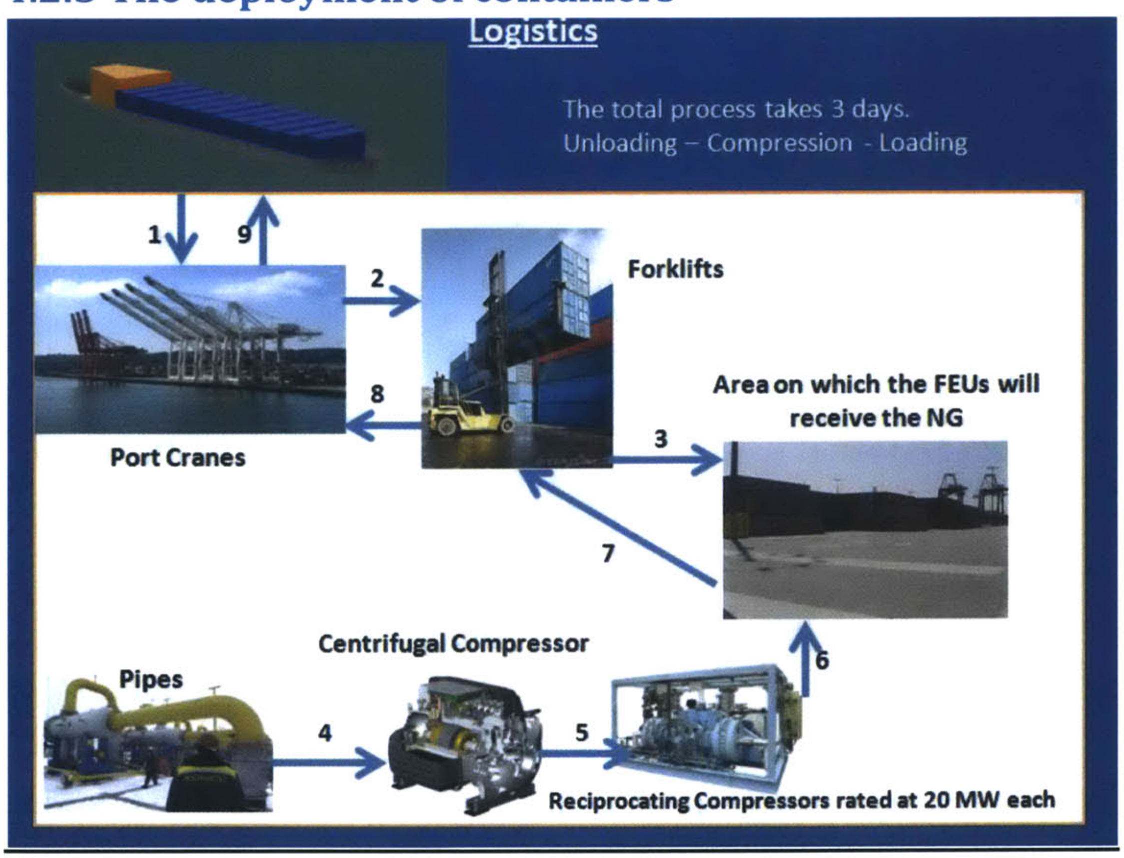


Figure 60: The deployment of the containers

Between voyages, the containers must be delivered to a place near the compressor's area where the compressed natural gas can be loaded or unloaded. Afterwards, they are collected and relocated for the next cargo. The handling costs of the container in the terminal include loading and unloading the ship, and the expenses of moving, stacking and storing the TEU within the port. The handling charges are limited to a single rate of $250 per lift.

4.2.6 Extra Costs

Additional Costs for a shipping company are the insurance, maintenance, repairs, tugs and canal dues. It is estimated that the average additional costs for each vessel is $500,000 per year.

4.2.7 Crew Costs and Administrative Expenses

Crew Expenses include all the direct and indirect charges incurred by the crewing of the ship such as basic salaries and wages, social insurance, pensions and repatriation expenses. Crew expenses depend on the size of the seafarers and the ship's flag state. Today, current levels of technology on modern vessels allow a basic crew of 17. Crew costs and administrative expensive are taken to be around $100,000 per month for each ship.

Fuel Consumption per vessel	$ 54.400.000	at 25 knots
	$ 4.243	per TEU
Electricity Costs per vessel	$ 10.893.600	
	$ 850	per TEU
Port charges per vessel	$ 2.210.000	
	$ 172	per TEU
Lift Costs per vessel	$ 217.948.718	
	$ 17.000	per TEU
Extra Costs per vessel	$ 500.000	
	$ 39	per TEU
Crew Costs per vessel	$ 1.200.000	
	$ 94	per TEU
Annual Cost per vessel	$ 287.152.318	
	$ 22.398	per TEU
	$ 2.010.066.226	per fleet

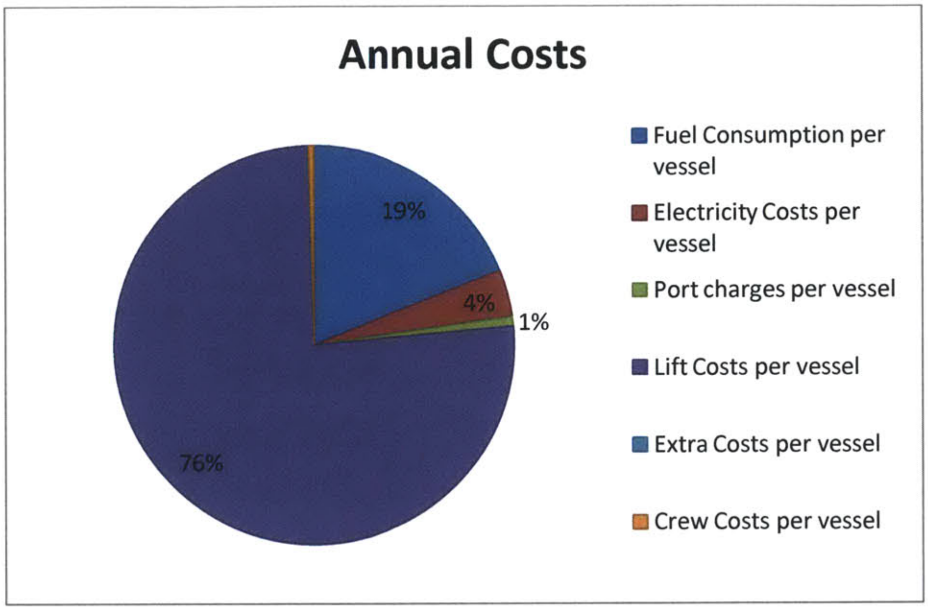


Figure 61: Annual Costs per vessel

4.3 Operating Income of the fleet

Operating income is the total pre-tax profit a shipping company generates from its operations. The operating profit of this particular shipping company depends on the arbitrage of the different prices of natural gas around the world.

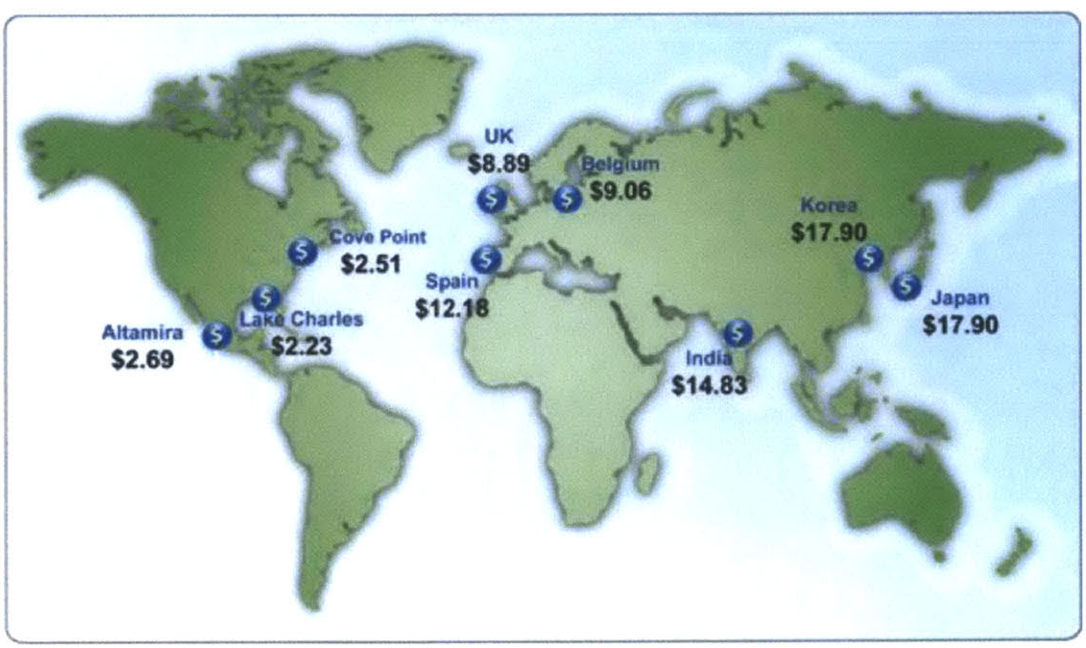


Figure 62: Natural gas prices around the world

Natural Gas carried	5000	kg per TEU
Energy	55	MJ/kg
Total Energy	275000	MJ
	275	GJ
Cost to buy NG	$ 4	per GJ
	$ 1.100	per TEU
Selling Price	$ 18	per GJ
	$ 4.950	per TEU
Total profit	$ 3.850	per voyage per TEU
	$ 65.450	annual profit per TEU
Total Annual Profit of the Fleet	$ 5.873.717.949	

4.4 Unleveraged Internal Rate of Return

IRR can be used to measure the profitability of a project. A project with high IRR can be considered profitable and attractive to potential investors.

$$\text{IRR} = \frac{\text{Annual Operating Profit} - \text{Annual Costs} - \text{Depreciation}}{\text{Capital Costs}}$$

$$\text{IRR} = 34.4\% \text{ for this project}$$

4.5 Return on Invested Capital (ROIC)

Return on Invested Capital (ROIC) is used to observe how well companies generate earnings from capital invested in their business. It is essentially the return a company earns on each dollar it invests in a business. ROIC is defined as Net Operating Profits Less Adjusted Taxes (NOPLAT) divided by the Invested Capital.

When a company's return on invested capital is greater than its' capital cost, then it creates value by investing in its projects, otherwise it destroys value.

$$ROIC = \frac{\text{Net Operating Profits Less Adjusted Taxes}}{\text{Invested Capital}}$$

$$ROIC = 24.1\% \quad \text{for this project}$$

Tax rate is taken to be 30%.

4.6 Return on Equity (ROE)

ROE is the amount of net income returned as a percentage of equity. Return on equity determines a company's profitability by depicting how much profit a company creates with the money investors have invested.

The levered cost of equity ROE is given by the formula:

$$ROE = ROIC + \left([ROIC - (1-t) \cdot k_d] \cdot \frac{D}{E}\right)$$

where:

k_d = Cost of debt

D = Market value of debt

E = Market value of equity

C = D+E = 100%

t = tax rate

It is assumed that k_d is 5% and the tax rate is equal to 30%. Concerning D/E, this ratio is 1 when D = E for a leverage of 50% and it is 4 when D=4E for a leverage of 80%.

Cost of debt	5%
Market value of debt	60%
Market value of equity	40%
C	100%
ROE	54,94%

4.7 WACC (Weighted Average Cost of Capital)

WACC is an estimation of a company's cost of capital in which each category of capital is proportionately weighted. WACC increases as the beta and rate of return on equity rises. An increase in WACC shows a reduction in valuation and a higher risk.

Therefore, a shipping company's assets such as ships are financed by either debt or equity. WACC is the average of the costs of these assets of financing, each of which is weighted by its individual use. By calculating the WACC, it can be observed how much interest the maritime company has to pay for every dollar it invests.

It is assumed that the cost of equity is 20% and a growth rate of 5%.

A Company's value is equal to the addition of the market value of debt and the market value of equity.

$V = D + E$

By multiplying it with a complex fraction of 1,

$$V = (D + E) \cdot \left(\frac{CF_d \cdot (1 - t) + CF_e}{CF_d \cdot (1 - t) + CF_e} \right)$$

$CF_d = Cash\ flow\ to\ debt\ holders$

$CF_e = Cash\ flow\ to\ equity\ holders$

The cash flow to debt holders is stable; the perpetuity formula is used to measure the debt:

$$D = \frac{CF_d}{k_d}$$

$k_d = cost\ of\ debt$

$$CF_d = D \cdot k_d$$

The same is for

$$CF_e = E \cdot k_e$$

By substitution,

$$V = (D + E) \cdot \left(\frac{CF_d \cdot (1 - t) + CF_e}{D \cdot k_d \cdot (1 - t) + E \cdot k_e} \right)$$

Therefore by dividing the denominator by (D+E),

$$V = \left(\frac{CF_d \cdot (1 - t) + CF_e}{\frac{D}{(D + E)} \cdot k_d \cdot (1 - t) + \frac{E}{(D + E)} \cdot k_e} \right)$$

The expression in the denominator is the WACC.

Hence,

$$V = \left(\frac{CF_d \cdot (1 - t) + CF_e}{WACC} \right)$$

and

$$WACC = \left[\frac{D}{D + E} \cdot k_d \cdot (1 - t) \right] + \left[\frac{E}{D + E} \cdot k_e \right]$$

Cost of equity	20%
Growth Rate	5%
WACC	10,10%

4.8 Value/Capital for the shipping company

Since the shipping company increases its cash flows at a constant rate, the famous perpetuity formula can be used to value the firm.

$$Value = \frac{Free\ Cash\ Flow}{WACC - g}$$

Where, g is the growth rate.

$$Free\ Cash\ Flow = Net\ Operating\ Profit - Taxes - Capital\ Invested$$

$$Net\ Operating\ Profit - Adjusted\ Taxes = NOPLAT$$

But,

$$Investement\ Rate = \frac{Capital\ Invested}{NOPLAT}$$

Hence,

$$Free\ Cash\ Flow = NOPLAT - (NOPLAT \cdot IR)$$

$$Free\ Cash\ Flow = NOPLAT \cdot (1 - IR)$$

$$growth\ rate = ROIC \cdot IR$$

$$IR = \frac{g}{ROIC}$$

Now build this into the free cash flow equation:

$$Free\ Cash\ Flow = NOPLAT \cdot (1 - IR)$$

$$Free\ Cash\ Flow = NOPLAT \cdot (1 - \frac{g}{ROIC})$$

Substituting,

$$Value = \frac{Free\ Cash\ Flow}{WACC - g}$$

$$Value = \frac{NOPLAT \cdot (1 - \frac{g}{ROIC})}{WACC - g}$$

It is known that:

$$ROIC = \frac{NOPLAT}{Capital\ Invested}$$

$$NOPLAT = ROIC \cdot Capital\ Invested$$

Hence,

$$Value = \frac{NOPLAT \cdot (1 - \frac{g}{ROIC})}{WACC - g}$$

$$Value = \frac{ROIC \cdot Capital\ Invested \cdot (1 - \frac{g}{ROIC})}{WACC - g}$$

$$\frac{Value}{Capital\ Invested} = \frac{ROIC \cdot (1 - \frac{g}{ROIC})}{WACC - g}$$

V/C	3,74

4.9 Sensitivity Analysis for buying the ships

Market Value of Debt	Market Value of Equity	IRR	ROIC	ROE	WACC	Value/Capital
50%	50%	34%	24,10%	44,65%	11,75%	2,83
60%	40%	34%	24,10%	54,94%	10,10%	3,74
70%	30%	34%	24,10%	72,08%	8,45%	5,53
80%	20%	34%	24,10%	106,38%	6,80%	10,6
90%	10%	34%	24,10%	209,25%	5,15%	127,17

4.10 Economic Evaluation for leasing the vessels

Annual Expenses for the fleet of seven ULCS:

Fuel Consumption per vessel	$ 54.400.000	at 25 knots
	$ 4.243	per TEU
Electricity Costs per vessel	$ 5.467.200	
	$ 426	per TEU
Port charges per vessel	$ 1.530.000	
	$ 119	per TEU
Lift Costs per vessel	$ 217.948.718	
	$ 17.000	per TEU
Extra Costs per vessel	$ 500.000	
	$ 39	per TEU
Crew Costs per vessel	$ 1.200.000	
	$ 94	per TEU
Lease Rate	$ 70.000.000	
	$ 780	per TEU
Annual Cost per vessel	$ 351.045.918	
	$ 22.702	per TEU
	$ 2.457.321.426	per fleet

4.10.1 Sensitivity Analysis for leasing the ships

Market Value of Debt	Market Value of Equity	IRR	ROIC	ROE	WACC	Value/Capital
50%	50%	41%	28,90%	54,36%	11,75%	3,55
60%	40%	41%	28,90%	67,08%	10,10%	4,69
70%	30%	41%	28,90%	88,27%	8,45%	6,94
80%	20%	41%	28,90%	130,65%	6,80%	13,29
90%	10%	41%	28,90%	257,81%	5,15%	158,54

4.11 Comparison of the above two options

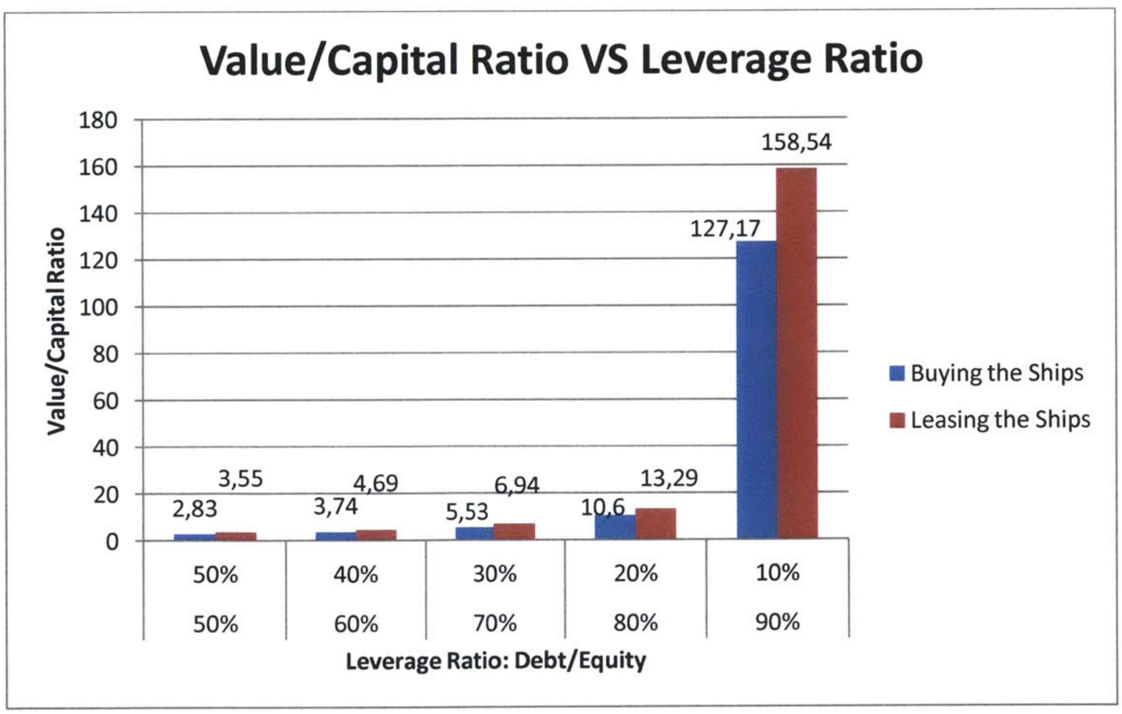


Figure 63: Value/Capital Ratio over Leverage ratio

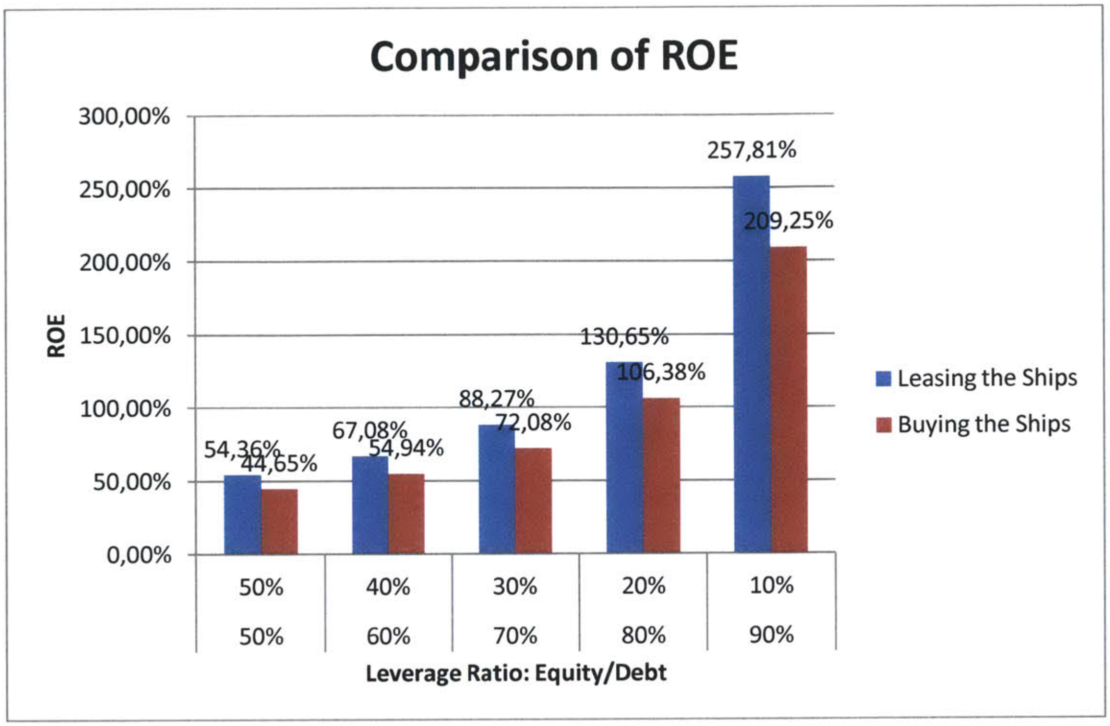


Figure 64: Return on Equity of the two options

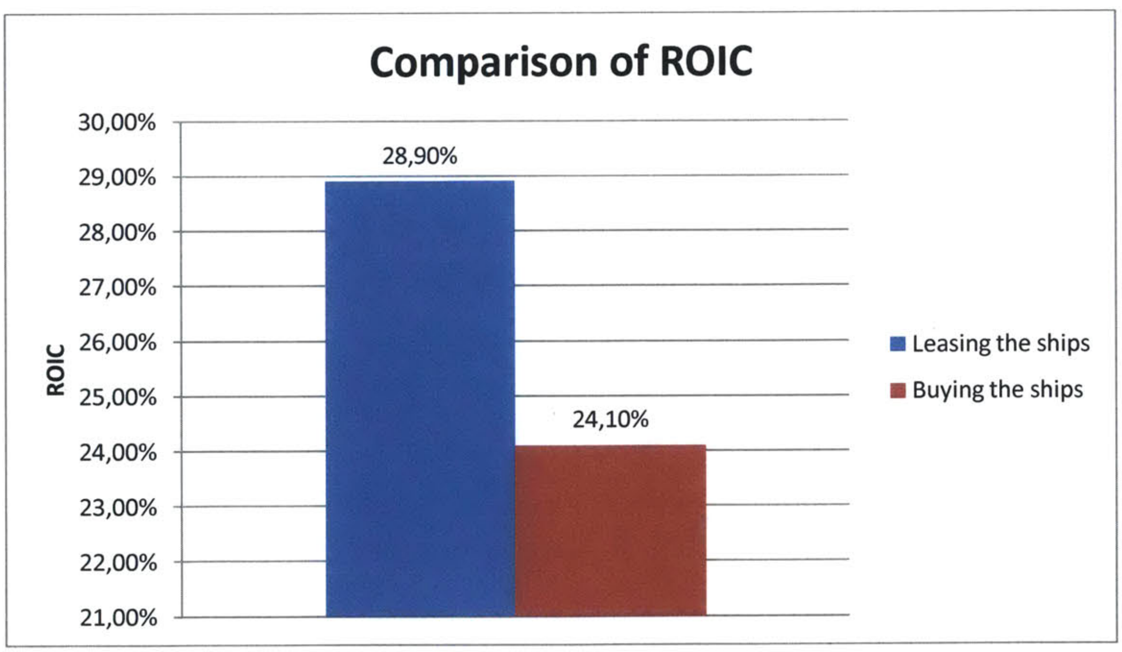


Figure 65: Return on Invested Capital of the two options

5. Comparison of LNG Carriers and ULCS carrying CNG containers

5.1 Energy savings

In order to calculate the energy savings of our project it is assumed that our cylinders are filled by liquefied natural gas.

Volume of TEU = 29 cubic meters

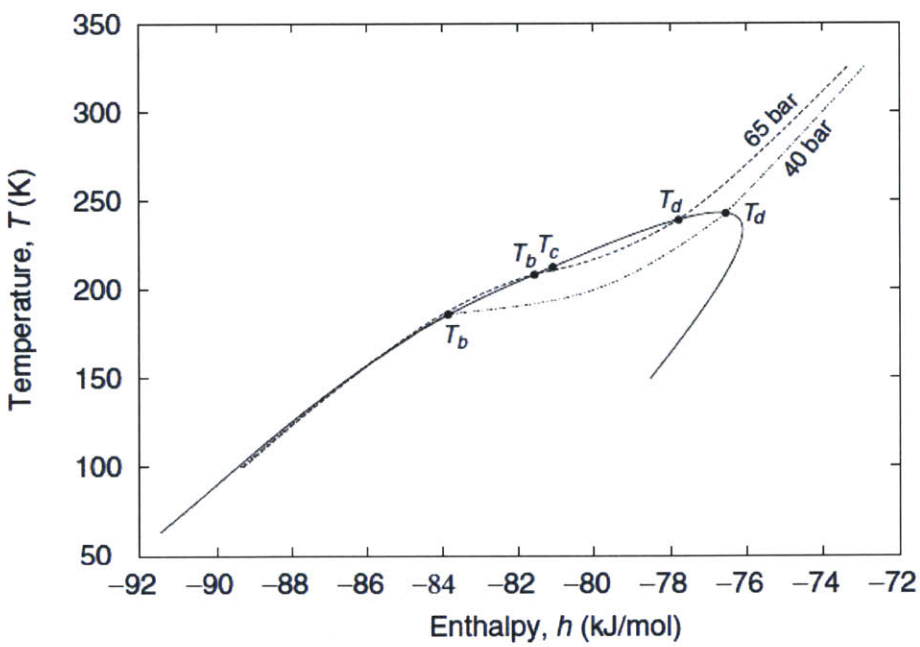
Density of LNG = 450 kg/cubic meters

Mass inside cylinders = 13050 kg = 13 tons

Energy Carried by the TEU = 13050 * 55.6 = 725,580 MJ

The liquefaction of natural gas can be achieved by three stages:

$$35^oC \rightarrow -40^oC \quad -40^oC \rightarrow -85^oC \quad -85^oC \rightarrow -160^oC$$



$$Work\ done = mass \cdot \Delta h$$

$$W_{stage\ 1} = 13000kg \cdot 62.5mol \cdot \left(-76\ {}^{kJ}\!/_{mol} - 0\right) = -61{,}750{,}000\ kJ$$

$$= -61{,}750\ MJ$$

$$W_{stage\ 2} = 13000kg \cdot 62.5mol \cdot \left(-84\ {}^{kJ}\!/_{mol} - \ (-76\ {}^{kJ}\!/_{mol})\right) = -6{,}500{,}000\ kJ$$

$$= -6{,}500\ MJ$$

$$W_{stage\ 2} = 13000kg \cdot 62.5mol \cdot \left(-89\ {}^{kJ}\!/_{mol} - \ (-84\ {}^{kJ}\!/_{mol})\right) = -4{,}062{,}500\ kJ$$

$$= -4{,}063\ MJ$$

$$W_{Total} = W_{stage\ 1} + W_{stage\ 2} + W_{stage\ 3}$$

$$W_{Total} = 72{,}313\ MJ$$

$$Percentage\ of\ the\ TEU\ Energy = \frac{72{,}313}{725{,}580} \approx 10\%$$

For our TEU (CNG), 20.5 kW rated compressor is needed (492 kWh for 24 hours).

For a TEU (LNG), 500kWh/ton * 13ton = 6500 kWh

$$\frac{492}{6500} = 7.6\%$$

Total electricity savings of 7.6%.

5.2 Comparison of the revenue of LNG ship and the ULCS of this project

	LNG Vessel	ULCS Vessel (12821 TEUs of CNG)
Density (kg/m^3)	450	0,7
Volume (m^3)	140000	192000
Deadweight (tonnes)	63000	64105
kilograms	63000000	64105000
Specific Energy (MJ/kg)	53,6	53,6
Energy of the cargo (MJ)	3376800000	3525775000
Energy of the cargo (GJ)	3376800	3525775
Energy of the cargo (MMbtu)	3201206	3342434,7

Number of Voyages (yearly)	10	17
Total Revenue from Japan	$441.766.483	$784.135.181

5.3 Summary of advantages

Hence, the advantages of using the ULCS carrying CNG containers are:

- Simple design of cylinders and pressure management
- Mature technology
- Less energy consumption
- Gas/vapor instead of cryogenic
- Lower maintenance expenses
- Higher revenue due to the high speed of containerships
- Higher deadweight
- The life cycle fuel cost is lower
- No need of re-gasification and liquefaction

6. Conclusions

The purpose of the current thesis was to study the viability and feasibility of installing four carbon fiber cylinders inside a TEU container. It can be seen that the results are reliable and an Ultra Large Container Ship can carry these specially constructed containers.

In addition, thermodynamic analysis was used to determinate the total power required for a compressor to fill 12,821 TEUs, in one day. It is concluded that a 267 MW compressor is needed for this purpose. MATLAB was used to calculate the total work done and three parameters (Pressure, Temperature and Word done) were tested over a period of time.

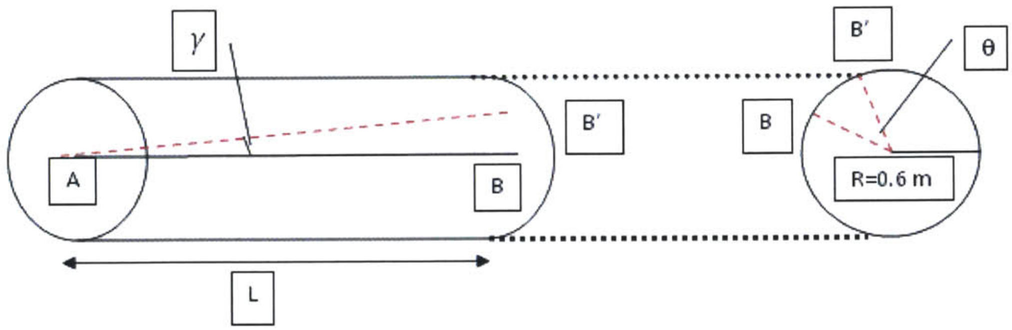
Moreover, it is observed that financial parameters such as Return on Invested Capital and Return on Equity are very attractive for a potential investor. The conclusion is that leasing the ships, is a more profitable option than buying the vessels.

Finally, it was shown that this project is more profitable than conventional CNG projects and LNG Ships. The Ultra Large Container Ship can carry more natural gas than the LNG ship can. The Container ship is more profitable to use due to its high speed.

By the dramatic expansion of container ships, it can be seen that natural gas will probably be transported by containers for the next several decades.

7. Appendices

Appendix A - Torsion of our Cylinders



$$BB' = R \cdot \theta$$

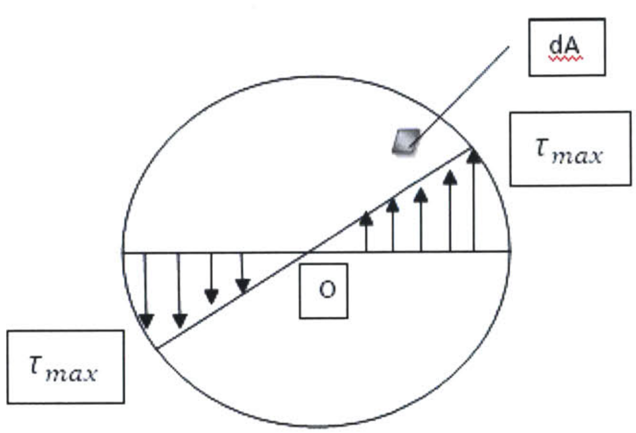
$$BB' = L \cdot \gamma$$

$$R \cdot \theta = L \cdot \gamma$$

$$\gamma = \frac{R \cdot \theta}{L}$$

<u>Hooke's Law for Torsion:</u>

$$\tau_{max} = G \cdot \gamma = G \cdot \frac{R \cdot \theta}{L}$$



$$F_{dA} = \tau_{torsion} \cdot dA$$

This force creates an internal Moment M_{dA} in the dA section of a distance r from the center of the beam.

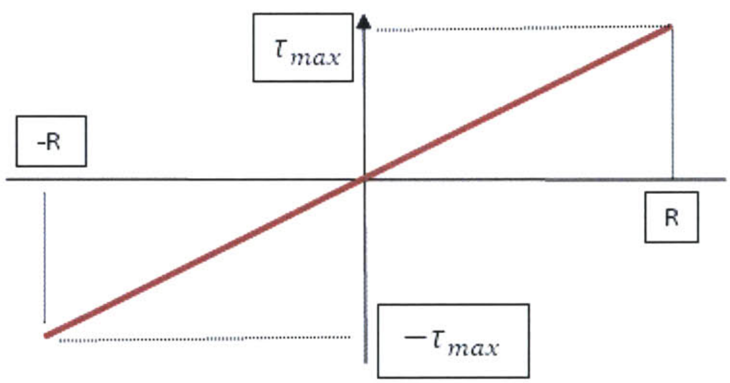
$$M_{dA} = F_{dA} \cdot r$$

$$M_{dA} = \tau_{torsion} \cdot r \cdot dA$$

Since the cross-sectional area is in equilibrium, the sum of the moments M_{dA} of all small sections of our area is equal to torsional moment.

$$M = \int_A \tau_{torsion} \cdot r \cdot dA$$

$\tau_{torsion}$ is not stable and is proportional to the distance from the origin of the cross-sectional area. $\tau_{torsion}$ is decreasing as it reaches the center of the section.



$$tan\theta = \frac{\tau_{max}}{R}$$

And

$$tan\theta = \frac{\tau_{torsion}}{r}$$

Hence,

$$\frac{\tau_{max}}{R} = \frac{\tau_{torsion}}{r}$$

$$\tau_{torsion} = \frac{\tau_{max}}{R} \cdot r$$

Therefore, the above formula of the sum of moments can be written as:

$$M = \int_A \tau_{torsion} \cdot r \cdot dA = \int_A \frac{\tau_{max}}{R} \cdot r^2 \cdot dA = \frac{\tau_{max}}{R} \cdot \int_A r^2 \cdot dA$$

It is observed that:

$$\int_A r^2 \cdot dA = Polar\ Moment\ of\ Inertia = I_o$$

Moreover,

$$\tau_{max} = \frac{R}{I_o} \cdot M$$

In addition, the above formula can be expressed as:

$$\tau_{max} = \frac{1}{W_o} \cdot M \quad because\ W_o = \frac{I_o}{R}$$

Wo is the polar moment of resistance.

For a cylinder the polar moment of resistance and the polar moment of inertia cab be calculated by the following equations:

$$I_o = \frac{\pi}{32} \cdot D^4$$

$$W_o = \frac{\pi}{16} \cdot D^3$$

Hence,

$$\tau_{max} = \frac{R}{I_o} \cdot M = \frac{32 \cdot R}{\pi \cdot D^4} \cdot M$$

In order our truss to remain stable in case of a torsional moment, the tensile breaking strength of the material that will be used for the elements should be given in order to calculate the allowable torsional stress.

$$\tau_{allowable} = 0.8 \cdot \sigma_{breaking\ strength}$$

<u>Calculation of the Maximum Torsional moment of the cylinders:</u>

$$\tau_{allowable} \geq \tau_{max}$$

$$\tau_{allowable} \geq \frac{32 \cdot R}{\pi \cdot D^4} \cdot M$$

$$\frac{\tau_{allowable} \cdot \pi \cdot D^4}{32 \cdot R} \geq M$$

$$\tau_{allowable} \cdot 0.34 \geq M$$

<u>Angular deformation:</u>

$$\tau_{max} = G \cdot \gamma$$

$$\gamma = \frac{\tau_{max}}{G}$$

The allowable angular deformation is:

$$\gamma_{allowable} = \frac{\tau_{allowable}}{G}$$

Hence,

$$\gamma_{allowable} \geq \gamma$$

$$\gamma_{allowable} \geq \frac{R}{I_o \cdot G} \cdot M$$

$$\gamma_{allowable} \geq \frac{32 \cdot R}{\pi \cdot D^4 \cdot G} \cdot M$$

<u>The rotation of the beam can be calculated by:</u>

$$\theta_x = \frac{\gamma}{R} \cdot L$$

Therefore,

$$\theta_{x,allowable} \geq \frac{M}{I_o \cdot G} \cdot L$$

$$\theta_{x,allowable} \geq \frac{32 \cdot M}{\pi \cdot D^4 \cdot G} \cdot L$$

Appendix B - Buckling

Slenderness of a beam:

$$\lambda = \frac{l_a}{Radius\ of\ Gyration}$$

$l_a = a \cdot length$

α is a coefficient

$Radius\ of\ Gyration = \sqrt{\frac{I}{A}}$

I=Moment of inertia

$$\lambda = \alpha \cdot l \cdot \sqrt{\frac{A}{I}}$$

Euler's Formula for Buckling:

$$F_{cr} = \frac{\pi^2 \cdot E \cdot I}{{l_a}^2} = \frac{\pi^2 \cdot E \cdot I}{a^2 \cdot l^2}$$

Critical buckling stress:

$$\sigma_{cr} = \frac{F_{cr}}{A} = \frac{\pi^2 \cdot E \cdot I}{A \cdot {l_a}^2}$$

$Radius\ of\ Gyration = \sqrt{\frac{I}{A}} \qquad \leftrightarrow \quad R^2 = \frac{I}{A}$

$$\sigma_{cr} = \frac{\pi^2 \cdot E \cdot R^2}{{l_a}^2}$$

$\lambda = \frac{l_a}{Radius\ of\ Gyration}$

$$\sigma_{cr} = \frac{\pi^2 \cdot E}{\lambda^2}$$

Limit Slenderness:

$$\sigma_{cr} \leq \sigma_{limit}$$

$$\frac{\pi^2 \cdot E}{\lambda^2} \leq \sigma_{limit}$$

$$\frac{\pi^2 \cdot E}{\sigma_{limit}} \leq \lambda^2$$

$$\sqrt{\frac{\pi^2 \cdot E}{\sigma_{limit}}} \leq \lambda_{limit}$$

The limit slenderness for steel has a range of 88-100.

In addition,

$$safety\ factor = \frac{\sigma_{cr}}{\sigma_{allowable\ for\ buckling}}$$

The safety factor for steel is around 5.

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